Natural Resources Sustainability: An introductory synthesis

NATURAL RESOURCES SUSTAINABILITY: AN INTRODUCTORY SYNTHESIS

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PREFACE

This text on Natural Resources Sustainability: An Introductory Synthesis has evolved from my 30 years of experience in teaching undergraduate and graduate students at Southern Illinois University (SIU) and at Utah State University USU), both state institutions that resemble many of the mid-size to large state universities in the United States. In particular, it has grown from my 20 semesters in teaching Geography 300I: Geography, People, and the Environment, at SIU and Environment and Society 2340: Natural Resources and Society at USU, courses that attracted about 100 undergraduates, mostly sophomores and juniors, as part of those universities' core or general education curricula. The text is designed for freshmen through junior-level courses in geography, environmental studies, and natural resource management at junior, community, and four-year colleges and universities in the United States.

Natural resource sustainability is not a one-size-fits-all subject; each country and locality has a unique physical geography, history and culture, and economic structure from which must evolve a more sustainable natural resource use pattern. For this reason, I have unabashedly focused on the United States' situation with examples and colloquialisms, and

I have even resorted to using English units of measure whenever possible (while introducing metric measures in parentheses).

Over the years, I have found that there is a lack of understanding that pervades on opposite sides of the natural/ social science chasm that is discouraging to those who view sustainability as an essential goal. Economists, lawyers, political scientists, journalists, and others educated on the human side of the chasm sometimes mistake scientists for an interest group and the environment itself as a second-tier issue that humans may or may not choose to value. Natural scientists are more likely to view the environment as an all-enveloping and ancient life-support system as well as a source of essential resources. Natural scientists, however, sometimes fail to understand human perception, the political process, or the “socioeconomic driving forces” that dominate the human use and management of natural resources and, on a human-dominated planet, the environment itself.

My own education and extensive research experience, with over 50 peer-reviewed papers and millions in research grants, is in geography and water resources management, and you will find this perspective clearly evident. I have found, however, that if geography as a discipline provides a guide to the study of natural resources issues, it is only because geography is particularly open to integrating concepts derived from other disciplines. But what disciplines?

Among the sciences, some basic chemistry and a sense of technology is essential. A little geology certainly also aids the understanding of natural resources such as fossil fuels. Among the social sciences, a sense of modern history is invaluable as well as a basic understanding from political science of the roles of the private and public sectors and what "policy" really means. I have found, however, that a fundamental understanding of natural resource sustainability is founded even more firmly in the natural science fields of ecology and environmental science on the one hand and the social science of economics on the other. My most difficult decision in organizing this text was in how to treat economics for students who haven't taken a course in that subject. To many, economics (or, to say something quite different, the economy) is the problem, so why dwell on that? Yet this is exactly why we must dwell on it if we are to understand how the economy governs natural resource use and how it can govern it more sustainably.

You will find that this text does not view the sustainability problem through any one theoretical or disciplinary perspective, though the emergent field of ecological economics does have a special status, even if this is usually implicit. Geography, with its emphasis on what is actually out there on the ground (or in the water or the air) in specific places, especially American places that the students using this text may be familiar with, serves as an integrative package to keep us empirically honest. Geography also emphasizes the powerful technologies of Geographic Information Systems (GIS) and remote sensing that show us in great detail, with enormous datasets, what really is out there and how things interrelate. This is the interdisciplinary scheme used in this text as “an introductory synthesis.” It thus differs considerably from introductory texts on environmental studies or environmental science, such as Miller’s Living in the Environment, through its focus on the economic and political decision-making that guide the provision of human needs for food, water, energy, and ecosystem services. It also differs considerably, however, from introductory texts on natural resource and environmental economics, such as Tietenberg and Lewis’s Environmental & Natural Resource Economics, by delving deeply into what the environment is actually composed of and how this determines the nature and geography of natural resources.

What I hope to provide—in a one semester or one quarter undergraduate course that requires no prerequisites—is a fundamental background that provides students with the essentials they need to deal intelligently with natural resource and environmental issues as an informed citizen. Few students take a bit of ecology, economics, geography, and so forth and then proceed onto study natural resources sustainability. So the task here is—through the analysis of essential issues in natural resources sustainability—to provide a brief introduction to these disciplines that students can build on later if they choose to take one of these disciplines as their major or minor. In the meantime, they will have obtained a valuable lesson in how to draw from ideas and concepts from disparate disciplines to gain an understanding of essential real-world issues.

The journey of teaching thousands of undergraduates at typical state universities has taught me some pedagogical lessons that I hope can benefit other students who come to college motivated to learn and with an educational background that features a mix of As, Bs, Cs and perhaps even letters further down the alphabet. One of these lessons is that only a small minority of students have the motivation, skills, and preparation to learn challenging subjects such as natural resources sustainability simply by reading the text or other course readings on their own. This is true partly because most texts are written to appeal to the well-informed and prepared instructors who choose them rather than the students who struggle to learn from them. In my experience, students in the fat part of the bell curve often face three barriers to learning that make most scientific textbooks difficult to learn from:

1. technical terminology and units of measure that are not explained in everyday terms,
2. unnecessarily complex mathematics and the lack of a sense of context when it is used,
3. use of inferior visual aids that are poorly explained.

Each of these barriers can be overcome, not by "dumbing down," although some cutting-edge, avant-garde topics that faculty cherish (I go for complexity theory) really don't belong in an introductory undergraduate course. Rather, the challenge is to "write up," to use the English language and visual aids to speak to students directly and guide them through the learning process, even hold their hands a little. This puts the onus on the instructor and the course material to reach out to students—from the best students in the class to the ones struggling to pass the course—and thereby increasing the overall level of reading comprehension and student understanding of key concepts and retention of critical knowledge.

A second lesson is that some of the best reading material for developing conceptual understanding and motivation to learn among undergraduates is not found in the strictly "academic" literature of textbooks and peer-reviewed journal articles but in the world of high quality (if possible Pulitzer-Prize-winning) nonfiction literature. For example, in my course students select one non-fiction book, with my current list (which changes frequently as I find the time to read additional books) consisting of:

- *Guns, Germs, and Steel: The Fate of Human Societies* (Pulitzer Prize, 1999) by Jared Diamond
- *Collapse: How Societies Choose to Fail or Succeed* (2005) also by Jared Diamond
- *The Omnivore's Dilemma: A Natural History of Four Meals* (2006) by Michael Pollen

- *Water: The Epic Struggle for Wealth, Power, and Civilization* (2010) by Steven Solomon
- *1491: New Revelations from the Americas before Columbus* (2011) by Charles Mann
- *The Grid: The Fraying Wires Between Americans and Our Energy Future* (2018) by Gretchen Bakke.
- *The New Map: Energy, Climate and the Clash of Nations* (2020) by Daniel Yergin

In this text, I draw extensively from these and other excellent books and I recommend that they be used in some fashion to complement it. Through these books, students can begin their wrestling match with core issues of sustainability in a world that has long been characterized by inequality, power struggles, and poor decision-making but that has nevertheless succeeded in achieving an overall trajectory of human progress.

A third lesson is that undergraduate students can learn a great deal through visuals—photographs, graphs, maps, images, diagrams—but, like a beholder of paintings, only if their eyes are properly trained. Only a minority of undergraduate students correctly translate from legend to map or from axis to graphed data without direct help from the instructor or from the reading material itself. From Edward Tufte's excellent books, such as Envisioning Information, we learn that visual presentations of ideas or data can either mislead or inform and, if properly designed, are often the key to understanding. For this reason, this text includes over 100 pedagogically useful visuals both for the text itself and, simply by using snapshot in Adobe Acrobat, as PowerPoint slides for use in class.

This book was developed using many sources as listed in the recommended readings list at the end of chapters. I have refrained, however, from littering the text with citations, as most undergraduate readers find this a distraction, except when a particular publication is being discussed directly.

The text also includes a set of four computer games oriented around carbon, nitrogen, water, and energy with accompanying classroom exercises.

I would like to invite every instructor who uses this text to let me know what they like or dislike about it. Just e-mail me at chris.lant@usu.edu.

I would like to thank the Utah State University Libraries' Open Educational Resources program. I also thank a number of students who have helped with the visuals, including Amy Kovak and Samuel Adu-Prah at SIU as well as Ashley Peterson at USU.

PART I

PART I: INTRODUCTION

1.

CHAPTER 1: NATURAL RESOURCES SUSTAINABILITY IN A NUTSHELL

Sustainability has become a vague and politically manipulated word that can lack a precise or objective meaning. In one sense this is inevitable for any advanced concept. We know that "democracy" is "good," but we'd be hard-pressed to define it, no less to apply it correctly in every situation. We also know, however, that excessive vagueness can be exploited. Is the Democratic People's Republic of Korea a legitimate use of that term for the political system of North Korea? Our first order of business is, then, to explore what sustainability does and doesn't mean. Otherwise, someone can call "sustainable" a program to build a coal-fired power plant to produce electricity to be used to desalinate ocean water to irrigate hay and corn to feed to cattle to produce hamburgers to be sold in throw-away plastic containers to customers in air-conditioned

SUVs at a fast food drive-through window—and we'd have no basis for saying it's not sustainable.

The Modern Demographic and Economic Explosion on a Finite Planet

Human habitation of the Earth in the 21st Century is a fundamentally different challenge than it was in the 19th and 20th Centuries, perhaps even from what it has ever been since humans became a separate species from chimpanzees in the East African savannas several million years ago. Why is this the case? Two centuries ago, the Earth for the first time supported one billion people. In 2022 it supports 8 billion (see Figure 1.1). By 2050 it is projected to support 9 to 10 billion before stabilizing in the late 21st century. These increases in numbers have come along with a tremendous lengthening of the human life span from a mere 29 years two centuries ago to about 73 years as a global average today. Behind these numbers lies a great victory of much of humanity over disease and want, a victory that must be sustained, and in fact advanced, if human welfare and quality of life are to continue to improve, especially in the poorest regions.

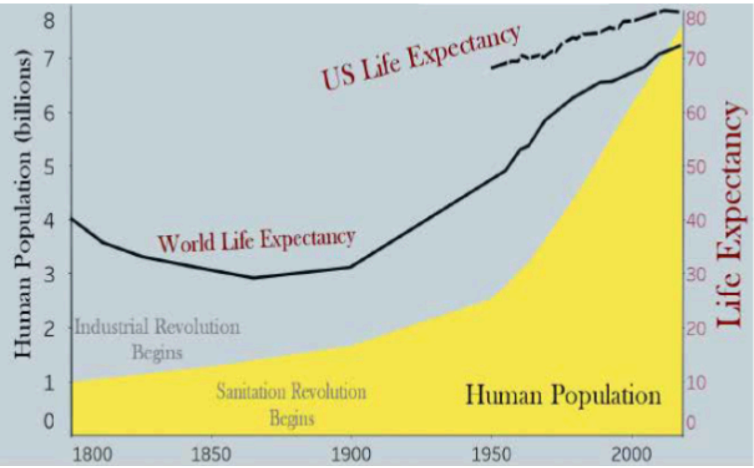

Figure 1.1. Growth in world human population, and U.S. and world life expectancy, 1800-2020

Vast increases in human numbers and longevity alone, however, do not explain why humans' relationship to the Earth has changed so fundamentally. The second critical factor is that population growth has been accompanied by an even greater increase in economic activity. Per capita income has exploded (the term explosion implies sustained exponential growth) over the past two centuries. While it increased from a meager $133/year in 1000 C.E. to only $195 in 1800, it more than tripled in the 19th century, and increased 10-fold in the 20th to reach about $20,000 by 2022 (see Figure 1.2). This represents over a 100-fold increase in two centuries on a per capita basis. Multiply this per capita increase by the 8-fold increase in human population and you get about a 1000-fold increase in the size of the human economic enterprise over the last two centuries, doubling every 26 years (about a generation). This is an astounding fact, and by and large is one that people can take great pride in, especially since it occurred despite world wars and other convulsive set-backs.

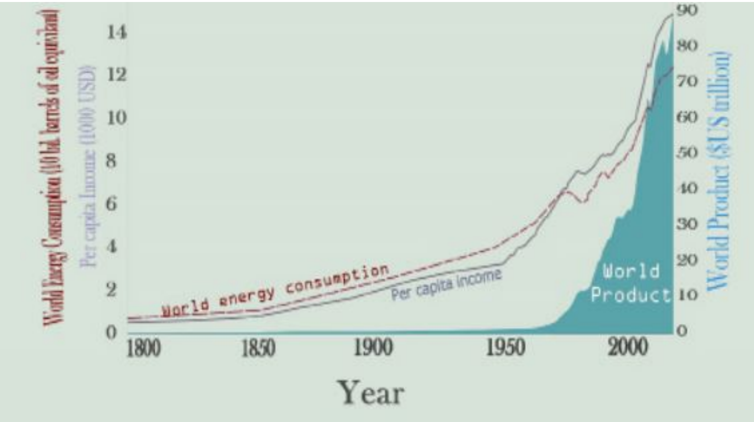

Figure 1.2. Growth in the world economy, per capita income and global energy use 1800-2020.

Humans' environmental impact on the Earth is driven by how many people there are, but even more by the size of the world economy. Most directly, the human footprint is derived from natural resource use when this entails extractions from the Earth and waste products returned to it. Over the last two centuries, growth in the world economy has required an increase in natural resource use. Accelerated natural resource use lies at the heart of the industrial revolution and has, on the whole, vastly improved the quality of human life.

We will use energy consumption as a surrogate for all natural resources because historical data on energy use are much better than for specific resources such as wood or aluminum. From 1850-2000 world energy consumption increased about 20-fold, doubling about every 35 years, and per capita energy consumption increased about 4-fold, doubling about once per human lifetime. Thus, natural resource use, as measured by energy consumption, has tracked the demographic and economic trends (see Figure 1.2).

What rate of natural resource use and waste emissions can the Earth accommodate? Do current and likely future rates fall well below these limitations or greatly exceed them? Here we have no one easy answer and will instead have to explore the issue in detail, issue-by-issue and sometimes region-by-region. Nevertheless, we can raise some overarching issues and perhaps get an approximate answer that will help us gain perspective on this issue of planetary limits to natural resource use and pollution emissions.

In 1986, Peter Vitousek, an ecologist at Stanford University, and his colleagues attempted to answer this question using human appropriation of global photosynthesis. Why, you may ask, use this measure? In ecology, plants are viewed as producers because they are capable of capturing solar energy and using it to turn carbon dioxide from the air and water from the soil into carbohydrates—the calories of energy upon which both the plants themselves and nearly all other life on Earth depends. So the rate at which the biosphere (a term that refers to all living things on Earth) can photosynthesize is an essential limit on how much life the planet can support. Importantly, more than 1000 times as much solar energy reaches the Earth than is captured by photosynthesis, so while photosynthesis is driven by solar energy, it leaves the vast majority of it utilized only as heat.

Total global photosynthesis (called gross primary production) has been estimated at about 120 billion metric tonnes (we'll use "ton" for 2000 English pounds and "tonne" for 100 metric kilograms, about 10 percent heavier) of carbon captured from the atmosphere per year. About half of this—60 billion tonnes—is fixed by plant growth as net primary production, the energy supply for all other living things. Researchers at the Institute of Social Ecology in Vienna estimated that, from 1910 to 2005, "human appropriation of net primary production" (HANPP) doubled from 7 to 15 billion tonnes, 13 to 25 percent of global terrestrial net primary production, primarily through agricultural activities such as crop production and livestock grazing as well as forestry. Population more than doubled during that century, meaning that per capita HANPP fell, an important accomplishment, yet the overall impact presses against the limits of the biosphere.

At first, you may think that if humans are only using a quarter of the Earth's ecological capacity, what's the problem? But think again. Even 25 percent is a very high proportion because at least 10 million non-domesticated species of plants, animals, fungi, and microorganisms must live on the remainder. They are having a great deal of trouble doing so; the rate of species extinctions is now at least 100 times and perhaps over 1000 times faster than it has been over long spans of time in the past. Looking at just mammals, 36 percent of the total weight is humans and 60 percent is domesticated livestock, leaving a mere 4 percent for wild mammals from bats to elephants, Yet wild mammals outweigh wild birds by 3 to 4 times. While fish are more abundant, the total weight of fish in the oceans is only about 10 percent of what it was a few centuries ago. So humans are driving non-domesticated animals to a few remaining marginal ecological niches.

Moreover, humans depend on natural ecosystems for services as essential to human life as oxygen production, the delivery of fresh water, the buffering of natural disasters, and the pollination of crops. Therefore, we must conclude that human appropriation of net primary production is rapidly approaching the limits of what can be harvested from Earth's biosphere. Remember this inconvenient truth because it is a key factor in natural resources sustainability.

What this means is that the size of the human ecological footprint can no longer continue to rapidly rise (as illustrated in Figure 1.3). This makes the 21st Century fundamentally different from the 19th and 20th Centuries when it doubled nearly every generation.

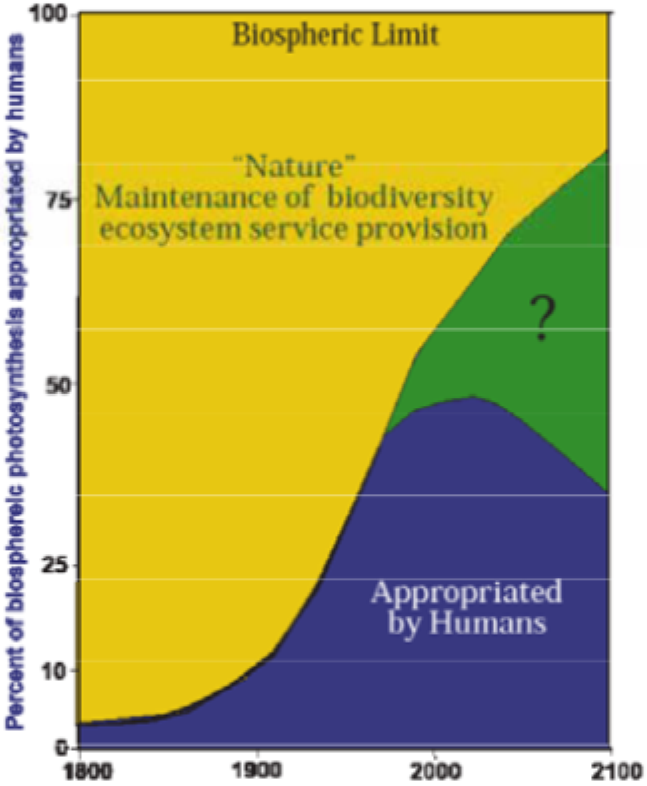

Figure 1.3. The relationship between human appropriation of nature within the biospheric limits established by photosynthesis, 1800-2100.

In 2006, Paul Crutzen first termed the new era where human activities dominate Earth's metabolic processes as the "Anthropocene," a new geologic era like the "Pleistocene" or the "Miocene." Johan Rockstrom and numerous other environmental scientists have identified several planetary boundaries; crossing these is a clear sign of unsustainability.

Currently, humans are within the safe operating space for ocean acidification, stratospheric ozone loss, phosphorus flux to the ocean, global freshwater use, and land system change, but have crossed the boundary for climate change, rate of biodiversity loss and nitrogen fixation.

At first, this seems like a deeply discouraging thought because improvements in human welfare such as lengthening life expectancies and increases in economic goods and services that make our lives better have, for the last two centuries, been closely tied to increases in natural resource use and economic growth. An end to the expansion in natural resource use seems to imply an end to human progress. Fortunately, this is not necessarily so. In fact, one key to sustainability lies in decoupling improvements in human welfare from increases in natural resource use.

Perhaps the steepest challenge of our time lies in simultaneously meeting these two overarching goals of improving human well-being while restraining humanity's ecological footprint. But there is reason to think that it is doable, beyond the assertion that it must be done, and in fact even some evidence that this great transition, this decoupling, is already underway. Figure 1.4 adds two new measures—energy consumption per capita and energy consumption per dollar of goods and services produced. Note that the amount of energy the average human consumes, measured as tonnes of oil per year, increased from 3.3 in 1850 (though at that time it was mostly wood and coal) to about 12 tonnes in 1990. It then peaked, however, and now shows signs of declining, if only a bit. This means that the doubling in the value of goods and services that the average human received between 1980 and 2000 was achieved without increasing their average energy consumption. That's an encouraging trend.

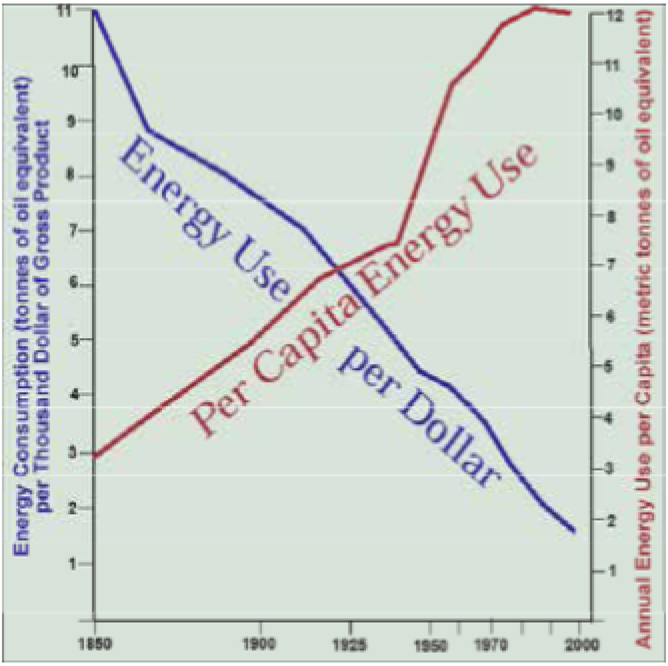

Figure 1.4. World per capita energy use and energy use per unit of economic productivity, 1850-2000.

Now take a look at energy consumption per thousand dollars of gross product. In 1850 it took 11 metric tonnes of oil equivalent to produce a thousand dollars worth of goods and services but this has steadily fallen to 1.8 tonnes in 2000, even correcting for inflation. This is excellent news because it shows that humans have steadily gotten more and more of what they really need—nutritious food, comfortable and even fashionable clothing, solid housing, accessible transportation, entertainment, quality health care and education, and so forth—for every unit of extraction of natural resources from this finite planet. The reason I can be optimistic about the prospects for natural resources sustainability is that I think we can accelerate this process, along with bringing population growth to a halt, in the 21st Century. Keep this hopeful vision for a sustainable and prosperous future in mind, not only because it is a central theme of this text.

What Sustainability is and is Not

In March 2009, *Scientific American* published a short article entitled "Top 10 Myths about Sustainability" that is very useful in keeping us from getting off on the wrong track. Here's the list of myths and a response that puts us on the right road.

Myth 1: *Nobody knows what sustainability really means.* We're already on the road to exploding this myth. In Chapter 7 on ecological economics, we'll nail down an even more precise definition.

Myth 2: *Sustainability is all about the environment.* It's also about sustaining human welfare —indefinitely—by making sure the environment is always there to sustain us.

Myth 3: *Sustainable is a synonym for "green."* Green is a marketing term, a political party, and, incidentally, a color; sustainability is a principle.

Myth 4: *It's all about recycling.* Recycling is a good idea but is not even the tip of the iceberg in reducing our ecological footprint through reforming agricultural, energy, industrial, and other social and economic systems.

Myth 5: *Sustainability is too expensive.* Sustainability is about making our lifestyles less expensive—when we count the environmental costs.

Myth 6: *Sustainability means lowering our standard of living.* To become more sustainable, we need to be willing to change more than to sacrifice. When we do so, our standard of living will be better, not worse.

Myth 7: *Consumer choices and grassroots activism, not government intervention, offer the fastest, most efficient routes to sustainability.* Government policies can block or advance sustainability in critical ways as we will explore in depth, especially in Chapter 15. The right government policies enable consumer choices and grassroots activism by giving them a downhill coast rather then an uphill climb toward sustainability.

Myth 8: *New technology is always the answer.* Sometimes it is very helpful, as can be illustrated with the examples of hybrid cars, wind turbines, solar panels and LED lights but many sustainable technologies are as old as applying manure to crop fields or living close to where we work or go to school.

Myth 9: *Sustainability is ultimately a population problem.* We will explore this idea in depth in Chapter 5 and find that the Earth's 8 billion can live sustainably or unsustainably—depending on their lifestyles.

Myth 10: *Once you understand the concept, living sustainably is a breeze to figure out.* If that were true, this would be the only chapter in this text. Instead we have to apply the sustainability concept resource-by-resource, place-by-place, and you will still have to figure out how to apply it in your own life.

Geographer Robert Kates and a long list of colleagues proposed in a 2001 article in the prestigious journal *Science* an interdisciplinary field that they call "sustainability science." Natural resource sustainability is thus at the heart of sustainability science, keeping in mind that this is not a theoretical or laboratory science, but a multi-faceted applied science where nature and people, principle and practice come together.

Sustainability as a Commitment to the Future

Paradoxically, we can know the past, but we can't affect it. In contrast, our actions in the present can and do affect the future, but we can never know with certainty what tomorrow will bring. Nevertheless, we can often develop a sense of the future and, if we're smart, identify key factors that will govern outcomes down the road.

I'll bet you've seen the 1997 disaster movie *Titanic*. Midway through the film, in the absence of radar (which was invented 23 years after the 1912 disaster), the shipmate on the bow first saw the fateful iceberg about a quarter mile dead ahead on a calm, cold night. Doing his duty, he immediately informed the captain, who ordered "reverse engines" and a hard turn to the left. Just before ramming headlong into the iceberg, the ship did start to slow down and turn, but it was too little, too late. Five compartments in the lower decks were torn open by the ice and began to fill with icy seawater. From that point, it was a mathematical certainty that the elegant ship was doomed to sink to the bottom of the North Atlantic on its maiden voyage. All those who couldn't fit into the inadequate lifeboats would perish from hypothermia.

But what if the shipmate had seen the iceberg a half mile off? What if the captain had ordered the change in course even faster, or the workers below deck could have altered the ship's tremendous momentum with greater agility? The ship would have slipped harmlessly by the iceberg and only cruise ship enthusiasts would have heard of the *Titanic*.

Sci-fi movies such as *Don't Look Up* have proposed an asteroid or comet on a trajectory to smash into the Earth, like the one that struck the Yucatan peninsula in Mexico 65 million years ago and brought the dinosaurs to a sudden end.

If we could send out a space ship, say with nuclear weapons, capable of changing the asteroid's trajectory, nudging it as little as an inch when it was still out near Mars, that would be sufficient to keep it from hitting the Earth at all, but if we waited until it had passed the moon, there might be no force capable of preventing a catastrophe that could send humans into the abyss of extinction to join the dinosaurs.

What these examples show is that oftentimes the earlier we can identify and act upon threats or opportunities, the greater the leverage we have over the ultimate outcome. The present has power over the future (that is, your future) if there is a vision and an ethical commitment to improve future circumstances that we value, such as the quality of human life, and, perhaps, the bounty of non-human life on Earth, either for its own sake or for all that it offers us.

Sustainability as a Social Movement

Think globally, act locally—you've probably heard that before. Above, I hope to have given you the beginnings of a sense of how to think globally about natural resources sustainability. If progress is to be made, however, it must happen, to quote President George H.W. Bush, at "a thousand points of light."

As a global social movement, sustainability has evolved partly from the American tradition. We associate the

Conservation Movement of the late 19th and early 20th century with John Wesley Powell who explored the Colorado River and established the U.S. Geological Survey, President Teddy Roosevelt, who established the first National Parks, Gifford Pinchot, who established the U.S. Forest Service, John Muir, champion of wilderness and founder of the Sierra Club, Hugh Hammond Bennett, champion of soil conservation, and Aldo Leopold of *Sand County Almanac* fame. They also established a land ethic whereby the natural capital (though they never used the term) contained in forests and soil needs to be conserved for the prosperity of future generations.

The modern environmental movement emerged in the 1960s as rapid industrial growth generated severe air and water pollution, dammed the rivers, sprawled the suburbs, and inundated "consumers" with goods, not all of which were wholesome. It coalesced with the civil rights, women's rights, and peace movements of that decade. Beyond conserving natural resources for use by our children, Rachel Carson, Ralph Nader, and many other leaders focused on the threat of toxic pollution and flawed consumer products to human health and the beauty and permanence of intact natural ecosystems.

It was under the Nixon Administration (1969–1973) that many of our most important environmental laws were passed: The National Environmental Policy Act, the Clean Water Act, and the Clean Air Act. These were followed by the Endangered Species Act, the Safe Drinking Water Act, Superfund, and other regulatory laws, largely administered by the Environmental Protection Agency, which President Nixon established in 1970. These laws remain the means through which government protects the environment, and thus us, from abuses emerging from private sector industries. In this way, the environmental movement evolved from an upper-class white male issue into a concern for environmental justice. Why is it always the poor and people of color that suffer from the health and aesthetic impacts of industrial development while the affluent build summer homes in scenic recreational areas?

Sustainability takes this evolution to the next level. The economy has now become globalized, and so the movement must follow suit. Protecting the environment is largely about protecting people. But this can't be accomplished entirely through greater regulatory constraints, imposed in detail from Washington, on private-sector economic activities. It has to be grassroots, local, centered in non-governmental organizations and within farms and companies as they re-examine how to produce goods and services in more environmentally sound ways. It requires an ecological consciousness, a deep sense that in a world crowded with people, humans need to live in a manner consistent with the welfare and survival of other living beings. Like in the popular 2009 movie*Avatar*, the natives have grown restless of the exploitation and are organizing to resist.

Paul Hawken's 2007 book *Blessed Unrest* counts over a million organizations, mostly non-government, not-for-profit, that are active in the myriad aspects of creating natural resources sustainability. And that was over a decade ago. Like websites on the Internet, these organizations are not coordinated, but they can communicate and share information and points of view. Most are locally-based, and focused on one or two specific issues that relate to quality of life: water quality, access to transportation, the availability of safe, nutritious food. These organizations are acting locally.

Overview of this Text

The commonly accepted definition of sustainability comes from a 1987 convention of the United Nations World Commission on Environment and Development in Stockholm led by Norwegian Prime Minister Gro Brundtland and the subsequent book *Our Common Future*: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." There are many other definitions of sustainable development and sustainability, but there is no good reason to depart from this one, which clearly leads the list. This book explores natural resources sustainability from multiple perspectives.

To complete Part I, Chapter 2 searches environmental history for the lessons it has to teach us. Has unsustainable natural resource use ever caused a human catastrophe? How have societies successfully avoided this outcome? Can we adopt some of these same strategies today?

In Part II, Nature's Role, we will examine how natural resources are created through ecological, geological, and astronomical processes, why they are distributed unevenly across the Earth and over time, and even how our definition of natural resources changes over time alongside our needs and desires and, even more powerfully, our technological capacity to turn natural substances and processes into human value. In this exploration we will be guided by two relatively recent concepts from the emerging field of ecological economics: natural capital and ecosystem services.

In Part III, Society's Role, we explore human population and then take a dive into the deep pool of economics and politics. Remember, the last two centuries have been characterized by economic growth, a 1000-fold economic explosion. How do various economic perspectives, especially neoclassical and ecological economics, view natural resources and how do they instruct us on how best to utilize, conserve, and allocate them? We will also explore the political system, not just the three branches of government (come on, you can name them), but even more deeply-rooted institutions such as property rights. Who owns the resources? What difference does this make? What powers do owners have and what powers does government, which may or may not represent the community, have over natural resources?

We also explore the contemporary debate about scarcity and abundance. Not everyone agrees with the perspective that I have outlined in the first few pages of this chapter. Some argue that the Earth has no natural resource limits that technological innovation and free enterprise cannot readily overcome, that conserving natural resources and protecting the environment will erase the progress in human welfare that has been so arduously achieved over the past few centuries. Others argue that any form of economic growth is anathema and will accelerate a global ecological collapse that is already nearly inevitable. To many, "sustainability development" is an oxymoron, a contradiction in terms, or, worse, a vague and meaningless term that helps mask the normal pursuit of self-interest.

In Part IV Resource-by-Resource we will look in turn at each of the major natural resource sectors, starting with land and soil as natural resources for agriculture and forestry. We then proceed to fresh water, mineral resources, and energy. We will see that agriculture and energy, two irresistible topics, are the linchpins of humanity's relationship to the Earth, but it is often water that makes both possible. No two places on Earth are the same with respect to this people-food-water-energy nexus, so we must explore the issues geographically, focusing on the United States, but drawing upon examples from elsewhere, to sift through the fascinating variations and possibilities.

Finally, in Part V: Policy and Sustainability, we will explore the realm of natural resources and environmental policy. What is policy? For one thing, it is not all-powerful; the founding fathers made sure of this when they built a system of checks and balances into the constitution (those three branches again), divided powers between the national, state, and local governments, while also ensuring a strong private sector and civic culture that includes churches separate from the state. Nevertheless, in a country where even giant corporations have to take the law very seriously, policies are very important in determining outcomes. What kinds of policies advance natural resource sustainability? What kinds of policies undermine it? By the time we reach the end, you'll have a much better grasp of this, but no one has all the answers.

We close by digging deeper into the meaning of sustainability and develop a realistic vision of how the future can feature a less antagonistic relationship between humans and the Earth while, not despite of but because of this, human progress can continue for more astonishing centuries.

Further Reading

Hawken, P. 2007. *Blessed Unrest. How the largest movement in the world came into being and why no none saw it coming.* Viking Books.

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CHAPTER 2: LESSONS FROM ENVIRONMENTAL HISTORY

We study history for a variety of reasons: for its stories of heroism, suffering, and intrigue; to find out what really happened; to see how the world that we experience in the present came into being; or to learn its lessons because, as the saying goes, those who do not know history are doomed to repeat it. Amazingly, environmental history is considered to be a new field, though it merges with older scholarly traditions in anthropology, archaeology, geography, and what was once called natural history. Environmental history is the chronicle of how human societies have been shaped by the climate, ecosystems, geography, and natural resources available to them and, in turn, have modified those environments.

Here we take a brief look at environmental history to distill from it four lessons that are essential in our study of natural resources sustainability: 1) *Homo Sapiens* is a species capable of expanding their ecological niche, but 2) some humans have expanded their niche more than others. 3) Undermining or overshooting your ecological niche is bad news, but 4) such disasters can be avoided.

Lesson 1: Homo Sapiens are a Species Capable of Expanding their Ecological Niche

If a biologist from another planet had taken a tour of Earth, say 40,000 years ago, she would have been awed by the splendor and diversity of life she witnessed both in the sea and on land. Enormous glaciers covered as much as 30 percent of the Earth's land surface, including much of Europe, northern Asia, and North America, but to their south, the Earth was teeming with life. Moving her gaze beyond the stupendous flocks of birds of several thousand varieties to the largest mammals, she would have witnessed elephants, giraffes, zebras, and various antelopes roaming the African savannas in their attempt to avoid the lions and hyenas. Over a dozen species of whales were plying the oceans in considerable numbers. Unlike today, however, she would have seen abundant wild cattle, goats, and sheep grazing in the rich grasslands of southwest Asia and wild pigs foraging there and in the lush forests of eastern Asia. She would have noticed humpless camels and 20-foot-tall sloths lumbering through the diverse forests and grasslands of South America, and mammoths, mastodons, horses, and saber-toothed tigers roaming right up to the edge of the glaciers in the grasslands and tundra of North America. If she was particularly thorough, she would have noticed the flightless birds, like the dodo, of South America and the Pacific Islands from Hawaii to New Zealand and two species of upright ape, one a little shorter and stockier, the other taller and lighter of build, exchanging complex utterances as she approached.

These largest of primates other than the African gorilla could be found only in small numbers, dwelling often in caves and roaming in hunting, gathering, and fishing clans of a dozen to a few hundred from East Africa across southern Eurasia and even into Australia-New Guinea. With sea level as much as 400 feet lower than it is today, she would have found this medium-sized continent separated from the large, lush peninsula of southeast Asia by only several, narrow warm seawater channels. Australia-New Guinea was then populated by large marsupials like the kangaroo rather than true placental mammals. These were rapidly diminishing or disappearing altogether, however, wherever she found the taller apes, which had apparently recently arrived from Asia on some kind of raft or outrigger canoe. The lower sea level also revealed the British Isles as an ice-covered peninsula of Eurasia, and North America and Asia connected by a 1000-mile wide land called Beringia.

If her descendent were to return 30,000 years later (10,000 years ago), he would find Earth to be as splendid as his predecessor had foretold but also a lot that had changed. Two-thirds of the glaciers had disappeared, retreating to only Antarctica, Greenland, and high mountain valleys. Associated melt waters had caused sea level to rise 400 feet, producing the world map we now know.

What would have most surprised him was that the short, stocky upright apes could no longer be found while the taller, thinner ones had migrated wherever the ice had retreated, throughout Eurasia and even to the Americas, where numerous bands resembling those in Siberia were working their way south through South America, feasting on large, unwary prey. To their north, however, the populations were smaller and most of the large mammals his predecessor had observed, even the horse, were gone.

Even more surprisingly, in southwest Asia (what is now called the Middle East) and a few river valleys in eastern Asia, the tall upright apes had become truly numerous. They were constructing houses to form settlements of thousands, surrounded by arduously tended fields of wheat, barley, millet, and chickpeas, as well as herds of goats and sheep, expertly controlled in partnership with what appeared to be, based on his predecessor's report, mutated wolves. Of all the wondrous animals—large, small, and medium-sized, four-legged and winged, herbivorous and carnivorous—that his predecessor had admired on her exploratory adventure 30,000 years before, he found it incredible that this one species of rather large, upright omnivorous ape was coming out on top in the competition for life on Earth. Humans were expanding their ecological niche.

Every living thing has an ecological niche within which it can survive and outcompete other species (and other members of its own species) for critical ecological resources. For plants, these include sunlight, water, nutrients, and a favorable temperature range. For animals, they include food, a fertile mate, and a place to hide from predators and shelter from severe weather. For example, various species of oak trees (white, red, black, pin) usually outgrow other species of plants in the central hardwood forests extending from Pennsylvania to eastern Texas, wherever: (a) rainfall is fairly plentiful year-round, (b) frost-free growing seasons are 6–10 months long, (c) soils are well-drained, (d) abundant sunlight can pass through the forest canopy to the leaves of oak saplings, (e) farmers have not removed the forest and plowed the fields or turned in into cattle pasture, and (f) squirrels are forgetful of their stashes of buried acorns.

The feisty smallmouth bass I like to catch (and release) usually outcompete other predatory fish where (a) water temperatures between 50–75°F can be found for all but the coldest months of the year, (b) waters are well-oxygenated and relatively clear to aid in spying prey, (c) gravelly stream, river, or lake bottoms provide for fertile spawning beds, and (d) small fish, amphibians, and especially crawfish are available as prey.

The microscopic malaria parasite is one of the most dreaded diseases throughout human history with half a billion cases and one to three million deaths each year. It thrives where people and anopheles mosquitoes live in close proximity, freezing temperatures are rare, stagnant water is common, and pesticides are not used to protect people from mosquito bites. We could similarly describe the ecological niche of other familiar species of plants, animals, and microorganisms. But what is the ecological niche of humans? How has it changed and expanded over time?

There are many ways in which humans have risen, over time, above the animals. We have spoken and written language and can therefore interrelate and coordinate with other individuals in ways far more complex than a wolf pack, a flock of Canadian geese, or an ant colony. We can think abstractly, make plans, and, through determination and sense of purpose, see those plans come into effect (like writing this book!) With little effort, you can think of many more examples, but superior brains do not exempt humans from having an ecological niche.

It has been well demonstrated that our species evolved over several million years, from an ancestor we have in common with the chimpanzee, in small hunting, gathering, and fishing bands in the highland savannas of East Africa. In this ancestral homeland, temperatures are usually in the 50–90°F range, the sun shines brightly about 12 hours per day year-round, fresh water can usually be found (though with difficulty in the dry season), fruits, grass seeds (i.e., grain), and meat (dead or alive) is fairly abundant, and large predatory cats, hyenas, and venomous snakes are a very real threat, especially to children.

To this day, humans feel most comfortable in temperatures not too far from 70°F; in landscapes that combine trees, grasslands, and water; where a menu founded on grains liberally augmented by fruits and vegetables and meat or fish is available. Like Tom Hanks in *Cast Away*, we crave the company of others, to share this favorable environment with a household of a favored few close relatives within a community of dozens of people we know personally and with whom we share a common language, hopes, and fears. Have you found your village?

Also held over from ancestral times in East Africa, small children are afraid of monsters that want to eat them, many people get a bit depressed in northern winters with short cloudy days and limited outdoor activity, and nearly all of us, let's admit it, are startled by snakes not captured behind glass cages. Most of us also enjoy gathering together around a warming fire, especially if there's some good food to be had (or beer, but that wasn't invented until about 4,000 years ago in Egypt when someone let the barley bag get wet and sit around for a while to ferment).

Of course, humans moved beyond the East African homeland a long time ago. *Homo erectus*, with a considerably smaller brain than we command, did so first, about one million years ago, populating the entire southern tier of Asia, which offered grasslands full of edible seeds and grazing animals and riverine and coastal fisheries that far exceeded the limited carrying capacity of the East African highlands. Much later, they slipped back west to populate southern Europe (Figure 2.1). Eurasia was likely not an easy place to live for an African species. In these subtropical (warm wet summer, mild winter) and Mediterranean (warm dry summer, cool wet winter) climates, clothes derived from hunted animal skins or agricultural byproducts had to be invented for use in winter, a season that doesn't occur in equatorial East Africa. But, even despite the tigers, they made it, if never in large numbers. That is, until *Homo Sapiens* came through.

Evolving in the original homeland of East Africa around 100,000 years (i.e., 5,000 generations) ago, this large-brained hominid, genetically identical to us, also found the narrow isthmus at Sinai (now spanned by the Suez Canal) or the narrow strait of Bab el Mandeb at the southern end of the Red Sea about 50,000 years ago. Eurasia lay before them. As language-speaking, tool-using, observant fruit and seed gathers, net-throwing and hook-baiting fishers, spear-wielding pack hunters, clothes-sewing masters of fire, *Homo Sapiens* found the habitats of Eurasia even more to their liking. They likely drove *Homo Erectus* into extinction by 30,000 years ago, and interbred with *Homo Neanderthalensis* as they expanded their population to probably several million—no larger than the population of many other large mammals or a single metropolis today, but a base to build upon and a cushion against extinction.

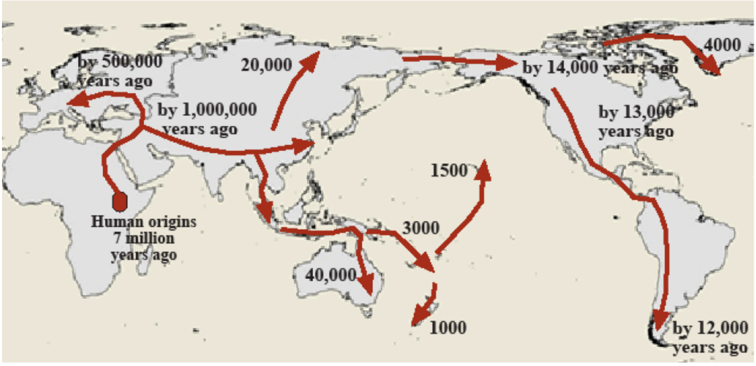


Figure 2.1. The peopling of the Earth starting with migrations of *Homo Erectus* from East Africa to Southern Asia by 1,000,000 years ago and Europe by 500,000 years ago. Much more recently, *Home Sapiens* first reached Australia by 40,000 years ago, Siberia by 20,000 years ago, and the Americas about 14,000 years ago where they quickly spread through both continents. Greenland, New Zealand, and the Pacific Islands were first reached by humans in historic times.

While it is obviously true that humans' ecological success is largely due to our superior brains, humans also have other advantages that overcome the disadvantages of an uncommonly long period of childhood dependence (whether upon parents or the village that it takes to raise a child). Humans are not grazers, like cattle, who utilize the meager nutritional value of ordinary plant cellulose by possessing a large digestive organ called a rumen and eating grass or chewing their cud most of their waking hours. Nor are we strictly carnivores, like the cats and many fish, whose diets are packed with protein, but who teeter at the narrow top of the food chain. (Any ecosystem contains, at most, 10 percent as much animal as plant matter as we will explore further in Chapter 4.) Rather we are omnivores who utilize the more fortified plant foods, especially grains (that is, human's ecological niche is founded on consuming grass seeds), augmented by fruit and vegetables and meat or fish when we can get them. Our diets are therefore somewhere between those of two similar-sized mammals we domesticated long ago: the pig, which eats our high-energy plant-based diet but less meat, and the dog, primarily a carnivore. This dietary strategy allows us to live on a wide variety of ecological resources (Michael Pollen has called this the "omnivore's dilemma") without confining us to the small ecological carrying capacity of carnivores or the endless chewing of grazers.

If you've ever watched the Olympics, you're probably as amazed as I am at the athletic possibilities of an upright posture on two sturdy legs, with two arms connected to amazingly dexterous hands freed from service in locomotion. Young women stand on a balance beam, jump in the air, do a back flip with a full twist, only to land cleanly back on the beam. Young men do triple somersaults only to catch the high bar on the way back down. Athletes swim at a speed faster than a vigorous walk using four different strokes.

Not even the fastest of human runners at the Olympics can sprint as fast as a horse, and my dog delights in my inability to catch him, but with only two legs, Usain Bolt of Jamaica hit a top speed of nearly 30 mph in winning gold medals in 2008, 2012, and 2016. Kenyan and Ethiopian male marathoners cover 26.2 miles at an average speed of over 12 mph, women at 11 mph. So with only two legs, humans are remarkably good distance runners and we can easily outdistance any other primate on the ground, though of course not in the trees—the price we pay for an upright posture.

This sacrifice in sprinting speed compared to our four-legged friends and branch-swinging compared to other primates enables the arms and hands to do things no other animal can achieve. Even if your pet dog, cat, horse, or rabbit were as smart as you are, I can't imagine how any of them could drive a car or sew a new shirt, cook a nice dinner or play the violin, guitar, or piano. Nor could they swish a jump shot, pitch a baseball or hit that pitch with a wooden bat, nor shoot a bow and arrow or rifle accurately. Moreover, human's sense of sight is unique in the animal world; eyes are propped up about 5 feet off the ground when standing, and humans have excellent binocular vision and therefore depth perception. Moreover, like the birds and reptiles, but only primates among the mammals, we have excellent color vision (that's right, your pet cat, dog, horse, or rabbit are color-blind but the snake in your garden is not).

Of critical ecological importance, humans armed (note the anatomical reference) with a sharp bit of stone or bone lashed to a stiff wooden stick can accurately throw or jab this weapon with great effectiveness in hunting (or battle), especially when working in teams. The human body plan is uniquely adapted to throwing, critical in successful hunting. It's a scary thought, a dozen fit, determined humans, probably mostly young adult males, executing a coordinated plan to rush at you from various directions with a skillfully wielded weapon that can kill you from a distance. That's likely what happened to the unwary marsupials of New Guinea-Australia upon the arrival of humans around 40,000 years ago, the large mammals of North America 13,000 years ago, and flightless birds of the Pacific in historical times. It may even be what happened to *Homo Erectus* and *Homo Neanderthalensis*. The point is not to say that humans are vicious, though sometimes they certainly are, but that we have a potent package for winning for ourselves an ecological niche on a planet where that process is inherently competitive. We must also keep in mind, however, that "our" ability to effectively cooperate gives us a competitive advantage over "them" (whoever "us" and "them" happen to be at the time).

Lesson 2: Some Humans Have Expanded Their Ecological Niche More than Others

Jared Diamond's 1997 Pulitzer Prize-winning non-fiction book *Guns, Germs, and Steel* takes the human ecological story from the origins of agriculture about 10,000 years ago to the beginning of the modern age a few hundred years ago. In teaching from Diamond's excellent, but controversial, book in class, I have found that the title should have been *"Farms, Germs, and Steel"* since this better captures his thesis, but perhaps "Guns" are more eye-catching and make for better marketing than "Farms" on a book cover.

Some scholars have critiqued Diamond's widely-read book (note that in academia, having your work criticized is far better than having it be ignored) as being environmental determinist and others as being social Darwinist. The first charge means that it puts nature in command of human history rather than human ideas, institutions, values, and free will. I find, however, that the book does nothing of the sort. Diamond is a possibilist rather than a determinist—nature does not dictate human outcomes, but it does limit what can happen and what is beyond the range of possibility. In fact, until the relatively recent rise of environmental history, historians have been seriously remiss in leaving nature almost completely out of the human story, except when geography is invoked to explain military outcomes, as if there were no ecological laws that apply to humans.

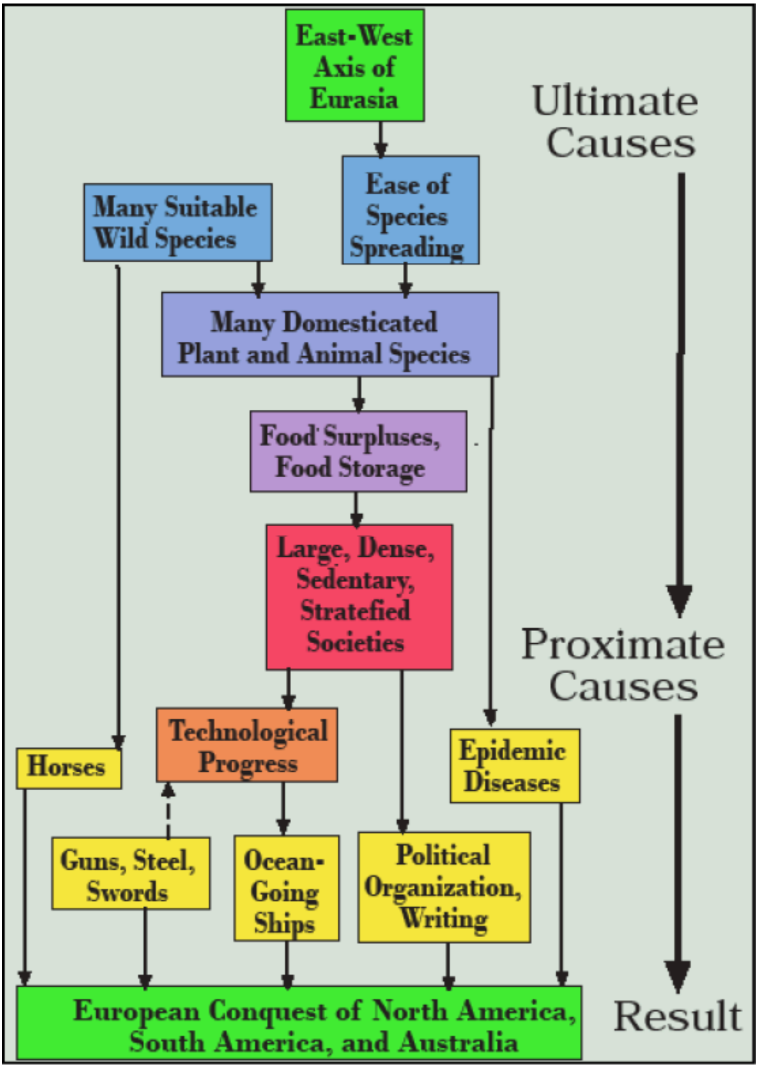


Figure 2.2. This adaptation from Jared Diamond's 1999, book *Guns, Germs, and Steel* summarizes his central argument of why Europeans were able to conquer three continents—North America, South America, and Australia—(plus the southern tip of Africa), but not Asia or the remainder of Africa. Causes are shown at the tops of

arrows and effects at the bottom or point of the arrows. The immediate or proximate causes explaining historic events—such as Pizarro's conquistador's rout of the Incas and Cortez's victory over the Aztecs—are shown in yellow at the bottom. Prior causes of these factors are shown through the rainbow to the ultimate factors of the East-West axis of Eurasia, with its availability of many suitable wild species for agricultural domestication, especially in the Fertile Crescent and China. Similar arguments explain the Austronesian expansion of south China throughout east and southeast Asia and the Pacific, as well as the Bantu expansion from West Africa throughout the remainder of SubSaharan Africa.

The second charge of social Darwinism means that human history is viewed as a struggle for the survival of the fittest societies, like the competition among and within species. *Guns, Germs, and Steel* certainly does have an element of social Darwinism, and yet it seems to lead Diamond to draw many correct conclusions about why "the fates of human societies" (the subtitle of the book) have come out the way they, in fact, have. For this reason, I find it to be the most important book in environmental history written so far, though Alfred Crosby's *Ecological Imperialism* drew some of the same conclusions thirteen years before Diamond.

According to Diamond, the evolution of hunting into herding and gathering into cropping, that is, the development of agriculture in what is referred to by archaeologists as the Neolithic Revolution, is the central event in human history. (Agriculture is also a key characteristic of Earth in the 21st Century and lies at the heart of natural resource sustainability as we will see in later chapters.) It is what has made humans the dominant animal and some humans dominant over others. Diamond states his thesis this way:

> Thus, food production, and competition and diffusion between societies, led as ultimate causes, via chains of causation that differed in detail but that all involved large dense populations and sedentary living, to the proximate agents of conquest: germs, writing, technology, and centralized political organization. Because those ultimate causes developed differently on different continents, so did those agents of conquest (Diamond, 1997, p. 292).

Figure 2.2 captures Diamond's overall argument and gives us a road map to follow through major themes of environmental history. It is important to note that earlier theories explaining the Europeanization of the Americas and Australia and enslavement of Africans had invoked racism—genetic superiority. Following all available scientific evidence, Diamond rejects this notion. In fact, the African, East Asian, and Caucasian strains of humans separated less than 100,000 years ago, far too short a time to evolve significant differences that are more than skin deep. Instead, Diamond, as well as Crosby, argue convincingly that Europeans had a superior ecological inheritance than the Native Americans and Australians they conquered in recent centuries.

The Fertile Crescent is a wide arc of highlands east of the Mediterranean Sea in what is now Israel, Palestine, Lebanon, Jordan, Syria, and Turkey, extending into the highlands straddling Iraq and Iran. It surrounds the low-lying deserts of Syria, Jordan, and western Iraq through which flow the Tigris and Euphrates Rivers (Figure 2.3). The area spans latitudes of 32-38°N (the same span as from San Diego to San Francisco) and its physical geography and climate resemble California.

Hunters and gatherers there possessed an opportunity that humans in other regions lacked—a few key species of wild plants and animals that had the potential for domestication. Gatherers there discovered that the grains of two varieties of wheat, einkorn and emmer (staples to this day for making bread and pasta), could be greatly encouraged by clearing an area of other plants and placing the seeds in the ground, especially in autumn at the beginning of the rainy season. Around the same time, hunters found that two tasty species of animals—goats and sheep—could be controlled, with the help of a dog and fertile pastures, to live according to human desires to produce milk, meat, wool, and fertilizer for the crop fields. Offspring could be selected for reproduction from among the best of the herd (see Table 2.1 for a summary of the earliest domesticated crops and livestock). Thousands of innovations followed, including:

a. a third and fourth species of animal (pigs and cattle, which could be used for heavy farm labor),
b. a few new crops (olives, barley, and chickpeas),
c. ways of storing last year's crop to prevent spoilage, and tide over a poor harvest,

d. tools for more efficiently clearing areas to be planted,
e. social rules for sharing labor at planting and harvest time, and the crops that labor produced,
f. methods for cooking the grains and meat to make them more digestible and tasty.

The quintessential human economic activity of farming had been born and, with it, the ability to manipulate an ecosystem to produce 10-100 times as much food per acre as hunting and gathering could provide.

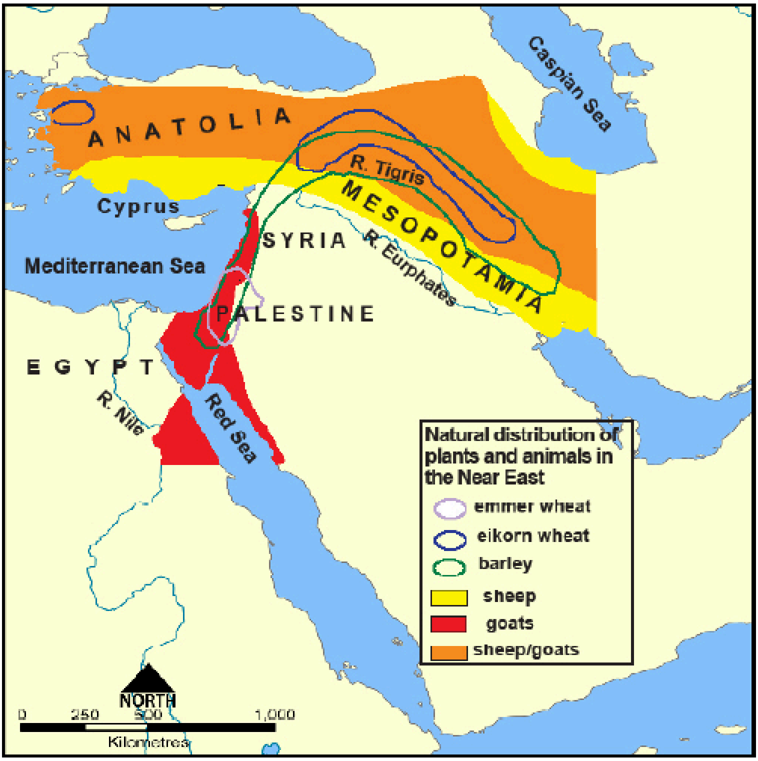


Figure 2.3. The Fertile Crescent showing the natural distribution of the earliest domesticated crops and livestock.

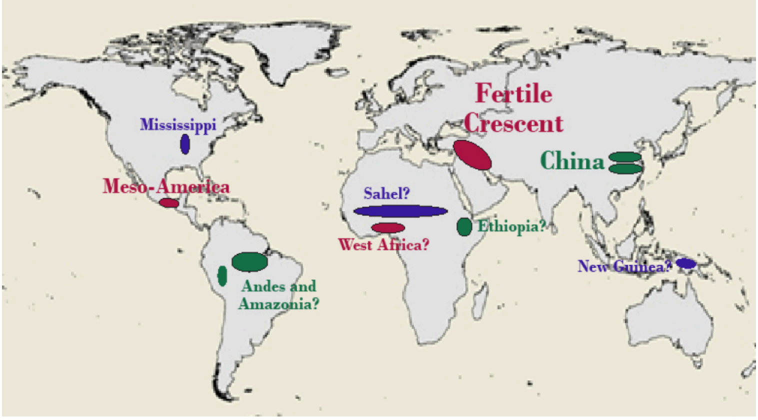


Figure 2.4. Map of likely locations of first domestication of major crops. Question marks indicate uncertainty. Font size indicates relative importance. .

A few centuries later, agriculture also developed, probably independently, in the Wei River Valley, a tributary of the Yellow River in what is now central China. The crops were millet, followed by water-loving rice, then soybeans, and the pig was the primary livestock, later augmented by the chicken.

Diamond argues that these two fountainheads of "western" and "eastern" civilization, respectively, were favored because these were the home ranges of the very few species of plants and animals on Earth that can be successfully domesticated for agriculture. Only four other instances where agriculture developed independently have ever been documented, and none of them has the variety of crops and animals of the Fertile Crescent or China:

1. New Guinea, based on sugar cane and bananas,
2. the Sahel, just south of the Sahara Desert in Africa, based on a grain called sorghum (or milo),
3. the Andes Mountains of South America, based on the potato and the similar root crop manioc, along with the camel-like llama,
4. Mesoamerica based on the three sisters of corn, beans, and squash (Figure 2.4).

Other regions, of course, had plenty of animal and plant species, but only a very few have been successfully domesticated, even in the 21st century (fortunately, one of them is the coffee bean native to Ethiopia). To this day, five grains (wheat, rice, corn, barley, and sorghum) alone provide half of all human food calories. If soybeans, potatoes, sweet potatoes, manioc, sugar cane, sugar beet, and bananas are added, the total climbs to over 80 percent. Just five species of animals—cattle, goats, sheep, pigs, and chickens—dominate world meat production. These heartlands of agriculture, especially the Fertile Crescent and China, loom large indeed because they had the plant and animal species upon which agriculture could be founded.

Table 2.1. Earliest domestication of major agricultural crops and livestock.

Crop Species	Years Ago	Geographic Location
wheat	10,500	Southwest Asia
pea, olive	9,500	Southwest Asia
rice, millet	9,500	China
sugar cane, banana	9,000	New Guinea
sorghum	7,000	Sahel
corn, beans, squash	5,500	Mesoamerica
potato, manioc	5,500	Andes, Amazonia
Animal Species		
dog	12,000	SW Asia, China
sheep, goat	10,000	Southwest Asia
pig	10,000	China, SW Asia
cow	8,000	SW Asia, India
chicken	8,000	SE Asia, China
horse	6,000	Ukraine
donkey	6,000	Egypt
water buffalo	6,000	China
llama	5,500	Andes
camel	4,500	Cen. Asia, Arabia

Source: Diamond, 1999

In fact, the world today produces almost no food from crops or animals that were domesticated since Columbus stumbled into the Americas in 1492. Take the typical Midwestern American farm. The three most important crops are corn, first developed 5,500 years ago in Mesoamerica (today's southern Mexico and Guatemala); the soybean, first developed in China even earlier; and wheat (Fertile Crescent, 10,000 years ago). The primary livestock are pigs (China and the Fertile Crescent, 10,000 years ago), and cattle (Fertile Crescent, 8000 years ago), though I hear that goat meat and milk (Fertile Crescent 10,000 years ago) are suddenly popular, as if this was something new. They were all brought to the fertile Midwest by people who had inherited the agricultural traditions of these heartlands of civilization, with crops and livestock improved over hundreds to thousands of generations of artificial selection—breeding from the best seeds and sires, with "best" defined by what the farmer wants.

The Fertile Crescent constellation of crops and livestock came to Egypt and India, adjacent to the Middle East, about 9,000 years ago, and from east to west across Europe from 8,000 to 6,000 years ago. Chinese-style agriculture spread to Korea and Japan about 8,000 years ago. Note that these vast lands are all contiguous and lie in the northern subtropics (about 23–35°N latitude) to midlatitudes (about 35–50°N latitude) where the Fertile Crescent and Chinese crops and livestock were originally found wild. In this way, Eurasia jumped way ahead of other world regions in developing an expanded human ecological niche, and therefore much larger populations, based on agriculture.

This did come with a terrible price, however. If you live close to cows and pigs, dogs and ducks, you will eventually catch their diseases (Table 2.2). Smallpox, measles, tuberculosis (all from cattle), and influenza (from ducks and pigs) raged through the ancient world killing untold millions of people.

Table 2.2. Animal origins of some major human diseases.

Human disease	Animal
measles	cattle
tuberculosis	cattle
smallpox	cattle
flu	pigs. ducks
pertussis	pigs, dogs

`Source: Diamond, 1999`

Generation by generation, however, those whose genes gave them an immune system that better withstood these onslaughts were more likely to survive and pass on those traits to later generations. The intermixing of peoples across Eurasia also provided a degree of genetic variation, missing in the

Americas as we will see, that improved the chances that at least some of the population would be resistant to any one epidemic.

With this great increase in human population came the potential for technological innovation (e.g., pottery, metallurgy), along with the necessity of maintaining the agricultural enterprise. The replacement of a nomadic life by sedentary, fixed settlements allowed people to build permanent structures. A division of labor and social stratification followed. Written language and the number system were first developed to keep track of who had paid their tribute in crops and livestock to the dominant military classes.

One innovation, metallurgy, was particularly potent because it allowed first copper (which is very easily fashioned into useful shapes) and later iron (which is more difficult to work but very abundant) to be used for everything from cooking knives and saws to plows and nails, to swords (and armor against them). Together with the domestication of the horse (first in what is now Ukraine about 6,000 years ago), metal swords gave agricultural societies a huge military advantage over hunting and gathering societies. An even more potent weapon was the diseases that agriculturalists had long shared with their livestock, but to which hunters and gatherers had never been exposed. The result was that every region with good agricultural potential was taken over by farmers, pushing hunters and gatherers to the margins of deserts, tropical forests, mountains, and the arctic where climate and soils needed for agriculture to thrive are lacking.

Both Diamond and Crosby utilize this explanation to explain why European explorers and conquistadors in the 15th–18th Centuries were able to conquer all but the most tropical and most arctic parts of three continents (South America, North America, and Australia) despite being outnumbered and sacrificing the home field advantage. (We'll leave it to others to explain why they were motivated to do so.) They had an insurmountable military advantage based on steel weapons (swords and later guns), wooden sailing ships, and a powerful, fast, and compliant military vehicle known as a horse. They had written languages and national-level military organization to supply and coordinate their armies.

Most of all, they had germs. The arrival of Europeans was a catastrophe for Native Americans, and the greatest killer of all was not guns or steel swords—it was smallpox.

Its effects are terrifying: the fever and pain; the swift appearance of pustules that sometimes destroy the skin and transform the victim into a gory horror; the astounding death rates, up to one-fourth, one-half, or more with the worst strains. The healthy flee, leaving the ill behind to face certain death, and often taking the disease along with them. The incubation period for smallpox is ten to fourteen days, long enough for the ephemerally healthy carrier to flee for long distances on foot, by canoe, or, later, horseback to people who know nothing of the threat he represents, and there to infect them and inspire others newly charged with the virus to flee to infect new innocents (Crosby 1986, p. 201).

Unfortunately, smallpox did not act alone. Measles, diphtheria, whooping cough, chicken pox, bubonic plague, malaria, typhoid fever, cholera, yellow fever, scarlet fever, influenza, and other Eurasian diseases found virgin ground among the Native Americans. Together, it is estimated they killed as much as 95 percent of the population, reducing the North American population from 20 million or more in 1500 to only about one million in 1700, in what can only be described as a holocaust. All those sci-fi movies you've seen about alien invaders and runaway plagues—to the Native Americans, that's what actually happened, though the greater part of it was, in fact, inadvertent, legends of whites giving smallpox-laden blankets to Indians as gifts notwithstanding.

By 1800, Europeans were the majority population on all three "new world" continents and the Fertile Crescent agricultural package controlled these vast Neo-Europes, as Crosby calls them. Adding immeasurably to the European's advantage, Eurasian plants and animals often ecologically outcompete North America species, and nearly always outcompete South America and Australian species that have evolved separated from Eurasia since the dinosaurs went extinct 65 million years ago. Razorbacks and wild boars—domesticated pigs gone wild—exploded in population to become the dominant animals of North American and Australian forests as they earlier had on the islands of the

Atlantic and Pacific. Wild cattle and horses similarly thrived in North America and Australia and exploded in the South American pampas to fill the prairies. Eurasian rats and many species of fast-spreading plants also found these three continents much to their liking. In Australia, rabbits multiplied in the billions in the absence of owls, hawks, coyotes, and cats to hunt them. Nearly every invasive species that North American ecologists struggle to control is of Eurasian origin, from the zebra mussel to kudzu. This is what Alfred Crosby terms *Ecological Imperialism: The Biological Expansion of Europe* in his wonderfully written 1986 book.

While Europeans have expanded their ecological niche over the greatest geographical extent, Asians and Africans who developed agriculture several thousand years ago have also expanded their range. The Austronesian expansion originating in southern China has brought Asian languages, crops, and livestock to every habitable scrap of land in the Pacific, even as far as Easter Island in the Western Hemisphere and New Zealand's cool marine climate where the Maori first landed about 1,000 years ago. The Bantu of West Africa, who first domesticated sorghum some 7,000 years ago, have similarly spread at the expense of hunters and gatherers across that vast continent, reaching South Africa just ahead of the Dutch and English colonists. These medium-scale examples reinforce the Crosby-Diamond thesis that ecological niche expansion through agricultural development and the conquering of hunter-gatherers by agriculturalists has been a central theme in human environmental history. It also looms large as a central feature of a 21st century world where European descendants are in the majority and European institutions dominate not only in Europe, but also in North and South America and Australia.

Lesson 3: Undermining or Overshooting Your Ecological Niche Is Bad News

The story thus far has been one of overall human ecological success, especially for the inheritors of the Neolithic Revolution. Environmental history is also littered with failures, however, some of them locally catastrophic. Again, Jared Diamond's work is fundamental. In his 2005 book *Collapse*, he chronicles a number of cases where human societies became locally overpopulated, undermined their natural resource base, failed to address the issue, and fell apart in a downward spiral of starvation and violent conflict.

Perhaps the archetypal example is Easter Island, an isolated island of 66 square miles situated 2,300 miles west of Chile in the southeast Pacific and 1,300 miles from any other inhabitable island. Easter Island, famous among archaeologists for its giant stone statues, was discovered by the Polynesians. Originating from Asia as part of the Austronesian expansion, Polynesians populated the entire tropical Pacific by following birds to new islands paddling outrigger canoes—with a cargo of bananas, taro, sweet potato, and sugarcane as seeder crops as well as pigs as seeder livestock.

At first, they thrived on Easter, but in reaching an overly dense population of 15,000–30,000, they completely deforested the island, cutting down the very last tree, to expand crop production. In doing so, they undermined those agricultural efforts through soil erosion while depriving themselves of the wood needed for fishing canoes—and cutting off their own escape. For this reason, Easter Island serves as a chilling metaphor for the environmental Armageddon that inspires doomsday films and science fiction books.

The Easter Islanders' isolation probably explains why I have found that their collapse . . . haunts my readers and students. The parallels between Easter Island and the whole modern world are chillingly obvious. Thanks to globalization . . . all countries on Earth today share resources and affect each other, just as did Easter's dozen clans. Polynesian Easter Island was as isolated in the Pacific Ocean as the Earth is today in space. When the Easter Islanders got into difficulties, there was nowhere to which they could flee, nor to which they could turn for help; nor shall we modern Earthlings have recourse elsewhere if our troubles increase. Those are the reasons why people see the collapse of Easter Island society as a metaphor, a worst-case scenario, for what may lie ahead of us in our own future (Diamond 2005, p. 119).

When European explorers first found Easter Island in 1722, all 21 tree species had been extirpated (gone extinct locally), and by 1872 only 111 islanders remained, less than one percent of the population when the statues were raised.

While Easter Island represents perhaps the purest case recorded in environmental history of human populations overshooting their local carrying capacity resulting in social collapse, it is, unfortunately, not the only one as we will see. In his study of these cases, Professor Diamond distills five key factors that contribute to environmental collapse:

1. environmental damage, especially of ecological resources critical to agriculture,
2. climate change, especially drought,
3. the encroachment of hostile neighbors that increase pressure and usurp resources,
4. the loss of friendly trading partners that had fulfilled essential needs, and
5. an inadequate or ineffective social response to these challenges.

Each of these factors comes into play to different degrees in different times and places; for example, at isolated Easter Island, 1 and 5 were the primary driving factors.

Figure 2.5. Map of Mayan area.

While Easter Island represents a microcosm, the Maya are a mesocosm (the prefix meso means medium-sized, larger then micro, smaller then mega) of Diamond's five factors. The Maya, perhaps the pinnacle of pre-Columbian civilization, thrived in the Mesoamerican agricultural heartland, straddling what is now southern Mexico, Belize, and Guatemala (Figure 2.5), reaching its zenith of temple building, hieroglyphics writing, astronomy, and calendar systems in the 8th century when it attained a population estimated at 3–14 million. When the Spanish conquistadors arrived in the 16th century, however, it was the Aztecs of the Valley of Mexico, not the Mayans to the south, who represented the height of Native American civilization. The Mayan population had been reduced to only about 30,000, no more than one percent of its peak 800 years prior. The pyramidal temples of Copan, Tikal, and Chichen Itza, which you can still visit today, were overgrown with tropical vegetation.

What happened to the Maya is likely another example of overshoot and collapse. As the populations of this hierarchical agricultural society grew, they expanded corn and bean farming from the fertile valley bottoms to the steep valley slopes by removing the forest. Soil erosion not only undermined crop productivity on the hills, despite some attempts at terracing and raised fields, but also filled the valleys with infertile sand. Then came repeated drought and crop failures. Environmental refugees fled the southern regions for the Yucatan, but that drier region could not accommodate them. Leadership fractured. Instead of reducing human fertility and augmenting food supplies, stressing soil and forest conservation, the bow-and-arrow was invented, multiplying the human cost of conflict among clans and tribes. We can hypothesize that a similar overshoot and collapse occurred about 10,000 years ago when the first wave of Native Americans prospered and multiplied in virgin hunting grounds, only to be reduced by starvation when those herds were decimated.

While we have seen how the Neolithic Revolution agricultural package spread from the Middle East to India and Europe and from there to the Americas and Australia, back in the original homeland, problems similar to those the Mayans faced were grinding away. Arid (dry) environments are inherently more fragile than humid (rainy) ones; and the soil has a long memory. The Middle East and North Africa has always been short on rainfall, but the deserts themselves are a human creation born of centuries of overgrazing and the accumulation of salt in soils through mismanaged irrigation. Soil erosion on the hillsides of the Mediterranean lands was a contributing factor in the fall of Rome. The slow historical rise of northern and western Europe over the Middle East and Mediterranean is partly due to the greater resilience of soils in Europe's cool, moist climate and their careful management through traditional animal husbandry that places livestock, crops, and soil in a mutually beneficial, and thus sustainable, relationship. Crops feed the animals, who renew the soil with manure to nurture the growth of new crops.

Rather than tell that very long story in depth, let us turn our attention to two more recent examples of environmental collapse—the Dust Bowl of the 1930s in the American Great Plains and the ongoing demise of the Aral Sea in Central Asia.

America's Greatest

Environmental Collapse: The Dust Bowl

Zebulon Pike, who explored the southern part of the Louisiana Purchase following Lewis and Clark's more famous expedition, named not only Pikes Peak in the front range of Colorado, but also the Great American Desert in what we would now call the southern Great Plains (Figure 2.6). Stretching from north Texas to southwestern Nebraska, the semiarid southern plains offered a thin veneer of fertile soils protected by a sea of grass but almost completely lacked both trees and streams. "Miles to water, miles to wood, and only six inches to hell" (Egan 2006, p. 26) was the 19th century description of a land still controlled by the Comanche and Apache tribes, whose fabled skills on horseback were honed hunting bison with bow and arrow. Manifest destiny, however, would not leave this land to the Native Americans. The buffalo were exterminated to starve out the Comanche who were then rounded up and sent to the short-lived reservation that was soon to become Oklahoma. Cattle ranchers followed.

World War I (1914–1918) and the "Roaring Twenties" brought uncommonly generous rains to the southern plains and a belief that rain will follow the plow. The regional economy boomed on plentiful wheat harvests as America gained its first experience as the world's greatest food exporter. Southern plains farmers got rich, but the grass—whose tangled roots and dense carpet protected the fragile soil from the relentless wind and from the torrents of rain followed by extended drought—disappeared. Inevitably, beginning in 1932, the rains failed, and with them the crops of winter wheat that farmers plant in the fall and harvest in early summer. Exposed to the wind, the dry, unprotected soils blew away in a process known simply as wind erosion and, in the extreme form the southern plains would witness, desertification. Soil blew into drifts against fences and houses, forming dunes, even on lands that held their grass cover, smothering it. Dust blew into the stomachs of cattle and the eyes of chickens. Horses panicked. Only the birds could fly fast enough to outrun the dust storms.

Humans could not, even in the Model A and Model T Fords they had purchased with their wheat profits, because drifts would block the roads, dust would choke the carburetors, visibility was reduced to a few yards, and static electricity would short the engines or knock people to the ground if they touched the car or shook hands. In 1933 there were 70 days of dust storms; in 1934 there were 54, but things were not getting better. In the first four months of 1935, there were 117. Not only were the grasslands, crops, and soil fertility being destroyed but also the most essential service nature provides—breathable air—was being sacrificed to the relentlessly penetrating dust. Emergency hospitals in school gyms set up by Roosevelt's New Deal filled with patients suffering from "dust pneumonia"—lungs hopelessly damaged by the abrasive dust that worked its way through walls, windows, doors, wetted sheets, and surgical masks into the air sacks in the lungs of its victims. The sun was blocked and dust settled on windowsills, doorways, cars, and carpets in Chicago, Boston, New York, and the capital in Washington, DC. The heat would not relent and the rains would not come, no matter how much money people wasted on conmen's empty promises to seduce water from the cloudless skies.

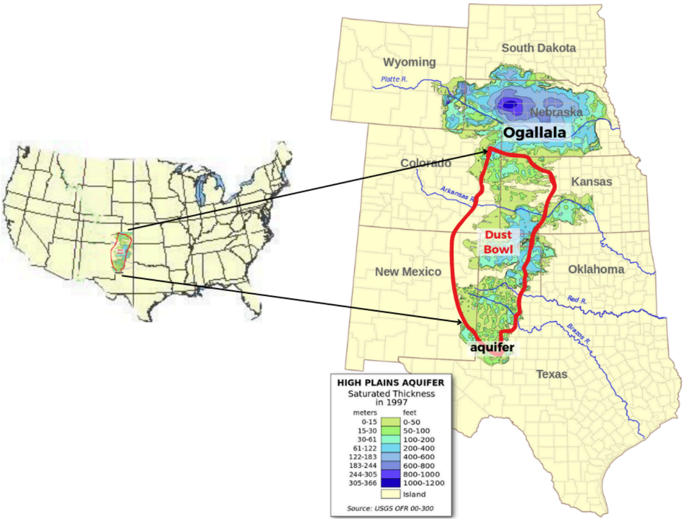


Figure 2.6. Map of the Dust Bowl region and Ogallala aquifer.

The High Plains lay in ruins. From Kansas through No Man's Land (the Oklahoma panhandle) up into Colorado, over in Union County, New Mexico, and south into the Llano Estacado of Texas, the soil blew up from the ground

> or rained down from above. There was no color to the land, no crops, in what was the worst growing season anyone had seen. Some farmers had grown spindles of dwarfed wheat and corn, but it was not worth the effort to harvest it. The same Texas Panhandle that had produced six million bushels of wheat just two years ago now gave up just a few truckloads of grain. In one county, 90 percent of the chickens died; the dust had gotten into their systems, choking them or clogging their digestive tracts. Milk cows went dry. Cattle starved or dropped dead from what veterinarians called "dust fever." A reporter toured Cimarron County, OK and found not one blade of grass or wheat (Egan 2006, p. 140-41).

Then, on April 14, 1935 in the fourth year of drouth (the local pronunciation of "drought"), with farmers in bankruptcy, hunger and poor health rampant, came Black Sunday. Starting in the Dakotas as a spring cold front came bearing down on the plains, the purple-black wall of 300,000 tons of dust raced southwards at speeds exceeding 40 mph. Anyone caught outdoors was unlikely to survive.

The Great Plains lost 850 million tons of soil that year, 480 tons per acre, 100 times more than what is considered a soil erosion "problem." Soil scientist and master politician Hugh Hammond Bennett made his fame on the Dust Bowl, arguing that it was a disaster authored by unsustainable farming techniques. Bennett asked Congress for funds to remedy the agony in the southern plains, not just on any day, but on April 19, 1935 as the dust clouds from Black Sunday settled on Washington. As the sunny day turned to gloom out the windows of the U.S. capital building, he spoke to Congress of soil conservation techniques and the need for the Federal government to fund them. The Soil Conservation Service (now Natural Resources Conservation Service) was born.

Most people stayed the course, but a million people left the Great Plains in the 1930s— environmental refugees who at least had a large country to absorb them, if not on favorable terms (as told by John Steinbeck of "Okies" fleeing to California in *The Grapes of Wrath*). Dust storms continued—134 in 1937—and when a few rains finally grew some grass, swarms of billions of grasshoppers or tens of thousands of rabbits consumed it all. Nature had lost all balance.

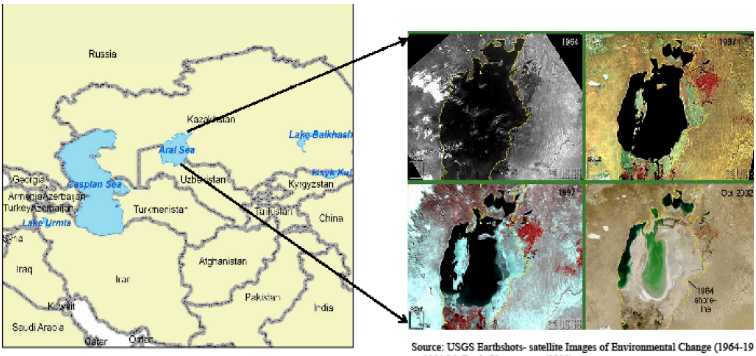
Rains returned in the 1940s and the land partly recovered, thanks largely to the Soil Conservation Districts that Bennett's work had helped form, and which still thrive today. Since 1986, the Conservation Reserve Program has paid farmers to keep permanent grass cover on the most highly erodible lands. On better lands, a new unsustainable resource has been tapped— groundwater.

The Ogallala aquifer (Figure 2.6) underlies nearly the same territory as the Dust Bowl, an enormous resource of approximately one quadrillion (10^{15}) gallons that supplies a third of all irrigation water in the U.S. With this water subsidy, southern plains farmers have been able to grow not only wheat but also the more profitable and water-demanding corn, soybeans, and cotton. In pursuing irrigation so vigorously, however, that resource too is failing. Water tables have fallen throughout the Ogallala south of Nebraska, depleting the aquifer at a stupendous rate of over 3 trillion (10^{12}) gallons per year. Some farmers have found it costs more to pump the water from deeper and deeper wells than it is worth in increased crop yields and have reverted to dry farming or cattle ranching. Another unsustainable southern plains crop boom is currently dissolving.

Finally, there is the relentless wind itself. The former Dust Bowl today boasts the largest fleet of wind turbines in North America, with Texas ranking first, Oklahoma third, and Kansas fifth among U.S. states as of 2020. Unlike the fragile soils and the depletable fossil waters of the Ogallala, wind is inexhaustible. No matter how thoroughly it is utilized today, tomorrow's supply cannot be diminished. Perhaps the southern plains will have finally found a sustainable utilization of natural resources by delivering renewable electricity to the transmission grid that serves the great cities of Texas and neighboring states. Even for the Dust Bowl, it is never too late to change to a more sustainable course.

The World's Greatest Current Environmental Collapse: The Aral Sea

In 1960 the brackish (less salty than the ocean, but not quite fresh) Aral Sea of Soviet Central Asia was the fourth largest lake in the world (behind the Caspian Sea, Lake Superior, and Lake Victoria) at 17,600 miles^2 (68,000 km^2). It supported the world's largest inland fishery at over 50,000 tons caught per year and 60,000 jobs (Figure 2.7). Wildlife was abundant; it was the muskrat king of the world with 500,000 pelts produced per year. Like Great Salt Lake or the Caspian Sea, the Aral Sea has no outlet to the ocean. Its water level is determined by a balance between, on the one hand, the Syr Darya and Amu Darya Rivers (plus a little groundwater) that flow into it—and rainfall that falls upon it— versus evaporation from the lake surface on the other. This matches the simple budget for any water body (even your body): input minus output equals change in storage.



Source: USGS Earthshots- satellite Images of Environmental Change (1964-19
and NASA Earth Observatory (2002)

Figure 2.7. Aral Sea shrinkage from 1964 to 2002.

By 2007 the Aral Sea had been reduced to three briny lakes totaling less than one-fourth of its original area, holding a water volume only 10 percent of what it was in 1960. The balance has been broken by drastically reduced inflows from the Syr Darya and Amu Darya rivers. Salinity has increased from 1.0 percent, surpassed the ocean's 3.0–3.5 percent, to reach 10 percent and climbing in two of the three residual lakes. The salt and loss of aquatic habitat has not only killed every single fish but also helped drive 135 of 173 animal species into local extinction. The regional climate has become more arid with hotter summers and colder winters.

The Islamic Uzbeks, Turkmens, and Kazakhs of the region have fared nearly as poorly. The thriving fishing port of Muynak is now over 60 miles from the shore and, like the region of Kazakhstan known as Karakalpakstan, a hotbed of tuberculosis, hepatitis, and respiratory and diarrheal diseases. Like in the Dust Bowl, the wind carries 43 million tons of dust per year, but in the now dry Aral Sea lake bed, sediments are laced with salts and pesticides, including DDT and PCBs, largely from cotton farming.

Salts are not the most poisonous contaminants in public drinking water supplies in a region with high rates of kidney and liver diseases. Vozrovhdeniya (Renaissance) Island in the Aral Sea was used by the Soviets for experiments in biological warfare using smallpox and anthrax. With the receding waters, it is no longer an island. The U.S. government has stepped in to prevent human exposure to these killers. Life expectancy in the region has fallen and infant mortality has tripled with respiratory problems and diarrhea from drinking contaminated water as the major culprit. Rates of mental retardation have soared, half the population suffers from symptoms of chronic stress, and over 100,000 have become environmental refugees. How did this happen? In a word—cotton.

In the 1960s, Soviet economic planners needed an industry to employ the rapidly growing Turkish and Mongolian populations of its Central Asian Republics (Figure 2.7). With the warmest climate in the Soviet Union, relatively fertile steppe soils, and the Syr Darya and Amu Darya fed by the snows and glaciers of the 20,000-foot high Hindu Kush Mountains, Soviet planners saw the potential for a cotton industry that could serve the needs of the Soviet Union's quarter of a billion people, with the surplus to earn cash as an export commodity. They built the Karakum Canal across Turkmenistan and other smaller canals to irrigate the deserts. Irrigation methods were wasteful, but the cotton earnings grew while, as Soviet planners had predicted, the Aral shrank due to huge increases in evaporation and transpiration (water used by plants) of the two rivers' waters. Like the Dust Bowl, the Aral Sea collapse is rooted in unsustainable agricultural practices.

Plans to divert large proportions of the great Ob River, and its tributary, the Irtysh, from the Arctic Ocean to supplement the Aral were completed and construction was about to begin when the Soviet Union collapsed in 1989–1991 making

Russia, Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan, and Tajikistan separate countries. The Aral Sea suddenly became an international river basin (Figure 2.7). Not only were the great river diversion schemes cancelled, but the remnants of the Aral lie largely in Kazakhstan, while the headwaters of the Syr Darya lie in Kyrgyzstan. The headwaters of the larger Amu Darya lie in Tajikistan, and it flows through Turkmenistan and Uzbekistan where a contraction of the cotton industry is not being contemplated. The regional cooperation to restore the Aral that may have been possible under Soviet command is thus increasingly unlikely. As Diamond would point out, friendly neighbors that may have generated an effective response are now less motivated to help solve the problem.

Kazakhstan has made some progress on its own by improving irrigation canals and building a dike to keep Syr Darya waters in the smaller north Aral. With water levels rising from 98 feet above sea level to 125, salinity dropping, and fish returning, initial signs are hopeful that they can salvage this remnant of the original Aral even as the larger sea to the south disappears entirely. For the five million residents of the Aral Sea region, however, the future is bleak as none of the major solutions to the world's greatest current ecological collapse—northern river diversions, huge reductions in water use for irrigation—are being seriously contemplated. This is despite so many scientific studies that locals complain that if every scientist came with a bucket of water, the Aral would be full.

Lesson 4: Disaster Can Be Avoided

An often-heard complaint is that the environmental literature delivers an oversupply of bad news, that it is an enclave of pessimists predicting doomsday. While our environmental challenges are steep, there is both some truth to this complaint and a danger in undue pessimism. Overly negative assessments of the state of the world and dire predictions about its future can inspire resignation or a have-fun-while-you-can attitude and thereby undermine the very commitment to the future that is the key ingredient in solving environmental problems and achieving sustainability. While it is true that one must correctly diagnose a problem before it can be solved, it is also helpful to learn about success stories because they provide the models we may wish to emulate. Fortunately, there are so many examples where natural resource problems have been overcome that the difficulty is in choosing from among them those that reveal larger principles. Below we will take a brief look at four different kinds of natural resource problem-solving that environmental history teaches us:

a. substituting an increasingly scarce resource with a more abundant one,

b. replacing a resource use system that damages or pollutes the environment,
c. developing and applying technology for cleaning up pollution, and
d. the most difficult problem of all, changing human behavior.

Natural Resource Substitution

The symbol of the 18th century English industrial revolution is the steam engine. Employed in textiles, metallurgy, and other new mass-production industries, steam engines required large amounts of fuel, which the English supplied by turning trees into charcoal. England was being deforested because the demand for industrial fuel was exceeding the rate at which photosynthesis could supply it through tree growth. The answer was to tap the chemical energy accumulated by photosynthesis over millions of years and stored in fossil fuels, especially coal. By the early 19th century, coal exceeded charcoal as an industrial fuel; charcoal was phased out and England's forests began to recover.

Contemporaneously, in a European and North American society that was first embracing universal education and literacy, but had not yet invented electricity, people illuminated their houses using oil-filled lamps, enabling them to read books (and do their homework) well into the evening.

The lamps were filled with whale oil derived from the blubber of those enormous marine mammals. Like trees, whales are a renewable resource, but the forest and marine ecosystems that produce these natural resources have very limited capacities that were being quickly exceeded by a world with increasing numbers of people utilizing new energy-intensive industrial technologies. Again, the answer lay in the storehouse of chemical energy from past ecosystems available in fossil fuels. Starting in northwest Pennsylvania in 1859, for the next half-century the rapidly growing oil industry was built on the demand for fuel to provide illumination in lamps. In this way it was oil, a nonrenewable resource, that saved the whales, a renewable resource, just as it was coal that saved the English forests.

Within my own lifetime, though perhaps not yours, natural resource substitution has played a key role in overcoming the tightening market for oil, especially imports from the Middle East. In 1972 oil sold for only $2.90 per barrel (a barrel is 42 gallons of oil because that's the size of the first wooden barrels in northwest Pennsylvania) and was an economical way not only to propel an automobile, but also to generate electricity and heat buildings. Then in 1973, in the context of the Yom Kippur War between Israel and its Arab neighbors, the Organization of Petroleum Exporting Countries (OPEC) imposed an embargo on nations supporting Israel, including the U.S. The sudden reductions in oil supply not only multiplied the price for a barrel of oil, and thus a gallon of gasoline, but they caused chaos as American drivers waited in long lines, hoping that there would be gasoline left when they finally reached the pump. In fact, the 1973 OPEC oil embargo is the central event that focused world attention on the modern prospects of natural resource scarcity and perhaps even induced a degree of paranoia in Americans that gasoline supplies will suddenly disappear. How else can one explain that on September 11, 2001, as TV news reports showed terrorists crashing jet planes into the World Trade Center towers, millions of Americans immediately went to the gas station to fill up?

In 1965 oil supplied 65 billion kilowatt hours (6.1 percent) of U.S. electricity, climbing to 365 billion kilowatt hours (16.5 percent) in 1978 on the eve of the Iranian Revolution when oil prices spiked again from $11 to $34 per barrel. Fortunately, in generating electricity, oil has many substitutes. By 1995, oil use had dropped to 75 billion kilowatt-hours, using only oil left from the refining of gasoline, only 2.2 percent of the U.S. total as coal, natural gas, nuclear fission, and hydroelectricity substituted for oil.

In summer 2008, the price of oil skyrocketed, reaching $147 per barrel in June, most of which went to power vehicles, only to crash to under $40 per barrel by the end of the year. Can we again find a substitute for an increasingly scarce resource with volatile and rising prices? Biofuels such as ethanol from corn are a possibility, but, as we will see in Chapter 8, this yields meager net energy gains and places the burden of our industrial energy needs back on the current photosynthetic capacity of ecosystems—reversing the charcoal to coal and whale oil to petroleum examples cited above. Remaining domestic oil resources offshore and in the arctic could be tapped, but these speculative resources take at least a decade to find and bring to market, and it is uncertain that substantial resources will ever be found. The 2010 Deepwater Horizon accident in the Gulf of Mexico clearly illustrates the risks.

Can the automobile be reengineered to run effectively on electricity, thus tapping into coal, gas, nuclear power, hydroelectricity, wind, and solar power, and so forth as possible fuels? Hybrid cars, first made popular by the Toyota Prius introduced worldwide in 2001, use onboard electricity generation to augment the gasoline engine and boost fuel efficiency by up to 50 percent. Plug-in electric cars, starting with the Chevy Volt in 2010, can be plugged in overnight. My 2018 Prius Prime travels 20-30 miles on electricity before gasoline kicks in and thus averages nearly 80 miles per gallon overall. Because the majority of driving occurs around town on a daily basis, plug-in hybrid technology can substitute electricity for a large proportion of gasoline use. Fully electric cars, first made popular by Tesla, are now becoming common, with most major auto companies offering lithium-ion batteries with ranges exceeding 200 miles.

Environmental Substitution

A second category of resource problem-solving is substituting a more environmentally friendly natural resource use system for a damaging or polluting one. Though probably not informed about the collapses in Easter Island and the Maya, the Japanese were able to turn a disaster of deforestation and soil erosion into a success of reforestation. Suffering from severe deforestation in the 17th and 18th centuries, as population increases (and therefore the need to clear forests for agriculture) combined with the predominant use of wood for both energy and construction, the Japanese Tokugawa regime implemented strict forest use regulations.

Today, the densely populated, affluent country enjoys 74 percent forest cover but is the leading importer of forestry products with 18–22 million tons of tropical hardwood imports annually in the early 1990s compared with domestic production of only 5 million tons in 1995. The leading source of imports is Indonesia, which exported over 12 million tons of sawed and raw logs and plywood to Japan each year from 1990 to 1995. As a result, Indonesia lost nearly 4,000 square miles of forest per year in a region second only to the Amazon for species diversity. By importing most of its forest products, Japan has gained access to the natural resource value of Indonesian forests while simultaneously preserving the ecological and cultural services provided by its domestic forests. These services accrue to Japan, as flood protection, soil binding, wildlife habitat, recreation, and aesthetics, rather than to Indonesia.

In the Tokugawa period, Japan also deemphasized agriculture as a means to supply protein to its population and took to the seas as one of the world's great fishing nations. While this shift in food sources helped save the Japanese soil and forests, it placed new burdens upon ocean fisheries, a resource the whole world shares. Thus, Japan has avoided the outcome of Easter Island and the Maya by terminating unsustainable forestry practices at home, but the substitutes they have found may be equally unsustainable – if for different reasons and for different human populations.

As anyone who has watched *Mary Poppins* (admit it, you've seen it) can attest, coal is a dirty fuel that only Dick Van Dyke could be moved to dance about. The rest of us just hope it doesn't end up in our Christmas stocking. Nevertheless, many of the world's great cities, not only London a century ago, have relied upon this abundant fossil fuel to heat homes and cook meals, and many still do. In particular, the rapidly growing cities of India and China are heavily dependent on coal, with the result that the world's 50 most polluted cities lie in these countries. Like London, American cities were also reliant on coal to heat buildings until the mid-20th century. Clean cities, like New York and Boston, were those that burned hard anthracite coal from the seams of northeast Pennsylvania upon which the cities of Wilkes-Barre and Scranton were founded.

Dirty cities, like Cleveland and Chicago, were those that burned softer and more abundant bituminous coal.

Fortunately, all these cities began to enjoy markedly better air quality in the 1930s when coal was replaced by cleaner-burning natural gas, delivered through high-quality steel pipelines from fields in the south central region of the country to furnaces and stoves in each home and public building. Emissions of sulfur, soot, mercury, radioactivity, and carbon dioxide from space heating all plummeted—though just in time to be replaced by automobile exhaust, which was, in turn, improved through the use of catalytic converters beginning in the 1970s. The question for us is whether we can repeat this history of air quality improvement through technological progress by replacing energy sources that emit greenhouse gases, especially gasoline and coal-fired electricity, with less polluting alternatives. We will explore this issue in depth in later chapters.

Environmental Cleanup Technology

On June 22, 1969, the Cuyahoga River, which runs through Cleveland, Ohio to Lake Erie, caught fire. Environmental disasters like these, which merit extensive media coverage and draw people's attention away from their daily activities, are usually the tip of the iceberg below which lie chronic abuses and nagging syndromes that we ordinarily tolerate or ignore.

This photogenic evidence of pollution, together with widespread emissions of sewage, phosphates, heavy metals, and other more toxic pollutants, however, sparked a movement which resulted in the passage of the Clean Water Act of 1972.

The Clean Water Act introduced wastewater (i.e. sewage) treatment to nearly every town and city in the U.S. and requiring industries to use "best available technology" to remove waterborne pollutants. This resulted in a steady improvement in water quality and aquatic ecosystems in the Great Lakes and major populous rivers like the Hudson, Potomac, and Ohio. It stands as one prominent example of an environmental success story, which too often goes untold, brought about through widespread application of an environmental clean-up technology.

Changing Human Behavior

After a century of plowing the fields annually, Midwestern farmers began to realize in the 1970s that this is simply unnecessary. Use of conservation tillage (leaving crop residues in the field to hold and build the soil and replanting in furrows often less than an inch wide) expanded steadily and, in various forms, was used on about half of all cropland acres in the U.S. by 2017. Saving soil is only part of the benefit; conservation tillage and no-till also saves energy and labor, generally without sacrificing yields. It stands as evidence that people will change time-honored ways of doing things when the evidence is clear that it furthers their own goals and they are empowered to implement a new way of doing things.

When I was a kid, American roadways were littered with every kind of trash from beer bottles to fast food-wrappers and “recycling” was a word that most people had never heard. What had been considered common and acceptable behavior is now considered to be “low life” behavior—where it’s not illegal. Nearly everyone I know now recycles at least some of their used articles and young people take recycling as the standard way of dealing with used bottles and cans and other everyday items. The definition of “normal” behavior has shifted.

Germany, a nation that has taken a leadership role in sustainable natural resource management, has taken recycling to the next level. By charging high rates for trash pickup and landfill disposal on one hand, while requiring stores to take back packaging returned by customers on the other, Germany has created a system where retailers have a strong incentive to minimize product packaging. They are working at the forefront of the phrase “reduce, reuse, recycle.” The result has been a quadrupling of recycling and a halving in solid consumer waste requiring landfill disposal. People can change—again, if the incentives are right and they are effectively empowered.

Americans love their cars—so much so that most visitors to national parks, where the splendors of nature abound like nowhere else, never leave them by more than a few hundred yards. Passenger trains reduce the energy to move people by 90 percent compared to cars and yield enormous benefits in urban land use, saving cities from being composed mostly of roads and parking lots. Mass transit is therefore a key element in achieving natural resource sustainability.

Here again, technology is on the move. The "hyperloop" uses trains powered by magnetic levitation, thus eliminating ground friction, and places them in vacuum tubes, thus minimizing air friction. Speeds exceeding 500 mph appear to be achievable. Uber and Lyft promise small, efficient robot cars in the near future, promising to greatly reduce the need for parking, which currently dominates urban spaces.

Within cities and towns, will the majority of Americans ever accept robot taxis, electric scooters and bikes, buses, street cars, subways, and trains as their primary mode of travel? What if these forms of transport are far cheaper than using the car, if the buses and trains run frequently and to numerous locations, feature comfortable seating, wireless internet access with free access to a menu of movies, uninterrupted cell phone use, and Hollywood spins them as a great place to meet your true love? Are those the right incentives enabling people to change?

Conclusion

This selective examination of environmental history has shown how humans have arisen as the dominant species on Earth by expanding their ecological niche to the point where, collectively, humans are now a force of nature. While there are numerous instances where humans have undermined nature's carrying capacity with disastrous results, there are also numerous cases of effective natural resource and environmental problem-solving ranging from resource substitution to technological innovation to changing behavior. This history has much to teach us as we face the even steeper challenges of natural resource sustainability in the 21st century. How will this history read a century from now? That is a question that we will all answer together. I look forward to watching it unfold and maybe even influencing it. I hope you will too.

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PART II

PART II: NATURE'S ROLE

3.

CHAPTER 3: RELEVANT FUNDAMENTALS OF PHYSICAL GEOGRAPHY AND GEOLOGY

The Earth is a dynamic planet of interacting spheres: the atmosphere, the hydrosphere, the lithosphere, and the biosphere. In Chapter 4, we will focus on the last of these, the biosphere, by taking a look at the fundamentals of ecology. In this chapter, we will examine the nonliving spheres that form the environment in which the biosphere thrives (we hope). We need not try to cover all of the fascinating fields of physical geography nor of geology here but only those parts that bear most directly on natural resources. We will accomplish this primarily by focusing on what are termed *biogeochemical cycles*—the Earth systems for circulating critical materials among environmental components. We will focus on the three most prominent biogeochemical cycles: water, carbon, and nitrogen. Lastly, we will discuss a critical natural resource that emerges when all these cycles come together: soil, the lifeline of the human species.

What is a cycle? We can start with the notions from thermodynamics that matter circulates and energy dissipates. A material cycle is thus a way of understanding the circulation of a particular substance, such as water or carbon or nitrogen, by first examining where the substance is stored—its stocks or pools—and then examining how it moves among these pools—its fluxes or flows. This gives us an understanding of that substance's metabolism, and by looking at how the cycles interact, we can gain a broad scientific understanding of the Earth as a working system. A quantitative approach is helpful since this gives us a sense of relative magnitude, provided we make an effort to grasp the units involved. For example, from daily life you probably have a thorough grasp of temperature in degrees Fahrenheit, people's heights in feet and inches and their weight in pounds, driving distances in miles, and prices of common items in dollars. Here we will expand that quantitative repertoire. We also want to examine trends: which stocks or flows are increasing and decreasing? Are these increases and decreases due to nature or human activity? Beyond this objective approach, we also need to evaluate stocks and flows as well as their trends. Which are valuable resources? Which are environmental problems?

The Hydrologic Cycle

We'll start with the hydrological cycle, with which you have some familiarity, and a unit of measure, the cubic kilometer (km3), that you should take a moment to imagine—0.62 miles long, wide, and deep, weighing 1 billion metric tonnes (we'll use "ton" for an English ton of 2,000 pounds and "tonne" for a metric ton of 1,000 kilograms or 2,204 pounds, 10 percent larger). Figure 3.1 is a simple representation of the Earth's pools of water, with the oceans containing 1,338 million km^3 (Pacific 680 million km^3, Atlantic 313 million km^3 , Indian 269 million km^3, and Arctic 17 million km^3 not counting adjacent seas) 97.2 percent of the world's total. All of it, unfortunately, has a heavy dose of 3.0–3.8 percent salt by weight.

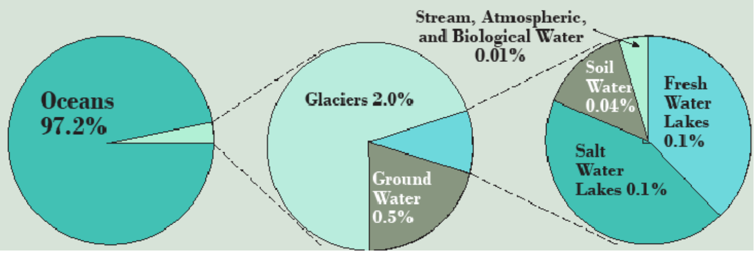


Figure 3.1. Pie Chart of the Earth's water pools or stocks.

Most—24 million km^3 of the 35 million km^3 of the freshwater on Earth—is contained in glaciers, of which 90 percent is in Antarctica, 9 percent is in Greenland, and the remaining 1 percent is scattered in high mountain valleys. The third largest pool is groundwater, 10.5 million km^3 of freshwater plus 12.9 million km^3 of saltwater saturating the pore spaces in rocks and capable of moving slowly and steadily whenever pressure and gravity push it, so long as there is a permeable pathway through the rocks. Permafrost (permanently frozen soils of the arctic and subarctic, especially in Canada and Russia), comes next at 300 thousand km^3. Next is lakes, both saltwater lakes, like Great Salt Lake and the far larger Caspian Sea, and freshwater lakes, where the ten most voluminous exceeding 1,000 km^3 each (Table 3.1) hold over 80 percent of the world's freshwater lake total.

Table 3.1. The world's largest freshwater lakes.

Lake	Location	Volume (km^3)
1. Baikal	Russia	23,600
2. Tanganyika	East Africa	18,900
3. Superior	North America	11,600
4. Michigan-Huron*	North America	8,260
5. Malawi	East Africa	7,725
6. Victoria	East Africa	2,700
7. Great Bear	Canada	2,236
8. Issyk-Kul	Kyrgyzstan	1,730
9. Ontario	North America	1,710
10. Great Slave	Canada	1,580

*Actually one lake with a strait at the Mackinac Bridge

The rest of the pools are small and are only worth mentioning because of their importance in evaluating water as a resource, which is to say there are large flows of freshwater through them and they are accessible for human use. Wetlands and soil moisture hold 17,000 km^3 each, the atmosphere holds 13,000 km^3, rivers hold 2,000 km^3, and living organisms, mostly plants, hold about 1,000 km^3.

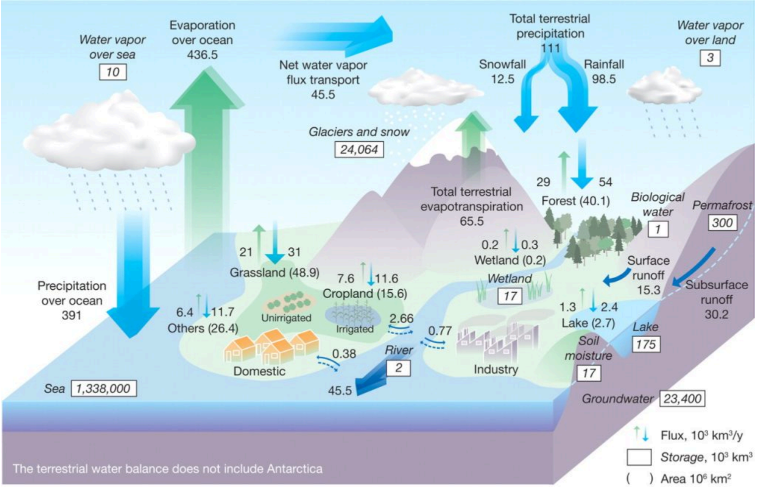


Figure 3.2. Global water flux diagram. Flow volumes are in thousand km^3 per year.

Of equal or even greater importance, and a bit more complex, are the fluxes or flows of water, where the atmosphere and rivers are of central importance. Figure 3.2 from an article in *Science* diagrams these flows among the pools in units of thousands of cubic kilometers per year. On average, 502,000 km^3 evaporate into the atmosphere each year—436,500 km^3 of this by applying solar energy to distill ocean saltwater into freshwater and 65,500 km^3 of this either evaporating from land or transpired by plants into the atmosphere. Because it can be difficult in practice to distinguish evaporation from transpiration, they are often lumped together and called evapotranspiration. This means that the atmosphere exchanges its water pool 39 times each year, calculated as total annual evaporation (502) divided by average atmospheric stock (13). This results in a residence time, or average length of stay, of less than ten days (365/39) compared to the oceans that have a residence time of over 2,500 years. This is calculated by taking the volume of 1,338,000 km^3 and dividing by the annual loss to evaporation of 502 km^3.

Precipitation is 391,000 km^3 over the oceans and 111,000 km^3 per year over land, so the lands have a net gain of 45,500 km^3 of precipitation over evapotranspiration. It is no coincidence that the flow of water down rivers to the oceans is also 45,500 km^3 with about a third of this (15,300 km^3) from surface runoff of rainfall and snowmelt and about two-thirds as base flow (30,200 km^3) from groundwater seepage.

Think a bit more about that equal exchange of a net 45,500 km^3 of water traveling through the atmosphere from the oceans to the land then returning to the oceans as river discharge. During the onset of an ice age, less water is flowing from the land to the oceans down rivers and the glacier pool on land is growing while the ocean pool is shrinking—hence sea level is dropping. At the end of an ice age, the reverse occurs; the glacial pool diminishes as it melts, rivers carry copious quantities of water to the oceans every summer, and sea level rises. Sea level is estimated to have risen by 120 meters (394 feet) at the end of the most recent (Wisconsin) glaciation between 18,000 and 6,000 years ago. In fact, this process is occurring now due to global climate change as we will see.

Still using Figure 3.2, let's look at some human uses of water in the context of the overall hydrologic cycle. Croplands receive 11,600 km^3 as precipitation plus 2,700 km^3 as irrigation and transpire 7,600 km^3 back to the atmosphere. The remaining 6,700 km^3 runs off crop fields to streams and rivers, often carrying pollutants such as fertilizers with it. Industries use less (770 km^3) while domestic applications in homes use only 380 km^3, with most of both returning to its source. We will return to these human uses of water in detail in the context of the hydrologic cycle in Chapter 12.

The Thornthwaite Water Balance

Using Figure 3.2, we have quickly learned a great deal about the global water cycle. This doesn't tell us much, however, about any particular place at any specific time. Charles W. Thornthwaite (1899–1963), an American climatologist and geographer, developed a water balance approach that compares precipitation and evapotranspiration over time at any location. Table 3.2 and Figures 3.3 and 3.4 show how Thornthwaite thought about water supply from the point of view of the primary user of water – plants, either natural or cultivated – and the amount of water that they can potentially utilize in the process of photosynthesis to maximize their health and growth if it is abundant—*potential evapotranspiration*.

Table 3.2. The monthly Thornthwaite water balance for a corn field in nor (unit is inches).

Element of Water Balance	J	F	M	A	M	J	J	A	S	O	N
Precipitation	1.6	1.7	3.8	2.3	5.1	5.4	2.4	3.7	2.2	3.7	3.
Potential EVT	0	0	0.2	1.6	3.3	4.8	5.7	5.0	3.3	1.7	0.
Precipitation – Potential EVT	1.6	1.7	3.6	0.7	1.8	0.6	-3.3	–	-1.1	2.0	2.
Change in soil storage	0	0	0	0	0	0	-3.3	–	0	2.0	1.
Soil storage remaining	3.5	3.5	3.5	3.5	3.5	3.5	0.2	0	0	2.0	3.
Actual evapotranspiration	0	0	0.2	1.6	3.3	4.8	5.7	3.9	2.2	1.7	0.
Water deficit for plants	0	0	0	0	0	0	0	1.1	1.1	0	0
Water surplus (runoff)	1.6	1.7	3.6	0.7	1.8	0.6	0	0	0	0	1.

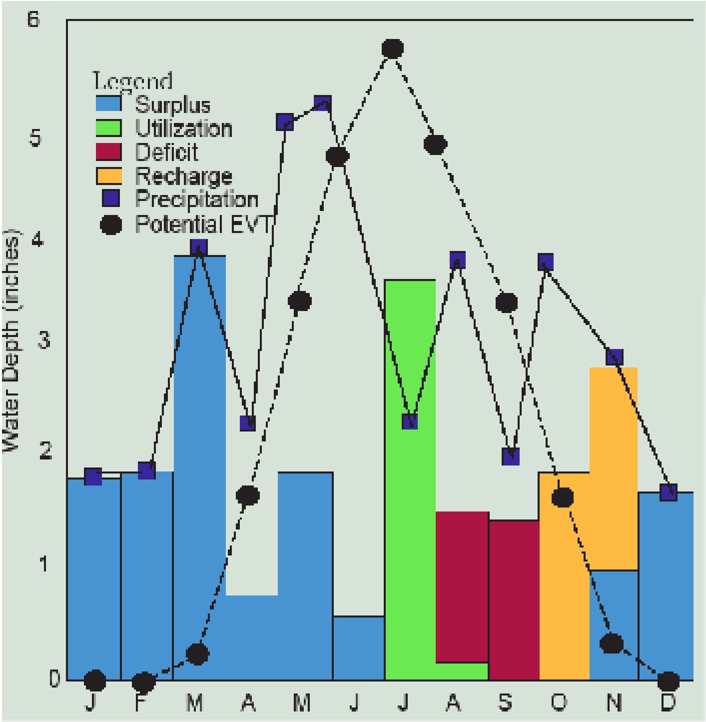


Figure 3.3. The monthly Thornthwaite water balance for a corn field in northern Illinois.

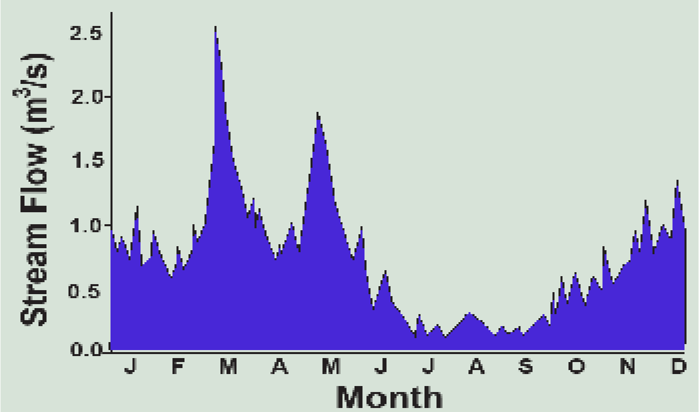


Figure 3.4. A representative hydrograph for the stream whose watershed contains the corn field.

The year begins in this example of a corn field in northern Illinois in January with the soil saturated with 3.5 inches of water. Note that how much water the soil can store, largely a function of organic matter content, is important and is therefore a key component of soil fertility. Rain and snowmelt that month amount to 1.6 inches, but since the corn is not in the field and temperatures are low, none of this is evaporated or transpired (EVT). It would soak or infiltrate into the soil, but the soil is already saturated, so instead it percolates into groundwater or runs off to streams as surplus.

February is similar, but in March there are heavy rains that melt the remaining snow for a total of 3.8 inches of precipitation. A bit of this evaporates (0.2 inches), but with the soil still saturated, 3.6 inches runs off, generating a moderate flood downstream (see hydrograph in Figure 3.4).

In April, the rains diminish, but evapotranspiration climbs to 1.6 inches. The soil remains saturated, but only 0.7 inches of surplus runs off to streams and the flood recedes. May brings heavy rain again and 1.8 inches of runoff while the seedling corn crop enjoys all the water it can use, now up to 3.3 inches. June remains rainy at 5.4 inches, but the growing corn in the warm temperatures uses almost all of it (4.8 inches).

In July, only 2.4 inches of rain falls, just as potential evapotranspiration hits its annual peak of 5.7 inches. Here's where soil storage comes to the rescue, making up the entire 3.3-inch difference and the corn grows unabated by the drought. That leaves only 0.2 inches of soil moisture for August, however, when potential EVT of 5.0 inches again exceeds precipitation of 3.7 inches. The crop uses the remaining 0.2 inches of soil moisture, but then it runs out of water. Actual EVT is thwarted by the drought and falls below potential EVT by a deficit of 1.1 inches. This happens again in a dry September with another deficit of 1.1 inches and the streams, which have not seen runoff since June, are reduced to a trickle of groundwater discharge (Figure 3.4). The farmer may wish he had installed an irrigation system since these two months with a deficit of 2.2 inches are reducing his crop to below average yields. Without it, he can only wish the flood-producing rains in March and May had fallen in late summer when the water was needed.

By October, the rains pick up again to 3.7 inches while the crop's needs fall to only 2.0 inches. Finally, the soil is replenished, gaining the 1.7 inches as storage, but the streams still aren't seeing much relief. In November, the crops have been harvested, the weather is chilly and potential EVT falls to only 0.3 inches while the cold rains deliver 3.0 inches. The soil regains its full storage of 3.5 inches and the streams finally see some runoff of 1.2 inches. The year ends in December with 1.4 inches of rain and snowmelt which pushes the annual total of 36.3 inches slightly above the average of 34.7 inches, all of which goes to groundwater percolation and stream flow.

Despite the slightly wetter than average year, the damage to the corn crop of the late summer drought is done. If the soil had a storage capacity of 5.7 inches instead of 3.5 inches, however, the corn would have had all the moisture it needed throughout the growing season. The spring floods would also have been less severe. Too bad half of the organic matter the soil contained when the prairies were first plowed has been lost to erosion and the atmosphere.

Farther west near Lincoln, Nebraska, annual precipitation averages only 28 inches and potential evapotranspiration is somewhat higher due to the air's greater aridity. Corn finds itself in water deficit for some of every growing season. Farmers there either have to drill wells to tap into the Ogallala Aquifer to irrigate their corn crop through the late summer drought or switch to less water-needy, but also less profitable, wheat. By the time we reach the semiarid lands along the Wasatch Front in Utah, annual precipitation of only 15–20 inches makes crop production hopeless without irrigation, and only a few locations in Utah get all of the irrigation water that is available. Ranchers graze herds of cattle looking for grass amid the sagebrush.

This Thornthwaite water balance narrative, "a year in the life of a corn field," illustrates how the timing of precipitation relative to plant needs, as expressed by potential evapotranspiration, is the key in determining the water balance in both agricultural and ecological settings. Most species of trees are less tolerant of water deficits than grasses, while cactus have adapted to arid conditions by storing water inside the plant itself, but sagebrush grows long tap roots to access groundwater and goes dormant during droughts. Corn, soybeans, cotton, rice (which requires seasonal flooding), as well as many fruit and vegetable crops, do poorly when water deficits persist. Wheat and some Mediterranean crops like grapes are more tolerant of drought.

Water storage helps balance temporal discrepancies. The first reservoir is the soil. In a place like California, the summer water deficit is severe, even in a moist year, and so farming is dependent on irrigation. Water surpluses from winter snows must be stored somewhere if they are to be delivered in the summer growing season. The snowpack in the mountains becomes a natural reservoir as it melts steadily over the summer to generate stream flow that farmers can access. But when this is also insufficient, the question arises of building dams on rivers to store water from wet years in reservoirs for use in dry years. Clearly, we can see that having enough water on average misses the point because we may not have the water when it is needed, though storage in reservoirs or aquifers can improve the imbalances.

Global Geography of Freshwater Resources

With the help of the Thornthwaite water balance approach, we can see that runoff, both surface and groundwater, represents the surplus of precipitation over evapotranspiration, taking into account soil and groundwater storage. It is the freshwater that is available in streams, rivers, and lakes for purposes beyond plant growth (including rainfed crops). We can then take a more geographic approach to the hydrologic cycle by looking at runoff (as shown in the hydrograph in Figure 3.4).

Figure 3.5 shows average annual runoff around the globe. First, note the scale. It is in millimeters per year (mm/y) (there are 25.4 mm in an inch) as the depth of non-evaporated rainfall and snowmelt that runs downhill to and through waterways. It is not a linear but a logarithmic scale, so it varies over three orders of magnitude, from less than 5 mm/y (0.2 inches, the width of your pen) to 5,000 mm/y (about 16 feet). The availability of fresh water varies enormously from place to place!

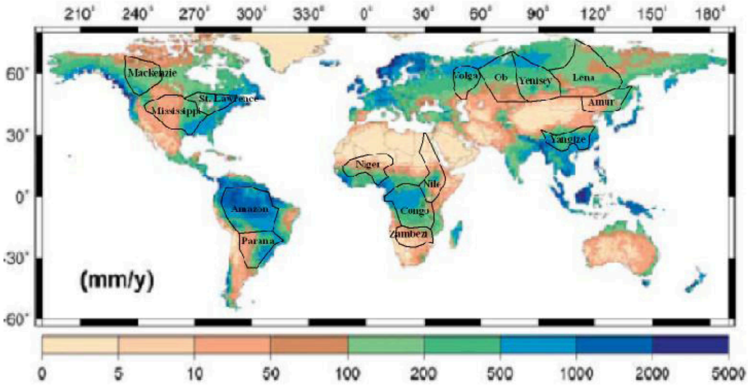


Figure 3.5. The geographic distribution of annual runoff in millimeters per year (source: Oki 2007) with the world's largest river basins overlaid. These rivers capture the runoff from their basin areas.

At less than 50 mm (2 inches) per year of annual runoff (the northern Illinois case had 12.6 inches), rainfed agriculture is all but impossible; plants do not cover most of the soil surface, leaving it vulnerable to erosion, and runoff does not give rise to permanent streams. This occurs on about a third of all land on Earth, including a vast arid stretch from the Atlantic coast of North Africa to northeastern China, in much of Australia and southern Africa, the Pacific coast of Peru and northern Chile and southern Argentina, and from central Mexico through the western U.S., except west of the Cascades. and the high Rockies. In these places, land is nearly worthless if it does not have available water, which is the limiting factor ecologically, agriculturally, and often in human economic development.

At more than about 2,000 mm (2 meters) per year of runoff, copious rainfall and infiltration leaches soils of nutrients, which must be completely covered by dense vegetation if they are to be protected from severe erosion. The human habitat is thus considerably defined by water – to areas where runoff is about 50–2,000 mm/y, or able to access irrigation water from wetter places. Note where this range occurs in Figure 3.5 in dark brown through green to medium blue. Over 90 percent of humans live in the third of the Earth's land surface where annual runoff is within this range and the mean annual temperature is above freezing (0°C, 32°F).

Watersheds

Water runs downhill to the ocean. This simple fact gives rise to the central geographic and topographic concept governing the hydrologic cycle—watersheds. Also known as a drainage basin, or in Australia as a catchment, a watershed is the area of land where water drains downhill to a particular point in a stream channel. Table 3.3 lists the 10 largest watersheds in the world along with the ten largest rivers by discharge (the volume of water that flows by a point on the river in a specific span of time). These are also mapped in Figure 3.5. Why is the Amazon's discharge five times larger than any other river on Earth at over 18 quadrillion gallons per year? It has the largest watershed by far and all of this area has over 20 inches per year (500 mm/y) of runoff.

Table 3.3. World's ten largest watersheds and rivers by discharge.

Watershed	Area (1000 km^2)	Area (1000 miles^2)	Rank	River	Average Discharge (m^3/s)	Annual Discharge (trillions of gallons)
Amazon	6,144	2,372	1	Amazon	219,000	18,257
Congo	3,730	1,440	2	Congo	41,800	3,485
Nile	3,255	1,257	3	Ganges	40,000	3,335
Mississippi	3,202	1,236	4	Orinoco	31,900	2,659
Ob	2,972	1,147	5	Yangtze	31,900	2,659
Parana	2,583	997	6	Parana	25,700	2,143
Yenisei	2,554	986	7	Yenisei	19,600	1,623
Lena	2,307	891	8	Lena	17,100	1,426
Niger	2,262	873	9	Mississippi	16,200	1,351
Amur	1,930	745	10	Mekong	16,000	1,334

We can also usefully define watersheds at smaller scales by utilizing tributaries. In this way, a watershed address can be determined for every place on land. For example, my old office at Southern Illinois University Carbondale is in the Mississippi watershed, the fourth largest on Earth at over 3 million km^2, but within that, it is in the Upper Mississippi watershed (490,000 km^2) that drains to the junction with the Ohio River at Cairo, IL, from the north. Within that, it is in the Big Muddy watershed (6,071 km^2) which drains to the Upper

Mississippi, and within that the Crab Orchard Creek watershed (213 km^2), a tributary of the Big Muddy. We can go to even smaller scales, placing my office in the Piles Fork watershed (about 40 km^2), but at scales smaller than that, it becomes difficult to identify a stream channel to which water falling on the roof of the building my office was in drains (Figure 3.6). Even U.S. Geological Survey topographic maps are inconsistent in their mapping of the smallest of stream channels.

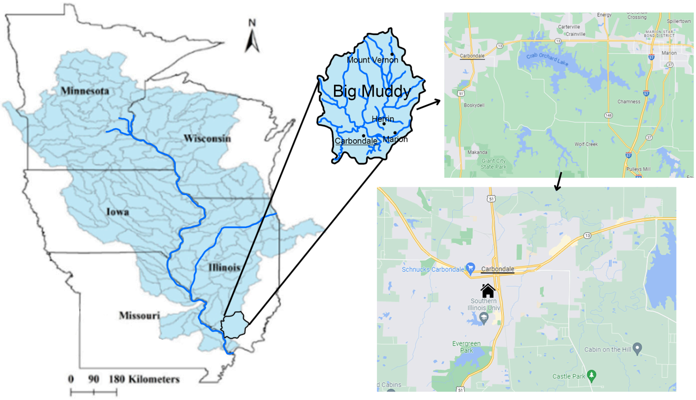


Figure 3.6. An example of a watershed address for the author's former office in Southern Illinois contrasted to his current office in Utah's Great Basin.

In the reverse direction, when it rains on my building's roof, some of the water takes the opposite route on its 1,700 kilometer journey to the ocean—down hills, rills, and narrow ephemeral channels to the Piles Fork less than a kilometer away, down to the Crab Orchard Creek, Big Muddy River, Upper Mississippi River and Lower Mississippi eventually flowing to the Gulf of Mexico.

My current office at Utah State University, however, has a very different watershed address. Rain falling on the Natural Resources building can quickly find its way down to the Logan River a mile away, which drains to the Bear River, which provides the majority of the water feeding into Great Salt Lake. Thus, like 18 percent of Earth's area and 5 percent of North America's area, I live in an area with no outlet to the ocean. Take a moment to identify your watershed address and water route to the ocean (or terminal lake) in a similar manner.

Watersheds usually have distinct boundaries called drainage divides that can be drawn from a topographic map. For example, the continental divide in the Rocky Mountains marks the western boundary of the Mississippi and Rio Grande watersheds, both of which flow to the Gulf of Mexico. To the west of this line, water flows to the Pacific Ocean via the Columbia, Colorado, and other rivers. Similarly, the Appalachian divide marks the eastern boundary of the Mississippi watershed and the western boundary of rivers that flow to the Atlantic, such as the Susquehanna and Potomac. Drainage divides can be mapped at smaller scales as well to delineate smaller watersheds.

Watersheds are critical in assessing the hydrologic cycle and water resource issues. As we have seen, the quantity and quality of water in a stream or river is determined by climate and land use—within the watershed area that drains to it. A rainstorm in a neighboring watershed will cause a flood in that watershed's streams, not yours, but a feedlot in your watershed will pollute streams in your watershed, not the neighboring watershed. Watersheds thus define the zone of water resource and aquatic ecological impacts of climate and climate changes, of human and ecological water uses, of water pollution emissions, of land use decisions, and of engineered alterations of streams and rivers such as dams and levees. Every watershed is unique. As Massachusetts Congressman Tip O'Neill said of politics, all water issues are local.

At this point, we have set the stage sufficiently for a more in-depth discussion of water resource sustainability in Chapter 12. Two other critical biogeochemical cycles we need to investigate at this juncture are the carbon cycle and the nitrogen cycle.

The Carbon Cycle, Fossil Fuel Formation, and Climate Change

A diagram of carbon stocks and flows, together constituting the carbon cycle, is shown in Figure 3.7. The carbon cycle is critical in understanding one class of vital natural resources—fossil fuels—and one overarching environmental problem— climate change. Like with water, the first question to ask when considering a cycle is “where on Earth is the carbon?” The largest pool or stock by far is carbonate rocks such as limestone (composed mostly of calcium carbonate—$CaCO_3$), which contains about 94 percent of all the carbon on Earth or 65,000,000,000,000,000 (65 x 10^{15}) tonnes. The second biggest is fossil fuels, mostly coal, that store most of the remaining 6 percent (4 x 10^{15}) tonnes. Though far smaller in tonnage, the remaining carbon pools are very important because they interact very actively with the biosphere and atmosphere. Ocean waters contain 39,000 billion tonnes (mostly as dissolved carbon dioxide), the soil contains 2,300 billion tonnes as humus and weathered limestone, land-based biomass (e.g. tree trunks) 550 billion tonnes, and the atmosphere 800 billion tonnes, mostly as carbon dioxide, but also as methane.

This last figure is critical because two hundred years ago it was 550 billion tonnes. The 250 billion tonnes of carbon that have accumulated in the atmosphere, largely from the combustion of fossil fuels, are at the heart of the climate change issue. Let’s focus first on the flows that store carbon as fossil fuels in the Earth and then at the flows that store carbon in the atmosphere.

Fossil Fuel Formation

Oil, gas, and coal—in a total of just ten letters we can spell out the energy source that has defined the industrial era. But what are they, where does their energy come from, and how did they get in the Earth's crust? To answer the first question, they are hydrocarbons. Chemically speaking, if we start with hydrogen gas (H_2), we can add on groups of one carbon atom and two hydrogen atoms to get first gas then oil, collectively known as petroleum. Natural gas is primarily methane or CH_4 but also includes C_2H_6, (ethane), C_3H_8 (propane), and C_4H_{10} (butane). Then comes C_5H_{12} (pentane), C_6H_{14}, (hexane), C_7H_{16} (heptane), C_8H_{18} (octane, used to measure the energy value of gasoline), and up through about $C_{15}H_{32}$, which constitutes most of what we put in the gasoline tanks in our cars and trucks. Here it is burned using oxygen gas (O_2) from the air to produce heat energy plus water and carbon dioxide according to the chemical formula $2\ C_8H_{18} + 25\ O_2 \rightarrow 18\ H_2O + 16\ CO_2$ + heat. Keep going up to $C_{16}H_{34}$ and you have diesel fuel. Note that when you burn (i.e. combine with oxygen) a hydrocarbon, you get water and carbon dioxide, plus a variety of pollutants due to impurities or incomplete combustion.

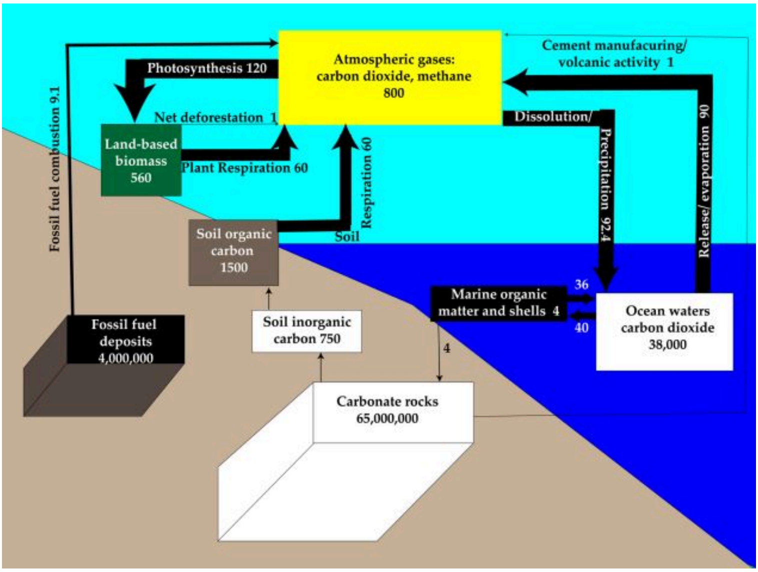


Figure 3.7. Overview of the global carbon cycle. Stocks are in billions of metric tonnes, flows are in billions of metric tonnes per year.

Coal is a heavier, more complex, and more carbon-rich hydrocarbon. For example, one analysis of abundant bituminous coal gives a formula of $C_{137}H_{97}O_9NS$ (N is nitrogen, S is sulfur) and one for less abundant, but cleaner burning, anthracite coal is $C_{240}H_{90}O_4NS$, but these are just examples of a diverse hydrocarbon that is often infused with water.

Hydrocarbons derive their energy from the sun, but this requires some explanation. Inside the sun, nuclear fusion produces helium from hydrogen releasing incredible quantities of energy. This radiates as shortwave radiation, much of which plants capture during photosynthesis, most typically expressed as the chemical formula $6H_2O + 6CO_2 + \text{solar energy} \rightarrow C_6H_{12}O_6 + 6O_2$. This reaction converts solar energy into the energy-packed carbohydrate molecule known as glucose. The chemical energy in fossil fuels is derived over millions of years from glucose, and so they are, in effect, stored solar energy.

When they die, most plants and animals lose their chemical energy through decay when their bodies are burned or devoured, and the energy dissipates through respiration, which is the reverse of photosynthesis. If they die in a water-logged environment lacking oxygen (this is called a reducing or anaerobic environment), however, the carbohydrates accumulate at the bottom of wetlands, shallow lakes, river deltas, estuaries, and continental shelves. Over millions of years, the carbohydrates are buried by sediments, crushed, and, as they are buried deeper in the Earth's crust, slowly cooked until the oxygen is driven out and hydrocarbons form. Higher temperatures and greater depths tend to produce gas while more moderate temperatures and depths produce oil, what petroleum geologists term the *oil window*.

Oil and gas often occur together in fields as much as five miles below the land surface or sea floor within sedimentary rocks like sandstone, limestone, or shale. There they coexist with groundwater filling in the tiny, interconnected pore spaces in the permeable reservoir rock (Figure 3.8). Oil is generally lighter than water, so it migrates above it. Gas is lighter still, but under the enormous pressures deep in the

Earth, much of it is dissolved in the oil like a carbonated drink. Petroleum will rise to the surface and evaporate or oxidize unless there is a geologic trap—an impermeable layer above that prevents its escape.

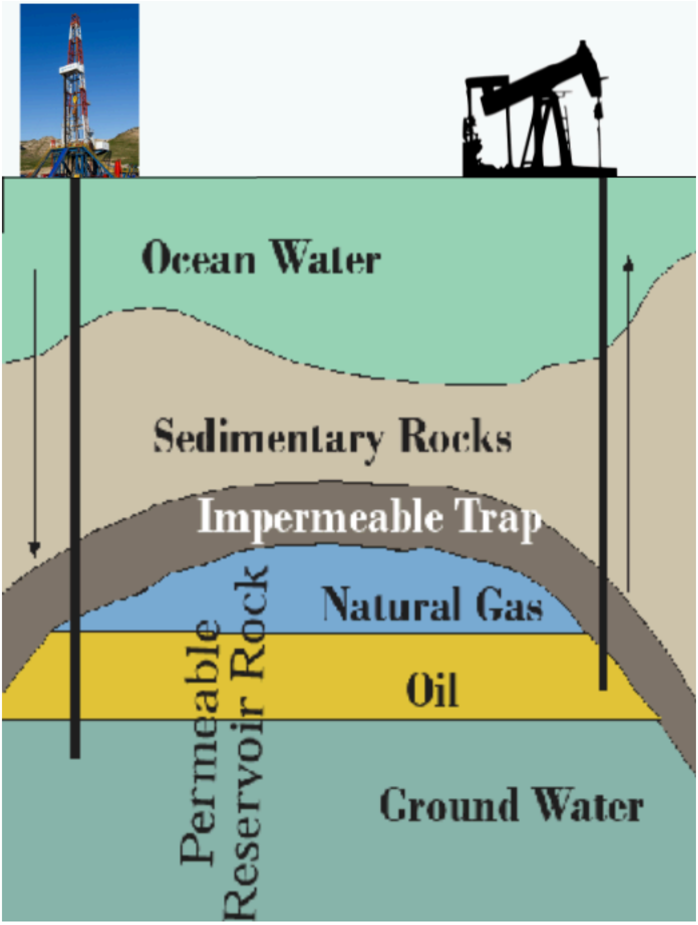


Figure 3.8. An offshore petroleum field producing crude oil and gas using improved recovery techniques.

If a well is drilled through the trap, the oil and gas will migrate to it under pressure, at first enough to generate a gusher like a shaken sodapop when opened. Once this pressure dissipates, however, it is difficult to get all of the oil out. It can get trapped in tight or impermeable places in the reservoir and heavier oils stick hard to the reservoir rock. Often, only a third of the oil in the reservoir can be recovered. This percentage can be improved by loosening the oil with steam or even detergents or by adding pressure by injecting water, natural gas, or carbon dioxide—a practice that can sequester that pollutant underground as we will discuss later. Fracking, however, can often substantially increase recovery as we will discuss in Chapter 13.

Coal, which is roughly ten times as abundant as petroleum, also starts with ancient plants that die and fall to the bottom of swamps and seas. Here they accumulate as organic-rich, wet peat, a fuel that is dug up by hand and burned in some countries. As the peat is buried by sediments and crushed, the water is driven off and it hardens into first lignite, a soft, poor-quality coal, then bituminous coal, which constitutes the vast majority of coal production on Earth, then hard anthracite coal. Extreme pressure can even produce diamonds.

As a solid, coal is not pumped from the Earth like water, oil, or gas using wells but must be dug out from a mine. If the overburden is less than about 100 feet thick, it can be stripped away, revealing the coal seam to the air, where enormous shovels and cranes dig it out to be shipped to the coal processing plant (Figure 3.9). Clearly, surface or strip mining has enormous environmental impacts ranging from land degradation to acid mine drainage to mountaintop removal, problems that plague coal mining areas wherever they occur.

Figure 3.9. Example of surface or strip mining of coal.

If the coal seam is deeper, underground mining techniques are employed. In room-and-pillar mining, columns of coal are left behind to hold up the roof of the mine in an effort to prevent collapse, and consequent land subsidence. In long-wall mining, essentially all of the coal is removed as the mine collapses and the land subsides above mined-out areas. While, on balance, underground mining is preferable to surface mining on environmental grounds, it is a dangerous occupation and land subsidence is a serious issue for any structures lying above it.

When the oil, gas, or coal are brought to the surface and burned as fuel, water and carbon dioxide are the primary products. Individual oil and gas fields and coal seams are thereby depleted over time as their products are produced, refined, and consumed, and the chemical energy in the hydrocarbons is released in the pistons of your car or truck, the furnace in your basement, or the power plant that generates the electricity for your computer. The global distribution, production, and depletion of fossil fuels is a topic for further investigation when we dig into the fascinating issues of energy in Chapters 13 and 14.

Climate Change

The critical environmental issue of climate change is also related to the carbon cycle. Figure 3.10 is a simple diagram explaining why atmospheric carbon warms the Earth. Because the sun's surface is very hot (5,400°C; 9,800°F), incoming solar radiation is shortwave. At this wavelength, light passes through nitrogen (78%), oxygen (21%), and everything else in the atmosphere except clouds. The proportion that is reflected from the Earth is called albedo, but except on ice and snow, most is absorbed, warming the Earth. The Earth then radiates heat as longwave radiation that you can almost see as waves on a blacktop road on a hot summer afternoon.

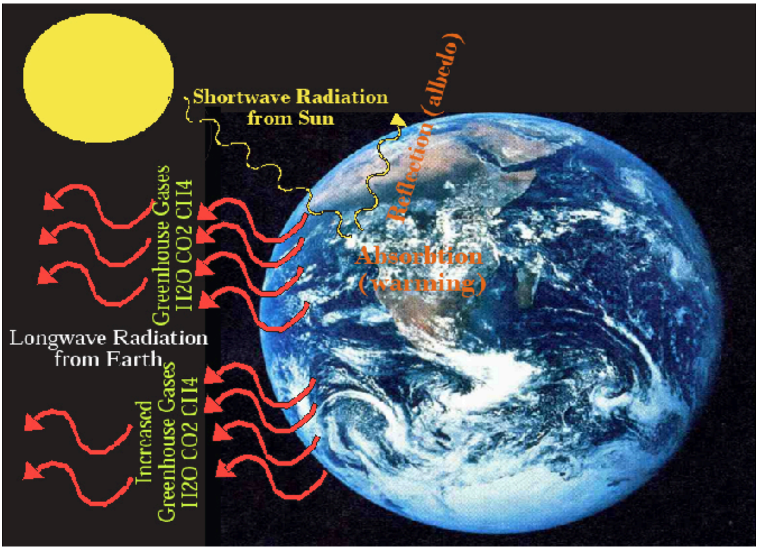


Figure 3.10. Diagram of the greenhouse effect. Increased greenhouse gases absorb a higher proportion of longwave radiation, preventing its escape to space.

On the moon where there is no atmosphere, all of this radiation escapes to space, but on Earth, the atmosphere contains greenhouse gases. In order of importance, these are water vapor (H_2O), carbon dioxide (CO_2), and methane (CH_4), plus more minor effects from nitrous oxide (N_2O), halocarbons (like CFCs), and ozone (O_3). This natural greenhouse effect raises the average temperature of the Earth's surface from about 4°F to 58°F and enables most life to exist on the planet. When carbon dioxide, methane, and other greenhouse gases are added to the atmosphere, however, they absorb more longwave radiation, warming the lower atmosphere. This impacts the weather (short-term) and the climate (long-term).

Water vapor, the most important greenhouse gas, also plays a crucial role because the warmer the atmosphere gets, the more water it can hold, as shown in Figure 3.11. Thus, a positive feedback process is initiated where greenhouse gases warm the atmosphere, which enables it to hold more water, which warms the atmosphere further, which enables it to hold yet more water, which warms it yet further. Greenhouse gases are thus a catalyst that sparks a warming process that is primarily carried out by water vapor. When you see scientific predictions of how much the Earth is expected to warm if carbon dioxide and methane concentrations reach certain levels, this positive feedback effect induced by water vapor is already taken into account.

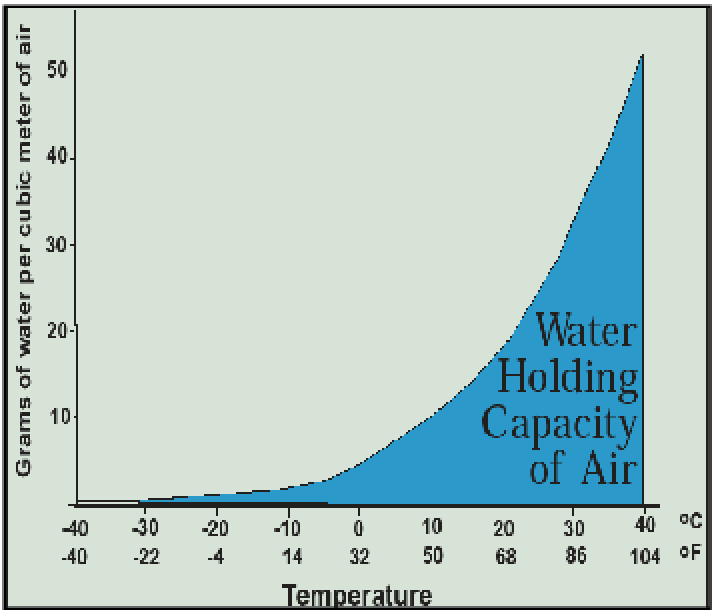


Figure 3.11. The effect of temperature on the capacity of air to hold moisture. As it gets warmer, air can hold more moisture at an accelerating rate.

Returning to Figure 3.7, also note the flows (or fluxes) of carbon shown as arrows to denote the direction of movement as well as relative volume of annual flow. The oceans absorb 93 billion tonnes per year from the atmosphere, releasing 90 billion tonnes for a net removal of about 3 billion tonnes per year, much of which forms marine organic matter and seashells. In fact, over hundreds of millions of years, this marine ecological process created the carbonate rocks from what was once carbon dioxide in the Venus-like atmosphere of early Earth.

At 102 billion tonnes per year, photosynthesis is the largest flux of carbon and removes over 13 percent of all atmospheric carbon each year, though on a global annual basis it is balanced by respiration, which returns the same amount back to the atmosphere. Seasonally, photosynthesis wins the race in spring and summer when atmospheric concentrations actually fall by about part per million by volume (ppmv) or roughly 12 billion tonnes, though they rise by about 8 ppmv or 15 billion tonnes in the autumn and winter. The Keeling Curve in Figure 3.12 shows both this seasonal pattern and the annual increase. The difference of about 2 ppmv or nearly 3 billion tonnes is primarily due to emissions from fossil fuel burning (and secondarily from cement manufacturing, which uses crushed limestone) at a rate now exceeding 10 billion tonnes per year, exceeding the rate of net uptake by the oceans (about 3 billion tonnes per year).

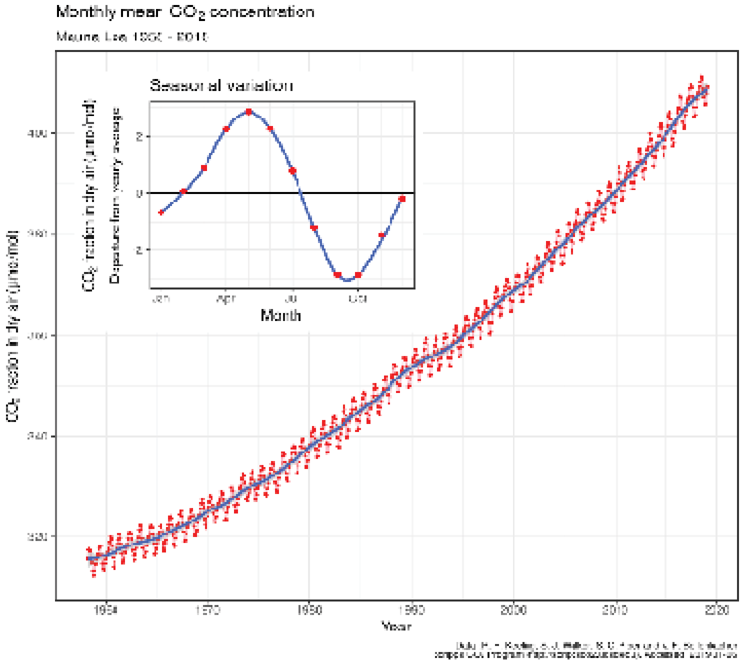


Figure 3.12. The Keeling Curve of atmospheric carbon dioxide concentrations. Note the seasonal variable due to the photosynthesis-respiration balance.

As a thought experiment on how to address the climate change problem as an accumulation of atmospheric carbon, look over Figure 3.7 and see how many ways you can think of to remove carbon from the atmosphere. Of course, we want to focus on this carbon pool since the other pools are a good thing (land-based biomass, soil organic carbon, fossil fuels) or neutral (e.g., carbonate rocks). Above some threshold size (say, 600 billion tonnes), where the negative effects of climate change become evident, removal of carbon from the atmospheric pool to some other pool is a positive thing from the perspective of human well-being and sustainability.

Here's my list of how the atmospheric carbon pool can be reduced:

- Reduce the rate of carbon emissions from fossil fuel burning
- Reduce the rate of carbon emissions from cement manufacture
- Reduce the rate of carbon emissions from volcanic activity
- Reduce the rate of respiration
- Reduce the rate of oceanic release of carbon
- Reduce the rate of weathering of carbonate rocks into soil inorganic carbon
- Increase the rate of oceanic uptake of carbon
- Increase the rate of oceanic carbon uptake by marine organisms
- Increase the rate of carbon uptake through photosynthesis
- Increase the size of the land-based biomass carbon pool
- Increase the size of the soil organic carbon pool
- Recycle fossil fuel emissions into the lithosphere (sequestration) rather than venting them to the atmosphere.

Now, some of these, like the rate of oceanic or volcanic carbon release, are completely out of human control. Others would have small effects. So here is a culled list of the five most viable options:

- Reduce the rate of carbon emissions from fossil fuel burning
- Increase the rate of carbon uptake through photosynthesis
- Increase the size of the land-based biomass carbon pool
- Increase the size of the soil organic carbon pool
- Recycle fossil fuel emissions into the lithosphere (sequestration) rather than venting them to the atmosphere

This list of five options, in combination, might actually do the trick of slowing and even reversing the buildup of carbon in the atmosphere that is causing climate change.

Consider a giant atmospheric carbon removal machine built by combining some of these factors. Grow trees on plantations (removing carbon from the air through photosynthesis), burn the trees in a power plant, capture the carbon dioxide gas, and sequester it in a geological repository. Carbon takes a one-way trip from air to Earth—and electricity is produced as a by-product.

Note again that the oceans absorb 3 billion tonnes per year more from the atmosphere than they release, so if we can get the net emissions to the atmosphere from other components down below 3 billion tonnes per year (compared to the current 10 billion tonnes), the oceans can absorb the rest, though at the expense of making them less alkaline (this is ocean acidification). For example, if (a) emissions from fossil fuel burning and cement manufacturing were reduced from 10 to 3 billion tonnes per year, through greater energy efficiency and switching to lower carbon fuels, (b) 1 billion tonnes of those emissions were stored in geologic sequestration sites instead of vented to the atmosphere, and (c) the combined land-based biomass and soil organic carbon pools were increased by 1 billion tonnes per year through photosynthesis, the atmosphere would be losing 1 billion tonnes per year. Problem solved! (at least in the long-run). Of course, those things are easier said than done, but would we even know what we want to try to achieve without examining the carbon cycle? We'll discuss these approaches to limiting atmospheric carbon in considerably more detail in the context of energy (Chapter 14) and environmental policy (Chapter 15).

Climate Change Impacts

There are many views on how severe a problem climate change is, ranging from a few that still assert that it is hoax, to absurd Hollywood disaster movies like *Waterworld* and *The Day After Tomorrow*.

For an objective view, we must turn to the best science, and there is no shortage—studying climate change and its consequences has been a mainstay for environmental scientists for over a decade and shows no signs of abating. The gold standard is the Intergovernmental Panel on Climate Change (IPCC), a large group of renowned scientists from many countries who received the Nobel Peace Prize in 2007. Climate change is far more subtle than a rise in the thermometer, though that is where our discussion must begin. From there we will look into impacts on the hydrological cycle and sea level, leaving further consideration of its effects on agriculture and ecosystems until later when we have established greater knowledge of those two important topics.

The story line on climate change is really quite simple and consists of five elements, the first of which we have explored and the second through fourth we will explore here, leaving the fifth until later chapters:

1. Human impacts on the composition of the atmosphere have thus far caused an increase in absorption of longwave radiation (called radiative forcing). Increases in the greenhouse gases carbon dioxide (76% of radiative forcing), methane (16%), nitrous oxide (6%), and halocarbons (2%) absorb longwave radiation at very well-determined rates, thus both warming the lower atmosphere directly and indirectly through their effect on increasing water vapor. These combined effects are about 1oC in warming from 1950–2020.
2. Atmospheric concentrations of carbon dioxide and

methane have increased in recent times and are at levels higher than have occurred over tens of thousands of years over which temperatures and greenhouse gas concentrations are very highly correlated.

3. The increase in atmospheric concentrations of greenhouse gases is due to human activities such as burning of fossil fuels, deforestation, and cement manufacturing.
4. The increase in temperature changes and other elements of the Earth's environment, such as a rise in sea level, an acceleration of the hydrologic cycle, and an altered geography of climatic effects on agriculture has, on balance, serious overall negative consequences for humans.
5. Humans have the power to ameliorate and even reverse climate change, and doing so presents less hardship than enduring its consequences.

Figure 3.13 from the 2007 IPCC report shows carefully gathered data from air bubbles in ice cores from Vostok, Antarctica. The concentration of carbon dioxide in parts per million by volume (ppmv) (rather than by weight) in the air bubbles is plotted on the y-axis compared to years before now on the x-axis. Clearly, prior to the industrial revolution in 1800, the range was only from 180–300 ppmv. Since 1800, it has climbed at an increasing rate to reach 400 ppmv in 2013, and 415 ppmv in 2019, a 48 percent increase over preindustrial levels and is climbing at a rate of about 2 ppmv every year.

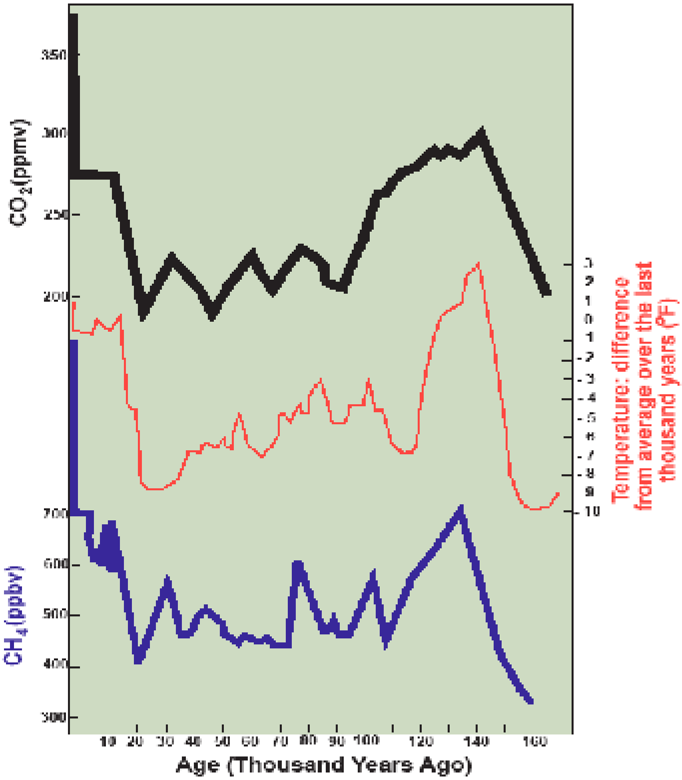


Figure 3.13. Variations in carbon dioxide and methane concentrations and temperatures from Antarctic ice core data over the last 160,000 years.

Over the same time period, methane concentrations have more than doubled from the pre-industrial range of 300–700 parts per billion by volume (ppbv) and now average over 1,850 ppbv as of this writing in 2020. Note that methane is over 200 times less abundant than carbon dioxide, but its radiation absorption capacity is much higher. In the first 20 years after emission it is 84 times as potent, but it has a shorter residence time in the atmosphere than does carbon dioxide; these balance to a century-long 21 times higher total climatic forcing effect per unit volume of gas. Thus the roughly 130 ppmv increase in carbon dioxide has about 4 times the radiation absorption effect than the roughly 1.3 ppmv increase in methane concentrations.

Past temperatures can be determined using isotopes, in this case the ratio of O_{16} to O_{18}. Using this accurate method of estimation, temperatures have ranged over the last 160,000 years from 6°C (11°F) colder to 2°C (4°F) warmer than today, very closely tracking the variations in CO_2 and CH_4 concentrations. The rock-solid relationship that CO_2 and CH_4 have on the absorption of longwave radiation points to CO_2 and CH_4 as the cause and temperature as the effect.

If you look closely, you can also see the cycle of ice ages with the current warm Holocene interglacial evident over the past 15,000 years, the cold Wisconsin glaciation going back from there to about 110,000 years ago, the quite warm Sangamon interglacial preceding that for about 30,000 years, and the very cold Illinoisan glaciation ending about 140,000 years ago.

Temperatures are indeed rising, about 1.0°C (1.8°F) since 1850, raising the average temperature of the surface of the Earth from 56.5°F to 58.3°F and on a steady rate of increase of about 1°C every 10–20 years. If you were to go outside, you probably wouldn't even notice this 1.8°F difference. But compare these changes to a fever. If your temperature was 98.0°F and it rose to 99.8°F, you may notice the slight fever. That's about where we are now with climate change. If it were to go up by another 1.8°F to 101.6°F, you'd be at home sick rediscovering how bad daytime TV is rather than going to class. One more 1.8°F to 103.4°F and you'll be at the doctor's office searching for a remedy. One more 1.8°F to 105.2°F and you'd be in the hospital going through a battery of tests to determine what's wrong before it's too late. One more to 107°F and you're in intensive care because if it doesn't come down soon it will quickly drop to room temperature because you're history. So, as described by Mark Lynas in *Six Degrees: Our Future on a Hotter Planet*, let's take a look at how the Earth changes with rising temperatures to see if this fever metaphor holds any water.

Predictions of the Earth's temperature are made using a couple dozen atmospheric-oceanic global circulation models that run on supercomputers. Depending on the model used and the assumptions made about whether greenhouse gas emissions will increase or decrease in the future, Earth's average surface temperature is predicted to increase by 1.5–4.0°C (2.7–7.2°F) by 2,100, in the range of the fevers described above.

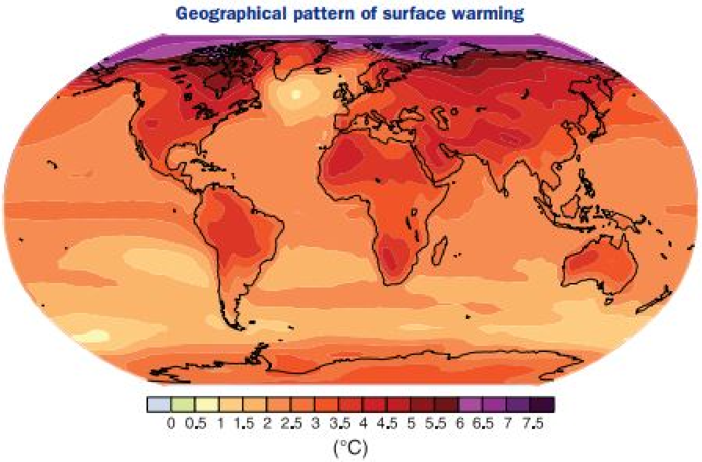


Figure 3.14. Predicted geographical pattern of temperature increases by 2100 using one Atmospheric-Oceanic General Circulation Model (AOGCM) scenario.

The temperature increases won't be the same everywhere, however. Figure 3.14 is one example of the predicted geography of temperature increase by 2100. The interior of continents such as Asia and North America are expected to warm more than the oceans, with their gargantuan capacity to absorb heat. As they do, the oceans delay the warming of the atmosphere but they lock in the effects of climate change long after greenhouse gas emissions have slowed or even ceased. Said another way, climate change has stored about 100 times as much heat in the oceans than in the atmosphere, so, even after greenhouse gas emissions cease, the slow release of this heat from the oceans will control the climate for many decades.

This means today's emissions have long-term climatic consequences.

Note that the maximum temperature increases occur in the arctic. In fact, we know that the ice pack in the Arctic Ocean is already melting, much to the consternation of polar bears, and it may become completely water in late summer by mid-century, opening up the long-sought Northwest Passage from the Atlantic to Asia. Will this melting also cause sea level to rise? The answer is no because the ice is already displacing ocean water like a melting ice cube in a glass. Sea level rise has other causes discussed below.

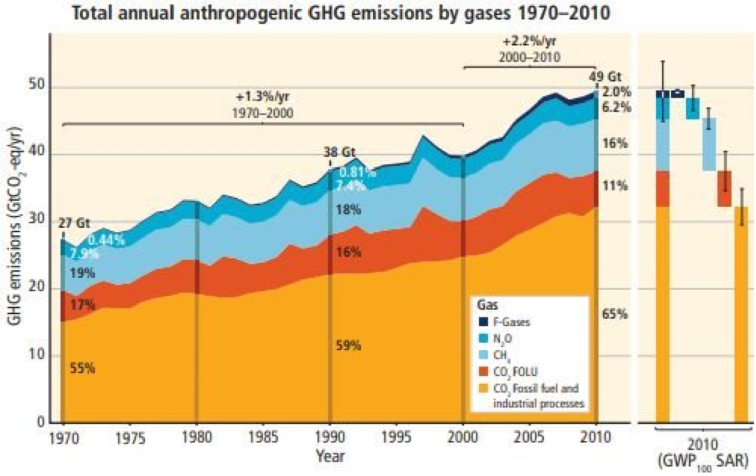


Figure 3.15. Human sources of greenhouse gas emissions, 1970–2010. The graph on the left shows trends from 1970 to 2010, with carbon dioxide from fossil fuel combustion creating the majority of the climatic effect, followed by methane, then carbon dioxide from forestry and land use changes, then nitrous oxide, and finally fluorine gases like CFCs. The graph on the right shows the 2010 climatic effects and the range of uncertainty overall and for each gas.

Where are these increases in greenhouse gas concentrations coming from? When the total radiative forcing effect of all greenhouse gases is taken into account, Figure 3.15 from the 2014 IPCC Report shows that global emissions have steadily increased from 28.7 gigatonnes (billion metric tonnes) in 1970, increasing each decade to 52.0 gigatonnes in 2010 and rising at 2.2% annually. In 2010 carbon dioxide emissions from fossil fuel combustion was the biggest source with 65 percent of all emissions, plus carbon dioxide emissions from land use changes such as deforestation at 11 percent. Next is methane at 16 percent, followed by nitrous oxide emissions from fossil fuel burning and fertilizer application at 6 percent.

When all the emissions are reorganized by economic sector, the energy sector, especially electricity production, leads at 25 percent, with land use changes at 24 percent, industry at 21 percent, transportation at 14 percent, residential and commercial buildings at 6 percent, and other energy and indirect emissions as the remaining 10 percent. We'll revisit this widespread distribution of sources from a policy and economic perspective in Chapter 15, but for now, what about the impacts?

As we have seen, sea level has always fluctuated, by up to 120 meters or 400 feet, due largely to enormous changes in the volume of glaciers as ice ages have advanced and retreated. Sea level has risen by 200 mm (about 8 inches) since 1870 and is now rising at a rate of 3 mm per year, which is expected to continue (Figure 3.16b). This is caused by the melting away of alpine glaciers, documented from around the globe, and glaciers in Greenland and Antarctica, as well as by thermal expansion of the oceans. Because atmospheric warming is increasing ocean temperatures to a depth of at least two miles, the water volume increases, just like air in a basketball or bicycle tire as it warms, but to a lesser extent.

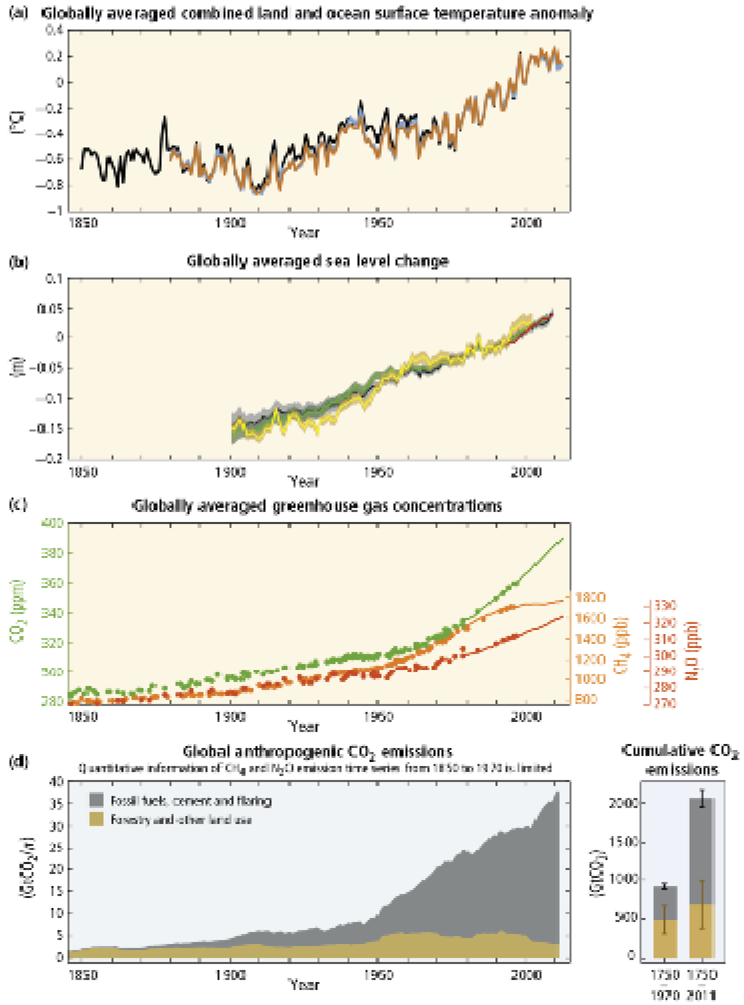


Figure 3.16. Changes in temperature, sea level, greenhouse gas concentrations, and CO2 emissions, 1850-2012.

What is less well understood is what effect climate change will have on the great ice sheets of Antarctica and Greenland.

Fortunately, the great East Antarctic Ice Sheet is unlikely to melt, because if it did, sea level would rise by 65 meters, over 200 feet, inundating every coastal city and ecosystem on Earth. Still scientists have been alarmed and puzzled by instability in the West Antarctic Ice Sheet. More troubling yet is Greenland, which holds enough ice to increase sea level by 7 meters (23 feet), a catastrophic outcome if it were to melt completely. Ice sheet collapse is notoriously difficult to predict. The melting of white and silver ice reduces albedo (reflection of sunlight), which warms the location, causing further melting and so on in a positive feedback or self-reinforcing process. Another positive feedback occurs because as the ice melts down, its elevation above sea level gets lower, which warms it further. Also, ice sticks hard to the rocks beneath it when it is cold, but it becomes slick when melt waters lubricate the ice-rock interface. Sometimes huge lakes of melt waters are held behind ice dams—until the dams suddenly break or holes form in the bottom, releasing a flood to the sea while scouring out more ice. James Balog has risked his life to photograph and film this fascinating and beautiful process in Greenland in a documentary called *Extreme Ice* which I highly recommend. Unfortunately, it's really hard to say whether there will be massive ice collapses in either West Antarctica or Greenland this century that causes sudden and substantial increases in sea level. Let's hope those massive glaciers hold up.

Beyond sea level, let's take a look at the effect of climate change on the hydrologic cycle by beginning with a simple fact: when it's warmer, there is more evaporation because the atmosphere can hold more water. Figure 3.11 should have convinced you of this. As we have seen, this reinforces temperature increases, but its effect on the hydrologic cycle is not so much that the atmospheric water pool is increased, because this effect is very small, but that the hydrologic cycle is accelerated—more evaporation means more precipitation. The question we would want to answer for any particular location is—will it get wetter or dryer? The increased evaporation makes it somewhat drier—in Thornthwaite's terms potential evapotranspiration increases—but does increased precipitation make up for it?

Globally it does, but for any specific location it turns out to be very hard to say. Computer simulations on Atmospheric-Oceanic General Circulation Models (AOGCM) don't always agree. So will the Colorado River have more or less water? We don't know, but most models indicate it will have even less. Will the corn belt contract eastward as well as shift northward? Will Iowa farmers have to switch to wheat or develop irrigation systems? We don't yet know, but the predictive capability of models is improving.

There are other trends that are becoming very clear. In the U.S. there has been a 5–10 percent increase in precipitation, generally a good thing, but there has been an increase in the number of days with more than 2 inches and more than 4 inches of precipitation. The added precipitation is coming in big rainstorms that are more likely to generate runoff, producing floods and erode soil. The Mississippi River set an all-time record flow in April–May 2011 following such downpours and in 2019 suffered from floods of record duration.

A second trend is toward less snow and more rain, combined with snowmelt occurring earlier in the spring. For California, this means that the steady melting of Sierra Nevada snows that maintains stream flow during the summer is instead producing spring floods while trout die in the warm, drying streambeds of summer. Similar effects are occurring throughout the mountain west. With the loss of snowpack as a natural reservoir, new dams have been contemplated as an adaptation to climate change.

Until the really big earthquake hits California, the biggest natural disasters in the U.S. have been floods, and damages are mounting. The price tag on the 1993 flood on the Lower Missouri and Upper Mississippi Rivers is estimated at $19 billion. Hurricane Katrina trumped them all at roughly $100 billion, most of it due to the collapsing and overtopping of levees that "protect" New Orleans from storm surges, flooding 81 percent of the city in 2005. In 2012 Hurricane Sandy became the second most costly natural disaster in U.S. history at $62 billion, but then Hurricane Harvey in 2017 deluged Houston, TX with 40 inches of rain in a few days, causing about $125 billion in damages to rival Katrina.

Are hurricanes increasing in intensity due to climate change? It's an interesting hypothesis because it is clearly the case that the warmer the ocean surface is, the more intense the hurricane passing over it will become. Because only a few hurricanes occur each year, it takes a long time to show conclusively that they are intensifying, but a statistical trend is developing.

There is also evidence that climate change will intensify over time due to *time lags* and *feedbacks*. Time lags means that greenhouse gas emissions raise atmospheric temperatures slowly over time rather than immediately. Because of this, we can expect global temperatures to rise by 1.5°F over the remainder of the 21st century even if greenhouse gas concentrations do not rise from their current 415 ppmv. Emissions now commit the future to a warmer climate. Secondly, positive feedbacks can further amplify the effects of emissions. Here are two important examples.

1) In the subarctic zone of Canada, Alaska, and Russia, permafrost is melting, releasing the powerful greenhouse gas methane to the atmosphere. Warming leads to accelerated warming.

2) Climate models show that in a warmer world, the Amazon Basin will become drier. This will increase the frequency of forest fires and release carbon from trees, soils, and underlying peat to the atmosphere. In this manner, moderate climate change induces more extreme climate change.

Climate change can be best understood as a human-caused modification of the carbon cycle. This is both a fascinating journey in understanding the planet's metabolism and a cause for concern that motivates progress toward natural resources sustainability.

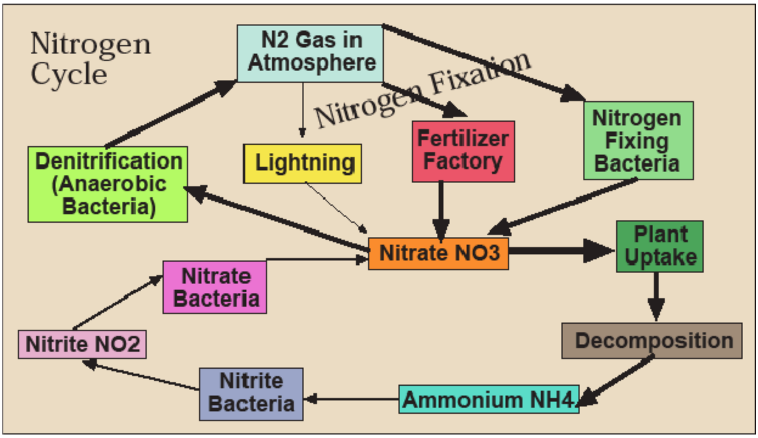
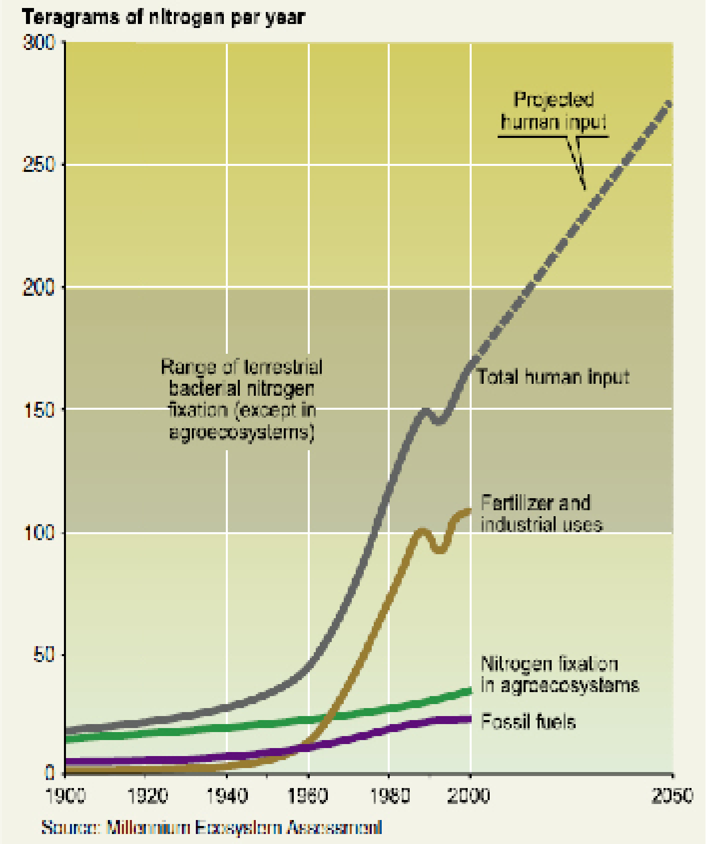


Figure 3.17. The Nitrogen cycle. Arrow widths are roughly equivalent to the volume of nitrogen processed. The atmosphere is the primary pool of nitrogen.

The Carbon Simulation

At Weidong's Projects Homepage you will find a simulation or game that allows you to manage human impacts on the carbon cycle. This is accomplished by employing a variety of management options in three sectors: energy efficiency (e.g., improve insulation), energy production (e.g., solar panels on rooftops), and land management (e.g., reduce quantity of cattle). Each option has different desirable effects on reducing atmospheric carbon and ocean acidification, conserving fossil fuels and adding biomass to the landscape, and thus scores a different amount of carbon points. If carefully employed in a cost-effective manner, you can maximize your carbon points. The Carbon Simulation makes for a very good classroom exercise or homework assignment.



Source: Millennium Ecosystem Assessment

Figure 3.18. Sources of manufactured nitrogen fixation in the 20th century with projections to 2050. Natural nitrogen fixation is between 100 and 200 teragrams (million tonnes) per year. Total human inputs may have now surpassed natural sources of nitrogen fixation and are projected to far surpass it by 2050.

The Nitrogen Cycle

Let’s look at the third and final cycle—nitrogen. Most of the nitrogen on earth exists as N_2 gas, which constitutes 78 percent of the atmosphere. While not technically inert, we've been breathing this in and out every few seconds our entire lives and it hasn't made much of a difference. Both plants and animals need nitrogen—it's a necessary component of protein from which most of our body is made—but neither can extract it directly from the atmosphere. Therefore, the issue is how to get nitrogen out of the atmosphere into some biologically usable form. Some bacteria can "fix" nitrogen—turn it into ammonium (NH_4), nitrite (NO_2), or, especially, nitrate (NO_3), which plants absorb greedily through their roots (Figure 3.17). Along with phosphorus (P) and potassium (K), nitrogen (N) is a fertilizer. In fact, if plants have warm temperatures, sunshine, and water, nitrogen is often the limiting factor in their growth. This means that their growth is constrained by the necessary resource in shortest supply. If you increase the supply of the resource that is the limiting factor, plants will grow faster, while if you increase the supply of a resource that is already sufficient, it will have no or a negative effect.

During WWII, American chemists working on weapons found a way to make inexpensive explosives by fixing nitrogen using the energy from natural gas. Serendipitously (i.e., in a fortunate accident), after the war they discovered that this anhydrous ammonia from explosives stimulated plant growth, and the chemical fertilizer industry was born. Humans joined legumes and bacteria to become nitrogen fixing species—in fact, the most important one (Figure 3.18). Crops responded to it wonderfully and yields went up, especially for corn that grows from a seed in April or May to a 6–8 foot tall stalk by August yielding 100–200 bushels of grain per acre. Geneticists bred crops that could respond to high doses of nitrogen to produce high grain yields. World food production has nearly tripled in the last 50 years and the nitrogen in manufactured chemical fertilizers has been a major reason.

Of course, at some point, nitrogen stops being the limiting factor and yields stop increasing when more fertilizer is applied because the plants can't absorb it or the rain washes it away before they do so. What happens to it then? Nitrates are soluble (i.e., they dissolve in water like salt), so they follow the water in the hydrological cycle. They evaporate and fall back down in the rain. They percolate into groundwater. They run off downhill to streams, rivers, lakes, and the ocean. In the water-logged, oxygen-poor soils of wetlands, anaerobic (this means not dependent on oxygen) bacteria perform a valuable service by transforming nitrates to harmless N_2 gas and releasing it back to the atmosphere (this is called denitrification).

Drinking nitrates is inadvisable; it has been associated with bladder cancer and other ailments. It's particularly hazardous for babies where it interferes with the delivery of oxygen in their bloodstream (this is called blue baby syndrome or the unpronounceable methemoglobinemia). Keeping them out of the public water supply is therefore essential and the EPA has set a drinking water standard of 10 mg/l (equivalent to 10 ppm).

In aquatic (e.g., streams, rivers, ponds, lakes) and marine (e.g., estuaries, oceans) ecosystems, nitrates are also fertilizers, just as they are in a crop field, but in these environments, this is rarely a good thing. They fertilize algae. Aquatic and marine ecosystems are categorized by the availability of nutrients, especially N and P, since one of these is usually the limiting factor in plant growth and therefore biological productivity. Oligotrophic (nutrient-poor) lakes common in the Canadian Shield, for example, often have beautifully clear water, but a low density of plant and animal life because of the lack of nutrients. Mesotrophic lakes are more nutrient-rich and therefore ecologically productive, while eutrophic (very nutrient-rich) lakes have an abundance of nutrients and therefore an abundance of plants, which seems like a good thing until you realize that the plants are predominately algae. Algae not only form a green scum that makes drinking or swimming in the water undesirable, they are ecologically destructive as well through the process called eutrophication.

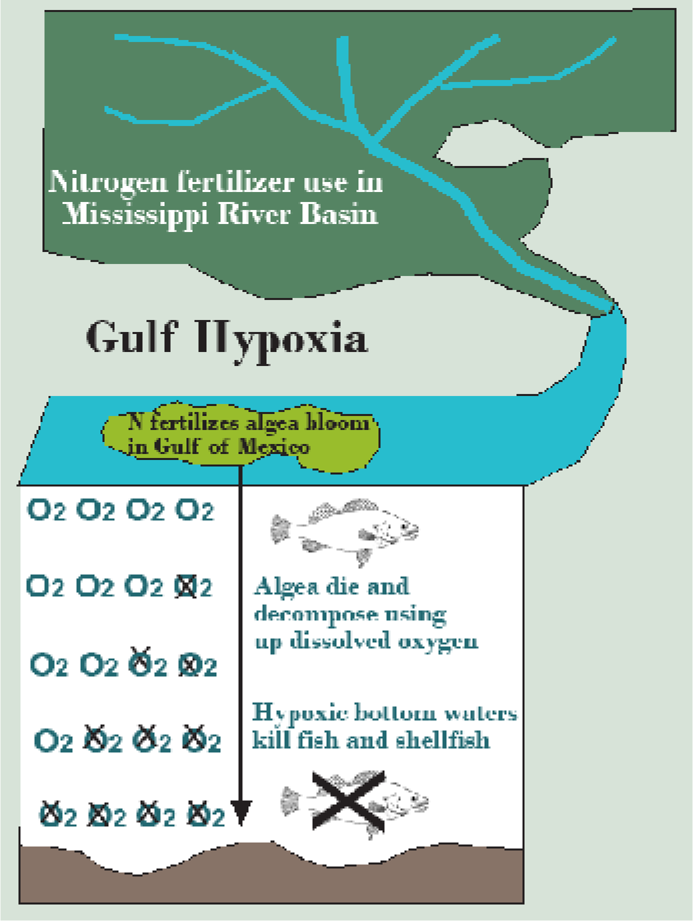


Figure 3.19. A simplified diagram of the eutrophication process that leads to hypoxia.

It's straightforward to see that algae make the water turbid (hard to see through because light is blocked). This alone inhibits the growth of larger aquatic plants that form excellent habitat for invertebrates and fish because solar energy cannot penetrate to the bottom to facilitate photosynthesis beyond a shallow depth (Figure 3.19). Some species of algae are also toxic. In 1997 swimmers in Chesapeake Bay, for example, contracted neurological problems from algae called pfiesteria and there was a major fish kill. Worse yet is algae's effect on the oxygen supply in the water. At first, you might think that algae produce oxygen through photosynthesis, and this is true, but algae have a short life span of around a month. When they die off, they sink to the bottom and their decay consumes oxygen. This results in episodes of hypoxia (oxygen levels below what is needed for breathing animals to survive) with consequent fish kills. Eutrophication is a widespread plague in aquatic ecosystems wherever fertilizers that crops and adjacent ecosystems fail to absorb runs off the land. Even the ocean is affected. The hypoxic zone to the west of the mouth of the Mississippi and Atchafalaya Rivers in the northern Gulf of Mexico sometimes grows to the size of the state of New Jersey (Figure 3.20). While it has received the most attention, Gulf hypoxia is only the tip of a very large iceberg. Nutrient enrichment (i.e., eutrophication), including both N and P, is the most important water pollution problem on Earth—at least from an ecological perspective (Figure 3.21). For this reason, perhaps we should start talking about our nitrogen footprint alongside our carbon footprint.

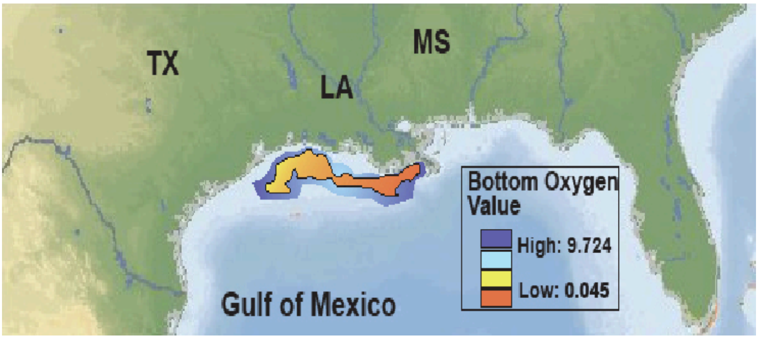
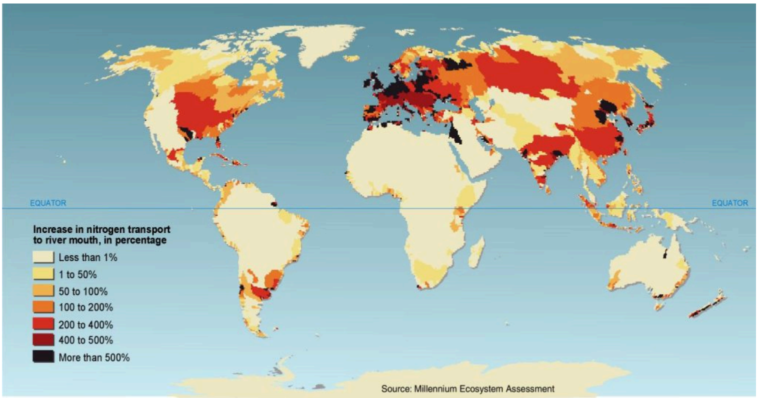


Figure 3.20. Left: The 3,800-square-mile Gulf hypoxic zone in July 2007. Areas in yellow-red lack sufficient oxygen for fish life.



Source: Millennium Ecosystem Assessment

Figure 3.21. Increased nitrogen flow through watersheds to the ocean in the 20th century.

Let's do another thought experiment like we did in thinking through how to keep carbon out of the atmosphere, but this time we're concerned with how to keep nitrogen out of the water by studying the nitrogen cycle in Figure 3.18. Make your list of options before looking over mine.

Here's my list, which is a lot shorter than for carbon:

- Decrease the rate of natural nitrogen fixation
- Decrease the rate of artificial nitrogen fixation and land application (especially through the manufacture of fertilizers)
- Increase the rate of denitrification

You will quickly note that the first option is both unviable and unwise, leaving only two options: restrict fertilizer use and enhance denitrification, especially in wetlands and filter strips. We'll explore these two options in Chapter 11 on land use and agriculture.

The Nitrogen Simulation

At Weidong's Projects Homepage you will find a simulation that allows you to manage the nitrogen cycle in the Mississippi watershed with the objective of minimizing or eliminating the Gulf Hypoxic zone. This is accomplished by employing only two management options: reducing fertilizer applications, which has nonlinear effects on yields, and restoring wetlands, which takes land out of crop production. These options can be employed either for the entire watershed or for its six major sub-watersheds (Missouri, Ohio, Tennessee, Arkansas-Red-White, Upper and Lower Mississippi) individually. Simulations can be run for dry, medium, or wet years and for a range of crop prices. Read more about the nitrogen simulation and its use in the classroom in Lant et al. (2016) listed at the end of this chapter.

Putting the Water, Carbon, and Nitrogen Cycles Together: Soil

Kids call it "dirt." Most farmers I've met call it "ground." I call it one of our most critical natural resources—the soil. Soil is a complex combination of weathered rock, air, water, and decayed plants as well as living roots, burrowing animals, invertebrates, fungi, and microbes. Plants can grow without it (e.g., hydroponics, stunted trees clinging to rocks in the mountains), but most grow so much better with it. As we have seen, it is the first reservoir of water supplying plants between rains. It stores and recycles nutrients (e.g., nitrogen, phosphorus, potassium). It anchors plants' roots, which in turn hold the soil in place and when they decay provide humus. Plants and soil have a mutualistic relationship; in fact, they make each other. Take away one and you lose the other.

What makes a soil fertile? (By fertile we mean helpful in growing plants, especially crops.) An ideal soil is deep, well-drained (meaning it is not always fully saturated with water), full of soil organic carbon (i.e., humus), and is a loam containing fine-grained (clay), medium-grained (silt), and course-grained (sand) particles.

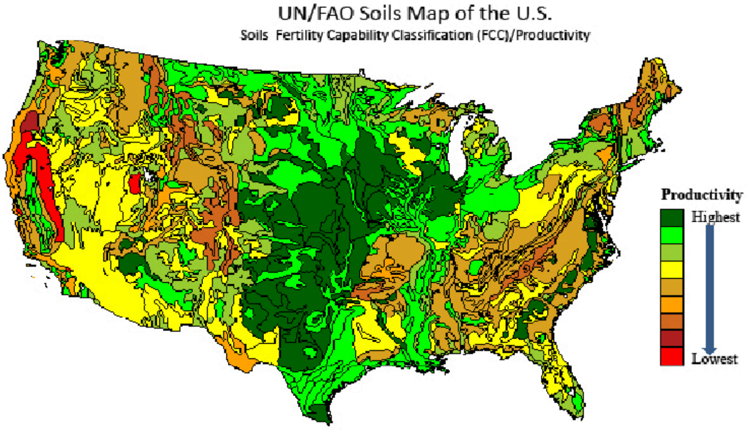


Figure 3.22. Map of U.S. soil fertility from SSURGO data.

The fertility of soils varies enormously (see U.S. map in Figure 3.22). The Midwest supports some of the most fertile soils in the world—thanks largely to the glaciers that scraped the Canadian Shield clean and deposited the glacial till from North Dakota to southern Illinois. Widespread wetlands also helped by accumulating organic carbon. The rocky Northeast and arid and mountainous West are not nearly as fertile, although southeast Pennsylvania, the Central Valley of California, and Willamette Valley of Oregon are grateful exceptions. The southeast is perhaps most intriguing with its favorable climate for agriculture, but soils that are most often lacking due to the absence of glacial till as well as heavy rainfall and high temperatures that leach the soils of nutrients. As one proceeds toward the equator, these factors intensify, making tropical soils generally infertile compared to those in the midlatitudes.

Soil scientists love taxonomies, so you'll be grateful that I'm sparing you their endless categories of soil types. For our purposes, it is important to know simply that humus is the silver bullet of soil fertility, constant waterlogging is not, and salt is a soil's undoing.

What makes soils erode or degrade? If the soil is completely protected from the wind and rain by plants—grass, shrubs or trees will do—it will continuously form and rarely erode. Not only do the roots hold the soil, but also the blades of grass, leaves, and leaf litter block the surprisingly forceful impact of raindrops. The same organic matter absorbs water. Little tunnels built by roots, fungi, worms, and all the other cornucopia of small living things in the soil that help dead plants and animals decay, increases the soil's porosity, giving the rain and snowmelt a chance to infiltrate. If it's raining so hard that it can't all infiltrate and starts to run off over the surface, the soil is anchored and has a protective barrier. Moreover, all the blades of grass and leaf litter give the runoff a tortuous obstacle course in its path downhill, slowing it down and giving it an opportunity to find another low spot where it can infiltrate. Therefore, under naturally vegetated conditions, erosion only occurs during the largest of rainstorms and only in low-lying swales where rushing water accumulates in temporary stream channels.

Even under natural conditions, however, soils in semiarid environments erode quickly because the rainfall is insufficient to support enough plant life to completely cover the soil surface, yet it does rain often enough to provide substantial erosive energy. This, along with the easily erodible nature of glacial powder called loess, is why the Yellow River in China is, in fact, yellow and why the Missouri River that Lewis and Clark explored was "too thin to plow and too thick to drink."

Figure 3.23. An agricultural field eroding badly during a rainstorm. This polluted runoff also contains fertilizers and pesticides.

In a city, covered with impervious roofs, roads, sidewalks, and parking lots, the rain runs off with little infiltration, but pavement is specifically designed to resist water erosion. The problem lies in barren agricultural soils unprotected by vegetation where raindrops form little craters in the soil. The debris from these little explosions plug up pore spaces in the soil, reducing infiltration. Now the water starts running downhill where its energy detaches soil particles, carrying them along until that energy is reduced wherever the water slows down (Figure 3.23). Here the soil is deposited. It might be at the bottom of the hill, or along a row of denser vegetation. In this sense, soil erosion is really downhill soil transportation. For this reason, valleys are usually more fertile than hillsides or ridge tops. If the soil reaches a channel, it will take a longer journey toward the sea as the sediment load of a stream or river, but it will still likely be deposited on a floodplain along the way. Rarely will it reach the sea at the mouth of a river. This is all a normal process that erodes away mountains and builds river deltas and coastal plains over millions of years. Exposed soil is subject to accelerated erosion, however, at 10 to 1000 times the natural rate.

Soil conservation largely consists of keeping as much of a vegetative cover in place as possible, consistent with the production of crops, and inhibiting rapid runoff during rainstorms. Tools in farmers' arsenals to keep their precious asset of the soil where it belongs—in the field, producing crops indefinitely, are listed. See if you can identify them in Figure 3.24.

- Reduced tillage and no till
- Leaving the residue of last year's crop lying in the field

- Adding manure
- Planting a nitrogen-fixing cover crop like clover
- Planting across the slope (contour) rather than up and down it
- Planting filters strips along stream channels
- Building terraces along slopes

Figure 3.24. An example of soil conservation techniques: contour plowing, terraces, filter strips, and grassed waterways. Look for these when driving across farm country.

While somewhat less common than water-based erosion, dry, unprotected soils are also vulnerable to wind erosion. In Chapter 2, we explored the catastrophe of the Dust Bowl in the American Great Plains, but wind erosion is also chronic in the drylands of Central Asia. The process of desertification occurs when dry grasslands are over-grazed by livestock. During the next drought, the remaining grasses wither and the soil is exposed to the wind, which removes it in some areas while building infertile dunes in others. Then when the rains return, the grasses can't recover, leaving the soil further exposed in a vicious cycle. Soil and plants either prosper together or, in desertification, fail together.

Soils can also be degraded—lose their fertility—without being transported downstream or downwind. The overapplication of irrigation water can create a wet corridor to underlying salts, which dissolve in the irrigation water and are carried toward the surface. When salts are left behind by evaporation, soil salinization destroys fertility. Soils can be depleted of organic matter and nutrients through intensive farming—hence the need to add manure or some other form of compost and fertilizer. Soils can be compacted by vehicles. Tropical soils are even more dependent on the plants they support to protect them and can turn to brick-like laterite when exposed to rain and sun.

The erosion and degradation of soil is not to be taken lightly or underestimated in its importance to humans. Soil has a long memory. Vast areas in the old cradles of agricultural civilization in the Middle East and the Mediterranean have eroded, salinized, and desertified soils that show little sign of recovering from abuses thousands of years in the past. In the U.S., the Dust Bowl has not fully recovered, and the old cotton lands of the South lack much of the fertility they had before the Civil War. As we will explore in Chapter 11, the world is already challenged, and will become even more hard-pressed, to meet the food needs, most of the fiber needs, and some of the fuel needs of the entire human population from the land. This world needs all the fertile soil it can get. The wise use of soil is thus a foundation of natural resource sustainability.

Conclusion

Geology and physical geography are fascinating topics that we have here only taken a glimpse at. Yet in this chapter we have examined much of what we need to know in the study of natural resources sustainability. The Earth runs on cycles such as the hydrologic cycle, the carbon, and nitrogen cycles. They are its metabolism. Often they interact, such as in the soil. These cycles are millions of years old, and will likely continue for millions more, with or without humans. From a human perspective, however, we can identify how we would like these cycles to work: a stable hydrologic cycle rather than one based on droughts and floods, a stable and modest pool of carbon in the atmosphere, a moderate flux of soluble nitrogen to water bodies.

We can also identify ways in which humans are affecting these cycles that produce negative consequences: erosion and depletion of soils so that they no longer store water and nutrients, emission of carbon-based greenhouse gases to the atmosphere leading to climate change, and overloading of aquatic and marine ecosystems with nitrogen, producing eutrophication and hypoxia.

Finally, an understanding of cycles suggests solutions that become cornerstones of natural resources sustainability. These include (1) protect soils from erosion by using plant cover to limit their exposure to wind and rain so they can store runoff during floods for use during droughts, (2) reduce greenhouse gas emissions and sequester carbon in the soil, forests, and geologic environments, and (3) reduce fertilizer use and utilize wetlands to return nitrogen to the atmosphere.

With this understanding of how the Earth's physical environment generates natural resources, we are prepared to delve into its living components—the biosphere—through the lens of ecology.

Further Reading

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4.

CHAPTER 4: RELEVANT FUNDAMENTALS OF ECOLOGY

Ecology is the study of the interactions among plants, animals, microbes, and the physical environments they inhabit. It is a relatively new science—the term was first used in 1935 and the first text was written in 1953—but over the last several decades, a core understanding of ecological processes and structure has emerged that we can call ecological theory. In this chapter, we will explore some critical elements of ecological theory that are very relevant in the analysis of natural resources sustainability. The first of these elements is the ecological process, focusing on energy and trophic structures, ecological niches, and nutrient cycling. The second element is geographical—identifying the major ecosystem types or biomes and where they occur on Earth. The third element is the study of ecological change over time, focusing on succession and disturbance.

With these concepts in hand, we'll take an ecologist's look at humans as a dominant species in the contemporary Earth ecosystem. We'll conclude with an exploration of the Millennium Ecosystem Assessment and the more recent Policy Platform on Biodiversity and Ecosystem Services, seminal global studies by the United Nations that tell us how ecosystems are faring in a rapidly changing world. Is a global ecological collapse imminent? Or is there nothing to worry about? Clearly the answers lie in the vast gray zone between these extremes in the realms of ecological degradation and biodiversity loss.

The Ecological Process: Energy and Trophic Structures, Niches, and Nutrient Cycling

The Odum brothers, Eugene and Howard, both American ecologists, made perhaps the single most important contribution to ecological science in the 1950s and 60s when they came to understand that an ecosystem is designed to process energy. How does this occur? It all starts with the sun, of course, where, as a typical star, fusion generates helium from hydrogen. This releases huge quantities of nuclear energy that radiate through space at wavelengths centered on what we see as visible light but extending well into the ultraviolet (shorter wavelengths) and infrared (longer wavelengths) ranges. At a distance from the sun averaging 93 million miles with a diameter of 7,926 miles, the Earth intercepts about one-half of one billionth of this solar energy. A considerable portion of solar radiation is reflected away by clouds, ice and snow, and other light-colored surfaces (this is called albedo), but the majority strikes the Earth or ocean surface and is absorbed, thus warming the Earth.

About a billion years ago, single-celled organisms known as algae evolved the capacity to use this solar energy, especially in the blue and red color ranges (not green, which they reflect and we see), to convert twelve common, low-energy, simple molecules—six of water (H_2O) and six of carbon dioxide (CO_2)—into a single, energy-packed molecule of carbohydrate or sugar ($C_6H_{12}O_6$) plus six molecules of oxygen gas (O_2). (Confirm to yourself that all the carbon, oxygen, and hydrogen atoms are accounted for in this chemical reaction). Photosynthesis was thus born in the chloroplasts of plant cells and with it an ecological energy source derived from plants termed primary producers. The total amount of photosynthesis accomplished by an ecosystem is called *gross primary production*. Ecologists measure the vibrancy of an ecosystem as *net primary production*—the photosynthetic energy fixed in carbohydrates and other biomass that remains on an annual basis after taking care of their own energy needs through respiration. Figure 4.1 shows a global map of terrestrial net primary production highlighting the central role of tropical forests and wetlands in the biosphere and the marginal role of polar regions and deserts. This is a map of how much life activity there is on various parts of Earth's land surface.

Photosynthesis accomplishes many things and can be thought of as the heartbeat of the biosphere. It produces oxygen gas as a byproduct. This constitutes 20.9 percent of the Earth's atmosphere and is the means through which nearly all living things capture energy from carbohydrates by eating and then burning them in the reverse process known as respiration (this occurs in the mitochondria of our cells). Photosynthesis removes carbon dioxide from the atmosphere and stores it as biomass (living tissue, much of which occurs in trees) and also funnels carbon into the soil as organic matter (i.e., humus) when biomass decays. The chemical energy contained in carbohydrates (i.e., calories) is available to animals as food. Together with oxygen, we can see that animals, including humans, are utterly dependent on plant photosynthesis for their survival.

The Odum brothers conceived of this transfer of energy from plants to animals as *trophic levels*, with plants as the first trophic level. Herbivores and decomposers that eat the plants are thus the second trophic level, carnivores the third, and a carnivore that eats carnivores is at the fourth level.

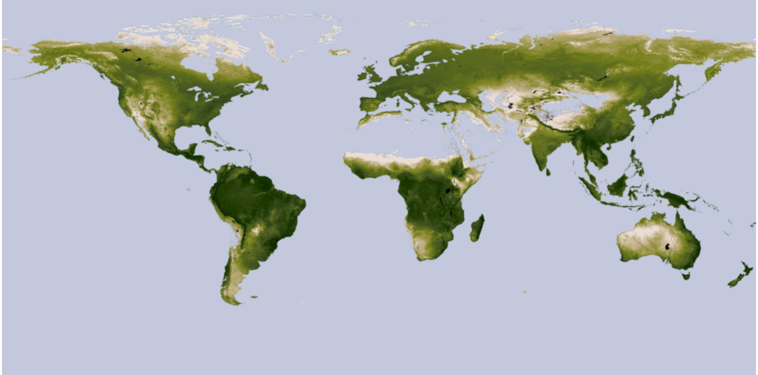


Figure 4.1. Global map of net primary productivity on land measured in kilograms of carbon per square meter generated annually through photosynthesis. Yellow/white is lowest, dark green the highest.

Energy rarely gets past the fourth level because it is lost along the way through respiration that plants, animals, and microbes use for their own needs. As a rule of thumb, each trophic level uses 90 percent of the energy it captures as its own energy supply and only passes on 10 percent to the next higher level (Figure 4.2). For this reason, plants, not animals, make up the vast majority of biomass on Earth and are appropriately the primary basis for characterizing ecosystems. For the same reason, carnivores are generally only one-tenth as common as herbivores, and few animals can survive solely by eating other carnivores. By the fourth trophic level, ecological energy has largely dissipated. It is important to recognize that about ten times more humans can live as herbivores (i.e., vegetarians) than as strict carnivores. This is a relevant issue in natural resources sustainability for a species like humans that is an omnivore.

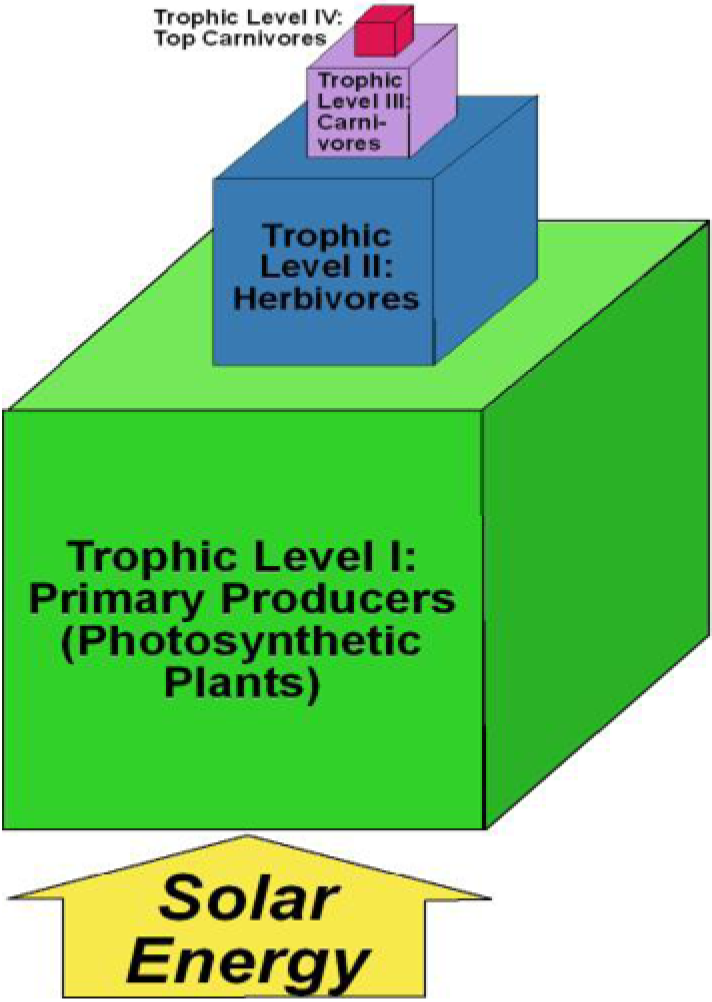


Figure 4.2. Trophic structures. The volume of each trophic level is proportionate to the energy supply it contains.

In any given ecosystem, these trophic levels make up the food chain, but where multiple species are present at each level, we have a food web. Food webs also include the detritus cycle—the decay of dead biomass, mostly plants, that is performed largely by fungi and bacteria, to a considerable extent in the soil and at the bottom of water environments. Square one in understanding any ecosystem is to get a handle on the food web and square one in understanding any species' ecological niche is to see where it fits in that food web, keeping in mind that food is largely about capturing chemical energy originating from the sun. In addition to its food supply, and how it in turn is consumed, a species' niche also includes its habitat—the climates it is best adapted to; whether it thrives on land, water, or both; whether it prefers forested, grassland, or other environments; and what circumstances are required for successful reproduction. What other species does it need to avoid and what species does it depend upon? Do events like floods and fires enhance its habitat or destroy it? We discussed the human ecological niche in Chapter 2 in comparison to that of oak trees, smallmouth bass, and the malaria virus. What is the niche of species we commonly experience: plants such as bluegrass, cattails, pine trees, and corn, vertebrate animals such as horses, deer, squirrels, and Canadian geese, invertebrates such as earthworms, crayfish, and grasshoppers, fungi such as mushrooms?

Ecosystems of the Earth: Biomes and Landscape Ecology

Geography and ecology meet in the categorization and mapping of the major ecological types on Earth called biomes. While there is no one universally accepted taxonomy (i.e., categorization system), it is fruitful to take a look at the factors that we can use to make important distinctions among ecosystems. The most fundamental division, of course, is between land and water—with wetlands intermediate between the two. Among water-based ecosystems, we make our next cut between salt and fresh water—with estuaries intermediate. Table 4.1 shows further divisions, such as between lakes and streams/rivers in the aquatic category and deep ocean, shallow and more productive continental shelves, and coastal ecosystems under the marine umbrella. We can continue to make distinctions almost indefinitely, but for our purposes it is sufficient to stop at this point.

Table 4.1. An example of a simple taxonomy of ecosystem types.

The Biosphere

I. Water and wetlands

  A. Salt water/marine
    1. Deep Ocean
    2. Continental Shelf
    3. Coastal/Wetland
      a. Mangroves
      b. Estuaries
  B. Fresh water/aquatic
    1. Lakes
    2. Streams and rivers
    3. Wetlands
      a. Marshes
      b. Swamps

II. Terrestrial
  A. Forested
    1. Tropical
    2. Temperate
    3. Boreal
  B. Water-limited
    1. Grassland
      a. Savanna
      b. Prairie/steppe
    2. Woodland/shrubland
    3. Arid
      a. Semiarid scrubland
      b. Desert
  C. Cold-limited

For land-based ecosystems, plant life is the key. Because they are primary producers and thus the first tropic level, about 90 percent of biomass in an ecosystem is plants. These form both the energy source and the habitat for higher, animal-based trophic levels. From this starting point, there are a number of ways to proceed. In Table 4.1, the next cut is made by acknowledging that wherever land has sufficient warmth and precipitation, a forest will grow (i.e., unless it is removed by fire, chain saws, or the plow). Climate is therefore critical to ecology and plays a large role in defining biomes. Forests can then be divided simply into tropical, temperate, and subarctic zones, the latter known as taiga or boreal forest. A second important distinction among forests is whether they are deciduous (the leaves fall in winter or the dry season) or evergreen, and whether they are broad leaf, like an oak or maple, or needle leaf, like a pine or fir.

Where rainfall is insufficient or fire too frequent for forests, we will find grasslands known as savanna in the tropics, prairie or steppe in the temperate zone. In lands with a Mediterranean climate (winters are wet, summers are dry), we may also find shrublands, often dominated by fire-prone oak shrub, sometimes referred to as chaparral. As precipitation declines even further, grasslands and shrublands give way to semiarid scrub such as interspersed sagebrush that dominates much of the American West, until these give way to a landscape largely devoid of vegetation—the true desert.

Where cold temperatures and short growing seasons prevent forests from growing, we find the shrub/grass/wetland mix known as tundra, except where glacial ice prevents all plant growth in most of Antarctica and Greenland. In mountains, alpine ecosystems place several of these ecotypes in close proximity based on elevation—with higher elevations resembling more polar climates—and, to a lesser extent, aspect—slopes facing the equator are warmer and dryer than slopes facing away because they receive more sunlight.

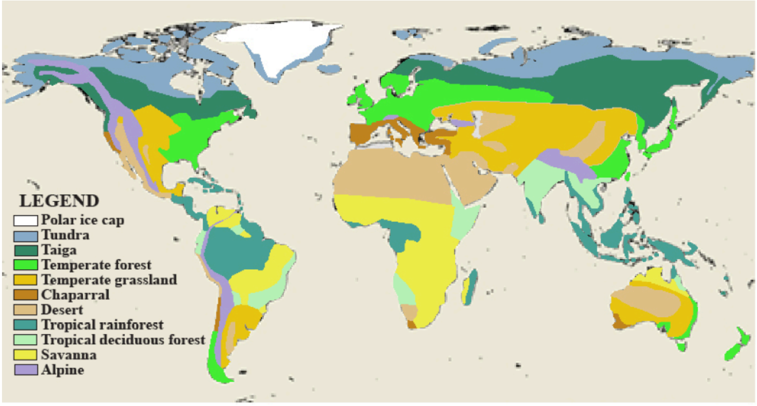


Figure 4.3. Map of Earth's land-based biomes.

So where on Earth do these biomes occur? Take a good look at the simple map in Figure 4.3 and let's take some time to point a few things out. It's no surprise that tropical rainforests straddle the equator in South America (the Amazon), Africa (the Congo), and southeast Asia, including the islands of Indonesia and the Philippines. These are surrounded by tropical seasonal forests that drop their leaves in the dry season (generally each hemisphere's winter, though in the tropics, of course, it doesn't get very cold) and by savannas, where interspersed trees provide shade for grazers and the predators that chase them.

Temperate deciduous forest is my "home" ecosystem – both where I grew up in upstate New York and where I taught for 26 years in southern Illinois where the corn fields end. You may have a different "home" ecosystem. It also occurs in much of Europe and northeast Asia, including Japan. An evergreen temperate rainforest occurs along the beautiful Pacific Northwest coast from northern California to Alaska and in New Zealand. Spruce and fir evergreen taiga is dominant in the subarctic zone of Canada and Russia.

Temperate grasslands epitomize the American Great Plains but also the interior of Asia, grading through scrubland into desert where rainfall is most stingy or centuries of overgrazing have degraded the soil. Bone-dry, rocky, or sandy subtropical deserts straddle the Tropic of Cancer, especially in North Africa and the Arabian Peninsula—the world's super desert known as the Sahara—more than in North America along the U.S.-Mexican border. The Australian outback, straddling the Tropic of Capricorn, is also a subtropical desert. Woodland/shrubland surrounds the Mediterranean and characterizes southern California. Tundra dominates the Arctic in both North America and Siberia while complex alpine zones are most evident in the Himalayas, Andes, and Rocky Mountain chains, though they occur elsewhere as well.

Through this examination of biomes, we can see that there is a chain of causation that runs from latitude, through climate, to dominant vegetation, to animal life. In any one place, however, other factors such as proximity to the sea, topography, soil, biological history, and, of course, human occupation also come into play in generating the complex geography of ecosystems across the globe.

The map in Figure 4.3 paints with a spray can, but it's also important to take a closer look, so let's break out the paint brushes. With a broad brush, we can identify ecoregions based on constellations of climate, topography, and vegetation, which often coalesce in determining a characteristic land use. Because there is no completely objective way to delineate ecosystems—or for that manner to draw lines between biomes—maps of ecoregions differ. The one I've found most useful is James Omernik's (1987) Ecoregions of the U.S. which has been adopted by the U.S. Environmental Protection agency. Take a look at Figure 4.4 and find the ecoregion(s) you grew up in, the one where you are obtaining your education, and places you have traveled frequently on outdoor-oriented vacation trips. What characterizes these places in terms of climate, topography, vegetation, and land use? Are the areas delineated in the map more similar within the boundary of an ecoregion than they are outside of it? Would you place the boundary somewhere else or redefine an ecoregion?

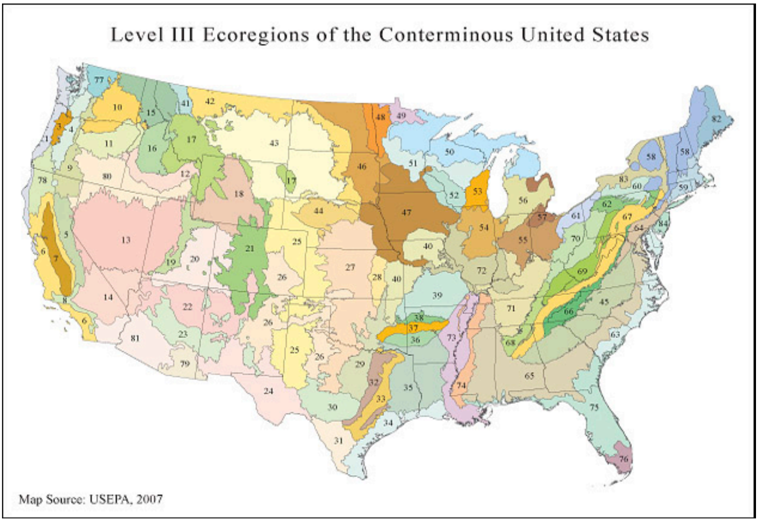


Figure 4.4. Level III Ecoregions of the United States. Source: U.S. Environmental Protection Agency. See Level I, II, III and IV ecoregion maps at EPA.

1. Coast Range
2. Puget Lowland
3. Willamette Valley
4. Cascades
5. Sierra Nevada
6. Southern and Central California Chaparral and Oak Woodlands
7. Central California Valley
8. Southern California Mountains
9. Eastern Cascades Slopes and Foothills
10. Columbia Plateau
11. Blue Mountains

29. Cross Timbers
30. Edwards Plateau
31. Southern Texas Plains
32. Texas Blackland Prairies
33. East Central Texas Plains
34. Western Gulf Coastal Plain
35. South Central Plains
36. Ouachita Mountains
37. Arkansas Valley
38. Boston Mountains
39. Ozark Highlands

57. Cross Timbers
58. Edwards Plateau
59. Southern Texas Plains
60. Texas Blackland Prairies
61. East Central Texas Plains
62. Western Gulf Coastal Plain
63. South Central Plains
64. Ouachita Mountains
65. Arkansas Valley
66. Boston Mountains
67. Ozark Highlands

12. Snake River Plain
13. Central Basin and Range
14. Mojave Basin and Range
15. Northern Rockies
16. Idaho Batholith
17. Middle Rockies
18. Wyoming Basin
19. Wasatch and Uinta Mountains
20. Colorado Plateaus
21. Southern Rockies
22. Arizona/New Mexico Plateau
23. Arizona/New Mexico Mountains
40. Central Irregular Plains
41. Canadian Rockies
42. Northwestern Glaciated Plains
43. Northwestern Great Plains
44. Nebraska Sand Hills
45. Piedmont
46. Northern Glaciated Plains
47. Western Corn Belt Plains
48. Lake Agassiz Plain
49. Northern Minnesota Wetlands
50. Northern Lakes and Forests
51. North Central Hardwood Forests
68. Central Irregular Plains
69. Canadian Rockies
70. Northwestern Glaciated Plains
71. Northwestern Great Plains
72. Nebraska Sand Hills
73. Piedmont
74. Northern Glaciated Plains
75. Western Corn Belt Plains
76. Lake Agassiz Plain
77. Northern Minnesota Wetlands
78. Northern Lakes and Forests
79. North Central Hardwood Forests

24.	Chihuahuan Deserts	52.	Driftless Area	80.	Driftless Area
25.	High Plains	53.	Southeastern Wisconsin Till Plains	81.	Southeastern Wisconsin Till Plains
26.	Southwestern Tablelands	54.	Central Corn Belt Plains	82.	Central Corn Belt Plains
27.	Central Great Plains	55.	Eastern Corn Belt Plains	83.	Eastern Corn Belt Plains
28.	Flint Hills	56.	Southern Michigan/ Northern Indiana Drift Plains	84.	Southern Michigan/ Northern Indiana Drift Plains

Now let’s get out the finer paint brush and take a look at landscape ecology at the scale we would see from an airplane window. You will likely see a dominant land use that covers the majority of the landscape—forest, grassland, cropland, or desert most likely. This is called the landscape mosaic. Within that, there will be patches of something else—wetlands, towns, industrial areas, lakes —and linear corridors—roads, rivers. These components of the landscape interact with one another and their spatial arrangement or layout is important. What serves as a corridor for easy movement to one species (e.g., roads for humans, rivers for fish) is a barrier for others (e.g., turtles, bobcats). Some species thrive at the edge of ecosystems. Deer hide in the woods and wetlands but browse in the fields. Others prefer the interior like owls and woodpeckers in a forest. Wet areas along a river valley, the riparian zone, are critical habitats in arid regions because this is where vegetation grows far more productively. Riparian zones are also important in humid climates because this is where flood waters spill over the riverbank depositing sediment and seeds and exchanging nutrients and species.

Biologists are interested in ever-smaller scales, from plots of a few yards square where they may find plants, invertebrate animals, fungi, and microorganisms tangled together in relationships that are often mutualistic (benefiting both parties) to the individual plant or animal organism with its interdependent organs and systems, down to its cells, DNA, and molecules. For the purposes of understanding natural resource sustainability, however, we'll stop here, but I hope you see fit to study ecology and biology at these smaller scales.

Ecological Change: Succession and Disturbance

Ecosystems vary geographically, but they also have a history. It is revealing to dip into the debates among ecologists focused on temporal dynamics because it tells us something about the ever-changing nature of ecological reality. "Succession" is a century-old idea first authored by Frederic Clements. It is increasingly in disfavor, but let's take a look at what many ecologists have taken pride in shooting down.

A pioneer farmer in the Ohio Valley clears a forest to plow the field for crops. A generation later, the farm is proving to be unprofitable and so (s)he stops plowing it and moves on. What happens now? Some plants specialize in spreading their seeds so they can quickly and opportunistically colonize a newly available niche, which open soil that receives rain and sunlight clearly represents. We call them "weeds," but they are simply fast, colonizing plants, many of which have positive characteristics. In this abandoned field, the weeds hold the soil and maintain the flow of carbon and nitrogen, thus setting the stage for fast-growing woody plants like cottonwood or poplar that also distribute seeds in the wind, looking for a new home. These eventually outgrow the "weedy" grasses and forbs and form a dense stand. Next come the oaks and hickories that use nutrients, water, and sunlight more effectively and are thus able to outgrow the cottonwoods and poplar over time. These tree species are shade-intolerant, however, so their own saplings are not viable in the shade of their parents. More shade-tolerant maples and beeches thus succeed oaks and hickories over the course of a few centuries. Clements called this a climax forest because no other plant species would succeed maple-beech. He thought that the ecosystem had reached equilibrium.

In a quiet world without fire, floods, climatic extremes, storms—and humans—Clements was largely correct, but we don't live in that world. We live in a world of ecological disturbances, and they generally come more frequently than the time it takes to reach the “climax” state. So rather than ask “what is the climax state and what stage are we in the progression toward it?” ecologists are now asking “what is the disturbance regime and how does the ecosystem adapt to it?” Fire is a mainstay of chaparral, grassland, and drier forests dominated by oaks, pines, or aspen. Floods are a mainstay of wetlands, moister forests in riparian zones, and wadis or arroyos (usually dry riverbeds in the desert that explode with water when it finally does rain). Storms less severe than hurricanes can knock forests flat. On May 8, 2009, a super-derecho, or straight-line winds, knocked down so many trees, including 20 in my yard, including four 100-foot oaks, that my home county received federal disaster assistance. A herd of bison or a swarm of tent caterpillars can eat up every green blade or leaf in sight. And then come humans with chain saws, matches, plows, herbicides, even concrete, and a changing climate.

With all of these disturbances, ecosystems rarely reach Clement’s imagined climax equilibrium. Instead, we have ecosystems in various stages of recovery from past disturbances of different forms and intensities. That’s not all bad, because they can often have a rejuvenating effect, creating niches, mobilizing nutrients, restoring the opportunity for growth. When is a fire or a flood good? When is it bad? It’s not an easy question to answer. Nevertheless, an understanding of the disturbance regime is now considered to be central to an understanding of any ecosystem.

Biodiversity and its Loss

It is difficult to fathom the diversity of life on Earth. Microbes live a mile deep in the Earth's crust, in pressurized water hotter than the boiling point, and in the dry valleys of Antarctic—wherever more than a few molecules of liquid water accumulate, even occasionally.

Figure 4.5. Hotspots of Biological Diversity.

Thirty-five "hotspots" of biological diversity together cover only 1.4 percent of the world's land surface but contain nearly half of plant and over a third of animal species (Figure 4.5). In these special places, new species are being discovered at astonishing rates. Eminent Harvard biologist Edward O. Wilson in *The Future of Life* describes how he has discovered dozens of new species of insects in a single day from a single tropical tree but that other biological explorers have surpassed even his accomplishments. Science has clearly identified 1.5–1.8 million species, 205,000 of these in the United States, but estimates of how many there really are vary from 3 to 100 million! New mammal and even new primate species continue to turn up once trained scientists start an intensive search. Unfortunately, this cornucopia of biodiversity is eroding away like soil exposed to the rain and the wind.

According to E. O. Wilson, the Earth is today going through a great extinction, if far less suddenly than when a meteor strike on the Yucatan Peninsula of Mexico wiped out the dinosaurs 65 million years ago. For example, the declining amphibian phenomenon (more popularly, the frog die-off) has resulted in the loss of half the Earth's population of amphibians in the last 35 years. We are losing species at 100–1,000 times the average rate that has occurred over the past several million years. This is a biodiversity crisis. Many problems of natural resource sustainability are reversible—soils can be restored, forests regrown—or substitutable —wind energy can replace depleted oil supplies. But extinction is forever. Why is this happening?

Biological conservationists use a simple acronym—HIPPO—to summarize the drivers of biodiversity loss: Habitat destruction, Invasive species, Pollution, Population, and Overharvesting. They are all results of human actions on a planet where humans have become the dominant species and an irresistible ecological force. In order to further explore the HIPPO factors, let us now turn to the seminal

2005 study known as the Millennium Ecosystem Assessment and its 2019 successor, the Policy Platform on Biodiversity and Ecosystem Services (PPBES).

The Millennium Ecosystem Assessment and the Policy Platform on Biodiversity and Ecosystem Services

In 2000 Secretary-General of the United Nations Kofi Annan called for a “millennium ecosystem assessment,” a study of the ecological state of the world with a focus on how ecological changes affect human well-being, the causes or drivers of those ecological changes, and remedies that may lie in the realm of policy and changes in human behavior. The resulting assessment published in 2005 was the most intensive and rigorous worldwide study of the interactions between humans and nature ever conducted. It involved over 2,000 scientists and researchers from nearly every country who published dozens of separate studies totaling several thousand pages. Fortunately, the Millennium Ecosystem Assessment has been condensed into shorter and more accessible forms, including a 28-page message from the board titled *Living Beyond Our Means: Natural Assets and Human Well-being* and a 155-page synthesis report containing a 24-page executive summary.

These distillations of a study that rivals the Nobel Peace prize-winning Intergovernmental Panel on Climate Change reports in quality and scope can be downloaded free on the Millennium Ecosystem Assessment website. As of this writing, the successor study called the Policy Platform on Biodiversity and Ecosystem Services has released a Summary for Policymakers and a summary paper was published in the prestigious journal *Science* in December 2019. We eagerly await the main body of this foundational report.

How do ecosystems affect human well-being? The first human need is for the basic material elements of survival—oxygen from the air, clean water, food, shelter—all of which are derived almost entirely from ecosystems. The second need is for security from harm. While we may need police and defense establishments to protect us from other humans that wish to do us harm, ecosystems also provide a buffer from nature's extremes—floods and droughts, hurricanes, and tsunamis. Ecosystems are also a psychological resource providing beauty, comfort, places to explore, and fun things to do on weekends and summer vacations, even a haven of spiritual enrichment.

In recognition of these connections, the two U.N. studies adopt ecosystem services as a point of departure in assessing how ecosystems are faring. These come in four conceptually distinct forms: provisioning, cultural, regulatory, and supporting. Provisioning ecosystem services meet human needs through use or consumption of natural resources such as food, fresh water, raw materials, energy supplies, and so forth. Commonly these services are bought and sold as components of the market economy, though there are many exceptions such as the gathering of fuel wood, subsistence and recreational hunting, fishing, and farming.

Cultural ecosystem services are experiential. Whenever we escape from our offices, classrooms, and homes filled with digital media and experience the genuine analog world around us, even through a car's windshield, we are being provided with cultural services from ecosystems. Gardening, fishing, hunting, and hiking are activities that account for most of the time Americans spend outdoors – and three of the four can potentially produce food, though this is rarely why we do these things. More likely, it makes us happy and provides some much-needed exercise. Reverence for a sacred place, the challenge of climbing a mountain or running a rapid river, or the experience of wilderness take cultural ecosystem services to a deeper psychological level in the subjective world where beauty is in the eye of the beholder and to each his own. Ecotourism, a term that includes everything from safaris to the Serengeti Plain to guided fly-fishing trips and nature documentaries are examples where these experiences are purchased from outfitters or the media, but the majority of cultural ecosystem service experiences are not directly sold. For many, the absence of buyers and sellers is a key to making the experience of nature authentic, yet the lodging, vehicles and equipment needed to facilitate these experiences is an enormous industry.

Regulating ecosystem services are a little less straight-forward and so are best explained through examples. Because atmospheric carbon absorbs long-wave radiation and therefore contributes to climate change, storing it in biomass (that is, as part of a plant, such as a tree) rather than in the atmosphere helps regulate the climate. Wetlands help remove nitrate pollution from water through denitrification and uptake of this fertilizer by plants. They also absorb flood waters in low-lying areas, river floodplains, and hurricane-prone coastlines. Wetlands thus provide the regulating services of water purification and flood control. Bees pollinate crops. Other insects and birds eat pests that destroy crops and spread disease. These examples of regulating services are rarely bought and sold—though that is beginning to change, as we will see in Chapter 15.

Supporting ecosystem services include everything we studied earlier in this chapter and in Chapter 3, from (yet again) photosynthesis to soil formation and the cycling of nutrients. They are the basic infrastructure and metabolism of the planet upon which everything else is based. While humans benefit more directly from provisioning, cultural, and regulating services, there would be none of these if it were not for the supporting services that nature provides free of charge and we all take for granted—until they start to disappear.

Now that we better understand how ecosystems service humans, how are they faring across this beautiful planet? The PPBES report provides four main conclusions that we will explore.

1. Nature and its vital contributions to people, which together embody biodiversity and ecosystem functions and services, are deteriorating

2. worldwide.

   Direct and indirect drivers of change have accelerated during the past 50 years.
3. Goals for conserving and sustainably using nature and achieving sustainability cannot be met by current trajectories, and goals for 2030 and beyond can only be achieved through transformative changes across economic, social, political, and technological factors.
4. Nature can be conserved, restored, and used sustainably while simultaneously meeting other global societal goals through urgent and concerted efforts fostering transformative change.

Ecological changes have human consequences because they change the quantity and quality of ecosystem services provided to specific people in specific places, thereby improving or diminishing their well-being. What is causing these often troubling and occasionally encouraging ecological changes? The causes are complex, but we can start by identifying the direct drivers and then work backwards to identify indirect drivers. Figure 4.6 will help us do that.

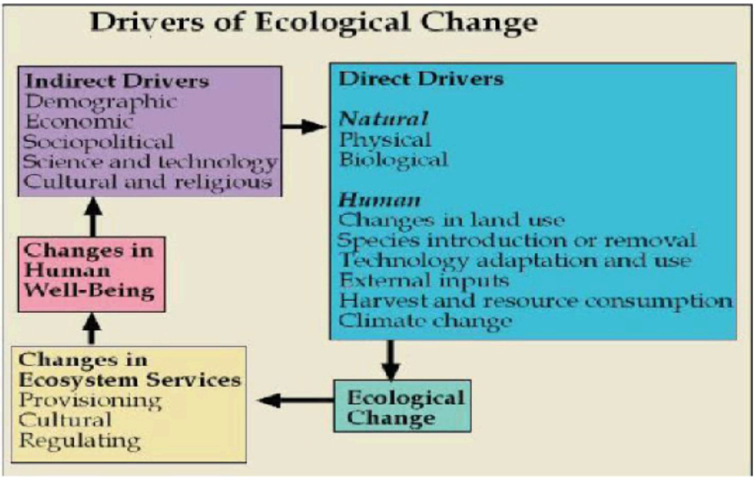
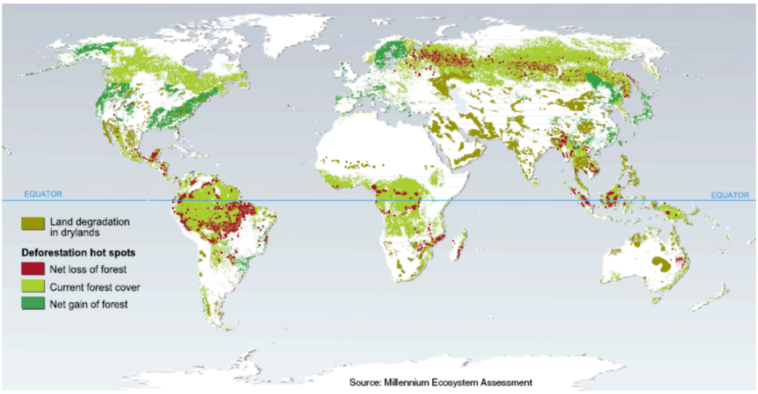


Figure 4.6. Drivers of ecological change and its relationship to human well-being.

Direct Drivers

Ecosystems change due to natural causes falling in either the physical realm (e.g., earthquakes, hurricanes, meteor strikes) or the biological realm (e.g., the evolution of a viral or bacterial disease). They also change due to human causes such as habitat destruction.



Source: Millennium Ecosystem Assessment

Figure 4.7. Regions of land use change focusing on losses and gains in forest cover, 1980–2000.

Land-use changes. Changes in land use, such as development of forested or agricultural areas for urban uses, the conversion of wetlands or forests into cropland or pasture, or their reversion back to wetland or forest, have profound effects on ecosystems and are identified by the PPBES as the most important driver of biodiversity loss. Figure 4.7 from the Millennium Ecosystem Assessment shows the areas of the Earth that have maintained forest cover over the period 1980–2000 in light green. A band of tropical forests straddling the equator in South America, Africa, and Southeast Asia is evident as well as a band of boreal forest (or taiga) especially in Canada and Russia. Net gains in forest area have occurred in parts of Europe, Japan, and the eastern United States, which is the global center of reforestation (dark green). Deforestation is rampant in the Brazilian Amazon, as you have no doubt heard, but also in Indonesia and other tropical countries as well as in Russia (dark red).

The map also shows where dry grasslands are being degraded, usually through livestock grazing, into more desert-like conditions in several localized areas of Asia, Australia, and near the U.S.-Mexico border (olive). In most instances, land uses are relatively stable, but where they are not, ecosystems are being altered radically. The questions arise: Why these directions of change? Why these places and not others?

Species introductions and removals. While more subtle than wholesale land-use change, species introductions and removals have ripple effects that can be difficult to predict. The accidental release of the zebra mussel from the Black or Caspian Sea into the Great Lakes resulted in a population explosion of these tiny shellfish that numbers in the trillions. In addition to being a very expensive nuisance on water intakes and other human structures, many native species of mussels are losing the ecological competition to this invasive species. The zebra mussel is a filter feeder, however, and their presence has improved water quality and clarity throughout the Great Lakes. Sight-feeding predator fish such as introduced Chinook salmon, brown and rainbow trout have benefited from the zebra mussel's water-cleansing services, and therefore so have anglers and outfitters. Conversely, the removal of sea otters in the Pacific Northwest through over-hunting has led to a population explosion of their prey (sea urchins) that have subsequently devoured the undersea kelp forests, home to many species of fish. The kudzu vine, "the plant that ate the south," can grow two inches in an hour to smother less exuberant plants. Fortunately, cattle can graze on it and it can be used to protect exposed soils, but other invasive species lack any silver lining. The chestnut fungus introduced on imports of Asian logs in 1904 completely wiped out the most important tree in the central hardwood forest of the eastern U.S. in the first half of the 20th century. The Asian subterranean termite causes billions of dollars of property damage in New Orleans and other southern cities. Asian carp now dominate the Mississippi River and many of its tributaries.

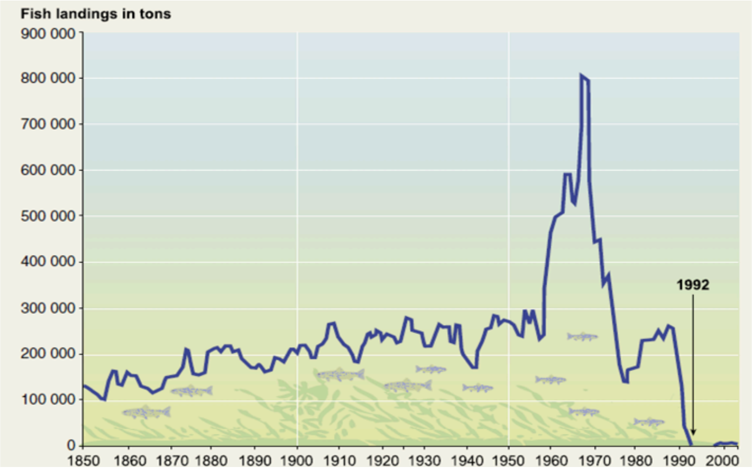


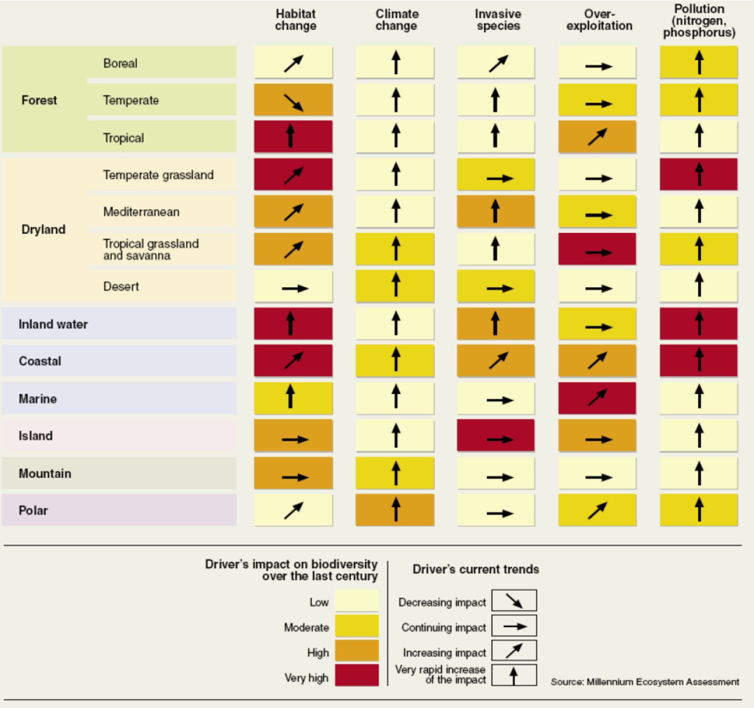
Figure 4.8. The North Atlantic cod fishery collapse of the late 20th century.

Technology. Human domination of the planet has been achieved in large measure through use of technologies, from chain saws to plows, through which humans can impose their will on how to use a parcel of land, to antibiotics and pesticides, chemicals that humans use to protect themselves and their food supplies from biological competitors. As these technologies are diffused from one society and one ecosystem to the next, and as they are adapted to changing circumstances, their ecological impacts also change. Repeatedly plowing the soil in Iowa can induce erosion; repeatedly plowing the soil in the Amazon can permanently destroy it. Perhaps you can think of other examples discussed elsewhere in this text where the introduction of a technology was as devastating as huge drag nets were to the North Atlantic cod fishery in the 1980s (Figure 4.8) or as helpful as the introduction of the disk used in conservation tillage to replace the moldboard plow.

External inputs. Rachel Carson's 1960 classic *Silent Spring*, which helped launch the modern environmental movement, told the story of how the pesticide DDT was wreaking havoc on birds and other wildlife because it is both persistent (i.e., it doesn't readily break down or biodegrade, so it stays in the environment for decades, even centuries) and bioaccumulative (this means that its concentration increases as it moves up the food web to toxic levels in carnivores). Nitrogen in the form of fertilizers is another critical external input that we explored in Chapter 3.

Ecological harvesting. When humans use natural resources for provisioning purposes, resources are usually extracted or harvested and subsequently consumed. Mining coal, metallic, and other ores, cutting timber, catching fish and game, harvesting crops, and sending livestock to the slaughterhouse, all have ecological effects. These include the effects caused by the game, fish, trees, crops, and livestock no longer being in the ecosystem, and the disturbances caused in the process of extraction. These disturbances include surface and underground mining, clear-cutting or selective harvest of timber, and road building. Figure 4.8 shows the stark example of the North Atlantic fisheries when record harvests of cod and haddock in the 1960s and 1970s caused the fishery to collapse. How is the marine ecosystem adapting to the loss of these key predator species?

Climate Change. Ecosystems are closely adapted to climates and when these change so do the ecosystems. Some species are favored by the higher temperatures, carbon dioxide concentrations, sea level rise, the changes in rainfall, or decreases in snow and ice that climate change brings. Some species are placed at a disadvantage, like the poor polar bear as their sea ice habitat melts away. Moreover, as the direct climatic effects play out, ecosystems end up with a different constellation of species, which causes further changes as they adapt to one another. For example, some species can readily migrate poleward to the climate they do best in, others can spread their seeds to new niches, while others are stuck in place to adapt or die out. Is there a migratory pathway they can take or is the next available habitat too far away to find and travel to?



		Habitat change	Climate change	Invasive species	Over-exploitation	Pollution (nitrogen, phosphorus)
Forest	Boreal	⬜ ↗	⬜ ↑	⬜ ↗	⬜ →	🟨 ↑
	Temperate	🟧 ↘	⬜ ↑	⬜ ↑	🟨 →	🟨 ↑
	Tropical	🟥 ↑	⬜ ↑	⬜ ↑	🟧 ↗	⬜ ↑
Dryland	Temperate grassland	🟥 ↗	⬜ ↑	🟨 →	⬜ →	🟥 ↑
	Mediterranean	🟧 ↗	⬜ ↑	🟧 ↑	🟨 →	⬜ ↑
	Tropical grassland and savanna	🟧 ↗	🟨 ↑	⬜ ↑	🟥 →	🟨 ↑
	Desert	⬜ →	🟨 ↑	🟨 →	⬜ →	⬜ ↑
Inland water		🟥 ↑	⬜ ↑	🟧 ↑	🟨 →	🟥 ↑
Coastal		🟥 ↗	🟨 ↑	🟧 ↗	🟧 ↗	🟥 ↑
Marine		🟨 ↑	⬜ ↑	⬜ →	🟥 ↗	⬜ ↑
Island		🟧 →	⬜ ↑	🟥 →	🟧 →	⬜ ↑
Mountain		🟧 →	🟨 ↑	⬜ →	⬜ →	⬜ ↑
Polar		⬜ ↗	🟧 ↑	⬜ →	🟨 ↗	🟨 ↑

Driver's impact on biodiversity over the last century		Driver's current trends	
Low	⬜	Decreasing impact	↘
Moderate	🟨	Continuing impact	→
High	🟧	Increasing impact	↗
Very high	🟥	Very rapid increase of the impact	↑

Source: Millennium Ecosystem Assessment

Figure 4.9. Degree of impact and current trends of 5 primary direct drivers on biodiversity in 13 primary eco-system types.

Figure 4.9 from the Millennium Ecosystem Assessment summarizes the effects of these direct drivers on each of the major ecosystem types. Note that only one arrow is pointed down—habitat change in temperate forests where forests in the eastern U.S., Europe, and Japan are improving. All the arrows are pointed up under climate change and pollution where rapidly increasing external inputs of atmospheric carbon as well as nitrogen and phosphorus from fertilizer are changing all ecosystems. These pollutants, especially nitrogen, have very high impacts on biodiversity in temperate grasslands (which are often farmed), and on inland (fresh) water and coastal ecosystems, to which much of the nitrogen is flushed through runoff.

Take a few minutes to go down each column (representing a specific driver) and across each row (representing a specific ecosystem type) and see if you can surmise why the colors (representing that driver's impact on biodiversity in that ecosystem) and direction of arrows (representing the driver's current trends) are shown the way they are. For example, why is the effect of invasive species on inland water ecosystems high and rapidly increasing? Think of the zebra mussel cited above.

Indirect Drivers

While we can point to these six and other direct drivers as the cause of ecosystem change, what in turn causes them? Indirect drivers fall squarely in the realm of social science. Let's briefly identify them. In a world where the human population has grown from 2 to 7.8 billion in the last century, demographic (that is, population) changes are obviously at work. They are more than just a multiplier of the other drivers, however, as we will see in Chapter 5.

Economic growth and change is the irresistible force of all of the direct drivers, as we will explore in chapters 6 and 7. Sociopolitical change often occurs more slowly, then bursts forward when regimes change, such as fall of the Soviet Union in 1989–1991, the radical shift of China from communism to capitalism under Deng Xiaoping in the 1980s, and the expansion, then contraction, of the European Union over the past generation. Social movements, including the environmental movement—along with civil rights, women's rights, gay rights, Islamic fundamentalism, and other movements—can take societies in a new direction.

Science and technology are so often lumped together that we forget that they play two separate roles in society. Science has taught us that we live in an unimaginably old, enormous, and complex universe that began with a big bang and that we evolved over millions of years on a 4.5- billion-year-old planet we share with millions of other species in communities called ecosystems. Technological advances, usually founded in science, have uniquely empowered humans within this community and will continue to do so as we perhaps learn how to do things like inexpensively desalinate seawater, safely store carbon emissions in the Earth, replicate the photosynthesis process outside of plants, cheaply capture solar energy for electricity, or develop vaccines for coronavirus outbreaks. Each of these advances, if and when achieved, will change our relationships in the ecological community—hopefully for the better but quite possibly for the worse.

Culture and religion help us work out the meaning of all this in terms of what we should care about, what's right, what's wrong, what we hope for, and what we fear. These things are different to different people, change over time, and even change for each of us as individuals as we grow.

This brief introduction to indirect drivers serves as our segue way to a discussion of society's role in natural resource sustainability in Part IV.

Further Reading

Diaz et al. 2019. Global Conservation Summary Review: Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science* 336: 1327.

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, 2019. *Summary for policymakers*.

Millennium Ecosystem Assessment, 2005. *Ecosystems and Human Well-Being: Synthesis* (155pp).

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PART III

PART III: SOCIETY'S ROLE

5.

CHAPTER 5: HUMAN POPULATION AND SUSTAINABILITY

As we shift from Nature's Role in Part II to Society's Role in Part III we will explore how natural resource decisions are made, emphasizing the role of the economy. We begin, however, with the critical issue of population. In 2020 the world population is estimated at 7.8 billion, and its slowing growth rate is 1.08 percent, or about 82 million per year. The U.S. population is 331 million and growing at 0.7 percent, or about 2 million per year, growth rates that are also slowing. Even those numbers aren't worth committing to short-term memory, however, because population is dynamic. Demography (the study of population) is inherently a numbers game, one that is central to the analysis of natural resources sustainability. It is also important to go beyond head counting to understand how population intersects with human welfare and natural resource sustainability.

Population and Natural Resources Sustainability

So is the world overpopulated? That turns out to be a devilishly difficult question to answer. To start, what if all the 7.8 billion people in the world were placed in a single crowd, like at an outdoor concert. Let's give everyone a square meter (about 39 inches on a side)—more than enough room to stand without crushing against one another. How big would the crowd be? The U.S.? Alaska? Rhode Island? Woodstock? We know it would be 7.8 billion square meters, which is 7800 square kilometers, or 88.3 kilometers on a side (54.9 miles on a side). This is about the size of Delaware. Many counties are bigger than that. It would take 70,000 of these crowds to cover the Earth. So certainly the world isn't physically overrun with people. Rather the issue lies in the natural resources those people consume and the environmental sinks they pollute relative to the Earth's capacity to provide them.

The relevant ecological concept is *carrying capacity*, which can be applied, for example, to how many grazing livestock a pasture or section of rangeland can support, or how many wolves the moose population of Isle Royale in Lake Superior can feed. Scholars have tried to estimate this for humans by calculating how much food the Earth can produce and dividing this by the nutritional requirements of a human being. Unfortunately, the estimates range from 1 to 100 billion, although most are between 4 and 16 billion. It seems there's more to it than that.

Ecology provides us with a number of models of the relationship between the population of a species and the carrying capacity of its habitat: continuous growth, sigmoid or asymptotic approach to equilibrium, overshoot and oscillation, and overshoot and collapse (Figure 5.1). The continuous growth model asserts that the human carrying capacity of the Earth is not a constant. Rather it is as dynamic as technological development, from the evolution of agriculture in the Fertile Crescent over 10,000 years ago to the industrial revolution 200 years ago that harnessed fossil fuels to the service of humans, to ongoing developments to desalinate seawater, capture solar energy, and master nuclear fusion. History gives this cornucopian model the upper hand, but are we now facing more fundamental ecological constraints such as the photosynthetic capacity of the biosphere (over a fourth of which humans now appropriate) the exploding rate of biodiversity loss, and exceeding other planetary limits, such as for atmospheric carbon?

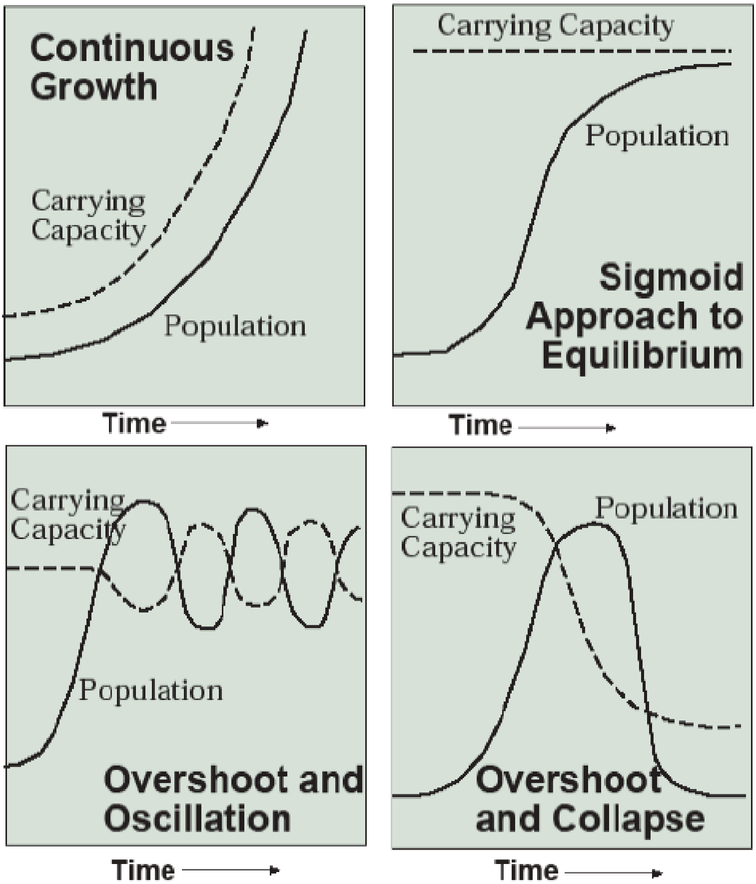

Figure 5.1. Four ecological models of the relationship between the population of a species and carrying capacity.

The second model, sigmoid or asymptotic approach to equilibrium, asserts that these carrying capacity constraints are fundamental. The exponential population growth of the 20th century must slow to a stop in the 21st short of the carrying capacity. As we will see, the worldwide decline in total fertility rates since 1970, when the annual rate of world population growth peaked at over 2 percent, seems to capture what we would hope can be achieved by the demographic transition.

If fertility declines fail to slow population growth sufficiently, however, we could face the overshoot and oscillation model. This model characterizes the populations of many wildlife species and the human population during the long millennia between the agricultural and industrial revolutions. Here death rates periodically act as a brake on population growth—not the course any of us would wish for on ethical grounds.

Even worse is the fourth model, overshoot and collapse, where not only does population outrun the carrying capacity, but in desperation to survive, humans undermine that carrying capacity by depleting ecosystems of soil, forests, species, and clean water. They leave behind toxic pollutants and disrupt the climate, leading to a long-term decline in carrying capacity. This model is the epitome of unsustainability where the Four Horsemen of the Apocalypse (pestilence, war, famine, and death) punish humanity for its lack of restraint. It can and has happened, on Easter Island, the Mayans, and other examples documented by Jared Diamond in *Collapse* and by other authors of environmental history such as Joseph Tainter in *The Collapse of Complex Societies*.

The debate then comes down to how much restraint is required in the short-term, and what forms that restraint should take, to avoid such a catastrophic long-term outcome—when we don't know what the carrying capacity is or how it will change. These are issues that have no simple answer and I am not going to provide you with one. Rather I would ask that you keep this mega issue about the threat of overpopulation in mind as we explore demography in this chapter.

The Current World Population

Mapping the distribution of human population on Earth is an interesting exercise in cartography (the art and science of making maps). My preferred method is a dot map precisely because half of the world's people now live in cities and towns that occur in specific places. In this type of map, we can see geographical detail as long as the size of the dots and the number of people each represents (100,000 in Figure 5.2) are chosen carefully so that the dots merge together in densely populated areas, but the sparsely populated regions can be differentiated from the uninhabited. This technique clearly shows the world's largest population clusters in East Asia, South Asia, and Europe, followed by the eastern U.S. It also shows the sparsely populated zones in northern North America and parts of the U.S. West, the Amazon, the Sahara Desert of northern Africa and the Arabian Peninsula, Siberia, parts of Central Asia, and most of Australia. Of course, Antarctica and the oceans are uninhabited.

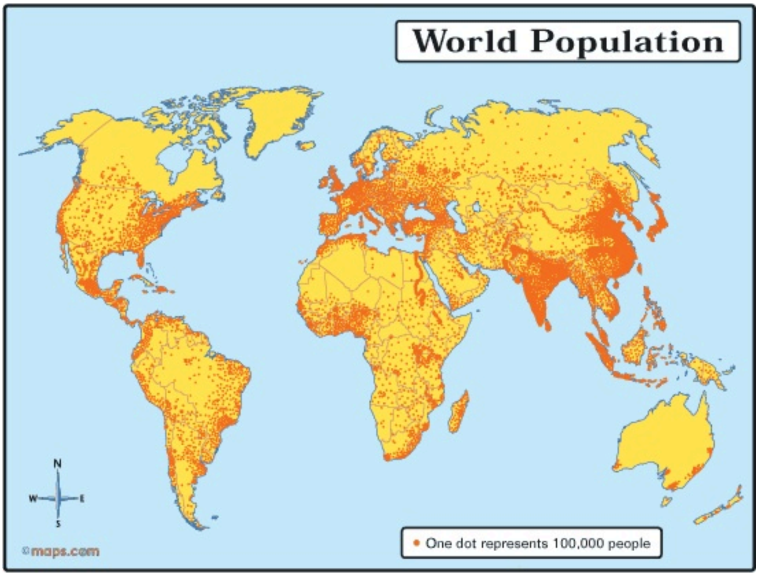

Figure 5.2. Dot map of world population. Each dot represents 100,000 people.

In Africa, note the Nile Valley surrounded by nearly uninhabited desert in the northeast, the West African cluster centered on Nigeria, and the cluster around the East African Great Lakes. In populous Asia, the Indus Valley of Pakistan, the Ganges Valley of north India and Bangladesh, the Yangtze Valley (including its Sichuan Basin) of Central China, the plains of northeast China, the Indonesian island of Java, and the Indian, Chinese, and Japanese coasts stand out as the demographic hubs of humanity. More people live within 200 miles of the Chinese Pacific coast, for example, than in all of South America, Canada, and Australia combined.

A second, more radical, cartographic approach is the cartogram (Figure 5.3), where each country's size is proportionate to its population. While we lose the shapes of countries and continents that have become burned into our brains from seeing so many maps, this technique easily conveys the relative population sizes of countries. It is also an appropriate technique for mapping information (e.g., the percentage of people living in urban areas, income, access to safe drinking water, fertility) that pertains to people rather than to land areas.

Figure 5.3. Cartogram of world population showing each country's size proportionate to its population.

The History and Future of Population

Table 5.1. Continental distribution of population over the past 2,000 years. Source: Livi-Bacci, 1989.

Continent/ Year	0	1000	1900	1990	2013
Asia	170	152	903	3113	4302
Europe/ Russia	43	43	422	787	740
Africa	26	39	138	642	1100
Americas	12	18	165	724	958
Oceania	1	1	6	26	38
World	252	253	1634	5292	7137

As discussed in Chapter 1, the world of biblical and Roman times, even the world of Christopher Columbus, was empty compared to the 21st century world (Table 5.1). We reached our first billion only about 200 years ago.

Table 5.2. Top ten countries in population 2019 and projected to 2050. Source: Population Reference Bureau.

2019 Population			2050 Population	
Country	**(millions)**	**Rank**	**Country**	**(millions)**
China	1420	1	India	1652
India	1369	2	Chine	1314
United States	329	3	Nigeria	440
Indonesia	270	4	United States	400
Brazil	212	5	Indonesia	366
Pakistan	205	6	Pakistan	363
Nigeria	201	7	Brazil	227
Bangladesh	168	8	Bangladesh	202
Russia	144	9	DR Congo	182
Mexico	132	10	Ethiopia	178

Interestingly, Asia has long been the Earth's demographic center of gravity (Table 5.1). Asia today hosts 60 percent of the world's population and this fraction has varied only from 55–67 percent over the past 2,000 years. Nor is it anticipated to change; 5 of the 10 most populous countries in 2050 are projected to be Asian as well, including the top two demographic giants with India anticipated to pass China in the next few decades (Table 5.2). In fact, essentially all population growth anticipated in this century will occur in developing countries, especially South Asia (India, Pakistan, Bangladesh, and smaller neighbors) and the 56 nations of Africa (Figure 5.4).

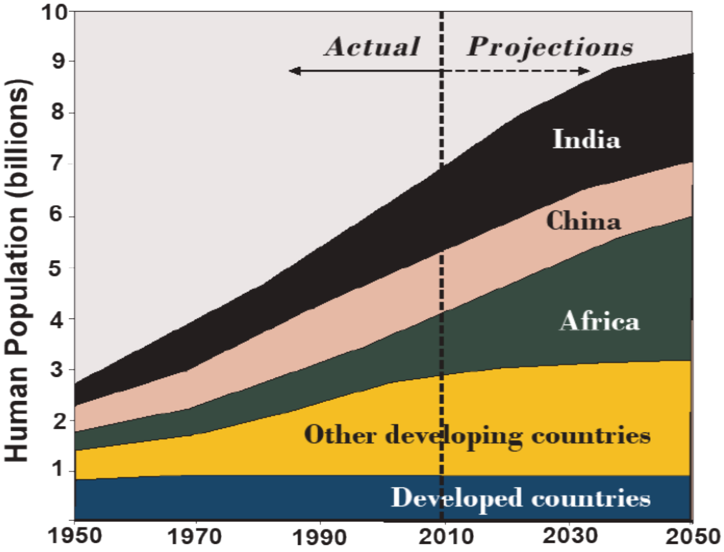

Figure 5.4. Allocation of world population in billions among India, China, Africa, other less developed countries, and more developed countries from 1950 with projections to 2050.

Population Pyramids

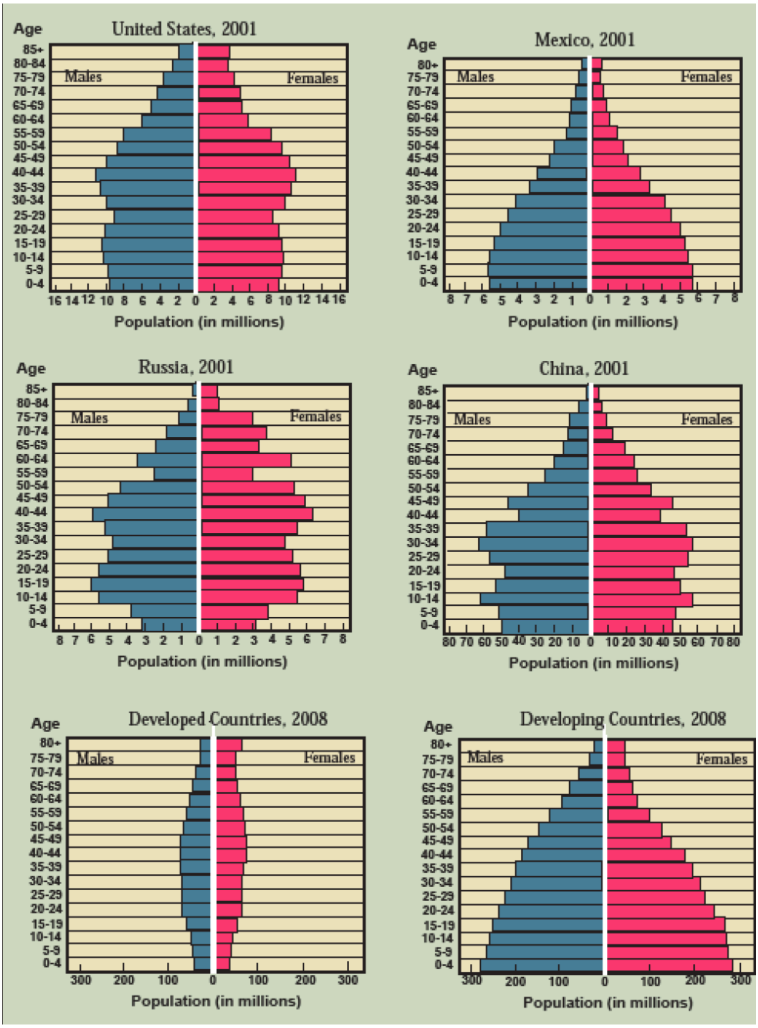

Figure 5.5. Population pyramids in 2001 for the United States, Mexico, Russia, and China. At bottom are population pyramids for 2008 for all developed countries (left) and all developing countries (right). Note that the pyramid is constructed as horizontal bar charts.

Population pyramids are a visually appealing way to display not only the total population of a country but its age and gender distribution by constructing horizontal bar charts of population around a center line with males on the left and females on the right. Look at the population pyramids for 2001 in Figure 5.5 and see what patterns you can discern.

In all cases, over age 70 or 75 females outnumber males due to longer life expectancies. For the U.S., there is a bulge at ages 30–55 representing the "baby boom" from, counting back from 2001, 1946–1971 and a smaller "echo boom" in the ages 5–25, representing the children of the baby boomers born 1976–1996. The Mexican pyramid shows high fertility and a rapidly expanding population until about 20 years prior, or about 1981, after which the pyramid base stops expanding. The oddly shaped Russian pyramid exaggerates the longer life expectancy of women, partly due to male soldiers dying in WWII, and a marked lack of people 55–59 years old. These are the babies that were not born and small children that died during Adolf Hitler's ruthless invasion of the Soviet Union in 1942–1944. The base of the pyramid is also shrinking. Over the past 20 years, Russians have been having fewer and fewer children, considerably less than the two who would replace their parents.

The Chinese pyramid resembles the Mexican with the decline in fertility coming sooner and falling farther. The birth dearth during the 1959–1961 famine of Chairman Mao's Great Leap Forward and its echo 20 years later are also reflected in smaller populations in the 40–44 and 20–24 age cohorts. Overall, China enjoys a large percentage of hardworking young adults in the 25–40 age group, contributing to its recent economic success. This demographic bonus will not last, however, as China's baby boomers reach retirement age in the 2020s and 2030s. For this reason, China rescinded its one-child policy in 2013.

The aggregate 2008 population pyramid for developed countries of North America, Europe, Australia, and Japan shows a relatively even distribution of people with a diminishing number of children. This is in sharp contrast to the aggregate developing country pyramid where each age cohort is larger than the one before, producing an actual pyramidal shape with a much younger average age than in developed countries. The budgets of developed countries are strained under the weight of retirement and health care programs. The meager budgets of developing countries are often insufficient to provide even an elementary education to the huge number of children aspiring to it.

Population Projections

If there are 7.8 billion people on Earth in 2020, how many people will there be in 2025? 2050? 2100? To begin to answer this question, let's take another look at the population pyramid for China in 2000, with a projected pyramid for 2050

(Figure 5.6). Here's a paradox—in 2013 the average Chinese woman had 1.5 children (this is called the total fertility rate), less than the replacement level of a little over 2, yet China's population is expected to continue to grow through 2050. Why is this the case? It's called *population momentum,* and here's how it works.

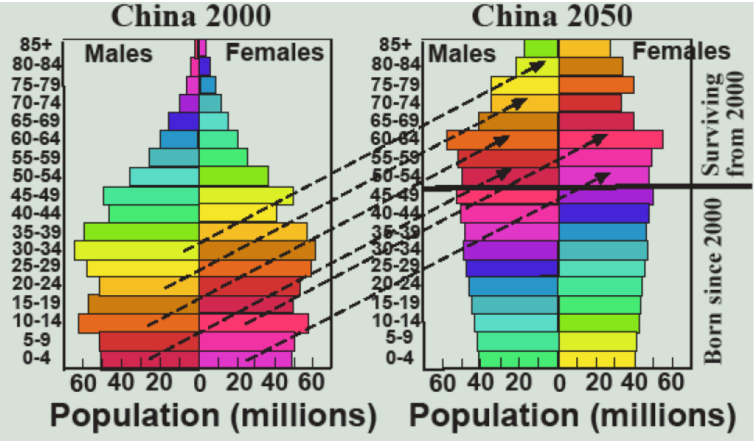

Figure 5.6. China's population pyramid in 2001 and projected to 2050.

Let's take the bottom bars on the 2001 pyramid of about 51 million boys and 47 million girls age 0–4. By 2006 they are in the 5–9 cohort, except for those few unfortunate enough to die as babies (this is called the infant mortality rate) or young children (child mortality rate). By 2050 there are about 45 million men and 42 million women aged 50–54 with 4 million of the 51 million males and 3 million of the 45 million females having, unfortunately, died before their 50th birthday. From age 50 and older, the pyramid in 2050 can be derived in a similar way by moving the 2001 bar up by 50 years, while subtracting those who die in the intervening 50 years as estimated by age and gender-specific mortality rates, which, of course, rise as people get older. We must keep in mind here, however, that life expectancy has been steadily increasing, globally at a rate of about one year for every four, from 53 in 1960 to 72 in 2017, so age-specific mortality rates are falling. Some researchers project that life expectancy will continue to climb through the 80s and well into the 90s, while others project that it will reach a maximum in the low-to-mid 80s, the level currently achieved by Japan. Time will tell.

Chinese under the age of 49 in 2050 will have been born since 2001. How do we estimate the number of babies born of each gender each year? Here we refer to age-specific fertility rates (Figure 5.7). While, of course, the probability of men giving birth is always zero, woman have a statistical probability of giving birth that is above zero during the ages of 15–50, corresponding approximately to puberty and menopause. If you add up the annual probabilities, you get the total fertility rate, which was 2.0 in 2001 (red bars), but had declined to 1.6 in 2008 (orange bars), and is projected to decline to 1.3 by 2050 (yellow bars). With this information, we can add babies to the bottom of the pyramid each year simply by multiplying the number of women at each age, times the probability of giving birth at that age from Figure 5.7.

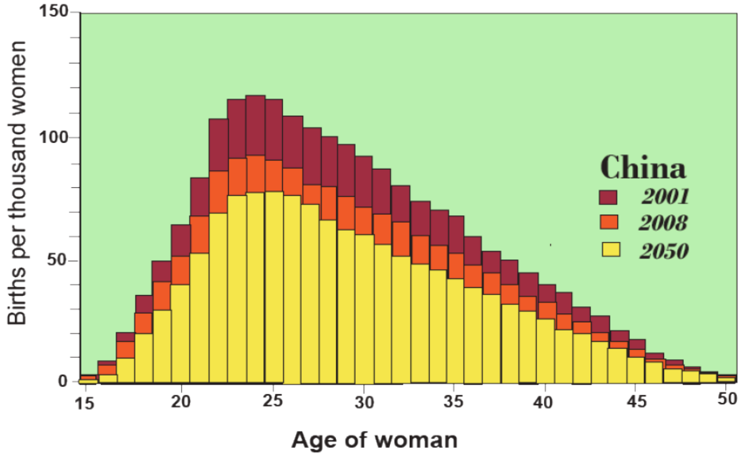

Figure 5.7. Age-specific fertility rates for China in 2001, 2008, and projected to 2050. Note the range from 15–50, the years in which women are biologically capable of giving birth (puberty to menopause), with highest fertility in the 20s and early 30s. Total fertility rates fall across all ages from 2001 (2.0) to 2008 (1.6) to 2050 (1.3).

The key to projecting the future population then lies in anticipating how age and gender-specific mortality rates will change over time to account for hoped-for increases in life expectancy and decreases in infant mortality, as well as how age-specific fertility rates will change—usually downward as we will see. Population projections then end up being based on scenarios in which different assumptions are made about how mortality and fertility rates will change in the future, partly guided by how they have changed in the past. Below we will explore the concept of descendant insurance that relates future birth rates to past child mortality rates.

If a population has a large proportion of young people, it will continue to grow, even if the total fertility rate is falling below two. Why? Because young people enjoy a long life expectancy—the age-specific mortality rates for people 5–50 are low compared with more vulnerable babies and older people. In addition, the more women there are age 15–50, and especially age 20–35, the more babies will be born, even if each of those women has on average fewer than two children. This is population momentum, and it is a primary reason why the world's population will continue to grow to reach 8 billion by about 2023, and likely reach 9 billion, and possibly 10 billion by 2050—depending upon how mortality and fertility continue to change in the future in each of the world's countries.

While of course we don't know exactly what will happen, we do have a working theory of population change known as the demographic transition.

The Demographic Transition

A demographic transition—from what to what, you may ask. The answer is from a state of high fertility, short life expectancy, and low population totals to a state of low fertility, long life expectancy, and high population totals. Figure 5.8 captures this graphically. At the beginning of the transition, total fertility rates are high. Women typically give birth to and rear 5 to 8 children, a task that dominates their prime years of young adulthood. The infant and child mortality rates are also high, and famine, pestilence, war, and other enemies of human life periodically drive death rates even higher, leading to a fluctuating population with little to no long-term growth. Note from Table 5.1 that world population grew little in the first millennium C.E.; in fact, modern population growth began only about three centuries ago.

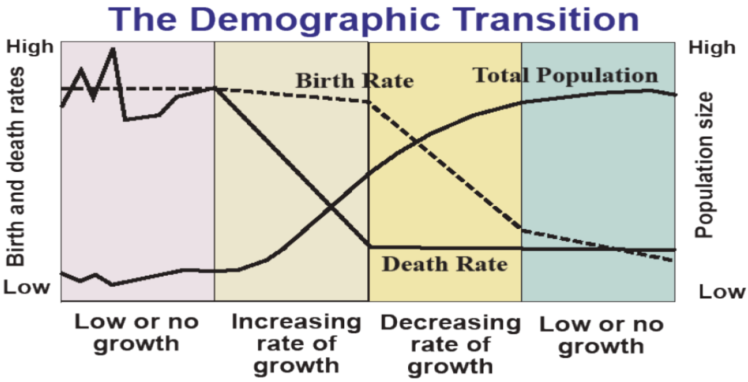

Figure 5.8. The demographic transition model.

By 1800, and especially by 1900 in Europe and North America, life expectancies began to rise and infant and child mortality began to fall. This was not due so much to advanced medicine, but due to public sanitation measures such as delivering piped, chlorinated water and providing sewage systems to urban populations. With the invention of the microscope and advances in microbiology came the germ theory of disease, the understanding that many ailments are caused by microscopic bacteria and even smaller viruses that multiply in our bodies, making us ill and potentially ending our lives. Exposure to germs can be minimized by keeping them out of the water and food supplies and minimizing contact with contagious diseases, partly through immunizations. Advances in medical knowledge that reduce mortality from childbirth and germs came coincidentally with the industrial revolution that made food supplies more secure, clothing more abundant, and modern comforts available to more than an elite few. People began to live longer and most babies born lived to reach adulthood for the first time in human history.

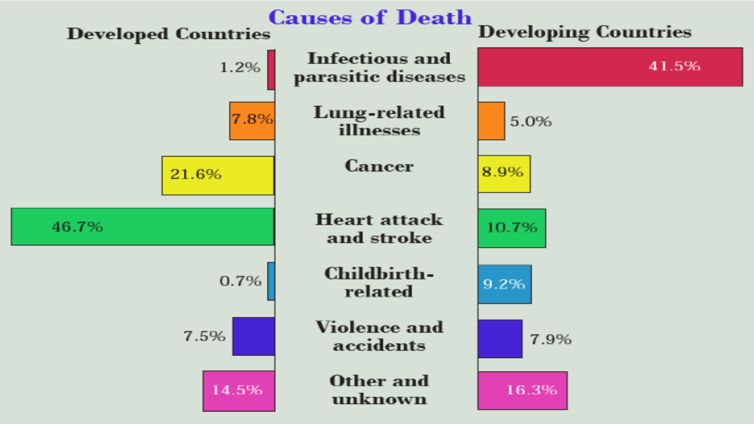

Figure 5.9. Causes of death in developed vs. developing countries (about 2000).

Figure 5.9 compares the causes of death in developed countries that have completed the demographic transition with those in developing countries that are at various stages within it. (Hopefully the rainbow of primary colors will compensate for the macabre subject matter). In developed countries, only about two percent of deaths occur in childbirth or due to germs—infectious and parasitic diseases. As a result, people live long enough to succumb to degenerative diseases, especially heart attacks, strokes, and cancer, which occur primarily in older people. In developing countries, in contrast, half of all deaths occur in childbirth or due to germs. The lower rates of death due to lung-related illnesses, cancer, and heart disease may in part be due to healthier diets and lifestyles but they are primarily attributable to people dying younger, before these chronic diseases develop.

Table 5.3. Changes in Italy's demographics 1881–2008 as it proceeded through the demographic transition compared to 2008 data for the Democratic Republic of the Congo.

Demographic Index	Italy 1881	Italy 2008	DRC 2008
Population (millions)	22	60	66
Annual births per 1000 people	37	10	44
Annual deaths per 1000 people	29	10	13
Growth Rate (%)	0.8	-0.01	3.1
Life Expectancy (years)	35	81	53
Total Fertility Rate	5.0	1.3	6.5
% Population 0-14	32	14	47
% Population 15-64	63	66	50
% Population 65+	5	20	3

Table 5.3 shows a case study of the demographic transition comparing the journey through the demographic transition of Italy (as a typical example of a developed country) to the

Democratic Republic of the Congo (as an example of one the world's poorest countries). Over the 127 year timespan from 1881–2008, Italy's population about tripled but has now stabilized, while its birthrate and deathrates have dropped by two-thirds. Life expectancy has expanded to over 80 years, while the number of births per woman has fallen from 5 to a very low 1.3. These changes revolutionized the age structure of an Italian population that on average is much older than it was in 1881. In contrast, the DRC is finally experiencing a dramatic decline in child mortality, but total fertility remains very high at 6.5, leading to a population explosion that is likely to continue because of the disproportionate number of young people with long life expectancies that include their childbearing years. This is population momentum. Over time though, can we expect the demography of DRC to resemble Italy's in 2008? Global experience says that we can, though whether this happens in a few or several decades remains to be seen. We thus now turn to a deeper look at the dynamics driving fertility rates downward across the planet.

From Death to Birth: A Look at Descendant Insurance

In 1968 Stanford biologist Paul Ehrlich wrote *The Population Bomb*, in which he brought to the world's attention the dangers of overpopulation depleting the world's natural resources in an unsustainable manner, and thus arguing that birth control was urgently needed. At the time, the global average total fertility rate was 4.9 and population was growing at 2.2 percent, yielding a doubling time of 32 years, or an 8-fold increase in a century.

Yet, over the intervening half-century the population bomb has been largely defused as total fertility rates have fallen by half to reach 2.4 in 2018. Viewed another way, if replacement level is 2.1, global total fertility rates have fallen by 90 percent of the distance from where they were during the population explosion to where they need to be to stabilize the global population in the long run. Most of us can see this decline in birth rates in our own family histories. In my case, my mother was last of 9 children, while my father was youngest of 2 for an average of 5.5; I am the 3rd of 4 children who have a total of seven offspring for an average of 1.75, just about the current U.S. total fertility rate. You can probably trace a pattern of declining fertility in your own family tree. How did this fertility transition happen? To answer this question, we need to grasp what factors determine birth rates, or more technically, total fertility rates.

Of the many theories proposed, the one I find most convincing, on the cold, hard basis that it fits the empirical data, is called *descendant insurance*. This idea follows from the simple notion that people would like a high probability, on the order of 99 or 99.9 percent, of having a child that survives to adulthood. This simple notion, however, generates a surprising mathematics that fits remarkably well to data on child mortality rates and total fertility rates around the world in recent decades.

The basic mathematics is quite simple. The number of children one must have to assure a survivor depends upon the child mortality rate and the level of insurance to be achieved. In the simplest example, if the probability of a child's death is zero, only one child is required to achieve a 100 percent probability of a surviving child. This would lead to population reductions – a population half-life of one generation. If the probability of each child's death is 50 percent, however, eight children are needed to reach a 99.6 percent probability of a surviving child. A 50 percent child mortality rate seems terribly high by modern standards, yet was typical as recently as the 19th century in the U.S. and the 20th century in many developing countries. With half of these children surviving, the net mean descendants expected is four, leading to population doubling every generation. At a 99.9 percent level of insurance, mean net descendants peaks at 4.5 at a child mortality rate of 37 percent (Figure 5.10).

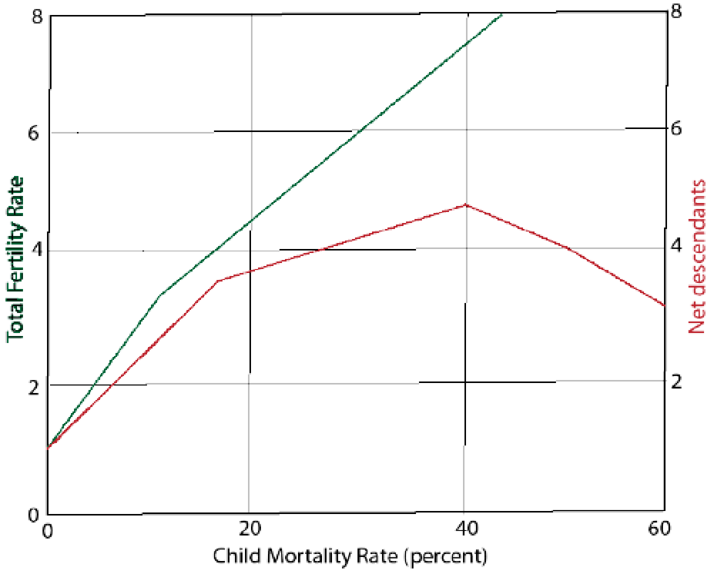

Figure 5.10. Total fertility rates and net descendants that result from varying child mortality rates under descendant insurance with an insurance rate of 99.9 percent.

What this proposes, in a bit of a paradox, is that population growth is driven by high child mortality—starting from roughly 60 percent and continuing until it falls to about 20 percent—and people's response to this social condition in their efforts to guarantee or ensure at least one surviving child. In recent decades, child mortality rates have continued to fall throughout the world, in a success story that is too seldom told, to below 10 percent, and in some developed countries to as low as 1 percent. We see in the green line in Figure 5.10 that corresponding total fertility rates fall from about 3 at 10 percent child mortality, to reach the replacement level of two at 3 percent child mortality and continue to decline to about 1.5 at a child mortality rate of 1 percent.

Table 5.4. Correlations between actual total fertility rates and those pr descendant insurance for the world's most populous countries at early, mi stages in the fertility transition.

	Time Period				
Country	**1960-2011**	**1970-2011**	**1980-2011**	**1960-2000**	**1960-199**
Ethiopia	0.75	0.94	0.97	Early in fertility t	
Pakistan	0.79	0.93	0.98		
China	0.97				
India	0.99				
Indonesia	0.98				
Brazil	0.99				
Bangladesh	0.98		Middle of fertility transition		
Mexico	0.98				
Philippines	0.98				
Vietnam	0.98				
Egypt	0.99				
Iran	0.98				
Turkey	0.99				
Japan	0.97				
France	0.84			0.94	0.95
Germany	0.83	Late in fertility transition		0.86	0.87
U.S.	0.64			0.66	0.74

This is a nice, clean theory and it stands up to the empirical test against real-world experience across the many countries of the world in recent decades for which demographic data are recorded? Table 5.4 sizes this up using correlations; this is a widely used statistical measure of how closely things vary together. If there's no relationship at all, the correlation is 0, if they go in exact opposite directions, it is -1, and if they follow one another exactly, it is 1.0. In general, a correlation above about 0.7 is high and 0.9 is very high. Table 5.4 shows mostly very high correlations between actual total fertility rates and the total fertility resulting from descendant insurance calculations. These correlations are remarkably high in some cases, such as for the world's demographic giants like China (0.97) and India (0.99). So for these countries and others in the middle or heart of the fertility transition, (when child mortality rates are falling from 15–25 percent down to 1–3 percent, and total fertility rates are falling from 4–6 down to 1.5–2.5) it seems that descendant insurance predicts remarkably well how total fertility rates respond. There is usually a short lag of 5–10 years between the child mortality rate stimulus and the total fertility rate response. This means that if we know the child mortality rate we can predict quite closely the total fertility rate over the next decade or so.

There are a few exceptions. Countries that haven't yet begun or are just starting the fertility transition have correlations that aren't as high. So for example, Ethiopia and Pakistan started to fall in line with descendant insurance starting in the 1970s when they first saw major sustained reductions in child mortality. At the other end of the transition, France, Germany, and the U.S. were all following descendant insurance quite closely from 1960 to 1980 or 1990, but as child mortality started to bottom out at very low levels, their fertility began to depart from descendant insurance. What this means is that descendant insurance is right on target during the critical middle stages of the fertility transition (see Figure 5.8 and compare it to Figure 5.11), more so than when it is just beginning or in the completion stages.

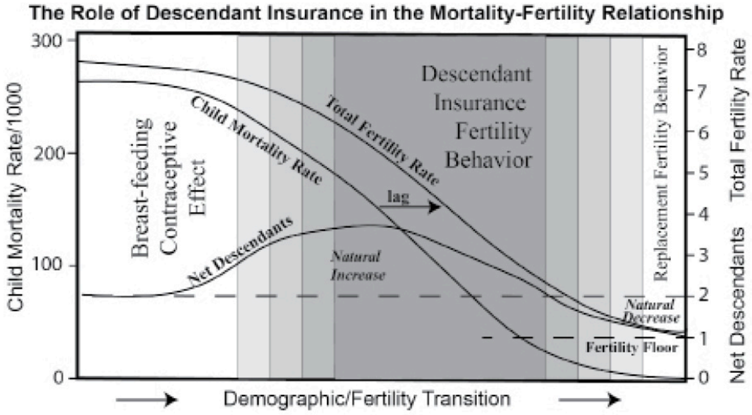

Figure 5.11. The role of descendant insurance in the mortality-fertility relationship.

In prior periods, other explanations for people's fertility hold sway, such as the spacing of births through the contraceptive effect of breast-feeding. Also, towards the end, other explanations like replacing the rare lost child, hold sway. Figure

5.11 captures these relationships over the course of the fertility transition.

This tight relationship between child mortality and subsequent fertility has substantial implications for how we think about the issue of overpopulation, which is really about natural resource sustainability. Figure 5.12 captures the relationships as a system that represents a virtuous cycle, the obverse of a vicious cycle, where the positive feedback loops drive outcomes that we would desire. Let's start in the center-left at "falling child mortality." If perceived, this leads to falling fertility due to descendant insurance behavior – if access to contraception enables it. Fewer children means more investment in each child, especially in the form of health care and education. Better education for girls leads directly to falling child mortality, completing one virtuous cycle, while it also reinforces falling fertility through better economic opportunities, changing cultural norms and rising costs of having large families.

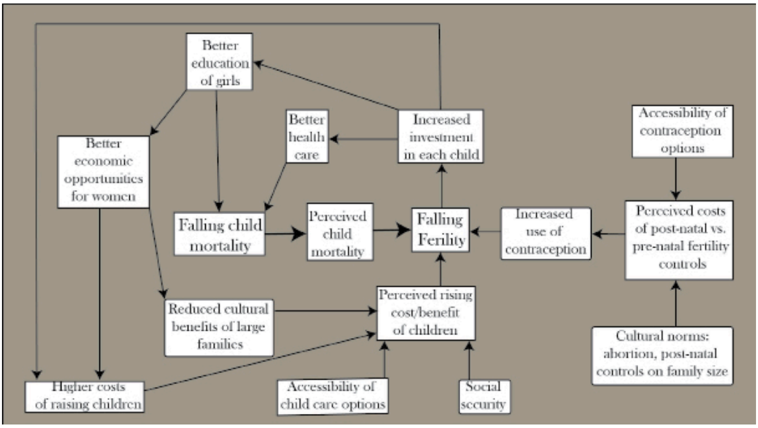

Figure 5.12. A model of factors that lead to a decline in fertility during the demographic or fertility transition.

Thus, reducing child mortality, beyond being an unquestioned good in itself, is a linchpin of population stabilization and therefore of natural resource sustainability. Low child mortality leads to a stable, or even slowly shrinking, population of healthier, better-educated people. High child mortality leads to high fertility, rapid increase in a population that is less well-educated and cared for, high demand on basic resources such as water and land for food, and degradation of those resources, leading to continued high child mortality—and the vicious cycle continues.

Thus by taking a systems approach and including descendant insurance behavior in that system, we can see that devoting resources to reducing infant and child mortality has the important secondary benefit of population stabilization. Returning to Figure 5.1, the result is the most sustainable one—the “sigmoid approach to equilibrium.” It is through investments in public health and making contraception widely available that the population bomb has been defused, thus controlling one of the most important threats to natural resources sustainability, while improving human welfare immeasurably.

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6.

CHAPTER 6: THE NEOCLASSICAL ECONOMICS APPROACH TO SUSTAINABILITY

So we now delve into economics, which has declared itself the "queen of the social sciences" but others have labeled the "dismal science." Before we start working through the ubiquitous graphs that characterize economic analysis, we need to take a philosophical detour. First there is an essential distinction between *empirical* and *theoretical*. "The economy" is an empirical, real-world phenomenon in which real human beings engage. It takes place in geographical space and changes through historical time. Economic geography and economic history are fascinating fields that tell us much about how real human economies have evolved. "Economics" consists of a group of theoretical schools of thought through which we might hope to understand that complex empirical economy.

For comparison, this distinction also applies in the physical sciences. The movie *The Matrix* notwithstanding, the universe is a real, empirical thing that physicists and astronomers try to understand—partly through the concept of gravity. Do you *believe* in gravity? I do, and I'll bet you do too. It seems self-evident. But have you ever seen or heard it? Gravity is a theoretical construct; once we propose that masses attract one another in a specific mathematically manner, as Isaac Newton did, all kinds of things start making sense: the apple falls from the tree and hits us in the head, when we jump we come back down quicker than when LeBron James jumps, people on the other side of the Earth don't fall off, the moon orbits the Earth, the Earth orbits the sun, and so forth. Albert Einstein proved that Newton's idea of gravity was oversimplified, however, and today superstring theorists are revising Einstein's concepts from his general theory of relativity. So something as seemingly simple and clearly evident as gravity is in fact a theoretical construct that science periodically revises based on new evidence and understanding. This also happened to the idea of ecological succession if you recall the discussion from Chapter 4. Thomas Kuhn called this a "paradigm shift" in his 1972 classic *The Structure of Scientific Revolutions*.

In economics, the situation gets even more complicated because we also have to deal with the philosophical distinction between *positive* (the way things are) and *normative* (the way things should be). Debates among physicists over the true nature of gravity are positive—they focus on which idea of gravity best explains empirical phenomena in the universe—like the Big Bang and black holes. *Subjective* human values need not be discussed, freeing the debate to be purely *objective*. In the social science of economics, we have to delve not only into what is true about society but what is best or right. Subjectivity and human values return in *normative* debates about the relative value of efficiency, equity, and sustainability, among other worthy goals for human betterment.

If all the positive and normative debates could reach a permanent resolution, we would have a single school of economics that would form a core of social science, but such is not, and is unlikely to become, the case. So we have partly competing and partly complementary schools: neoclassical economics, ecological economics, institutional economics, and political economy (based partly in Marxist economics), from which is derived political ecology.

Now you would probably roll your eyes if someone told you that they were simultaneously a Christian, a Jew, a Muslim, a Hindu, a Buddhist, and an Atheist! Fortunately, we don't have to make that kind of commitment to a particular school of economics, though nearly everyone who studies the subject has a favorite. Mine is ecological economics, which comes as no surprise given that this text is titled Natural Resources Sustainability. Fortunately, we can use each of the schools of thought like a lens. Since we are considering four schools, let's call them "quadfocals," where each lens helps us see some things clearly that the other lenses leave fuzzy. This is like the physicist who calls light an energy wave when (s)he wants to understand, say, wavelengths of the electromagnetic spectrum, and a particle when (s)he wants to understand how photons are refracted by a lens. The truth is that "wave" and "particle" are both inadequate scientific concepts for understanding the real empirical phenomenon of light. Similarly, no one school of economics can give us the complete picture of natural resource use.

So in the next five chapters, I will introduce you to a number of economic ideas that are relevant to natural resources sustainability. In this chapter on neoclassical economics, we will explore supply, demand, marginal cost and utility, efficiency, cost-effectiveness, cost-benefit analysis, and optimal pollution. In Chapter 7 on ecological economics, we will delve into natural capital, ecosystem services, and a rigorous definition of sustainability before splitting off industrial ecology into its own chapter, Chapter 8. In Chapter 9 on institutional economics, we will delve into non-excludability, rival consumption, and the tragedy of the commons. In Chapter 10 on political ecology, we will talk about power and economic classes, core and periphery, and how people become marginalized through lack of access to natural (and other) resources. Just as the physicist finds both the wave and the particle ideas useful in understanding light, I find all of these ideas, and the schools of thought that generate them, useful in understanding our central topic of natural resources sustainability. Keep in mind, however, that none of these theoretical constructs is as solid as physical theories of gravity—and even they are a moving target.

Of course you could say, then let's forget the theories and stick to the facts! It turns out that we don't have that option for at least two reasons. Facts pile up like a big heap of leaves you rake in the fall; we can't differentiate one from another. Theories give us a structure—like the trunk, limbs, branches, and twigs each leaf was growing on through the spring and summer. A good theory will tell us where on the overall tree of knowledge each leaf, each fact, lies. So theory is the way in which we evaluate the significance of each of a stupendous number of individual facts and the relationships among them, even if one school of thought arranges the facts into an oak while another arranges them into a maple.

The second reason is that facts are not independent of the theories in which they have significance. We measure and collect facts on the prices and production of goods, on gross domestic product, on the value of ecosystem services, and on inequality in land ownership, for example, because they inform our thinking about the empirical world through a particular theoretical lens. In fact, it is generally the theories that tell us what to collect facts on!

Before we proceed, a final note is required about where we humans are in our historical, geographical, economic evolution on this planet. We live in the age of *global capitalism*. Capitalism developed in the 16th and 17th centuries in northwest Europe and spread from there to every inhabited continent, often by force, while it continued to evolve as an economic system. More recently, after the death of Mao Zedong in 1976, under Deng Xiaoping's leadership, China switched to a capitalist approach to economics (without relinquishing the political authority of the Communist Party). Russia and its neighbors also did so, to a lesser extent, following the collapse of the Soviet Union in 1989–1991, ending the long Cold War. That means that for the last generation, with a few minor exceptions such as Cuba and North Korea, capitalism is the economic system of the globe at this moment in history. So when we are talking about the economics of natural resources sustainability, we are talking about capitalism. Let's take a minute then to define what capitalism is, while recognizing that it is always evolving.

An oil corporation explores for, produces and transports crude oil, refines it into gasoline, and delivers it to the gas station you last visited when your car or truck fuel gage moved toward E. Delivering this product to you takes a lot of money and effort from a lot of people. So who is the constituency (meaning the group of people it is obligated to serve) of the oil corporation that does this? One would be the employees who did all of that work to get gasoline to you and millions of other drivers. Another is the customers like you who are willing to part with some of their money to get the gasoline product. A third is the investors who own the company and its facilities. A fourth is other companies the corporation buys its equipment or services from. A fifth is the towns and cities where its headquarters, oil fields, refineries, and so forth are located. A sixth is the governments of the nations, states, and municipalities to which it pays taxes, but expects roads, water, and educated employees in return. A seventh is everyone on Earth who breaths the air into which the water, carbon dioxide, and other polluting remains of the gasoline are emitted.

Do all of these constituents have the same interests in the corporation? Could they all get together and decide what the company should do? Let's see. The employees want to make high wages and good benefits and work under good conditions and get vacations, but that raises the costs of production, making the corporation charge the customers more. But the customers want a quality product at as low a price as possible. The company wants low taxes, excellent public services, and lax regulations, but governments want high tax revenues, low service demands, and stricter regulations to protect people from pollution and workers from abuse. However, they also want the corporation's facilities to operate in their jurisdiction to provide jobs and expand the tax base. The investors want to make a profit so they get a rate of return higher than other investment opportunities they could be pursuing, but this is best achieved by paying low wages and low taxes and charging high prices. It seems there is no consensus at all about what the oil corporation's management should do! So if all the constituents have different goals, who does corporate management listen to?

Management listens to the Board of Directors who has the authority to hire and fire them. The Board of Directors represents the *investors* who own the corporation's capital (that is, its stock). That is the answer and it defines *capitalism*. Investors want to make as high a profit as possible to maximize the return on their investment.

But it's not that simple either. Customers like you will buy their gas elsewhere if the price is cheaper at some other convenient location. Employees may have other career options that they will pursue if the corporation makes them work under poor conditions, pays them low wages, or eliminates benefits like health insurance, retirement accounts and paid vacations. Governments will enforce labor, environmental, and tax laws to which the corporation must comply. So capitalism ends up as an ever-changing strategic game involving many players.

Nonetheless, we must keep in mind that, from the point of view of corporate management, the object of the game is to maximize profits for the investors who hold stock in the corporation. Employees, customers, taxes, laws, and so forth are means to that end whose interests can represent a *constraint* on achieving the profit objective. So when we want to understand why private-sector corporations, companies, small businesses, and farmers are doing what they are doing, we need to keep in mind that they are working first and foremost in the interests of their owners or stockholders. This is for the better (most neo-classical economists would assert), for the worse (as Marxist economists argue), or somewhere in between (where most ecological and institutional economists tend to stand)—normatively speaking, that is.

The Starting Point of Neoclassical Economics: Supply and Demand

So now that we have explored the notion that economic concepts like supply and demand are theoretical constructs that are specific to the capitalist system, and may someday be modified or rejected in favor of better ideas, let's take a look at them, starting with demand. *Demand* is the quantity of a product that customers are willing to pay for at any given price. The higher the price (p2 compared to p1 in Figure 6.1), the less they will buy (q2 compared to q1), making the demand curve downward sloping.

Why is this the case? Certainly because customers can afford less as the price goes up, but that is not a very precise answer. In order to draw from your own personal experience, let's say the good under discussion is slices of pizza being sold for $1 each from a food truck on campus. How many slices will you buy? If you don't like pizza (I prefer Chinese food myself), it's zero—you'll have something else for lunch. If it's past noon, you haven't had lunch yet, you like pizza, and you have $10 in your wallet, you'll buy a slice of pizza for $1 because you'd rather have $9 in your wallet and a slice of pizza to satisfy your hunger than have $10 in your wallet and no pizza. You think it's worth it. If you're still hungry, the pizza is good, you're engaging in pleasant conversation with the other people buying and eating slices of pizza, and you're not trying to lose 10 pounds right now, you may part with a second dollar for a second slice of pizza. Or, you may not because that first slice of pizza really hit the spot while the second would just leave you feeling full and sleepy at your next class.

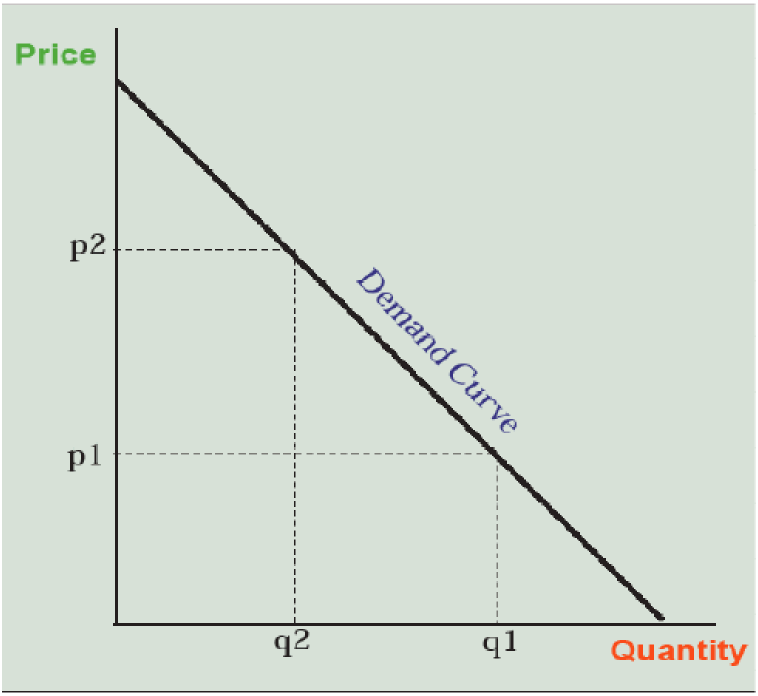

Figure 6.1. The demand curve. Price is on the y-axis and quantity demanded on the x-axis.

In economic terms, the first slice has a marginal utility exceeding $1 while the second may or may not—it's up to you to decide. *Marginal* here means the next unit, the next slice of pizza, given the ones you've already had. *Utility* means the use value that it has for you as the buyer. So, in this context, marginal utility means how much value to you one more slice of pizza has.

Let's say you go for the second slice, which is to say that you've decided the marginal utility of the second slice also exceeds $1, leaving you with $8 while digesting two slices. Now would you rather have $7 and a third slice or $8 and walk away having eaten two slices? How about $6 and a fourth slice? At some point, the marginal utility of another slice of pizza falls to less than $1 (in fact it may become negative if you regret that last slice—something you may have experienced more dramatically with beer).

So, each of us keeps buying slices of pizza (0, 1, 2, 3, 4 . . .) until the marginal utility—the added value to us on top of the value of the previous slices—falls to less than the $1 price. If the price was $2, we may find that the second or third slice that we were willing to pay for at $1 is not worth it, so we buy fewer slices. At $5 a slice, we can only afford 2 slices, but would likely buy zero, even if we were hungry and like pizza, because we know for less money we can get a good slice of pizza, or something else for lunch that we also like, somewhere else—unless we're really hungry and stuck in an airport with no other options (a captive market). This is why the demand curve is sloped downward—because each customer is purchasing the product until the marginal utility (the additional value to them) of one more item falls below the price. At a price of p1, this occurs at quantity q1 in Figure 6.1. At a price of p2, it occurs at quantity q2, and so forth along the demand curve.

We'll draw our demand curves as straight lines for simplicity, but they need not be; in fact, more commonly they are concave curves. Note that the more money we have, the fewer other options we have, the more we like (or have been convinced that we like) the product, and the more the product complements another product that we have already bought, the more of the item we will buy. But we will still buy it until the marginal utility of the next item, as we define it, falls below the price.

Now let's turn our attention to the pizza producers. How much pizza will they *supply* for sale? At a price of zero (free) they won't offer any. We lose our chance at a free lunch because the producer has to pay production costs—labor, ingredients, an oven, and a building to put it in. Will they supply any pizza slices at $1? That depends; if it costs less than an additional $1 to make one additional slice of pizza, given the pizza slices they have already made, they will, because the $1 they receive in *marginal revenue* exceeds the *marginal cost* of producing that last slice of pizza. Marginal revenue is the price of the next slice sold. Marginal cost is a little trickier. It is the extra costs needed to produce one more slice. If this is less than the price (i.e., marginal revenue), producers increase their profits by producing and selling one more slice. At some point, though, as they keep baking pizzas, they have to buy a bigger, more expensive oven or even move to a bigger restaurant building, driving up their marginal costs of production. The $1 per slice may not cover this cost, but at $2 per slice it does. So the higher the price of pizza they can charge, the more pizza they can afford to produce at a profit because the marginal revenue (the price charged) for that last slice of pizza equals or exceeds the marginal costs of producing it. This makes the supply curve upward sloping—the higher the price, the more is produced and placed on the market because each producer keeps making more of the product until the marginal costs of production reach the level of marginal revenues from sales—the price (Figure 6.2).

Figure 6.2. The supply curve.

Now let's put supply and demand together in what is called *price theory*. Price theory is the heart of neoclassical *microeconomics*—in contrast with macroeconomics that deals with national-scale issues like unemployment, inflation, the national debt, and interest rates. Figure 6.3 helps us do this. Let's say the price of pizza is high—$3 per slice. What happens? Suppliers produce a lot of pizza, hoping to cash in on the profits to be made, but at $3 per slice, customers are unenthusiastic and buy very few of them. We end up with a surplus of unsold slices of pizza on which the production costs have already been paid, but no one has benefited from eating them—clearly not a good situation. What's the solution? The producers lower the price to say $2 per slice, more customers buy and eat the pizza and the surplus disappears.

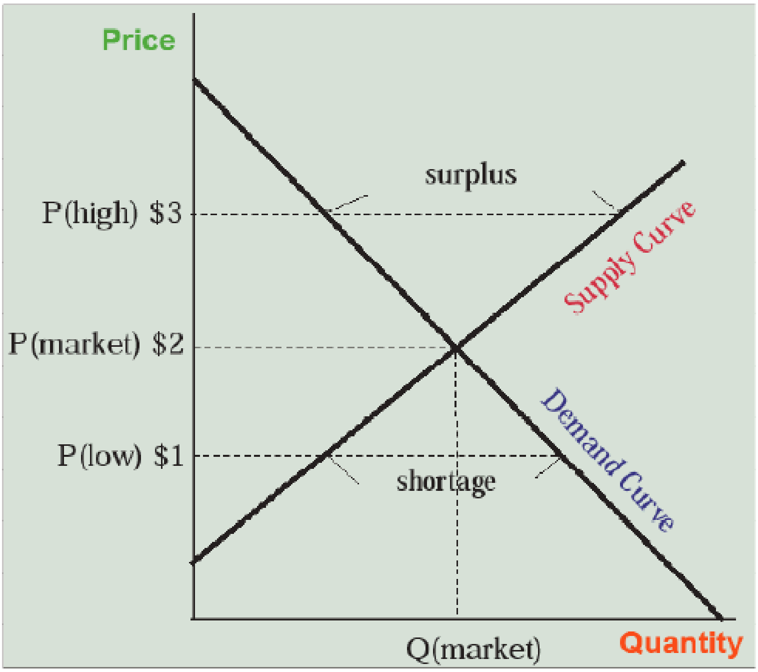

Figure 6.3. Supply and demand determine market price and the quantity produced and sold.

Now let's say the price is low—$1 per slice. What happens? Sellers are unenthusiastic about hiring people or buying ovens to make more pizza, so they only produce a small number of slices. At $1 per slice, though, the customers come flocking. Unfortunately, only the first few get any pizza and the others wish they had grown up in New York City so they would have learned the art of pushing their way to the front of the line. There is a shortage. What's the solution? Increase the price to $2 and the sellers will make more pizza while some of the customers will move on and the shortage disappears. In fact, someone waiting in line might offer $2 to the pleased seller in order to get to the front of the line, possibly forcing all the other customers to offer $2 as the scarce pizza slices go to the highest bidder. So it seems as though a price of $2 per slice gets producers and customers on the same page—they make and buy the same number of pizza slices. Prices of $1 or $3 per slice do not—they generate shortages and surpluses, respectively. Note also that the market helps both producers and sellers to find the market-clearing price by forcing sellers to respond to a surplus by cutting prices and to a shortage by raising them. Partly on this basis, neoclassical economists often argue that markets can be self-governing and self-organizing. This is true only to a limited extent, however, as we will see in subsequent chapters.

Production Costs, Consumer and Producer Surplus, and Net Economic Benefits

So is society better off from all this pizza making, selling, buying, and eating? Who in society is better off? Once again, a graph helps us think this through. Figure 6.4 uses the same information and shows the market-clearing price (let's stay with $2 per slice) and quantity (let's say 100 slices of pizza to make the math easier). First of all, we now know that the customers took $200 out of their wallets and handed it to the pizza sellers. That's clear, real, and easy to understand. Now let's look at it from the producers' standpoint. The trapezoid in red below the supply curve and up to the quantity of pizza produced represents their production costs. Let's say it's $120 that they spent on employees, ingredients, ovens, and so forth. The remaining $80 of revenue represents their profit or what neoclassical economists call producer surplus (Marxist economists call it surplus value) that they walk off with as an economic benefit. This is shown graphically as the green triangle in Figure 6.4.

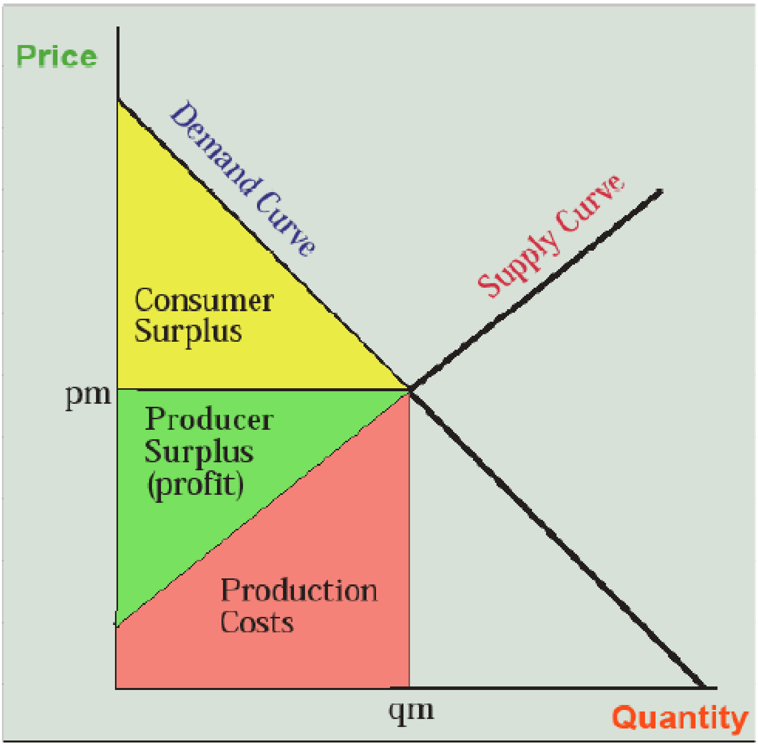

Figure 6.4. Consumer surplus, producer surplus, and production costs in relationship to supply, demand, and the market-clearing price and quantity produced.

Do the customers also benefit? Yes, because they were all buying pizza until the marginal utility of the last slice purchased was at or above $2. As long as marginal utility is decreasing, their willingness to pay for slices prior to the last one they bought was more than $2. This is reflected in the demand curve which shows some demand for pizza at prices above the market price of $2 (pm in Figure 6.4). For example, if some customers would have paid $3 for one slice of pizza but they only had to pay $2, they got a *consumer surplus* of $1—its use value to them minus the price they paid for it. This is shown graphically as the yellow triangle between the demand curve and the price line in Figure 6.4. So both producers and customers come out ahead in the exchange and society is better off, by the total of both consumer and producer surplus, than it would have been had nobody made and eaten pizzas and instead stayed home playing computer games. Note that these *net economic benefits* (yellow plus green areas) are different from the total sales (green plus red areas) and are also different from the total value of the pizza (yellow plus green plus red areas).

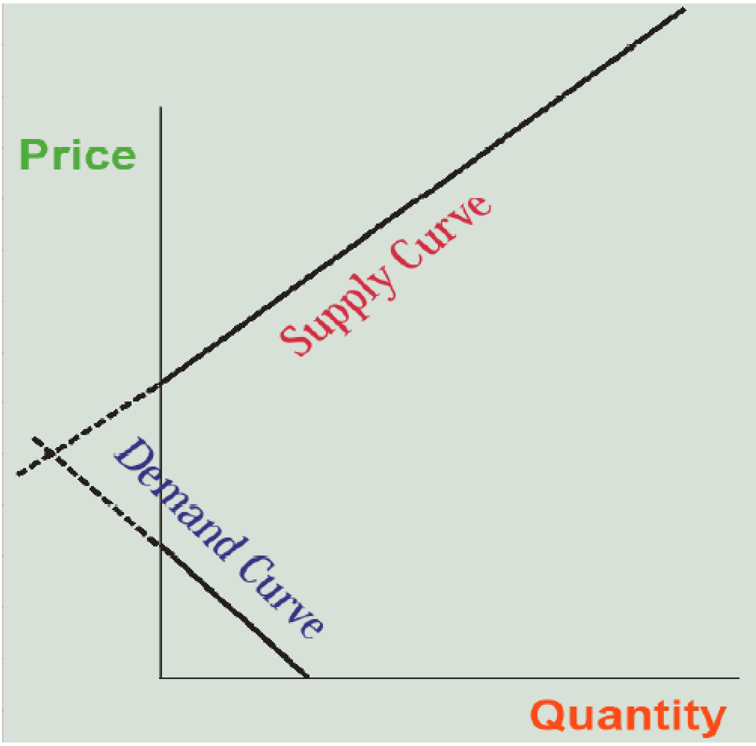

Figure 6.5. The supply and demand for a product that produces no net economic benefits. If the market-clearing quantity is less than zero, the product will never be produced.

As a counterexample, production of something doesn't always result in net benefits. What if someone wanted to make gold eyeglass frames and sell them at Walmart? They would be very expensive to produce, driving the supply curve upward. They would also be gaudy, driving the demand curve downward—only a few people would be willing to spend a lot of money on gold frames when you could just as easily paint them gold if that's your favorite color. So what's the market result? Figure 6.5 shows the market-clearing quantity as negative. The market will produce zero (well, maybe a few in Hollywood).

This odd example tells us that the market instills a rigorous discipline, weeding out the production of things that are expensive to make and nobody wants but encouraging the production of things that have reasonable production costs (which producers have an incentive to drive even lower) and a high value to people, who will then become paying customers. Like biological evolution, where poorly adapted organisms and species are driven to extinction and removed from the ecosystem, producers who can't control production costs or who can't find willing customers for their products are driven to bankruptcy and eliminated from the economic system—hopefully to find something more socially beneficial to do with their careers. At the same time, however, new ideas to produce at reasonable cost a good or service that people value are encouraged and work their way into a dynamic economic system that employs a form of social selection that is not too different from biological evolution's natural selection.

Market Effects of Changes in Demand and Supply

Let's take our discussion of supply and demand to the next level by facing the fact that they are always changing. We have all modified our consumer preferences for specific products—maybe you tried being a vegetarian but discovered you can't live without hamburgers, or you got tired of the sneakers, torn blue jeans, and expressive t-shirt "grunge" look and started preferring "office casual." More substantively, maybe the price of gasoline went through the roof and you realized you were much better off with a hybrid car than an SUV. Or you lost interest in buying a fax machine or even a printer because it's become so simple to text message or attach documents to an email and save trees at the same time. These are all examples of changes in your demand for products that goes beyond the effects of price that we discussed with pizza slices. So how do these increases or decreases in demand change the market for a product?

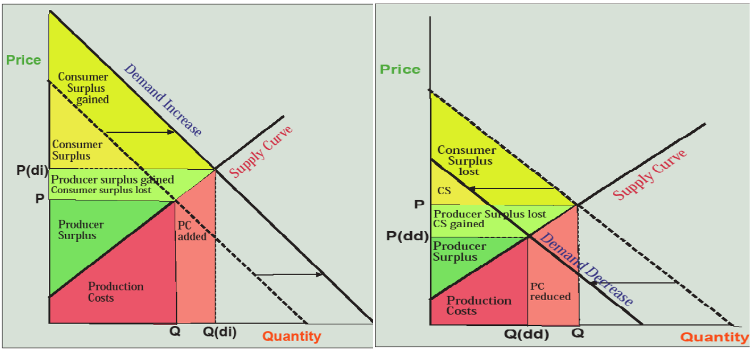

Figure 6.6. The market effects of an increase (left) and decrease (right) of demand for a product.

Let's first take the hamburgers, office casual clothes, and hybrid car examples, where demand is increasing. On the left side graph in Figure 6.6, the demand curve has shifted to the right (increased) from the dotted line where it started to the solid line where it has now arrived. The new demand curve slides up the supply curve to cross it to the right and upward of where it did before. The price has now increased from P to P(di) (demand increase) and the quantity sold has increased from Q to Q(di). This should make intuitive sense to you. If people start wanting something more, more of it is produced and they are willing to pay more for it.

What happens to consumer surplus, producer surplus, and production costs? Production costs increase (note the "PC added" area in Figure 6.6) because more of the product needs to be produced. But producer surplus increases nevertheless (light green "producer surplus gained" area in Figure 6.6) because producers can now sell more of the product at higher prices.

This is an important outcome—producers make more profits if the demand for their product increases. For this reason, producers are constantly trying to increase the demand for their products. That's why you are inundated with advertisements and commercials on TV, the radio, and the Internet. If you're smart, you'll ignore them all, except perhaps as entertainment, because marketers are just trying to use psychology to increase your demand for their product. That way they make more profits off the money that used to be in your wallet. It's better to teach yourself to use your money to buy only what you've previously decided you need or want.

Moreover, the desire of firms to increase demand encourages overconsumption of goods. Our closets are full of unworn clothes, our garages and basements of products we purchased but never integrated into our lives in a constructive manner. The companies that make these products make a profit off our income or even our debt, and natural resource sustainability is undermined by this simple economic fact that producer surplus increases when demand increases—it's all in that light green trapezoid on the left-hand graph in Figure 6.6.

Now let's look at the case of a decrease in demand such as with the "grunge" clothes, the SUV, the fax machine and printer mentioned above. In the right-hand graph in Figure 6.6, the new demand curve slides along the supply curve, crossing it to the left and below where it did before, resulting in a lower price and a lower quantity. Producer surplus is reduced. Companies that make SUVs and fax machines lose profits and may discontinue these products. They may even go bankrupt. A decrease in demand for the product you make is the nightmare that haunts the dreams of capitalist producers. This can make "conservation" a hard sell to producers because it results in a decrease in demand and therefore profit.

Note that changes in demand are always associated with how much customers value the product. Changes in supply, on the other hand, are always caused by conditions of production. Technological advance, nearly by definition, causes a reduction in production cost and therefore an increase in supply. This is especially true for incremental improvements, such as in membranes for desalination of seawater through reverse osmosis; bigger, more efficient wind turbines; cheaper solar photovoltaic cells; better methods for turning plant cellulose or algae into ethanol or biodiesel; or computer chips that hold more data and run even faster. It is also true, however, for technological breakthroughs. For example, the cost of sending a human to Mars is infinite—it cannot not be done at all—while in the future it may be possible for a steep price of many billion dollars.

In each of these cases, technological advance is the best example of an economic free lunch, and for that reason, has been an enormously progressive force in the world, especially in the last two or three centuries. We are deeply indebted to the nerds and geeks of the past! It is likely to be even more of a bonus in the future. Note, however, that decreased costs of production can also occur by moving production to regions with lower wage rates, lower taxes, and more lenient labor and environmental regulations, one of the key points of contention in modern globalization.

Increasing costs of production and resulting decreases in supply can also occur when labor becomes more expensive (e.g., due to rising health care costs), taxes and environmental regulations become more onerous, or raw materials or energy become more expensive. This occurred, for example, in the

2008 surge in oil prices that drove up costs of production for most industrial and agricultural goods.

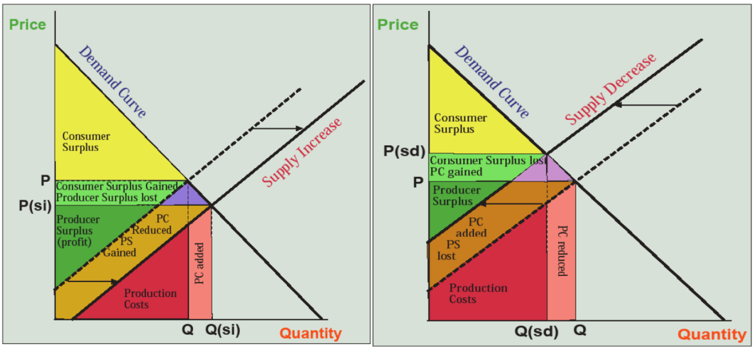

Figure 6.7. Effect of an increase (left) or a decrease (right) in supply on price, quantity produced, consumer surplus, producer surplus, and production costs.

Figure 6.7 graphs the market effects of changes in supply with a supply increase on the left and a supply decrease on the right. Supply increases lower prices while increasing quantity produced—we get more for less! This increases consumer surplus (the light green and purple areas). Producer surplus is harder to gage because the decrease in prices reduces profits (light green area) while the reduction in production costs and the increase in product volume increase it (brown area). In practice, the companies that first master the technological advances driving supply increases make the gains and the ones that lag behind are punished. Production costs per unit fall (brown area), but this may be compensated by greater volume (pink area). In nearly every case, supply increases are good news for everyone—except companies left behind using obsolete techniques and making obsolete products. This makes development, adoption, and mastery of technological advance a core challenge for capitalist firms, whether they are leading the race (e.g., Tesla's electric cars) or desperately trying to stay in it (e.g., Chrysler, which needed a bailout).

A decrease in supply (right side of Figure 6.7) borne of increased production costs is difficult to cope with because prices (P(sd)) rise while quantity shrinks (Q(sd)). Consumer surplus declines (light green plus purple areas) as customers get less product for more money. Producers lose profits (brown area) as per unit production costs rise, though this may be offset by higher prices (light green area), especially for firms that avoid the problems driving production costs higher. These market effects are cited by those opposing environmental regulations, and they also make an argument for vigorously expanding the supply of natural resources, especially energy, rather than allowing prices to rise, even though high prices reduce quantity demanded and thus encourage conservation.

So we can see that changes in demand and supply make the market dynamic, constantly altering prices and the quantities of goods produced. Moreover, these changes raise difficulties for pursuing natural resources sustainability. In particular, producers have a built-in incentive to encourage consumption, not conservation, and customers have an incentive to avoid the cost increases that can sometimes accompany environmental restraint. Only technological progress can avoid these head-on collisions of economic interest where environmental sustainability is usually the underdog.

Applying the Concepts: The Price of Oil

No product's price draws more interest than oil, and its rises and falls are watched more closely than any other market, except perhaps the Dow Jones, S&P500, and Nasdaq stock market indicators. Figure 6.8 charts the price of oil over a half-century, starting from 1965. Note that the price of gasoline follows crude oil prices. Currently in the U.S, you can divide the world price of crude per barrel by 42 (gallons per barrel) then add about $1.00, with local variations, to estimate the price of gasoline (e.g., $42/barrel yields $2.00 gas; $84/barrel yields $3.00 gas; $126/barrel yields $4.00 gas).

Rising crude oil prices, such as in the 1970s and 1998–2008, have been more common than falling ones, but there have been some interesting price collapses as well (e.g., early 1980s, late 2008–2009, late 2015). In this time period, I have chosen seven snapshots where the world price of oil per barrel, corrected for inflation by sticking with 2000$U.S. dollars, is plotted against world oil production in billions of barrels (that's right at 24 billion barrels we surpass one*trillion* gallons). Note from our philosophical discussion at the beginning of the chapter that the prices and the quantities of oil produced are real, measured empirical data, while the demand and supply curves are a bit murkier theoretical constructs that we assume lie behind the data the way gravity lurks behind the shape of planets' orbits (that's why I colored them gray). What we see in the volatile prices is changing supply and demand—prices rise as supply falls and/or demand rises, prices fall as supply expands or demand declines—but there's a political story to be told explaining why these key levers are changing.

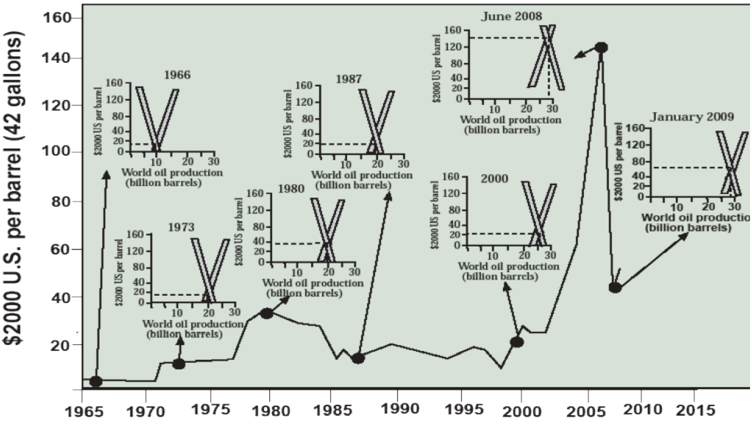

Figure 6.8. A half-century of oil prices, 1965–2015. World oil production and assumed supply and demand curves are shown for 1966, 1973, 1980, 1987, 2000, 2008, and 2009.

Here's how I tell that story, drawing from the Pulitzer Prize-winning book by Daniel Yergin *The Prize: The Epic Quest for Oil, Power, and Money*. In 1966 oil prices were below $10/barrel because oil companies (e.g., the "seven sisters" Exxon, Mobil, Chevron, Gulf, Texaco, British Petroleum, and Shell) could set prices for crude oil pumped from countries belonging to the Organization of Petroleum Exporting Countries (OPEC). World demand was low, though rapidly growing, because only North America had at that time developed an automobile-dependent society, and world population was only 3 billion. The huge oil discoveries of the Persian Gulf had just been brought on line, and the U.S. was a significant world oil producer, making cheap-to-produce oil supplies abundant. In 1973 this all changed. In protest of U.S. support for Israel in its Yom Kippur War against the Arabs, OPEC cut off oil exports (this is called an *embargo*). By this time, U.S. oil demand had shot past domestic production, and this politically motivated reduction in supply, enabled by OPEC's wresting of control of crude oil prices from the oil companies, forced oil prices rapidly upward. Global demand had also sky-rocketed, doubling in less than a decade, due to the economic recovery of Europe and Japan. In 1980 these conditions of high demand and politically limited supply became even more extreme as a result of the Islamic fundamentalist revolution in Iran.

By 1987, the oil-importing developed countries had succeeding in fighting back, not militarily but economically. They found oil in Alaska and the North Sea, expanding supply. More importantly, fuel-efficient Japanese cars filled the highways, and the electricity industry phased out oil-fired power plants in favor of coal, natural gas, and nuclear plants. These efforts controlled demand sufficiently to bring prices down to below 1973 levels.

By 2000, however, trends had again reversed. Americans were driving SUVs, minivans, and pickups instead of hatchbacks, and the great Asian economic miracle, especially in China, was increasing demand again. Meanwhile, U.S. oil production was falling due to depletion of spent oil fields, and even the giant Persian Gulf fields were finding it difficult to expand production at a whim. These high demand and falling supply conditions hit the fan in 2007–2008 as prices sky-rocketed to hit an amazing $147/barrel in June 2008. Probably exaggerated by speculators, this oil price peak was short-lived and prices crashed to only $40/barrel by January 2009 in the midst of a deep global recession that plummeted demand for oil. As of this writing, the price has recovered from a 2015–2016 low of under $30/barrel to hover in the $50/barrel range, a mark that has been held at low levels due largely to the influx of North American sources driven by new technologies for extracting and refining oil sands from Canada's Athabaskan fields and by the 21st century technology of fracking.

So the price of oil has been determined by supply and demand throughout the last half-century, but these are the economic expression of political, technological, and other forces. While resource depletion and scarcity has played a role and will play a much larger role in limiting oil supplies in the future, Figure 6.8 is largely a graph of a power struggle between oil importers and exporters that shows no signs of abating. Consumer surplus resides largely in importing countries, including not only the developed countries of North America, Europe, and northeast Asia, but also most developing countries. They, therefore, want the low prices that arise from high supplies. But OPEC countries want high producer surpluses that come from high prices—which can be created through supply restrictions. That's the purpose of their cartel. The 21st century will also likely witness actual scarcity due to the inability of this diminishing, non-renewable resource to keep up with expanding world demands.

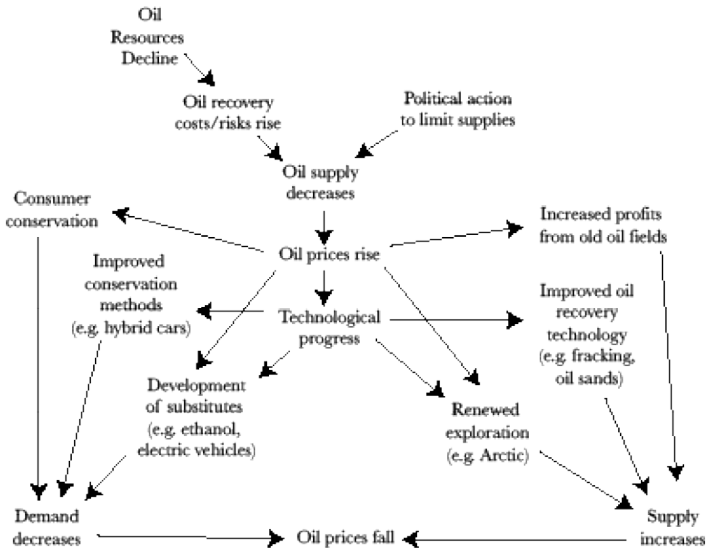

Figure 6.9. Ways in which markets react to resource scarcity or political disruption through price mechanisms: the case of oil.

For this reason, the future price of oil, and therefore of gasoline, will continue to be a tug-of-war between supply and demand. On the supply side, technologies for extracting difficult-to-reach oil supplies using oil sand refining, fracking, and deep-sea drilling will largely govern oil supply, but political factors like the current chaos in Venezuela are also critical. On the demand side, the continued expansion of the global middle class will increase demand while the replacement of gasoline-powered with electric vehicles will decrease it. Whether the overall price of oil and gasoline rises or falls will continue to be determined by the power struggle depicted in Figure 6.9.

Importing countries have some important cards that they can play. The very increases in prices induced by supply limitations, whether from political action or resource scarcity, can initiate an effective response. On the demand (left) side, consumers can respond to higher prices by driving less—up to a point. Through technological progress, more fuel-efficient cars like hybrids are developed and substitutes for oil like ethanol or electricity are created. New technologies like the hyperloop can also replace driving. These efforts all result in a decrease in demand that has the effect of lowing prices.

On the supply (right) side, price increases cause oil exploration to pick up, and old oil fields again become profitable through the use of improved recovery techniques, such as injection of water, steam, and detergents, or carbon dioxide. Oil sand and fracking activity accelerate. In 1974 the U.S. wisely established a Strategic Petroleum Reserve holding one billion barrels of oil in salt domes in Louisiana purchased when prices are low, so they will be available when prices are high or supplies are unavailable. These efforts result in an increase in supply that lowers prices.

Let's go back for a moment to the first demand and supply curves in Figures 6.1 and 6.2 where we were talking about pizza. Looking at the left-hand panel of Figure 6.10, this time in reference to oil, let's take the solid supply curve as the starting point with price of P and quantity of oil produced of Q. Now supply decreases ("reduced supply" curve) and we have a problem. Earlier we showed that a decrease in supply causes prices to rise and quantity to fall, but which changes more? The steeply downward sloping demand curve on the left panel of Figure 6.10 is *inelastic*—increases in price don't yield very much decrease in quantity demanded. So price jumps from P all the way up to P(rs,id) (reduced supply, inelastic demand) while the quantity consumed falls only a bit from Q to Q(rs,id). When customers are unable or unwilling to reduce their use of a product like gasoline when supply reductions increase the price, they take it in the teeth (in the form of a greatly reduced consumer surplus). If demand had been *elastic*, however, like in the green-labeled, dashed, shallow-sloping demand curve, the price would have only increased from P to P(rs,ed) (reduced supply, elastic demand), reflecting their responsive capacity to reduce quantity consumed from Q to Q(rs,ed). The adaptive capacity to reduce use of a product like oil is thus the primary means of defense customers and importing countries have when the resource becomes more scarce and expensive. They are therefore wise to develop such capacities through the means outlined on the left-hand side of Figure 6.9 and discussed above—conservation, substitution, more efficient technology.

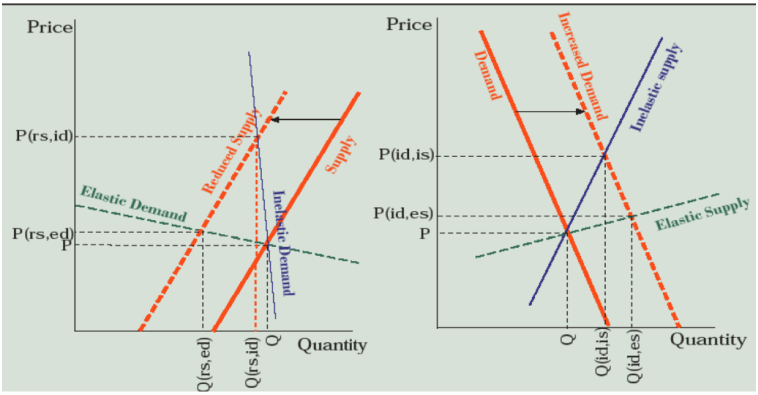

Figure 6.10. The effects of elasticity of demand on the market response to a decrease in supply. (Right) The effects of elasticity of supply on the market response to an increase in demand.

A similar situation follows when we examine the importance of elasticity of supply in response to rising demand. On the right-hand side of Figure 6.10, let’s again start with the curve labeled “Demand” and a market-clearing price of P and quantity of Q. Now, world population increases and economic growth in the Asian demographic giants leads to accelerating use of automobiles in the expanding middle class, increasing demand for gasoline derived from oil. If OPEC can’t or doesn’t respond by greatly increasing production (only from Q to Q[id,is]) making supply inelastic, the price skyrockets to P(id,is) (increased demand, inelastic supply). Supply might be more elastic, for example, if there is excess pumping capacity within OPEC and a willingness to utilize it, alternative sources of oil outside OPEC, the ability to accelerate fracking, or a strategic petroleum reserve that can be accessed. In this case, quantity supplied becomes more responsive (from Q all the way out to Q[id,es] [increase in demand, elastic supply] and prices rise only from P to P(id,es). So again we see that the capacity to adaptively respond through increases in supply is the best way to prevent increasing demand from forcing prices sky-high.

If even my colorful graphs don't make these market effects apparent to you, I have summarized them in Table 6.1. Working across the rows, demand increases or supply decreases cause prices to rise while demand decreases and supply increases cause them to fall. Note the importance of elasticity on consumer and producer surplus. You can similarly work your way through the other rows, or use Table 6.1 as a quiz to see if you understood the graphical analysis.

Table 6.1. Summary of effects on price, quantity produced, consumer surplus, producer surplus, and production costs when supply or demand change.

Market Change	**Demand Increase**	**Demand Decrease**	**Supply Increase**	**Supply Decrease**
Price	Rises	Falls	Falls	Rises
Quantity	Increases	Decreases	Increases	Decreases
Consumer Surplus	Increases if supply is elastic Decreases if supply is inelastic	Decreases if demand is elastic Increases if demand is inelastic	Increases	Decreases
Producer Surplus	Increases	Decreases	Decreases if demand is elastic Increases if demand is inelastic	Increases if demand is elastic Decreases if demand is inelastic
Production Costs	Increase overall	Decrease overall	Decrease per unit	Increase per unit

Benefit-Cost Analysis

We have now seen how markets regulate rewards, and thus behavior, in the private sector. Governments, the public sector, also need to know when investments are worthwhile through economic analysis. This issue came especially to the fore when, as told by Marc Reisner in *Cadillac Desert*, the U.S. Army Corps of Engineers (Corps) in the East and the U.S. Bureau of Reclamation (BuRec) in the West were allying with local private sector beneficiaries and members of Congress (whose districts stood to gain federally funded projects) in an iron triangle of pork-barrel spending. This resulted in the great dam-building era of about 1955–1980 when the Missouri, Columbia, Colorado, and other rivers systems came under the control of human engineering.

The central economic question is: when is a dam or other public investment worth it? The answer is if it has a net economic benefit, or "the benefits, to whomsoever they accrue, exceed the costs." This is known as the potential Pareto criterion after the Italian economist who argued that if the economic beneficiaries of a project could compensate the economic losers and still have something left over, then the project is worthwhile. Now here's some easy math. If benefits exceeds costs ($B > C$), which is the same as saying if net benefits are positive ($B - C > 0$), which is the same as saying if the benefit-cost ratio exceeds one ($B/C > 1$), the project is worth it.

One catch that complicates the easy math is that money is a two-dimensional object: amount and time. Would you rather get a check for $10,000 tomorrow or 30 years from now? I'll bet there's unanimous agreement on tomorrow. Why? The first reason is that there's a time preference for money—we are simply focused on the here and now (an ever-present difficulty to achieving sustainability, which is inherently oriented toward the future). The second reason is that if we invested the $10,000, we'd have a lot more than that after 30 years (especially if we can avoid financial disasters like in 2008–2009 or in 2020). The answer to this time dilemma is called *discounting*.

Let's say you can make 6 percent interest on your investments (around the average over the past century). That \$10,000 in the present (P) becomes \$57,435 thirty years in the future (F) based on the formula F = P(1+i)n where i is annual rate of interest, or rate of return, and n is the number of years this rate is applied. So $57{,}435 = 10{,}000\ (1.06)^{30}$. (Try this on a handheld calculator using y^x as the "raise to the power of" key.) Remember the doubling-time formula from Chapter 5 on population (DT=70/percent growth rate), where $1.01^{70} \sim 2$. After 50 years, the typical period of analysis on public infrastructure projects, the \$10,000 is worth \$16,446 at 1%, \$26,916 at 2%, \$71,067 at 4%, \$469,016 at 8%, and \$16,707,038 at 16%. The interest rate makes an enormous difference if applied over a long time frame!

The mathematical power of exponential growth also works in reverse where we have half-lives (for example, $0.99^{70} \sim 0.5$) rather than doubling times. This means that if a project is predicted to produce \$10,000 in benefits every year for the next 50 years, we have to discount the future benefits relative to the present benefits to calculate the *present value* using the similar formula $P = F/(1+i)^n$. Try this on a future value of \$57,435 at 6% over 30 years and you'll get \$10,000 ($10{,}000 = 57{,}435/(1.06)^{30}$). The present value of that \$10,000 benefit in year 50 is \$6,081 at a discount rate of 1%, \$3,715 at 2%, \$1,407 at 4%, \$213 at 8%, and a measly \$6 at 16%. To put it bluntly, at high discount rates, the distant future is worth next to nothing!

Table 6.2. Formulas for calculating present value.

Future value of a present investment $F = P(1 + i)n$
Present value of future benefits or costs $P = F/(1 + i)n$
Present value of an Annual benefit stream $P = A[(1 + i)n – 1] / [i(1 + i)n]$
i = annual interest rate; n = number of years

Figure 6.11 traces the costs and benefits for a typical dam or other infrastructure project using a *cash-flow diagram*, where costs and benefits are graphed over time with a discount rate applied—a low one on the left and a high one on the right. In each case there are large construction costs at the beginning and moderate maintenance costs thereafter. The initial annual benefits of hydroelectricity, recreation, flood control, and water supply are the same, but their present value declines faster over time on the right-hand side because of the higher discount rate. The result is that the total benefits (blue area) exceeds the total costs (red area) (B>C) on the left, but costs exceed benefits (B<C) on the right. So the discount rate determines whether this dam is "worth it" by the benefit-cost criterion. Oddly, this leaves environmentalists who oppose

dams arguing for high discount rates, even though discounting the future flies in the face of sustainability.

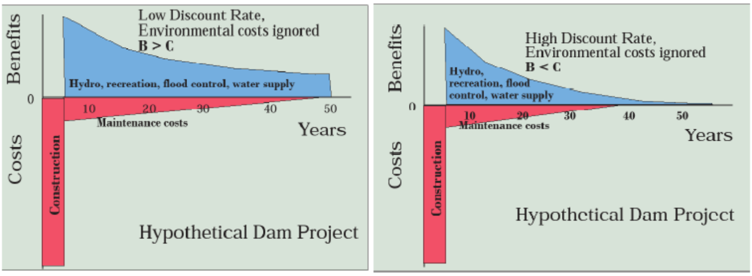

Figure 6.11. Cash-flow diagram for a dam project using a low discount rate on the left and a high rate on the right.

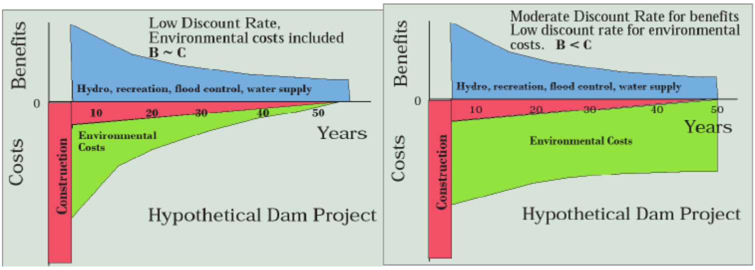

Figure 6.12. The same project with environmental costs included (left) and with environmental costs discounted at a lower rate (right).

Given the enormous mathematical power of discount rates in benefit-cost analysis, it seems that it would be critical to use the "correct" discount rate. But what is it? No one knows! Or rather the debate goes on. Given the over $26 *trillion* U.S. national debt (over $80,000 per American at the time of this writing), one argument that rests on solid ground is, rather than build the dam or other project, the money could be used to pay down a bit of this enormous debt by paying off treasury bonds. The rate of return varies, but in the 21st century has generally been between 2–5%, so that seems like a solid discount rate to use. But what if the project will make a fish species go extinct? Should the value of that species be discounted at 2–5% per year . . . forever? And what about other environmental costs like the flooded valley and altered stream and sediment flow below the dam?

Figure 6.12 (left) uses the same project but with environmental costs of the dam included and discounted. These can potentially negate the net benefits, making the dam not worth it. Economist John Krutilla, however, took the thinking one step further with the concept *technological asymmetry*. Technological development and economic growth make man-made goods and services ever more available (as we saw with supply increases), but this cannot be said for natural places (e.g., free-flowing rivers, rainforests, coral reefs, etc.) and wild species. Moreover, as population and incomes increase, the demand on the fixed supply of natural places will increase. This increases the value of those few that remain as we can observe, for example, in the sky-rocketing visitations to a fixed supply of national parks. This increase in value over time counteracts discounting as shown in the right-hand side of Figure 6.12. We're left with a dam project that clearly is not worth it.

In fact, the dam building era in the U.S. largely ceased by

1980 as these arguments gained sway. Moreover, prior to this time, the federal government paid nearly all the costs of projects through the Corps and BuRec so that, from the perspective of the location where the projects were built, the benefits were local while the construction costs were passed on to all the taxpayers in the country. This is the barrel of pork now known as*earmarks*. After 1980, locals had to pay up to 75 percent of the costs, making the local benefit-cost ratio closer to the overall one. The lobbying of Congress for dams almost ceased, raising skepticism about whether many of the dams built before 1980 were “worth it.”

So we can see that there is considerable room for maneuver in conducting a benefit-cost analysis of a public investment or regulatory decision. Not only will two different analysts arrive at different results, but their results may well reflect the outcome they would like to see. Given this imprecision (after all benefit-cost analysis is usually conducted in reference to the future, which is inherently unknowable) and opportunity for “fixing” the results, there have been many changes in policy in recent decades governing whether benefit-cost analysis should be required for all decisions on public investments and even on all environmental regulations.

In considering this issue, I am comforted by two facts. First, benefit-cost analysis is always an item of information to be considered in making public natural resource and environmental decisions, never a strict criterion for making decisions. Second, benefit-cost analyses have frequently shown that sound environmental management is very economically beneficial. For example, a *post hoc* (after the fact) analysis of the Clean Air Act obtained a benefit-cost ratio of 42:1! Benefit-cost analysis often reveals that managing natural resources sustainability is also economically beneficial.

Efficiency and Optimal Pollution

Optimal pollution is one of my favorite oxymorons (a contradiction in terms). It seems to make no sense, but then again, does it make sense to stop *all* soil erosion, *all* greenhouse gas emissions, *all* solid waste, and *all* nutrient runoff? If you wanted to stop *all* tooth decay, you'd spend half your life brushing and flossing; maybe stopping *most* tooth decay by brushing and flossing once a day makes more sense. Similarly, optimal pollution addresses the question—how much pollution is efficient? Let's look at the logic (yes, graphically) using the example of reducing greenhouse gas emissions.

Let's first introduce the idea of *cost-effectiveness*. No matter how much we might want to reduce carbon dioxide, methane, and other greenhouse gases, I think we can agree that we would want to do so in the least costly manner. Thought of in the opposite way, if we have a fixed budget for greenhouse gas reduction, we would want to reduce the most emissions possible within that budget. Let's look forward to 2050 when, if we do nothing, carbon dioxide concentrations will be, say, 500 ppmv (Figure 6.13).

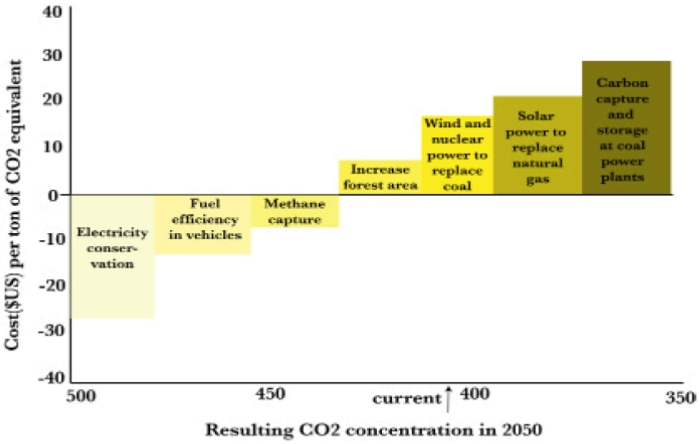

Figure 6.13. Ways to reduce carbon dioxide concentrations in 2050 by applying measures cost-effectively from the least costly to the most costly. Numbers are for illustration purposes only. Arrow is at 415 ppmv (the concentration as of this writing).

Let's start with carbon reduction measures that actually yield net benefits (i.e., have negative costs) such as electricity conservation in buildings, and fuel efficiency in vehicles, then turn to capturing methane emissions to use as fuel. These measures get 2050 carbon dioxide concentrations down to, say, 430 ppmv. Next, we increase forest area by reducing deforestation and planting trees at a cost of about $5/ton, which gets us down to 415 ppmv. Then we build wind farms and nuclear power plants to replace coal-fired power plants as they reach the end of their useful life. This gets us down to 390 ppmv or lower at $15/ton. Then we use solar power to replace natural gas power plants to get to 370 ppmv at $25/ton. Finally, we use carbon capture and sequestration at remaining coal plants to get down to 350 ppmv at $30/ton. By applying solutions from the least costly, in fact profitable, first to the most costly last we get the biggest bang for the buck. Of course, costs will vary within these categories, so the most cost-effective strategy may employ a mix of these options (remember the carbon game from Chapter 3).

While this tells us the order in which to apply our climate change abatement measures, it doesn't tell us when to stop. To answer that question, we also have to look at the benefits of abatement in an optimal pollution framework. The top graph in Figure 6.14 uses the same axes as Figure 6.13, so we can plot total costs of pollution abatement increasing at an increasing rate as we go from the least to the more expensive measures.

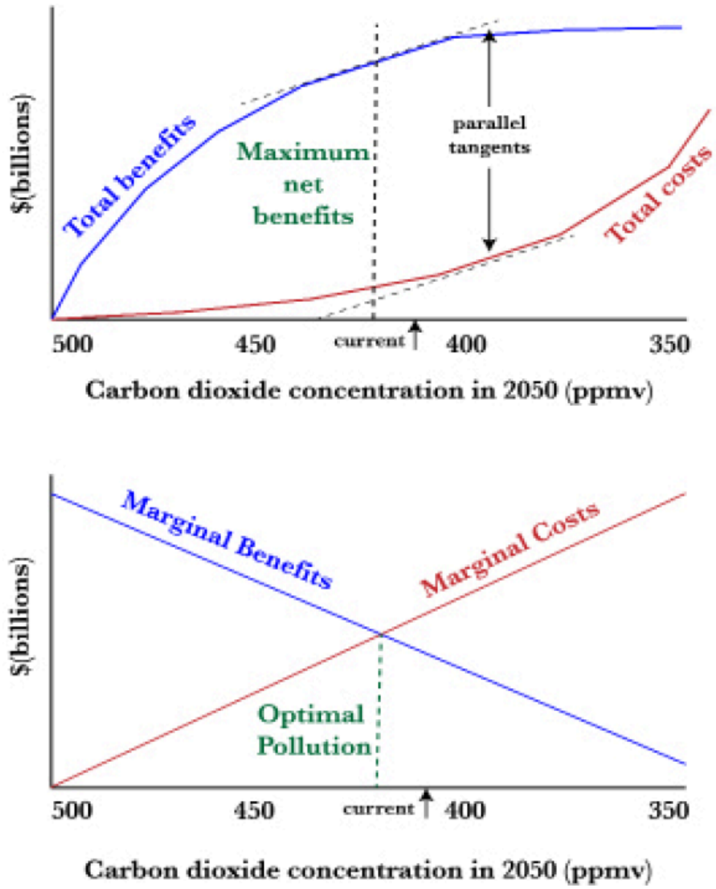

Figure 6.14. The optimal pollution framework using total costs and benefits on top and marginal costs and benefits on bottom.

Now, what are the benefits of reducing the 2050 greenhouse gas concentration? One way of looking at this is to acknowledge that as the carbon dioxide concentration goes up and up, the environmental effects become more and more costly. We've already seen some of the effects of 415 ppmv, though there is a lengthy lag between carbon dioxide concentrations and their ultimate effects. Sea levels are rising slowly, floods are intensifying, Arctic Ocean sea ice is melting, coral reefs are suffering, hurricanes and wildfires are intensifying, and so forth. At higher levels of greenhouse gases, we proceed through the sequence of intensifying impacts described in Chapter 4's discussion of *Six Degrees*.

This progression means that, starting from the origin in Figure 6.14, the benefits of avoiding the 6oC in warming catastrophe are enormously high, perhaps infinitely high. As we reduce carbon dioxide levels in 2050 further, resulting in the 5°C, then the 4°C, then 3°C, then 2°C, then 1°C scenarios, additional benefits accumulate, even if they are less than the benefits of avoiding the worst climate change disasters.

Still looking at the top graph in Figure 6.14, where is the best economic trade-off between the climate change disease and its many cures? Economic efficiency dictates that it is where net benefits (total benefits – total costs) are maximized. This is shown for illustration purposes at 420 ppmv where the total benefits curve has the greatest vertical distance above the total costs curve.

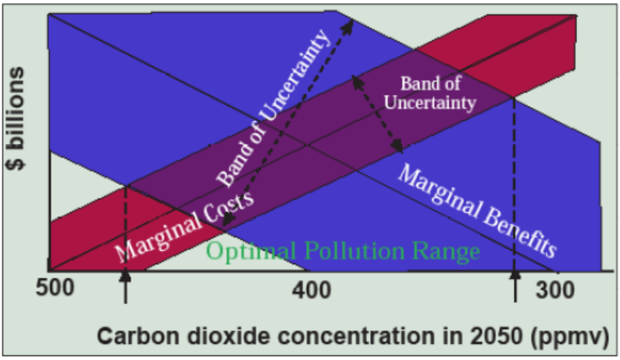

Figure 6.15. When there is uncertainty in estimating marginal benefits and costs, the optimal pollution level becomes a range, potentially a wide one, undermining its usefulness.

Now let's proceed to the lower graph, which uses the same axes. *Marginal* costs increase as we start reducing from 500 ppmv in 2050. This means that the costs of abating *an additional* ton of carbon dioxide go up as we proceed from the least to the most expensive measures. The marginal benefits of abating each ton go down because this allows us to avoid less and less catastrophic environmental costs.

The point at which these curves cross, 420ppmv, is the same as the point where the gap between total benefits and total costs (net benefits) are maximized in the top graph. Geometrically, the marginal curves are equal to the *slope* of the total curves at each point along the x-axis. Looking at the top graph, the dashed tangents to these curves are parallel at the optimal pollution point, meaning their slopes are equal and also indicating that marginal benefits and marginal costs are equal. Optimal pollution occurs at that point (in this example, 420 ppmv). That means that, in the hypothetical examples shown in Figure 6.13, we should conserve electricity in buildings and fuel in vehicles, capture methane, increase forest area, and replace coal with wind and nuclear power—but then we stop because further "cures" cost more than further reduction in the symptoms of the "disease."

Do you buy this economic argument? I find about half the people do and half don't. If we're looking at large volume, non-toxic pollutants like greenhouse gases, soil erosion, or nutrient runoff, the logic makes sense, but perhaps it doesn't for acutely toxic pollutants like dioxin, where the optimal pollution level must be zero, or species extinctions, where the reason for saving a species is ecological and moral, rather than economic, in the first place. We also run into practical problems in trying to estimate, no less implement, an optimal pollution level because we can't accurately estimate the nice lean curves shown in Figure 6.14. There is certainly considerable error in figuring out how much any of the abatement measures would really cost, turning the marginal cost line into a band (red in Figure 6.15). It gets even worse when we try to estimate the marginal benefits of avoiding one ton or one part per million of carbon dioxide because the chain of causation from emissions to effects is complex. So we end up with an even wider band of uncertainty when trying to estimate marginal benefits (blue in Figure 6.15, purple where these bands overlap). The result can turn the bottom graph in Figure 6.14 into the mess shown in Figure 6.15, where the optimal pollution level is somewhere in the wide range between 320 ppmv and 470 ppmv—as if we didn't know that already!

When we have this kind of uncertainty, we can retreat back to cost-effectiveness by setting the pollution target through political negotiation (which it always is anyway), say at the level which would result in 1.5°C or 2.0°C of warming, and then look for cost-effective ways to reach that politically-negotiated goal. Let's turn our attention to pollution taxes and tradable pollution permits as policies for implementing pollution controls in a cost-effective manner.

Pollution Taxes and Tradable Permits

Our earlier discussion of supply and demand tells us three things about human economic behavior:

- that which is cheap gets wasted
- that which is expensive gets conserved
- that which is rewarded gets produced

If it's cheap to dump waste (that is, pollution) into the air and water, the air and water's pollution absorption capacity will be wasted. If it's expensive, it will be conserved. If pollution prevention is rewarded, it will be adopted. Two economic approaches to incorporating these principles in the service of natural resource sustainability are *pollution taxes* and *tradable pollution permits*. As has been said, two certainties in life are death and taxes, so let's start with the lesser of these two evils.

What if polluters had to pay a tax to emit greenhouse gases into the atmosphere, making it more expensive to use the atmosphere as a carbon dump? Let's say the tax is $10/ton (Figure 6.16). Since electricity conservation in buildings, fuel efficiency in vehicles, methane capture, and increasing forest area cost less than $10 per ton, these measures are cheaper than paying the tax. They reduce production costs and therefore increase profits. So the tax induces pollution prevention behavior—up to a point. Raising the tax to $20/ton induces further pollution prevention through use of wind and nuclear power to replace coal. At $30/ton, solar power to replace natural gas and carbon capture and storage at coal-fired power plants become economical.

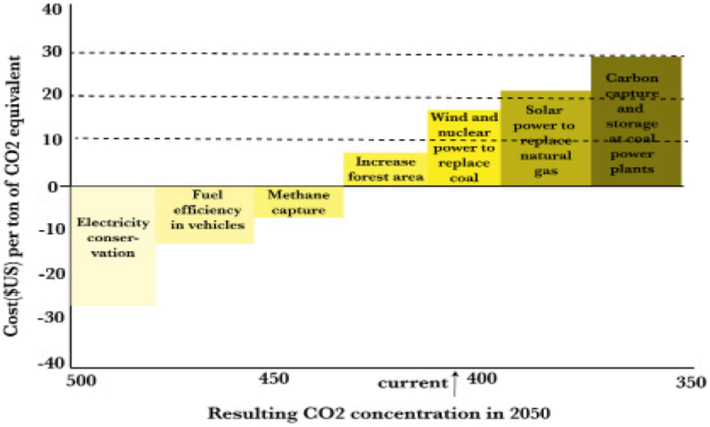

Figure 6.16. How carbon taxes of $10/ton, $20/ton, and $30/ton affect pollution behavior.

So it seems that taxes are a lot better than death! But we also have to ask the question, who will the taxes be paid to and what will be done with the money? I can guarantee you that polluters will lobby Congress to avoid having the tax policy implemented because it directly transfers money from their profits to the public coffers. But at least the tax is a predictable cost when considering, for example, whether to invest a billion dollars in a coal-fired power plant or a giant wind turbine farm, each of which will run for the next 50 years or more.

Like prices, pollution taxes also create an efficient condition that economists call *equimarginality*. Remember that everyone didn't buy the same number of pizza slices. Rather everyone bought slices until the marginal utility of the last slice equaled the price. So prices allocate resources in a manner such that the marginal value of the last unit used is equal among all users. Similarly, a pollution tax induces each polluter to reduce emissions until the marginal costs of the last ton abated equals the tax. In this manner, a pollution tax encourages equimarginality, and thus cost-effectiveness, just like a price does.

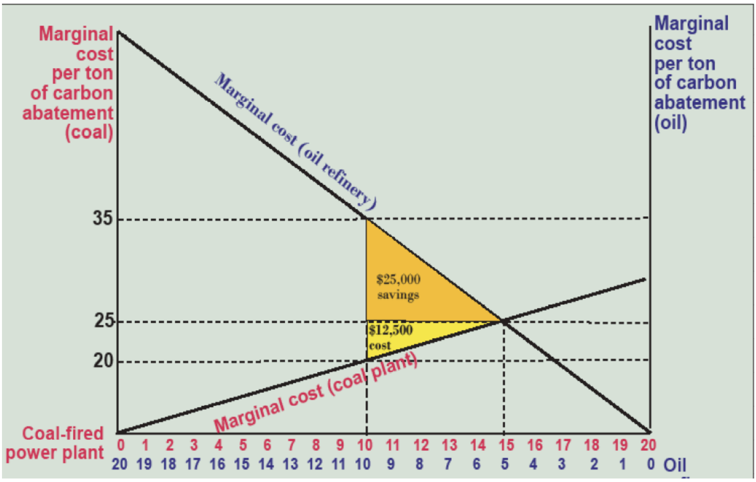

Figure 6.17. The basis of the Coase Theorem and tradable pollution permits in equimarginality.

Economist Ronald Coase explored these issues further, and it is on the basis of his ideas that I will try to convince you that tradable pollution permits also induce equimarginality, and therefore cost-effectiveness. Let's say we have a coal-fired power plant that can reduce its greenhouse gas emissions less expensively than an oil refinery (marginal cost line is steeper for the oil refinery in Figure 6.17). Each is annually emitting

20,000 tons of carbon dioxide, but the Environmental Protection Agency (EPA) says that everyone has to reduce their greenhouse gas emissions by half, in this case abating 10,000 tons each. This seems fair, but it costs the oil refinery $35 to reduce the 10,000th ton while it costs the coal plant only $20 to reduce its 10,000th ton. So the oil refinery manager calls the coal plant manager with a deal: "I'll pay you $15,000 to reduce your emissions an extra 5,000 tons if I can keep emitting those 5,000 tons."

Why does (s)he offer the deal? Because reducing that second 5,000 tons (from 5–10 in blue in Figure 6.17) costs the oil refinery $25,000, so they save $10,000 by making the transaction. Does the coal plant take the deal? Yes, because reducing an extra 5,000 tons (from 10–15 in red in Figure 6.17) only costs them $12,500, so they gain $2500 in the deal. It's a win-win! In fact, any offer between $12,500 and $25,000 produces a win-win because the total costs of abatement are reduced by $12,500 by having the coal plant do the abatement rather the oil refinery.

In theory, this is exactly what would happen if each firm were given 10*permits* to emit 1,000 tons of carbon, but they were allowed to *trade* them at an agreed-upon price. In fact, Coase showed that we'd end up at the cheapest solution of 15,000 tons of carbon abated (leaving 5,000 emitted) by the coal plant and 5,000 tons abated (leaving 15,000 tons emitted) by the oil refinery, no matter how the permits were initially allocated, simply by taking advantage of the costs savings when polluters have different marginal abatement costs and are allowed to trade. This made him famous—it's called the Coase Theorem! Note that the cost-effective solution occurs where marginal abatement costs are equal—$25/ton in this case.

There are some*caveats* (i.e., ifs, ands, and buts). If lawyers or the EPA charge $12,500 or more to negotiate the transaction, the gains disappear and everyone says the heck with it. Similarly, if it costs $12,500 to figure out what the costs are and how to implement the trade, it doesn't happen. Also, with $12,500 in gains to be had, which party gets them? If the oil refinery had offered $25,000—the full extent of their savings—the coal plant would reap the full $12,500 in efficiency gains, but if they had offered $12,500, the oil refinery would reap all the gains. In business, you don't get what you deserve, you get what you negotiate!

It can work, even for something as smelly as sulfur. Together with nitrous oxides, sulfur dioxide emissions cause acid rain, which damages forests, aquatic ecosystems, and human-built structures. They are also hazardous to human health. Title IV of the 1990 Clean Air Act Amendments set a cap on total sulfur dioxide emissions from coal-fired power plants at 8.95 million tons to be achieved by 2010, a level roughly half of emissions in 1980. The act allocated allowances to coal-fired power plants and allowed firms to trade these allowances throughout the 48 contiguous U.S. states. Phase I (1995–1999) applied to the dirtiest 261 electric power-generating units and Phase II (2000–2010) applied to most fossil-fuel units of 25 megawatts or greater.

There has been 100 percent compliance. In Phase I, sulfur emissions were reduced from 8.7 to 4.4 million tons, and in Phase II to 3.0 million tons. Benefits of the program have exceeded costs by a factor of 10, both because abatement costs have fallen from about $2 billion to about $1 billion and because of the health benefits of reduced exposure to sulfates in addition to reductions in acid rain.

The reductions in sulfur dioxide abatement costs came largely from utilities' agility in minimizing total abatement costs under the flexible regulatory environment, largely through switching from high-sulfur eastern coal to low-sulfur coal from surface mines in Wyoming and through mountaintop removal in the Appalachians. Initial transaction costs of 30–40 percent of the value of allowances fell to about 1 percent as participation in the program became routine. Despite this overall success, there were drawbacks, including a loss of jobs in high-sulfur coal areas.

Is this the best approach to reducing greenhouse gas emissions? Congress explored this issue when a cap and trade bill supported by President Obama passed the House of Representatives in 2010 but it floundered on a threatened Senate filibuster. We will explore these issues in more depth in Chapter 15.

Further Reading

Tietenberg, T. and L. Lewis, 2009. *Environmental and Natural Resource Economics.* Pearson: New York.

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7.

CHAPTER 7: LEARNING FROM OXYMORONS I - ECOLOGICAL ECONOMICS

An oxymoron is an apparent contradiction in terms like "open secret" or "jumbo shrimp." That's how you may at first view the term "ecological economics," but let's see if we can find in it a consistent logic that's helpful in understanding natural resource sustainability. Ecological economics is a relatively new school of thought, originating in the 1980s, but it has expanded very rapidly as more and more economists come to see the value in taking the Earth and sustainability seriously and as more and more ecologists come to realize that humans dominate most ecosystems. Of course, ecological economics uses all of the ideas we studied in Chapter 4 on ecology and in Chapter 6 on neoclassical economics, but in integrating these it also adds new ideas and a different perspective that challenges neoclassical economic approaches.

An Ecological Economics Perspective

As we have seen, neoclassical economics takes efficiency and economic growth as its normative goals. Ecological economics, in contrast, strives for sustainability. Does this mean that it takes the view that humans have reached or exceeded their ecological carrying capacity and that we're all doomed? Anglican clergyman Thomas Malthus first proposed this idea in 1798, and such ideas are often labeled "Malthusian" to this day. In 1972, at the peak of world population growth rates and just before the OPEC oil embargo, a group called the Club of Rome built a computer model of the interactions among population, resources, the environment, agricultural, and industrial production. Their *The Limits to Growth* study concluded that, under current trends, the world would run out of resources, leading to a global collapse. Even if new technologies like nuclear fusion unleashed huge new resource opportunities, the globe would still be overcome by pollution as agricultural and industrial production soar exponentially. The message was that only an immediate stop to population and economic growth can save us all from an Easter Island or Mayan-like global collapse.

Ecological economics rejects this modern version of Malthusianism. It also rejects, however, the "Promethean" denial of ecological limits to economic growth articulated by scholars such as Julian Simon in his *The Ultimate Resource* and, in more contemporary form, Bjorn Lomborg in *The Skeptical Environmentalist*. These authors argue that technological innovation and capitalist markets can overcome any environmental limitation. We need a more nuanced view that lies between these extremes.

Ecological economics offers the idea of *increasing marginal ecological opportunity costs* associated with economic growth that is driven by resource consumption. As human economies co-opt a larger and larger share of the biosphere's energy and materials and release increasing quantities of waste, the incremental ecological impacts of economic growth rise, and the flow of ecosystem services to society diminishes at an accelerating rate. That's a mouthful, so let's explore this notion in more detail.

Figure 7.1 shows the Earth's biosphere running on low entropy, high-quality solar energy and emitting high entropy, low-quality waste heat, just like your car runs on gasoline and emits exhaust. *Entropy*, a key concept in thermodynamics, means that concentrated or structured forms of energy—solar radiation, electricity, the chemical energy in gasoline—can perform work, but in doing so will dissipate into generic forms of energy like heat that spreads evenly throughout its environment and cannot do work. The biosphere can't run on waste heat and your car can't run on its own exhaust. Applied to raw materials, pure copper, for example, has low entropy, one percent copper ore has high entropy, and ordinary rocks that contain the average concentration of copper in the Earth's crust are at maximum entropy. The same could be said of high-entropy generic mixed trash and low-entropy sorted recyclable materials. Like the Earth and your car, your body runs on the entropy difference between (a) the high oxygen-content air you inhale, the calorie, vitamin, and protein-rich food you eat, and the pure, treated water you drink compared to (b) the high carbon dioxide air you exhale, the heat radiating from your 98–99°F body, and what you flush down the toilet.

The human economy is a subset of the biosphere, but it is a growing proportion of that whole (the white arrows expanding the blue box in Figure 7.1) as we have seen in previous chapters. What is the relationship between the economy and the biosphere? Of course, the economy uses low-entropy natural resources produced by the biosphere in the distant past (e.g., fossil fuels, ores), more recent past (e.g., soils, forests, fresh water) ,and the present (e.g., solar energy). It emits high-entropy waste such as heat and pollution to the biosphere. So the economy runs on the entropy differential between natural resource inputs and waste outputs just like you and the Earth. Physicists call all of these—the biosphere, the economy, your body—*distributive structures* because they all maintain their dynamic internal complexity only by continuously taking in high-quality energy and raw materials and emitting high-entropy waste.

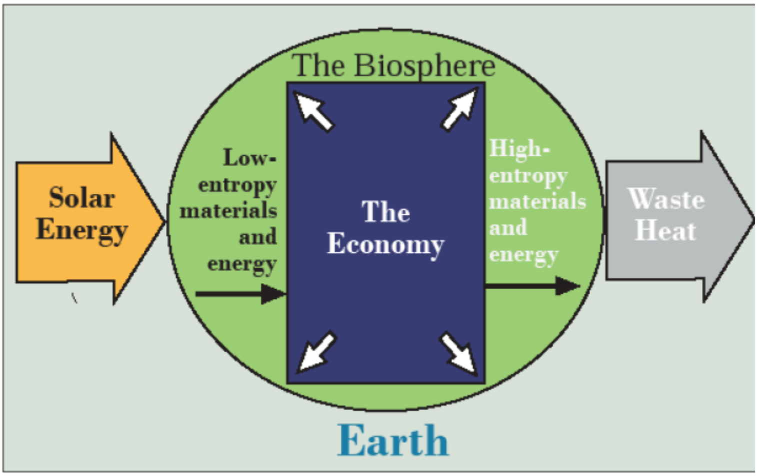

Figure 7.1. The relationships among solar energy, the Earth, the biosphere, and the economy, focusing on the entropy content of energy and materials. The economy is a distributive structure nested within the biosphere.

Let's penetrate the relationship between the biosphere and the economy a little deeper by traveling the pathways in Figure 7.2 below. At the heart (in the sense of a pump at the center of a circulatory system) is the market economy (the purple diamond). The output of the market economy is gross product as we have seen, but it is also the engine that integrates and transforms one form of capital into another. There are five different forms of capital shown: manufactured (in blue), intellectual (in orange), human (in red), natural (of course in green), and social (lurking in the background in—we'll call it mauve).

Capital is like a savings account, a fund that generates an ongoing flow of goods and services. The economic concept of capital is derived from manufactured capital and its critical role in the Industrial Revolution. Its symbol is the factory, but all around us is manufactured capital—the building you are in and the furniture you're sitting on, the road you traveled on and the vehicle you traveled in, the computer you're using and the electrical power plants and transmission lines that are powering it, the water supply system that enabled you to fill your water bottle at the faucet. Everything that humans have built and is not immediately consumed but stands in place as a resource for future productive use is manufactured capital. The Industrial Revolution represents an explosion in manufactured capital, and "developed" countries have a lot more of it than "developing" countries. Manufactured capital provides the infrastructures that are used for the production of goods and services, but it will depreciate unless it is maintained, updated, and expanded through new investment allocated as a portion of gross product. Currently in Washington, DC, one of the few things Republicans and Democrats can agree upon is that we need to increase investment in *infrastructure*—publicly provided manufactured capital.

Intellectual capital is accumulated knowledge that is written down in some sort of language where it can be accessed as needed—all the books, newspaper articles, websites and scientific journals, all the computer programs and data sets, all the blueprints and construction schematics, all the technologies, all the exploding reams of information in the information revolution we are currently experiencing. Intellectual capital has to be produced through investments in research and development, inventing and writing. Unlike manufactured capital that wears out, once made available, intellectual capital can be used again and again and by many people simultaneously without depreciation. It usually becomes obsolete, however, and loses its value over time. Only a small portion—like Shakespeare's plays, the Declaration of Independence, and Albert Einstein's equations —stands the test of time. I'd be very pleasantly surprised if this text was still in use 20 years from now. Most news stories, Twitter and text messages, social media postings, and web page materials lose their significance in a matter of weeks or even days—that is, if they had any significance to begin with. Those of us who learned to separate the "signal" from the "noise" in the 20th century find the 21st to be the Century of Noise.

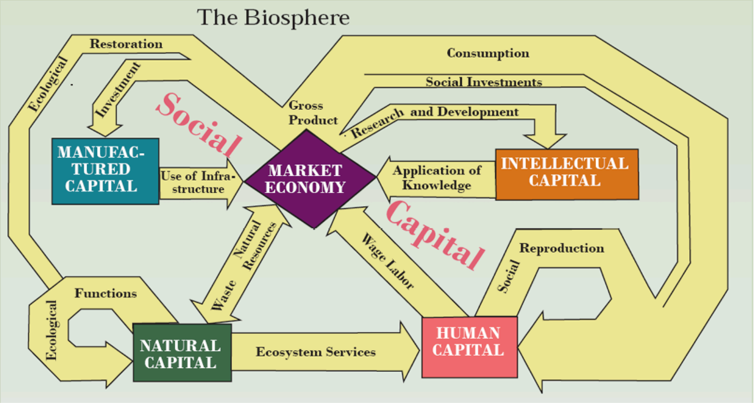

Figure 7.2. An ecological-economic conceptualization of the nature-society-economy system as flows of value among human, intellectual, manufactured, and natural capital with the market serving as a transformer and allocator. Natural and human capital are also maintained through nonmarket mechanisms of ecological functions and social reproduction. Sustainability consists of maintaining each form of capital so that the system can function in perpetuity.

Human capital resides within us as individuals. It is the knowledge and experiences in our brains, our physical skills, our powers of personality, and our character. These characteristics become inputs to the market economy through our jobs, and the more we have to offer, the more income-earning potential we have. Social investments like health care and education deliberately and directly invest in human capital because they maintain and expand the capabilities of individuals. The food, water, and shelter we need to survive and many other good and services we receive are also investments in human capital.

There clearly comes a point, however, where additional consumption is not an investment in, but may even depreciate, human capital. More is not always better. Is it a coincidence that obesity and screen time are increasing at the same rate? Moreover, human capital is not nurtured solely, or even primarily, through purchased or allocated goods and services but through the village that it takes to raise a child—communities defined by neighborhoods, school classes, sports teams, congregations, and perhaps Twitter, Facebook, and text messaging, though that is the subject of an intensifying debate. Families are also, of course, a cornerstone of what we'll call *social reproduction* for short.

Natural capital is not created and reproduced by humans, but by geological processes and, even more so, by ecological functions, as we studied in Chapter 3 and 4. It is the natural resources we depend upon today and will depend upon tomorrow—the fossil fuels and ores in the Earth, the soil and forests upon it, and the water running through it. It is also the ecosystems that photosynthesize, maintain biodiversity and build soil, recycle nutrients, and break down wastes and pollutants from human activities. Extracting natural resources faster than ecosystems can replace them and emitting wastes faster than ecosystems can process them depreciates the fund of natural capital available for the future. That's unsustainable, just like a savings account from which we withdraw money faster than it is replenished with new deposits and interest payments; in the long run, it will run out. On the other hand, deliberate investments in ecological restoration can complement ecological functions in restoring natural capital.

Natural capital is the factory that produces ecosystem services to benefit people. In a famous 1997 paper on "The Global Value of Natural Capital and Ecosystem Services," updated in 2014, Robert Costanza and colleagues estimated that the value of these services is, on a global scale, a total of $125 *trillion* dollars (see Table 7.1), about twice the value of global economic output and about $17,000 per person per year. While such estimates are rarely accurate, natural capital delivers enormous benefits directly to humans through provisioning, cultural, regulatory, and supporting ecosystem services— like a savings account delivers interest payments. Interestingly, ecosystems at the interface of land and water (estuaries at river mouths, swamps and floodplains along rivers, seagrass and algae beds in the shallow seas, tidal marshes and mangroves at the seacoast, freshwater lakes and rivers, and coral reefs along tropical coasts) provide 40 percent of all ecosystem services on 1.6 percent of the Earth's surface. These "ecological cities" should receive, along with tropical rainforests for their biodiversity, the highest priority for preservation.

Table 7.1. Area and estimated economic value of ecosystem services from Earth's biomes.

Ecosystem type	**Area (million year)**	**Value (2007$ per hectare per 2007$)**	**Total value (trillion ha)**
Marine	36,302	1,368	49.7
Open Ocean	33,200	660	21.9
Coastal	3,102	8,944	27.7
Estuaries	180	28,916	5.2
Seagrass/ Algae Beds	234	28,916	6.8
Coral Reefs	28	352,249	9.9
Continental Shelf	2,660	2,222	5.9
Terrestrial	15,323	4,901	75.1
Forest	4,261	3,800	16.2
Tropical	1,258	5,382	6.8
Temperate/ Boreal	3,003	3,137	9.4
Grass/ Rangelands	4,418	4,166	18.4
Wetlands	188	140,174	26.4
Total	**51,625**		**124.8**

Tidal Marsh/ Mangroves	128	193,843	24.8
Swamps/ Floodplains	60	25,681	1.5
Lakes/ Rivers	200	12,512	2.5
Desert	2,159	–	–
Tundra	433	–	–
Ice/Rock	1,640	–	–
Cropland	1,672	5.567	9.3
Urban	352	6,661	2.3
Total	**51,625**		**124.8**

Social capital is more subtle, and definitions of it abound. Robert Putnam in *Bowling Alone* defines it as "features of social organization such as networks, norms, and social trust that facilitate coordination and cooperation for mutual benefit." We live in communities of family, friends, and acquaintances, (even if Putnam thinks these are unraveling) and interact through institutions such as churches, schools, businesses, governments, and social media. We are governed by laws, but also by a social fabric of rules of conduct and social norms. For our purposes, social capital is the rules that societies construct to govern how the other forms of capital will interact, from the constitution of the United States of

America, to the institution of private property, to recently developed cultural norms that stigmatize as rude behavior throwing trash out the window of a moving car or smoking in a crowded room, or that govern expectations on responding to text messages quickly vs. emails in a few days.

Geographical Ecological-Economics

The ecological economics perspective presented above is enormously useful and insightful in considering issues of sustainability, but it fails to consider geography. How do the processes depicted in Figure 7.2 operate over and through geographic space? How mobile are different forms of capital? What roles do natural capital and ecosystem services play in defining places and providing benefits that accrue to specific people? It is clear that some forms of capital, such as financial capital, are so mobile that billions of dollars are routinely transferred between continents every day in the nearly costless world of the Internet. Intellectual and written forms of social capital can also be transported simply by pressing “send.” People, as carriers of human capital, have to be actually transported, by foot, bike, car, train, or airplane. They often migrate, such as from rural to urban and suburban areas or from developing to developed countries. The movement of manufactured capital in the form of produced goods is the heart of transportation and continues to increase due to globalization. The human and economic geography of specific places are partially defined by their roads, railroads, and ports, their electricity lines, water and gas pipelines, and their buildings that are geographically fixed.

In these terms, the mobility of natural capital depends upon its form. As a stock of natural resources, raw materials such as fossil fuels, ores, timber, and fresh water constitute the vast majority of freight moved by trucks, ships, trains, and pipelines. These components of natural capital nearly always have lower economic value per unit weight, however, than the manufactured goods for which they serve as raw materials. Ore refining is therefore most efficiently located at the mine and thermoelectric power plants at large sources of cooling water to avoid transporting these voluminous production inputs.

As an endowment that provides ecosystem services, however, natural capital is essentially immobile. Ecosystems cannot be picked up and moved. Moreover, climate, topography, hydrography, and other conditions that govern the formation of ecosystems are tied to geographical places. There is, therefore, great variation in the ecosystem services available to different places and regions. Regions such as the Sahara Desert, Siberia, or the Australian outback, for example, are sparsely populated partly due to the dearth of ecosystem services they offer. In contrast, the world's most densely populated areas—east Asia, south Asia, Europe, the eastern U.S.—can support so many people precisely because of their abundant ecosystem services. When we study basic physical geography in primary and secondary school, we are often describing the geography of natural capital, though generally neglecting that this geography is dynamic.

While immobile, the geography of natural capital changes as a result of four factors:

1. natural dynamics in ecological functions,
2. human influences on these through activities such as land transformation and engineering of water courses,
3. direct human depreciation of natural capital funds through the introduction of waste, and
4. directly harvesting natural resources.

Climate change is an intriguing example where the benefits of fossil fuel use—concentrated in the industrial regions of North America, Europe, Russia, and China—largely coincide with the geography of emissions of greenhouse gases to the global atmospheric carbon pool. While climate change is affecting hydrologic, agricultural, and ecological systems across the globe, the most severe consequences are distributed very differently from the emissions. Polar regions, coastlines and island nations, populous river floodplains and deltas, drought-prone agricultural areas, and impoverished regions of the tropics, especially in Africa, bear the greatest burden of changes in ecosystem services brought about by climate change. In this manner, the global atmospheric carbon pool is a mechanism through which ecosystem services are redistributed geographically, perhaps leading to some resentment of high-emission countries such as China and the U.S.

When we go from the abstract to the concrete, what we find is specific, on-the-ground ecosystems that deliver ecosystem services to specific, usually very nearby, human communities that rely on these services for their welfare. An ecosystem service like flood control may be extraordinarily valuable when it is provided immediately upstream of a city, but it is of little value in the wilderness of northern Canada or Alaska. Environmental aesthetics and outdoor recreational opportunities are similarly more valuable in densely than in sparsely populated regions. For some ecosystem services like carbon sequestration, however, geography matters little because the atmospheric carbon pool is global.

The Ecological Economics Challenge to Neoclassical Economics

Let's explore the relationships between the Earth, the biosphere, and the economy a bit further. As total economic output (gross product) expands, it produces benefits to people as they get, first, necessities like food, water, and shelter, then fundamental services like education, health care, and electricity, then middle-class accoutrements like nice furniture and dishes, TVs, computers and cell phones, cars and vacations, restaurant meals, presentable and functional clothing, college educations, and so forth, and then perhaps true luxuries like yachts, foreign junkets, fine wardrobes, jewelry, and the like. The idea here is that each additional unit of income adds to our quality of life, but to a lesser and lesser extent as we meet more and more of our essential needs and start spending money on extra stuff, even conspicuous consumption. This is just like the pizza slices of Chapter 6 but applied to our entire income—income yields diminishing marginal returns to quality of life as people get more and more of it. In Figure 7.3 this makes the total benefits curve in the top graph climb at a slower and slower rate and the marginal benefits of economic growth curve on the bottom graph trend downward.

We don't want to take moralizing about needs, wants, and luxuries too far, however. As a young adult without children, it's easier to live on the cheap than as a parent or as an older person with less physical wherewithal than a person in their 20s. Speaking for myself (as a middle-aged, primary bread winner with two children whose college tuition I recently completed paying for), I'll keep my family's middle-class accoutrements and the income that makes them possible, thank you very much. And nearly every member of the growing world middle class feels the same way. The notion that the majority of people will, as individuals, altruistically sacrifice their economic welfare for sustainability is unrealistic, but that doesn't mean we can't make enormous progress, as we will see.

It's also clear that as the economy extracts more and more resources and emits more and more waste, the ecological costs climb. In fact, they climb at a higher and higher rate as fewer ecosystems are left intact and their services diminish. This is the clear message from the 2005 Millennium Ecosystem Assessment and the 2019 report from the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services we studied in Chapter 4. In Figure 7.3, this is reflected in the rapidly rising total ecological opportunity costs curve at the top and the rising marginal ecological opportunity costs curve at the bottom.

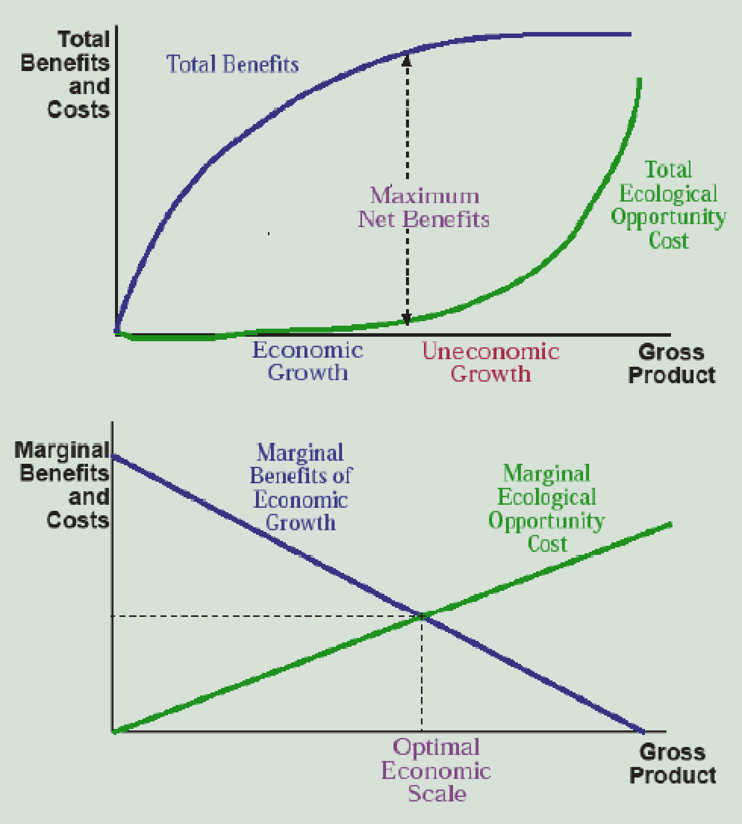

Figure 7.3. The benefits and ecological opportunity costs of economic growth and the optimal size of the economy. Optimal economic scale occurs where the net benefits of economic production are maximized; this occurs where the declining marginal benefits of economic growth equal the rising marginal ecological opportunity costs.

Drawing on the logic of optimal pollution from Chapter 6, what is the “best” level of gross product? Neoclassical economics would say its infinite—the more the better, that’s the goal. But ecological economics would say that we want to maximize the difference between the economic benefits and the ecological costs of economic growth. This produces maximum net benefits. So economic growth, increases in gross product, up to this point are good—they raise net benefits—but if gross product keeps going up, net benefits start to shrink. This then becomes *uneconomic growth*.

On the bottom graph in Figure 7.3, we see that the optimal economic scale occurs where the marginal economic benefits and the marginal ecological costs are equal. That is the point where the ecological costs of increasing gross product a bit more rise to the point where they equal or surpass the economic benefits of doing so. It is here that we should stop increasing gross product. Sounds simple enough but, for over a century, economic growth has been the driving force, the *raison d'etre*, the purpose and goal of nations around the world, with the U.S. being a prime example.

Taking the North American example, think about how the relative size (in Figure 7.2) of the manufactured, intellectual, human, and natural capital funds have changed over the last few centuries. In colonial times, there was a vast frontier fully stocked with all forms of natural capital—minerals, forests, rivers, aquifers, fish, and fertile soil. No one even thought of ecosystem services because they were so abundant and therefore taken for granted, as oxygen still is today. It was human-derived forms of capital that were scarce and therefore the limiting factor in human development. Westward expansion and industrialization enabled this surplus of natural capital to be transformed into manufactured, intellectual, and human capital, and the nation and economy grew. And we were better off for it—that is, we had been proceeding along the x-axis of Figure 7.3 from the origin and hadn't yet approached the optimal economic size.

Today, things are different. The U.S. has about a third of a billion educated people living in modern cities and towns in an information age—human capital is abundant! In contrast, oil supplies are running low, virgin forests are nearly gone, many soils have been depleted or eroded, fish stocks have plummeted, wild species of mammals and birds are a diminishing fragment compared to domesticated species, and half of the wetlands have been drained—our ecosystems are battered. Today, natural capital is more often the limiting factor in social development than was the case in the past. Therefore, the marginal value of remaining natural capital and ecosystem services has increased, implying that there are increasing marginal ecological opportunity costs when natural capital depreciates and ecosystem services are diminished. Moreover, technology has greatly accelerated the production of human forms of capital such as infrastructures and computer algorithms, but natural capital can be restored only on much longer time scales and does not respond as readily to technological advances. For this reason, the stock of natural capital within the biosphere and the rate at which it can produce energy, raw materials, and ecosystem services are the long-term limiting factors in human social development.

We are now in a position to consider more precisely what we mean by *sustainability*. What if Figure 7.2 was a movie, the capital rectangles were buckets of water, and the arrows were pipes? We have already seen that over historical time the natural capital bucket would be emptying while the other buckets would be filling. When does the movie end? When any one of the buckets goes dry. Why?

Manufactured, intellectual, human, and natural capital are interdependent parts of a nature-society-economy system, just like your muscles, nerves, digestive tract, and blood vessels are inter-dependent parts of your body. If any one of these becomes dysfunctional, none of the others can function and the entire system collapses.

Weak sustainability consists of maintaining the *aggregate* value of human, manufactured, intellectual, and natural capital. If these forms of capital are not completely substitutable, however, critical shortages in any one form of capital can cripple the entire system, just like a burst blood vessel in the brain causes a stroke which breaks down the nervous system, which paralyzes the muscles, and so forth. Capital depreciation in any area is the harbinger of long-term system decline.

Strong sustainability maintains that, for the system to function in perpetuity, the value of *each* form of capital must be maintained because different forms of capital are rarely substitutable. Occasionally, we can, at considerable expense, replace natural capital with manufactured capital, such as building a wastewater treatment plant to replace wetlands, or hydroponics to replace soil. More often, however, we cannot replace natural capital. Tropical rainforests cannot be produced in a factory or by writing a computer algorithm.

The depreciation of natural capital has become the focus of programs for reform of national income accounts—the ledgers that are used to measure gross product and the current measure of economic growth. Robert Repetto first brought this issue to the attention of global financial institutions by showing that Costa Rica's rapid economic growth in the 1970s and 1980s occurred alongside a depreciation of its forest and soil resources. When natural capital depreciation was calculated, a vigorous 4 percent rate of economic growth was shown to be, in fact, an economic decline. This debate about the measurement of economic vs. ecological-economic performance is central to assessing sustainability. For example, the Genuine Progress Indicator (GPI) developed by Redefining Progress, starts with gross product but adjusts for the distribution of income, adds in the value of volunteer work and parenting, and subtracts the costs of crime, pollution, and resource depletion. When the GPI is compared to the GDP for the U.S. over the period 1970–2004 (Figure 7.4), the apparent growth in per capita income from $25,000–$38,000 is shown to be illusory as the Genuine Progress Indicator shows stagnation at a level of about $17,000 per capita. The overall welfare of the average American hadn't improved in 34 years. And this was before the Great Recession and the Covid-19 crisis! Another example is the Index of Sustainable Economic Welfare used by several European countries as a measuring stick of sustainable development.

Now this all sounds pretty pessimistic, but let's think about it some more. What if we can use the vast expansion in intellectual capital that characterizes the information age to figure out how to reduce the ecological costs of economic growth? Since the Industrial Revolution, economic growth has meant extracting more fossil fuels and minerals, using more energy and water, building more vehicles and the roads and parking lots for them, sprawling the suburbs with big houses and filling them with furniture and electronics, filling the supermarkets with meat and the fast food restaurants with trash. This kind of economic growth has high ecological opportunity costs! But what if we pursue economic growth differently? We make everything energy efficient—lights, buildings, vehicles, appliances—and power it all with lower impact sources of electricity—like wind and solar, perhaps modular nuclear. We build energy-efficient hyperloop lines between cities and subway systems within cities, reversing suburban sprawl and making more walkable and bikeable cities and towns, drastically reducing passenger miles driven and flown. The hyperloop and subway stations become the hubs of commerce with energy-efficient houses with solar roofs clustered around them. People reduce meat consumption and replace fast food burgers in favor of local produce and relearn how to cook for family and friends. Pesticides become obsolete. The use of services like excellent education, health care, and culturally-enriching entertainment are the signs of wealth and status rather than a huge trophy house filled with stuff and three SUVs and pickup trucks in the garage. I think you get the picture but we'll explore it further in Chapter 16.

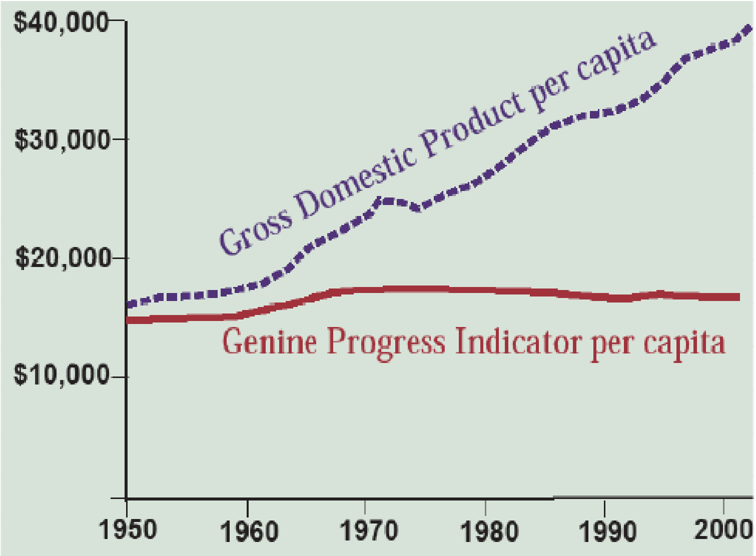

Figure 7.4. U.S. gross product per capita and genuine progress indicator, 1950–2004.

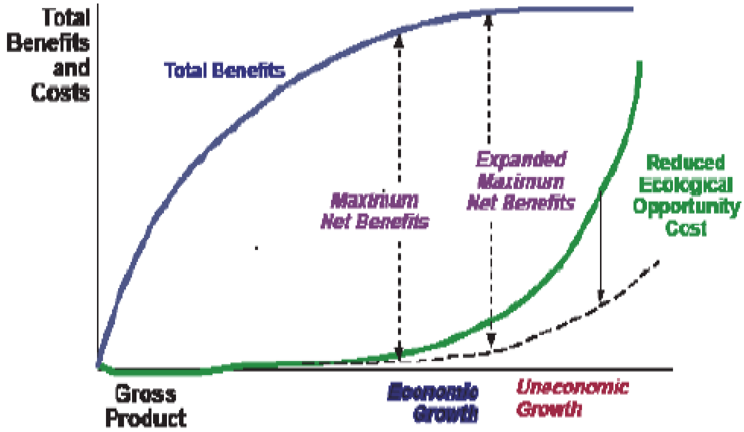

Figure 7.5. An ecological-economic strategy where the ecological costs of economic growth are reduced. The result is expanded net economic benefits and a larger optimal size of the economy.

When the ecological costs of economic growth are reduced (compare Figure 7.3 with Figure 7.5), many good things happen. Net benefits widen. The optimal size of the economy expands, yet ecological damages are reduced. Would you vote for that? I think this is what we're shooting for. It's an economic strategy to live both well and sustainably. But it's also a lot easier said than done. It requires change. We can't grow the economy in the same old way. We have to grow it in a new way.

Industrial economies, especially in North America, have evolved in a world where labor and manufactured capital were scarce and therefore had to be used very efficiently to maximize product output per unit of labor and manufactured capital. This has made workers enormously productive. For example, the average North American farmer feeds over 150 people. In contrast, since natural capital was in abundance, it could be used inefficiently. This is why the U.S. economy uses more than one *million* pounds of materials per person each year! We will explore these ideas in more depth in the next chapter on industrial ecology.

A Natural Resource Taxonomy

Now that we have an overarching concept of sustainability, let's focus on individual natural resources. You have probably heard of *stock* or *nonrenewable* resources in contrast to *flow* or *renewable* resources, but let's dig a little deeper into the meaning of these terms. All natural resources are created by a geologic (e.g., minerals), ecologic (e.g., forests), or astronomical (e.g., solar energy) process at a certain rate. All resources are utilized in a manner that may or may not consume them. For example, fossil fuels are burned away when they are used, but we don't use up water when we float a boat on it.

Let's start with stock resources like the fossil fuels (oil, gas, and coal) the formation of which we studied in Chapter 3 (Figure 7.6). These represent stored chemical energy from millions of years of photosynthesis, chemically transformed into hydrocarbons ready to burn to produce heat. This heat and the by-products of water and carbon dioxide (plus other pollutants) dissipate into the surrounding atmosphere. These resources are therefore "consumed by use." They are a non-renewable stock, like a bank account with no interest and infinitesimal deposits, reflecting the slow rate of the geological process that create them. In contrast, humans are burning up fossil fuels accumulated over millions of years at rates a thousand to a million times faster than they are renewed in the Earth's crust. They therefore have a renewability ratio (rate of creation/rate of use) with a denominator several orders of magnitude greater than the numerator. The exponent on the renewability ratio is shown on the bottom of Figure 7.6 (-4, for example, means that the rate of creation is 1/10,000 the rate of use). To put it simply, there is a fixed bucket of resources with a spout draining it (as shown in the bottom panel of Figure 7.6 below consumed by use resources), though abundant resources like coal have a bigger bucket than more scarce resources like oil or gas.

Metallic ores, such as bauxite that is refined into aluminum, are also created by geologic processes so slow that we can think of the supply as fixed. In this case, however, the materials, the aluminum atoms in this example, are not destroyed through use and can be recycled and used again and again. We have to think about how entropy and energy affect this process. The purest, lowest entropy, least cost ores are mined first and made into products that are part aluminum and part other materials and are then dispersed throughout the world. Then the second-best ores are mined and so on, keeping in mind that the lower the percentage of pure aluminum in the bauxite, the more energy it takes to refine it.

Over time, the quality of available ore declines, but more and more aluminum is lurking above ground in obsolete products available for recycling. We can think of the quality of accumulated aluminum in terms of how much energy it takes to gather, separate, and process it, just like ores. Over time, the stock of aluminum for recycling improves while the remaining stock for mining declines. Because of this, recycling constitutes a higher and higher proportion of raw materials used in new products. Other materials like glass (from abundant silicon) and plastic (from petroleum) follow a similar logic where virgin raw materials compete with recycled materials for the least-cost sources. We can never recycle 100 percent of a material, however, because human use disperses some of it irretrievably. Designing products so they can be easily dismantled and their various components recycled is a principle of industrial ecology as we will see in the next chapter.

Let's jump to the purple column on the right-hand side of Figure 7.6. Some sources of energy just keep on coming. Solar energy is first on the list, but geothermal sources of heat and the gravitational forces that produce tides are also *perpetual*. There is no fixed bucket of resources but a faucet that will also keep flowing, though at variable rates, and whatever we don't use just goes down the drain. The rate of creation of these resources is orders of magnitude higher than the rate of use (see exponents on the bottom of Figure 7.6), generating a renewability ratio in the hundreds, thousands, or even millions. Moreover, no matter how much we utilize the resource in the present, we can't decrease the future supply of the resource. For these reasons, these types of resources, especially those derived from solar energy either directly (e.g., solar panels) or indirectly (e.g., wind, waves, hydropower), have become the icons of natural resources sustainability. As we will see in Chapter 14 on energy, however, it's not that easy because it can be economically, and sometimes ecologically, challenging to capture these dispersed perpetual energy flows.

While at first it may appear that the most difficult issues of natural resources sustainability lie with the red consumed by use column, in fact it is in the green biotic resources column where our greatest challenges lie. These are flow or renewable resources, but they are fundamentally different from perpetual resources because they are created by ecological processes, starting with photosynthesis because of its foundational role in ecological productivity. As we saw in Chapter 4, less than 0.1 percent of solar energy is captured by photosynthesis. Solar energy flows out of a fire hose while biotic resources drip from a leaky faucet. Moreover, solar and geothermal energy flows occur due to basic physical processes that humans have little impact upon, while biotic resources depend upon viable ecosystems that humans have an enormous impact upon.

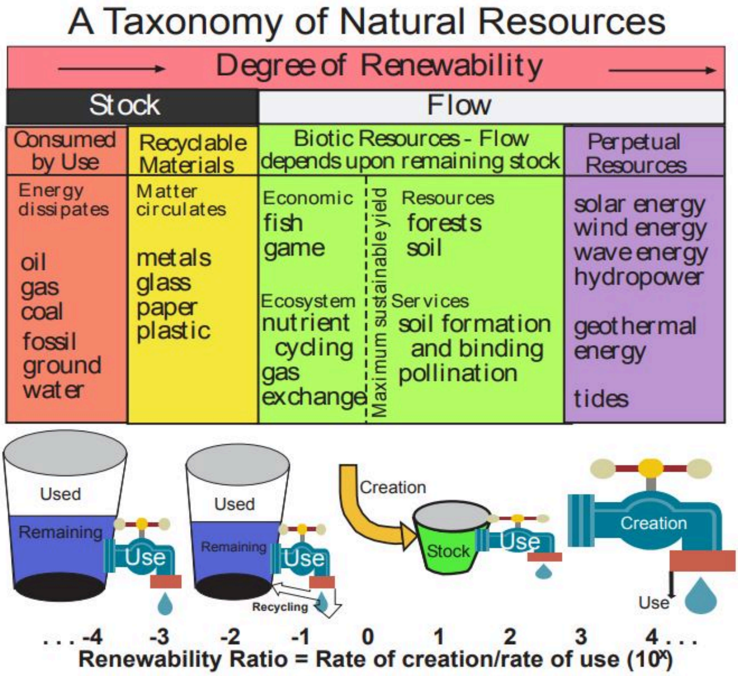

Figure 7.6. A taxonomy of natural resources based on their renewability. Below each category is a bucket and faucet diagram representing stock and flow relationships for that resource type. For example, consumed by use resources flow from a large, but fixed, stock of resources while perpetual resources have no stock, but a large inexhaustible flow. Note that the numbers along the bottom represent the exponent (x) on the renewability ratio.

Take fish and game. These animals occupy specific ecological niches at the second or third trophic level, rely upon ecological relationships with prey and other species for their survival, have sometimes quite specific habitat requirements for successful reproduction, and a parent population must be preserved if the resource is to be sustained. Each of the HIPPO factors (Habitat destruction, Invasive species, Pollution, Population, and Overharvesting) discussed in Chapter 4 can decimate the resource. Forests are also vulnerable to each of the HIPPO factors.

While renewable, fish, game, and timber are provisioning ecosystem services that are consumed when used. The natural capital of soil can likewise be depreciated, such as by exposure to erosion. Here is where the renewability ratio becomes most critical. Flow resources have smaller, more temporary reservoirs of resources—fish in the water, game in the field, standing timber in the forest, soil on the ground—that need to be constantly, or at least frequently, replenished. They are more like a checking account than a savings account. If they are not to be overdrawn, the rate of use must not exceed the rate of creation. The renewability ratio must exceed one (that is, the exponent x on 10 in Figure 7.6 must exceed 0). Using a renewable resource at a renewability ratio of 1 is called *maximum sustainable yield*; it is the highest rate at which fish can be caught, game hunted, timber cut, soil eroded, and groundwater pumped without depleting the stock over time and overdrawing the checking account. It's a solid concept for sustainable management of renewable resources, but we'll see later that other factors come into play, especially the variable rate at which biotic resources are created and occasionally destroyed.

Supporting, regulatory, and cultural ecosystem services are not necessarily consumed when they are used (as we will explore in depth in Chapter 9), but instead depend upon viable ecosystems as an endowment of natural capital from which these services flow, like interest from the checking account. The unsustainable consumption of biotic resources or the degradation of ecosystems by other means therefore depreciates the natural capital endowment. This in turn diminishes the ecosystem service interest received. For this reason, natural resource sustainability is not just about having enough extractable resources like timber and fish in the future; it is more fundamentally about maintaining ecosystems and the host of services they generate—supporting, regulatory, and cultural, as well as provisioning.

Rather than an oxymoron, ecological economics proves to be the most important lens through which we gain an understanding and a definition of natural resource sustainability. With its key concepts in place, we can now explore another apparent oxymoron—industrial ecology.

Further Reading

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Raskin, Paul Sutton, and Marjan van den Belt. 1997. The value of the world's ecosystem services and natural capital. *Nature* 387(6630): 253–60.

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8.

CHAPTER 8: LEARNING FROM OXYMORONS II - INDUSTRIAL ECOLOGY

If finance represents the circulatory system of an economy, *industrial ecology* is the digestive tract. It's about industrial throughput and metabolism, what happens at the back door of restaurants and stores, on farms and in food-processing plants, in factories, power plants, and mines. You may have been introduced to industrial ecology through the idea of *footprint* such as ecological or carbon footprint. As a positive science, industrial ecology analyzes and quantifies the flow of natural resources and energy through the economy to produce specific goods and services. If you're like others, you'll be amazed by the volume of natural resources you consume, most of it indirectly in the bowels of industrial and agricultural production and supply chains. As a normative strategy, it identifies how the economy's digestive tract can go on a diet, reducing the use of natural resources and energy used, and the waste produced, to achieve important results. Taken to an extreme, we can even talk of *dematerialization*, where little energy and few material goods are needed to perform many services. For example, as we have seen in response to the Covid-19 pandemic, communication can often substitute for transportation and need not consume paper, though it usually requires some electricity.

We'll start this chapter by taking a look at an energy and material flow analysis of the U.S. as compared to the European economy. After all, the Mecca of industrial ecology is the Institute for Social Ecology in Vienna, Austria. The Germanic-speaking countries of north-central Europe are leading the way among industrial regions in using natural resources most efficiently by employing industrial ecology principles. We'll then look more closely at the popularized versions of footprint analysis—ecological footprint, carbon footprint and water footprint—identifying their strengths and weaknesses. Next we'll apply these concepts in an in-depth industrial ecology analysis of a controversial product—corn-based ethanol. We'll finish with a discussion of how energy and material use can be reduced, making economies leaner and meaner from a natural resources point of view.

Energy and Material Flow Analysis

What do we mean by energy and material flow through an economy? Figure 8.1 shows this in simple form where domestically produced and imported raw materials and energy feed into the economy and waste emissions and exports flow out of it. Most of the material is throughput, but some materials may accumulate in manufactured capital, like wood in buildings or aluminum in airplanes. Most of the work in doing flow analysis lies in measuring and quantifying, and in so doing, methodological rules have to be developed. For example, is soil eroded during crop production counted as throughput? How about rain falling on the grass pastures cattle graze? Different analyses may yield different results because of variations in how these kinds of rules are applied. The devil can therefore lie in the details and we need to look at more than just the bottom line but at what the flows actually represent.

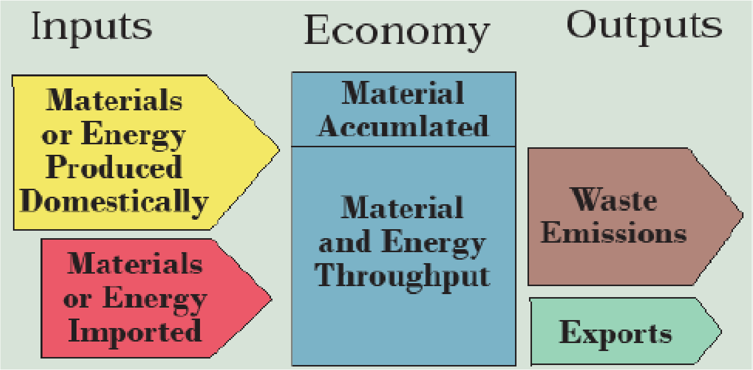


Figure 8.1. The logic of energy and material flow analysis.

You may have heard that Americans consume more than their share of natural resources. What does an energy and material flow analysis show? Table 8.1 compares the U.S. economy to that of the 15 member nations of the European Union as of 2000 (EU-15), a region of the world that enjoys a similar standard of living as the U.S. with a slightly larger population (361 million in 2000 compared to 281 million in the U.S. in that year).

We'll start with energy, including the energy content of food and wood from biomass as well as electricity and fossil fuels. In 2000 the U.S. consumed 125 exajoules (see Table 8.2 on energy units) compared to 79 in the EU-15 but more than twice as much per person (445 gigajoules vs. 210 GJ). The U.S. also imported slightly more per person (118 GJ vs. 102 GJ) even though the U.S. met a smaller total proportion (20 percent) of its energy needs from imports than did the EU-15 (40 percent). The mix of sources was similar, with the greatest reliance being placed on fossil fuels, but the EU-15 relied about twice as much on nuclear energy than the U.S., largely due to France's extensive nuclear power program.

Table 8.1. Comparison of U.S. and European Union energy and materials flows in 2000.

Sources: Weisz et al., 2006; Haberl et al., 2006.

	U.
Energy Flow Analysis	
Domestic Energy Consumption (EJ/yr)	12
Domestic Energy Consumption (GJ/capita/year)	44
Imports (GJ/capita/year)	11
Percentage from:	
Biomass (including food)	20
Fossil Fuels	73
Nuclear	6
Renewables	1
Imports	20
Biomass Energy Consumption (GJ/cap/yr)	88
Percentage of Net Primary Production Harvested	>1
Energy Consumed per dollar GDP (1980) (MJ)	24

Energy Consumed per dollar GDP (2000) (MJ)	16
Material Flow Analysis (tonnes/capita	
Biomass	7.0
Construction materials	No
Industrial minerals and ores	No
Fossil fuels	12
Total	>1

Table 8.2. Understanding units of measure for energy.

Metric Unit: Joule: the energy to raise the temperature of 2 kg of water from 0^{o}C to 1^{o}C.

English Unit: British Thermal Unit (BTU) = 1,054 joules

Prefix	**Exponent**	**English word**
nano	10^{-9}	billionth
micro	10^{-6}	millionth
milli	10^{-3}	thousandth
centi	10^{-2}	hundredth
deci	10^{-1}	tenth
deka	10	ten
hecto	10^{2}	hundred
kilo	10^{3}	thousand
mega	10^{6}	million
giga	10^{9}	billion
tera	10^{12}	trillion

exa	10^{15}	quadrillion

The biomass component of energy consumption is interesting because it reflects important geographic and ecological relationships that we will explore below under Ecological Footprint 2.0. Europe is more ecologically productive per unit area because of the vast dry areas in the U.S. West and cold areas in Alaska. It's four times more densely populated, however, leaving less biological productivity per person. Europe's 50 GJ of biomass energy consumption per capita is similar to other regions around the world, developed and developing, and reflects ecological requirements for food, fiber, and other basic needs. The per capita figure for the U.S. is higher (88 GJ) because Americans have inherited a great store of natural capital that they use liberally by eating meat-rich diets, building big wooden houses, and so forth. Europeans consume or appropriate at least 28 percent of the net primary production of their territory in this manner and are net importers of biomass while Americans appropriate at least 15 percent and are net exporters. Here we can see the extra "elbow room" that Americans enjoy in the sense that the human population is not pressing as hard against the ecological carrying capacity of the land as it is in Europe.

Each year, the average European consumes 4 metric tonnes of biomass (mostly in the form of agricultural and wood products), 7 tonnes of construction materials (e.g., concrete, sand and gravel, brick, paint), 1 tonne of industrial minerals and metallic ores, and 3.7 tonnes of fossil fuels (oil, gas, and coal). For materials, U.S. data comparable to those from the EU-15 are lacking, but fossil fuel and biomass comparisons can be generated from the energy data. They show 7 tonnes of biomass and 12.2 tonnes of fossil fuels. If the U.S.-EU ratios on construction materials and ores are similar, the average American consumes roughly 40 tonnes of materials per year, about 600 times their body weight. Over their lifetime, an American will consume over 3,000 tonnes, 45,000 times their body weight. And this does not include air and water. Only 6 percent of natural resources extracted end up in products, and only 1 percent in durable products. The rest is throughput. Only a few percent of the energy content of fossil fuels at the power plant provides light, washes dishes, or cools food. Less than 1 percent of the energy content of gasoline moves the driver forward (see derivation in Chapter 14).

Why is the European economy more energy- and resource-efficient than the U.S. economy? A large part of the answer is that the U.S. economy has evolved under conditions of greater natural resource abundance than Europe's. In fact, since 1980 both economies have begun to use fewer resources per dollar of gross product produced or, to put it another way, total energy and resource consumption have remained fairly constant despite population and economic growth. Using energy as a measure, the U.S. used 24 MJ of energy per dollar of gross product in 1980 but only 16 MJ in 2000 while the European economy improved from 15 MJ in 1980 to 12 MJ in 2000. So as the historic natural resource abundance of the U.S. has diminished, it has been catching up to Europe in resource use efficiency. This is the powerful ecological modernization trend that industrial ecology can help to continue and even accelerate. It is by reducing the need for raw materials and energy to maintain our welfare that natural resources sustainability can be achieved.

Footprint Analysis: Ecological, Car-bon, Water

Footprint analysis traces back the natural resources needed and the pollutants emitted in the production of specific products or for entire regional or national economies. It has become the popular face of industrial ecology and can teach us about how our lifestyles impact the planet. We also need to ask a lot of questions, however, about what the numbers really mean. Let's explore ecological, carbon, and water footprints.

Ecological Footprint 1.0

Mathis Wackernagel and William Rees developed the ecological footprint concept in the 1990s as the area of ecologically productive land and ocean that is required to continuously provide the resources consumed by a group of people (such as a country) and to process their wastes. According to their analysis in 1999, the average person in the world uses about 6 to 7 acres. Indians use only 2 acres, Chinese use only 3, Germans 13, Canadians 19, and Americans 25, the highest among any nation in the world. Moreover, the world only contains 5 productive acres per person, implying that we are overshooting our collective carrying capacity. Americans are using 9 of their 25 acres either from beyond their borders (by importing natural resources and exporting wastes) or by borrowing natural capital from the future. Canada, in contrast, has an ecological surplus.

We can also analyze the composition of the ecological footprint of the average person and how this is changing over time. Each of us utilizes the renewable resource capacity of land through our diet (crops, pasture, and fisheries), raw materials (forests), land developed for our use (urban land), energy needs (fuelwood and carbon dioxide absorption), and land contaminated by nuclear weapons and power development. Over time, the average footprint expanded from 1960 to 1980, but it has remained about stable since then as declining land requirements for crops has balanced increasing land needed to sequester the carbon dioxide emitted when we use energy.

These are interesting comparisons, and they illustrate important trends, but they are not without conceptual weaknesses. Why use an acre of generic land as a unit of analysis when ecosystems vary so enormously from place to place as we saw in Chapter 4? For food production the relationship is somewhat straightforward, but can we convert, for example, coal mined from the Earth, burned in a power plant, and emitting carbon dioxide into the atmosphere into an equivalent land area? Would this be the area of land required to absorb the carbon dioxide through photosynthesis? But what if the carbon dioxide is sequestered in geologic formations or simply left in the atmosphere as a greenhouse gas? Is nuclear area determined by the area left unfit for habitation by the Chernobyl accident and other nuclear wastes derived from weapons programs in the U.S. and the old Soviet Union?

There is also a problem of geographical specificity. Which land and ocean areas are supporting which people? Could you place your 25 or some other number of acres on a map? Moreover, generally only provisioning ecosystem services and waste processing “consume” land, and then only partially and temporarily while cultural, regulatory, and supporting services can be provided for large groups of people simultaneously and continuously from a single ecosystem. I’m left with regarding ecological footprint as a useful but seriously flawed tool of industrial ecology because it is divorced from the actual cycles (e.g., carbon, water, nitrogen, energy) that are affected by resource use and from the economic values, positive or negative, of human impacts on those cycles. Fortunately, we have a better approach: human appropriation of net primary production.

Ecological Footprint 2.0: Human Appropriation of Net Primary Production

One mark of a scientifically sound and valuable footprint measure is that it is directly linked to Earth's key biogeochemical cycles and ecological processes that we studied in Chapter 3 and 4. Net primary production emerges as the key measure of an ecosystem's capacity to photosynthesize and store biomass that, as the first trophic level, forms the foundation of the ecosystem. A measure of ecological footprint, then should focus on how humans utilize and impact this foundation.

In the 1980s, Peter Vitousek and colleagues calculated human appropriation of the products of photosynthesis. Conceptually identical but a bit more precise from the point of view of ecological energetics, human appropriation of net primary production (HANPP for short) has emerged in the 21st century as the most scientifically rigorous way to measure how humans, as the dominant species on the planet, are capturing their niche in the biosphere.

Figure 8.2 defines HANPP. We start with the rate of net primary production that an ecosystem could potentially achieve if humans were not affecting it. Because it's a theoretical potential rather than a measured actual quantity, it has to be modeled or estimated based on climate, soils, topography, and other measures. When the actual NPP is measured from satellites like MODIS or Landsat, the difference between the two becomes HANPP due to land use change. Map (b) in Figure 8.3 shows HANPP(land use change) as a percentage of NPP(potential). This measures the degree to which human uses of land have diminished (through deforestation, overgrazing, fire, soil erosion, urbanization and so forth) and occasionally augmented (usually through irrigation), the capacity of the ecosystem. HANPP(land use change) is rarely a good thing and, in fact, we can use it to measure how ineffectively humans are using the land. Desertification is perhaps the epitome of HANPP(land use change) where centuries of overgrazing or poorly managed irrigation have rendered the ecosystem a shadow of what it once was. Remember the stripping of soil in the Mediterranean and Middle Eastern lands from Chapter 2 as well as America's Dust Bowl.

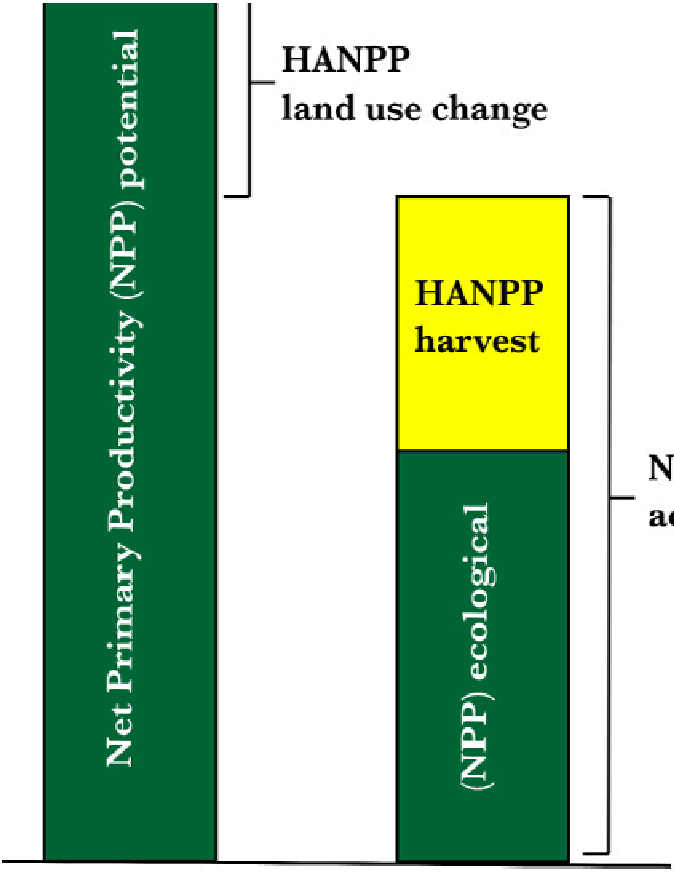
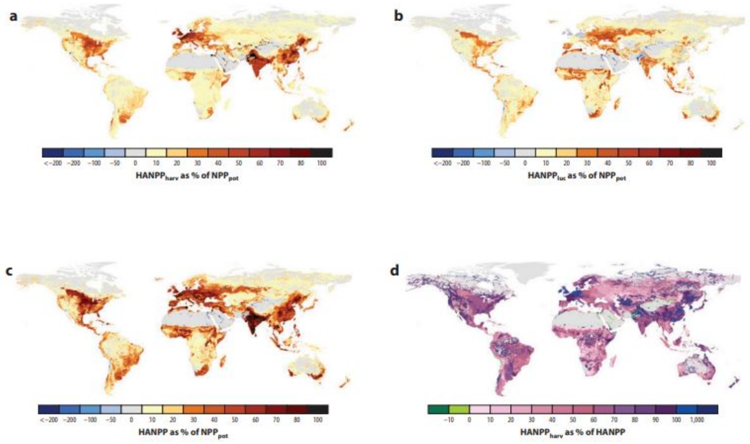


Figure 8.2. The definition of human appropriation of net primary production (HANPP). The difference between potential net primary production (NPP) and actual NPP is HANPP attributable to land use change. From actual NPP is derived HANPP harvest with remaining NPP as ecological.

From actual NPP, humans harvest the biosphere, primarily through cultivating crops, grazing livestock, and cutting timber from forests. All 7.8 billion humans on Earth are and always have been utterly dependent on HANPP(harvest) for all of their food as well as most of their needs for fiber (cotton, flax, hemp, wool, wood) and the biomass portion of their energy needs (wood, ethanol, etc). Map (a) in Figure 8.3 thus primarily reflects agricultural intensity. Map (c) shows total HANPP calculated as HANPP(land use change) plus HANPP(harvest). Densely populated and/or intensively farmed areas like India, eastern China, central Europe, and the American Midwest stand out as the ecosystems humans have appropriated to the highest degree. Map (d) shows the efficiency through which those impacts produce food, fiber, and biofuel that humans actually use.



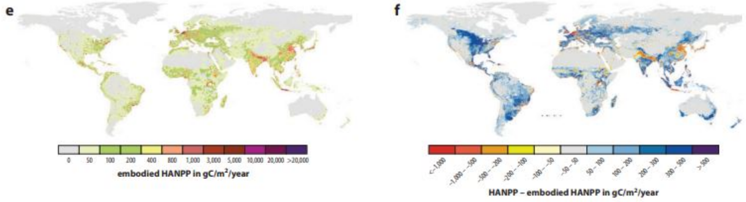


Figure 8.3. Global distribution of various measures of HANPP. a) HANPP harvest and as % of Net Primary Productivity (NPP) potential. b) HANPP(land use change) as a % of NPP potential. c) HANPP total as a % of NPP potential. d) HANPP(harvest) as a % of total HANPP. e) embodied HANPP in gC/m2/year. f) HANPP minus embodied HANPP in gC/m2/year.

There was a day long ago when the ecological products—provisioning ecosystem services that humans rely upon for their survival—originated where they live or close nearby. Trade, increasingly globalized but also important within regions, has changed all that, and so in the 21st century, humans often rely upon distant ecosystems for their food, fiber, and biofuel. Map (e) shows the consumption of HANPP, called embodied HANPP. While hard to see at a global scale, most consumption of food, fiber and biofuel occurs in cities, where a majority of people now live. So, while in past centuries, the production of HANPP(harvest) and it's consumption (embodied HANPP) would closely align, these are increasingly separated, with trade *teleconnections* along supply chains linking them together.

Finally, Map (f) shows the difference between HANPP production and consumption, so areas shown in blue are net HANPP exporters, while those in red are net importers. Of course, much of the map looks blue, because geographically large rural areas generally export HANPP, with the North American Midwest leading the way for the entire planet just as the Persian Gulf leads the way in oil exports. In the 21st century, eastern Brazil and northern Argentina has become the world's second most important food and HANPP-exporting region. Meanwhile, every city on Earth is reliant on rural areas somewhere—regional hinterlands remain critical but increasingly from across the continent or even the planet—to supply its food, fiber and biofuel. In addition to cities, some large densely-populated regions are also dependent on imports, such as northern India, eastern China, Japan, the heart of Western Europe, the Middle East, and America's eastern seaboard metropolis.

HANPP thus serves as a very perceptive lens through which we can explore ideas about ecological footprint with an expanded capacity to answer the critical questions: How much? How efficiently? From where? To where? How much nature is left? Compared to what it would otherwise be?

Carbon Footprint

Carbon footprint is straightforward because it takes one pool of carbon as bad—the atmospheric pool that drives climate change. Our carbon footprint is therefore the volume of carbon dioxide that our use of natural resources causes to accumulate in the atmosphere. While less severe than for ecological footprint 1.0, methodological issues remain. For example, why not also include the volume of methane released to the atmosphere (remember CH_4 traps many times as much heat as an equivalent volume of CO_2)? For this reason, CO_2-equivalent is sometimes used. What parts of the life cycle of products do we include? For example, the gasoline burned in our car certainly counts, but what about the fossil fuels used to make the car, or that the workers who built it consumed driving to work?

If you type "carbon footprint" in Google you'll get a long list of carbon calculators. One I find easy to use is Carbon Footprint Calculator. Table 8.3 shows how I calculated my carbon footprint at that website. At about 11.8 tonnes per year, my carbon footprint is just over half the U.S. average of 21.5 tonnes but more than twice the world average of 4.9 tonnes. My lower than U.S. average footprint is largely due to (1) I have solar panels installed on my roof, (2) I share a plug-in hybrid Prius with my wife and have a short 2-mile commute to work, (3) I don't eat red meat unless it would be rude to refuse it, (4) I'm stingy about turning on the air conditioning in favor of ceiling fans, (5) I buy Energy Star appliances, and (6) I'm a pragmatic rather than a recreational shopper. On the downside, however, I really need to look at how I can use less natural gas to heat my home. Time to add insulation and caulk the windows! Then I can get to less than half the U.S.

average and less than twice the world average (while saving on my monthly gas bill, especially in the winter). I'm sure you're dying to calculate your own carbon footprint at this or another website, but also try some hypothetical scenarios to lower your footprint and see how large an effect they have.

Table 8.3. The author's carbon footprint.

Component	**Relevant Data**
House	2 people $700 on electricity $1,600 on natural gas
Flights	3 round trips of about 1,000 miles each way
Toyota Prius	Plug-in hybrid 12,000 miles driven
Honda CR-V	6,000 miles
Food	white meat and fish, some organic, prefer local produce
Goods	I buy new clothes, furniture, and electronics only when needed b recycle, or compost about half of household waste
Total	

Table 8.4. The U.S. carbon footprint in 2017.

Sector Item	GHG Emissions (million tonnes)	%	GHG Emissions (million tonnes)	%
Transportation	1,866	28.9		
Light-duty vehicles			1,111	17.3
Medium- and heavy-duty vehicles			426	6.6
Aircraft			167	2.6
Rail			37	0.6
Boats and ships			37	0.6
Other transport			74	1.2
Electricity	1,778	27.5		
Industry	1,435	22.4		
Fossil fuel combustion			771	12.0
Natural gas and oil systems			260	4.1
Other industry			405	6.3
Agriculture	582	9.1		
Crop cultivation			287	4.5

Sector Item	**GHG Emissions (million tonnes)**	**%**	**GHG Emissions (million tonnes)**	**%**
Livestock			256	4.0
Fuel combustion			40	0.6
Commercial	416	6.5		
Fossil fuel combustion			235	3.7
Landfills/ waste services			131	2.0
Fluorinated gases			51	0.8
Residential	331	5.2		
Fossil fuel combustion			301	4.7
Fluorinated gases			40	0.6
Land Use and Forestry	-714	-11.1		
Total	5,694	88.9	6,408	100.0

Leaping scales from the individual to the nation, the U.S. carbon footprint of about 6.4 billion tonnes annually is summarized in Table 8.4, where electricity from fossil fuel combustion and transportation contribute about 28 percent each, followed by industry, agriculture, and commercial and residential emissions. Land use and forestry, largely the ongoing growth of trees in the eastern U.S., offsets 11 percent of emissions.

The greatest reductions in the U.S. carbon footprint can be found in:

- replacing coal as a source of electricity with lower-carbon (e.g., natural gas) and no-carbon (e.g., nuclear, wind, solar) alternatives;
- reducing fuel use in vehicles, such as by improving gas mileage or replacing car and plane traffic with hybrids and trains;
- reducing fossil fuel use in industry;
- reducing methane emissions from landfills and agriculture;
- making land use and forestry an even larger carbon sink.

We'll see this issue again when discussing our steep challenges in energy.

Water Footprint

It is perhaps understandable to exclude air and oxygen from energy and material flow analyses because they are so ubiquitous, but fresh water is a critical input to agricultural and industrial production and is not nearly so abundant.

Many products contain water embedded within them, but more meaningful is the amount of water that is used to make a product. The amount of water we drink (perhaps one gallon per day) or even use from the faucets, showerheads, toilets, and other household appliances where we live (an average of 70 gallons per day in the U.S.) is trivial compared to the amount of water that is consumed to produce our food and energy. In the U.S., irrigation accounts for 40 percent of water withdrawals and 83 percent of water consumed. Thermoelectric power generation—cooling coal, nuclear and natural gas power plants to keep them from melting when they generate electricity—accounts for 39 percent of withdrawals but only 1 percent of consumption because the water usually goes back to its source—albeit quite a bit warmer. Moreover, if we count rainfed agriculture, *94 percent* of our water footprint comes from the food and other agricultural products we consume because of the high rates of transpiration in crops and the large areas that are planted to them.

Given these data, food products have the highest water footprint, especially meat products reflecting the conversion ratios of feed to animal weight. Products like coffee and cotton, where only a small proportion of the crop is used in the final product, also have high footprints. Table 8.5 clearly shows how to reduce your water footprint—simply start at the top and work your way down. (I say this to you while drinking coffee and wearing a cotton shirt and pants!) Yes, you should turn off the faucet while brushing your teeth, but if you really want to make a difference by conserving water, look at Table 8.5 and have a tomato or two for lunch instead of a hamburger and orange juice.

Table 8.5. Water footprint as mass ratios (weight water: weight product) for common agricultural products in the U.S. Source: Chapagain and Hoekstra, 2004.

Product	**Water Footprint (mass ratio)**	**Product**	**Water content (gallons)**
Beef	13,193	Pair of leather shoes	2,100
Coffee	5,790	Cotton T-shirt	1,100
Cotton	5,733	Hamburger	630
Pork	3,946	Bag of potato chips	49
Chicken	2,389	Glass orange juice	45
Soybeans	1,869	Cup of coffee	37
Eggs	1,510	Glass of beer	20
Wheat	849	Microchip	8
Milk	695	Tomato	3
Corn	489	Sheet of paper	3

When we look at the water footprint of entire nations (Table 8.6), a 2004 UNESCO study identifies three water consumption giants—India, China, and the U.S.—followed by other populous countries, both developed (e.g., Russia, Japan) and developing (e.g., Indonesia, Nigeria, Pakistan). For comparison, the U.S. water footprint of 696 km^3 or 184 billion gallons per year is 36 percent greater than the flow of North America's largest river, the Mississippi. On a per capita basis, you guessed it, the United States consumes the greatest amount of water at 2,483 m^3 per year (note that a cubic meter of water weighs a metric tonne by definition) or 1,757 gallons per day. You only drink one of these gallons and use about another 70 in your home. Most of the rest goes to produce your food, raw materials for clothing, and biofuels on farms. The global average of 900 gallons per person per day is also overwhelmingly devoted to food production. Clearly, there is a water-food nexus that we'll need to explore in more depth in Part III.

Table 8.6. The top ten list for water footprint.

Country	Water Footprint km^3 per year	Water Footprint (billion gallons per year)	Water Footprint per cap m^3 per year	Water Footprint per cap gallons per day
India	987	261	980	709
China	883	233	702	508
U.S.	696	184	2,483	1,757
Russia	271	72	1,858	1,343
Indonesia	270	71	1,317	952
Nigeria	248	66	1,979	1,431
Brazil	233	62	1,381	998
Pakistan	166	44	1,218	881
Japan	146	39	1,153	833
Mexico	140	37	1,441	1,042
World Average	7,452	1,969		
World Average			1,243	899

Applying the Concepts in Depth: The Case of Corn-Based Ethanol

Ethanol and biodiesel are liquid fuels that can be mixed with gasoline or diesel fuel for powering cars and trucks. They serve well as additives, replacing cancer-causing MTBE as an oxygenate and improving engine performance. In 2006, the U.S. passed Brazil as the world's leading producer of biofuels. By 2018, production capacity reached 16 billion gallons with 98 percent of this coming from ethanol derived from corn. In that year, about 40 percent of all corn produced in the U.S. was used to make ethanol. About 98 percent of gasoline contains ethanol and this supplied about 10 percent of the liquid fuel supply.

The agricultural feedstocks that are used to make ethanol are a renewable resource while the oil it can substitute for is a nonrenewable fossil fuel that emits the greenhouse gas CO_2 when burned. Moreover, the U.S. has net imports of about 2.3 million barrels of crude oil per day, 11 percent of its consumption. While half of oil imports come from Canada and Mexico, much also comes from countries that present political challenges in U.S. foreign policy, such as Saudi Arabia, Iraq, and Venezuela. So there are strong reasons to think that a domestically produced renewable fuel to replace imported oil as a fuel for cars and trucks is consistent with natural resources sustainability as well as other legitimate and important economic and political goals. But does this idea hold up under the scrutiny of industrial ecology? Let's take a look.

The first question to ask is: Does ethanol deliver more energy than it takes to produce? This turns out to be a difficult question to answer, though we will see that ultimately the answer is just barely. Let's walk through a net energy analysis using Figure 8.4 adapted from an excellent 2006 study by Jason Hill and others as a visual guide. To get one unit of energy from corn ethanol, we need to use 0.29 units at the farm and 0.67 units at the processing plant. We do, however, also get 0.20 units as a by-product—distillers dry grain with solubles, a livestock feed. The net energy benefit is 0.24 units with a very low output/input ratio of 1.25. For soybean diesel, the ratio is a bit better – 1.93. So more energy comes out than goes in, but not much more. For comparison, Brazilian ethanol made from sugarcane has a ratio of about 8, several times higher. Unfortunately, we must conclude that the energy gains are meager.

Given that 18 percent of U.S. corn produced 2.4 percent of gasoline in 2006, the net gain was only 0.5 percent of the gasoline energy supply (applying the 1.25 ratio). These are discouraging numbers indeed, especially when compared with the effects of improvements in fuel efficiency. For example, with an average U.S. mpg of 21 for cars and light trucks in 2006, an improvement of only 1 mpg reduces oil use by 5 percent, ten times the net energy gain and twice the product output from all U.S. biofuel production!

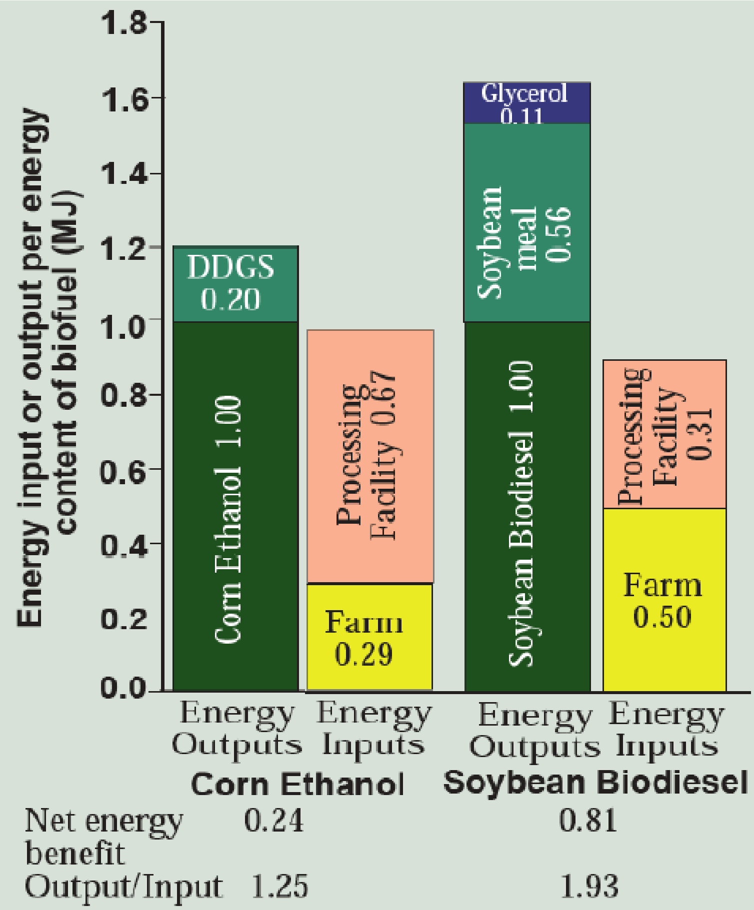


Figure 8.4. An example of a net energy analysis for U.S. corn-based ethanol and biodiesel production performed by Hill et al. (2006). DDGS is distillers dry grain with solubles. Farm energy inputs include manufacturing and use of farm machinery, fertilizer and pesticides, and a portion of farm household energy use. Processing energy inputs include construction and use of the processing facility, facility worker energy use, and feedstock transportation.

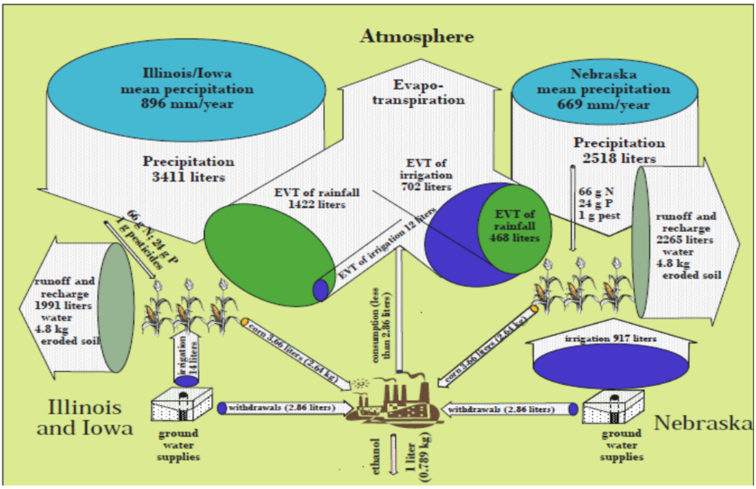


Figure 8.5. The water footprint of one liter of corn-based ethanol derived from rainfed corn in Iowa and Illinois and irrigated corn in Nebraska.

What about ethanol's impact on other natural resources like water? My graduate student Stanley Mubako and I investigated this question using a logic similar to the net energy analysis presented above. It starts with rain falling on corn fields in Illinois and Iowa, the two largest corn-growing states, and Nebraska, the leading irrigated corn-growing state (Figure 8.5). If the corn plants transpire this water to the atmosphere, it is part of the water footprint of ethanol. This amounts to 1,422 gallons of water in Illinois and Iowa and 468 gallons in Nebraska for every gallon of ethanol produced. (Note that these volumetric ratios also apply if we prefer to use liters.)

But wait! If the fields producing the corn for ethanol plants were growing another crop or were being used for pasture or forests instead, the rain would still fall on them, and much of it would still be transpired—perhaps a little more or a little less than from the corn field. These water footprint numbers represent a huge amount of water; when applied to all the land planted to corn in these states or to all the ethanol produced in the U.S., it amounts to the entire flow of the Illinois, Des Moines, or Platte Rivers, the largest rivers in Illinois, Iowa, and Nebraska, respectively. Water transpired by rainfed corn, however, does not present a demand on scarce freshwater resources that would not otherwise occur.

If the corn acreage is irrigated, however, the water footprint does represent an additional demand. This is especially evident in Nebraska, where 60 percent of corn is irrigated, almost all from pumped groundwater, and so the 702 liters of irrigation water that transpires to the atmosphere in corn fields does represent a very large additional demand on scarce freshwater resources in competition with other uses. The amount of water used in corn fields dwarfs the use of water at ethanol plants, though this can be significant as well. This comparison of water use in rainfed vs. irrigated corn shows us that you can't just look at the bottom line water footprint total. You also have to discern what the flows actually represent and what resource-allocation trade-offs are implicated. These same issues apply to the water footprint numbers provided in Tables 8.5 and 8.6.

From a water quality perspective, corn-based ethanol is also problematic because growing the 2.64 kg of corn needed for a liter of ethanol entails, on average, 66 grams of nitrogen and 24 grams of phosphorus as fertilizer, 1 gram of pesticides, and results in 4.6 kilograms of soil being eroded. Multiply these numbers by the liters of ethanol produced (about 20 billion in 2006) and we have a very significant water quality issue. Ethanol production is clearly a driver of polluted runoff, the leading water quality problem in the U.S. Biofuels are also the only energy source that substantially increases human appropriation of net primary production, which is in competition with food supply and biodiversity.

For better or worse, climate change currently leads the list of pressing environmental issues, and if ethanol can help, then perhaps this more than balances the meager net energy gains and high impact on land and water resources. As captured by the diagram in Figure 8.6, this appears to be the case because the carbon in oil is transferred from the earth's crust to the atmosphere, where it contributes to climate change when it is burned as gasoline in a car. In contrast, the carbon in ethanol originally came from the atmosphere and was embedded in the corn through photosynthesis and then ethanol. When we burn the ethanol, it is recycled to the atmosphere rather than emitting greenhouse gases from the lithosphere.

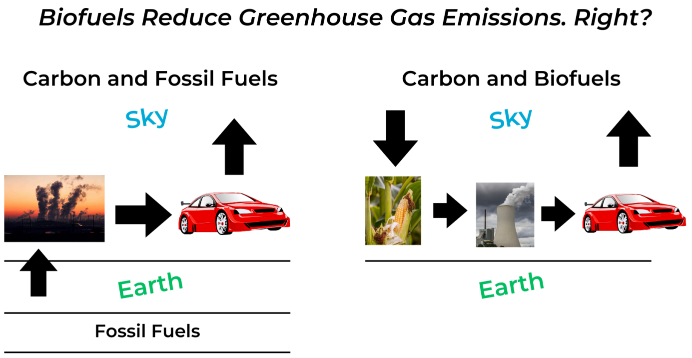


Figure 8.6. The simple view of biofuels as carbon neutral and therefore more sustainable than the fossil fuels they replace.

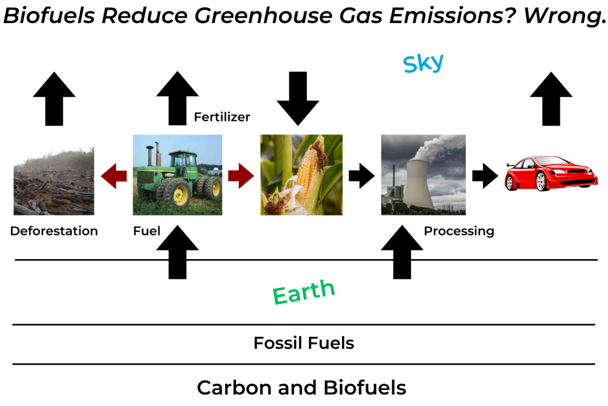


Figure 8.7. The industrial ecology view of biofuel's carbon footprint, which is not necessarily more sustainable than fossil fuels.

When we look closer, however, the situation changes (Figure 8.7). First, we have to include the carbon inputs of tractor fuel, fertilizer manufacture, and so forth that we examined in the net energy analysis. That leaves us with only a slight reduction in carbon emissions from biofuels as compared to gasoline from oil.

Moreover, the corn must be grown somewhere —on land that is currently used for something else. A 2008 study by Searchinger and others found that for every 5 acres devoted to corn for ethanol, 4 acres of grassland or forest are brought under crop production, largely in Brazil, China, India, or the U.S. This releases 25 percent of the soil organic carbon, plus all of the aboveground carbon in the grass and trees. Moreover, the carbon the growing forests or grasslands could have captured and stored as wood and biomass remains in the atmosphere. When this land use effect is included, ethanol ends up with twice as high a carbon footprint than gasoline over a 30-year period, and it takes 167 years for the slight improvement provided by ethanol over gasoline to restore the carbon released from the lands newly brought into crop production. So we end up with ethanol potentially exacerbating rather than ameliorating climate change.

What's the bottom line for corn ethanol? That depends on what you value. Industrial ecology tells us that it has limited potential to replace oil imports or conserve fossil fuels, and even this is achieved at high costs to the most pressing natural resource sustainability issues we face—climate change, water resource availability, polluted runoff, meeting future food demands, and preservation of biodiversity on lands not used for agriculture. Moreover, it flies in the face of the essential macro-ecological dilemma of sustainability by placing the demands of our industrial energy supply squarely in the competition for current photosynthetic potential on this finite planet. It is HANPP.

There may be cheerier news. Ongoing research in greenhouses and laboratories shows promise of developing ethanol from more abundant plant materials that are not used for food—cellulose or algae. Most of the stalks, leaves, and wood of a plant are made of cellulose, but since humans are not ruminants like cattle and camels, we cannot digest it. Cellulosic feed stocks for ethanol production can include wheat stalks and corn *stover* (the cobs, leaves, and stalks) as agricultural wastes, wood wastes from lumber and paper mills, the *slash* left on the ground during timber harvest, or dedicated energy crops such as fast-growing switchgrass or miscanthus.

Despite optimistic prospects for the future, a very active research and development program has not yet mastered a chemical process for transforming cellulose into ethanol in a cost-effective way. Moreover, cellulosic ethanol feed stocks compete with soil conservation for organic matter or require very considerable areas of land to be dedicated to production of energy crops that may require fertilizers and irrigation.

Recent experiments using algae to produce biodiesel are intriguing. Algae is made of 50 percent oil and can potentially produce 200 times as much fuel per acre than soybeans, currently the leading biodiesel fuel stock in the U.S. The starch in algae can also be fermented into ethanol. The process requires carbon dioxide that can be recycled from power plant emissions, sludge from wastewater treatment plants, and can thrive on abundant salty ocean water. While these experiments are far from producing a commercially viable product, they show that innovative thinking may be able to produce advanced biofuels that overcome the shortcomings of corn-based ethanol revealed by this industrial ecology exercise.

Getting the U.S. Economy on a Natural Resources Diet

There are so many ideas for improving resource productivity, most of them fascinating in their own right, that I must control myself and only discuss a few at this point that exemplify how we can think more insightfully about living with a lighter footprint and be better off for it. We'll explore more ideas specific to agriculture, forestry, water, and energy in Part III.

In 1990 Germany instituted its Green Dot system to reduce the disposal of solid waste in landfills and replace "extraction, depletion, and disposal" with "reduce, reuse, and recycle." In addition to creating 17,000 jobs, the Green Dot program has led to the recycling of 6 million tonnes per year of what would have been trashed. In 2003 recycling rates exceeded 100 percent for paper and cardboard (161%), aluminum (128%), and tinplate (121%) as Germans used the Green Dot system to recycle additional materials not included in the program. Recycling rates for glass (99%) and plastics (97%) were also remarkably high. How was this achieved? The Green Dot system makes manufacturers responsible for the life cycle of their products, including all packaging used. This generates a backward flow of materials from homes to stores to factories and creates incentives to minimize packaging. Customers can simply return obsolete products and packaging to the stores where they were purchased. Why would they take the trouble? Because they have to buy green dots for trash bags that are not sorted for easy curbside pickup recycling.

So Germany is using economic incentives, regulations, and a life cycle approach to consumer products to drastically reduce the raw materials that have to be extracted from nature to produce and market products and the amount of consumer waste that has to be disposed of through landfills and incinerators. The system makes money and creates jobs as well, which is why so many countries are emulating it. The U.S. uses a similar system but only for tires, batteries, and few other products. Deposits on beverage containers also help achieve these objectives in states that have passed bottle bills. Think about what a Green Dot program could do for plastics pollution in the oceans.

One-third of all energy, two-thirds of all electricity, and one-fourth of all wood is used in buildings. Yet a well-designed building can reduce energy use by 90 percent by placing and constructing windows so as to make best use of daylight, optimizing heating and cooling distribution systems with local feedback and control, and other simple ideas that don't add to construction costs.

Industrial ecology is, in many ways, the perfect complement to ecological economics. Why aren't people just implementing all these ideas to reduce natural resource use, invest in natural capital, and produce ecosystem services? It's all in the carrots and sticks. And to better understand that, we turn to institutional economics.

Additional Reading

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9.

CHAPTER 9: PROPERTY, POLICY, AND INSTITUTIONAL ECONOMICS

Who owns the land? That question proves to be relatively straightforward to answer, at least currently in the United States. Private individuals and firms own the majority of land—68 percent. The federal government owns 30 percent, mostly in the western states, and state and local governments own the remaining 2 percent. As the legend goes, however, Native Americans sold Manhattan Island, the heart of New York City, for some beads—or was it 60 guilders? Clearly, when they did so the Native Americans had a different idea of selling land than "now you can build a city here and we can never return."

Who owns the water? Now we're getting even more complicated. Technically, each of the 50 states has primary ownership of waters within its borders, but many individuals and institutions have a vested right to use the water in certain places and in specific ways.

Who owns the air or the deer in the woods? Well, no one; the Latin legal term is *res nullius*.

Property is a critical concept in natural resource management because it governs the outcomes of resource use by humans—efficiency, equity, and sustainability. So at risk of rubbing shoulders with lawyers—after all, property is a fundamentally legal concept—let's take a look.

The Idea of Property in Natural Resources

What does it mean to "own" land, water, air, minerals, fish or game? This turns out not to be at all as simple as you own the shirt you're wearing. In fact, it constitutes an entire branch of law whose written materials would fill many rooms. Ownership of natural resources entails a set of specific rights and responsibilities, like a bundle of sticks.

Let's start with something you may have thought was simple—privately owned rural land. A rural land owner has the right to clear vegetation and plant crops in the soil on his or her land, that is to farm it, but does (s)he have the legal right to allow soil, fertilizers, and pesticides to run off the land into streams, aquifers, and public water supplies? In general, the answer is yes, and that is problematic. Does (s)he have the right to drain wetlands, thereby releasing carbon into the atmosphere, destroying wildlife habitat, increasing flooding, and deteriorating water quality downstream? The answer was yes before 1972, then no when the Clean Water Act section 404 came into effect, but is now incrementally shifting toward yes due to recent court opinions. Does (s)he have the legal right to pump groundwater from beneath the land to irrigate crops, even if the water table is falling? In most states, the answer is yes. Does (s)he have the right to mine minerals or coal or pump oil and gas from beneath the land? In most states the answer is no—underground mineral rights are held separately from ownership of the land surface. If a farmer relies on bees living in an adjacent forest to pollinate crops, does (s)he have the right to stop a neighbor from cutting down that forest to turn it into cattle pasture? The answer is nearly always no. If it is determined that reforestation is the most cost-effective manner in which to remove carbon from the atmosphere, does (s)he have a responsibility to plant trees instead of crops? The answer is no. If the farmer is receiving public farm subsidies, can the government attach strings to them to prevent soil erosion, polluted runoff, wetland drainage, and so forth? The answer is yes, but the strings are rarely pulled. Watch out! I've already got you thinking like a lawyer!

Land at least stays put, but how about water, which evaporates, infiltrates, and runs downhill to the ocean? Here the states claim ownership and distribute *usufructuary* rights—permission to use the water. In the eastern states and most of Canada, precipitation exceeds evapotranspiration on average, and so Thornthwaite (see Chapter 3) would identify a water surplus—just like in drizzly England where the *riparian* water rights system was developed. Anyone with land adjacent to the water can put it to *reasonable use*—a term so vague that many lawyers can find employment interpreting what it means in specific cases. Is it "reasonable" for the burgeoning metropolitan area of Atlanta to take increasingly large amounts of water from the Tallahassee and Flint Rivers in Georgia, despite an ongoing drought, so that the vibrant oyster fishery in Apalachicola Bay at the mouth of the river in the panhandle of Florida is ecologically degraded? The answer to that question has been taken all the way to the U.S. Supreme Court. Is it "reasonable" for New York City to tunnel beneath the Catskills Mountains to bring Delaware River water to the Big Apple? You betcha. Is it "reasonable" for Chicago to get its water supply from relatively clean Lake Michigan, then reverse the course of the Chicago River so that its sewage goes down the Illinois River to the Mississippi? Yes, but it counts against Illinois's share of withdrawals from Lake Michigan water in a treaty with Canada governing the Great Lakes.

When settlers went west following Lewis and Clark, they found a dry land where potential evapotranspiration greatly exceeds precipitation and only high snowy mountains give rise to permanent streams. Crops require irrigation to thrive, but there is only enough water available to irrigate a few percent of the land. So who gets the water? At first, settlers would leapfrog one another upstream to get at water for irrigation or mining, but that's a terrible system of resource allocation leading to a chaotic race up the mountains. So the courts developed a system of *prior appropriation*—prior meaning "before" and appropriation meaning "diverting for economic use." This means that whoever is first to pump or channel water from a stream and put it to a beneficial use (usually meaning an economically productive use) gets that amount of water in perpetuity—for that use in that location as long as they keep using it. If not, the *use it or lose it* rule applies. They have vested senior rights that no one else, not even the government, can take from them. Later settlers may get junior rights, lower in the priority list, until all the renewable water flow is appropriated. The states may then grant even more rights to appropriate water unsustainably.

The prior appropriation system worked to encourage rapid settlement of the West and turn the region's limited water supplies into a factor of economic production, especially in irrigated agriculture. But what if Las Vegas or Phoenix, exploding with population and economic development, can put the water to a higher and better use? What if the water is needed in the stream channel to support an endangered species of fish, such as the Rio Grande silvery minnow of the Klamath River Chinook salmon? Can the system reallocate water from historic uses to current needs? That is the central dilemma of water resources management in the western prior appropriation states.

How much did you pay for your oxygen supply today? How much did you pay to release carbon dioxide into the atmosphere when you exhaled, or drove your car, or used electricity? Who controls the release of unhealthy air pollutants like sulfur oxides, carbon monoxide, ozone, or second-hand smoke? Often the answer is the federal government, which assigns the task to the Environmental Protection Agency (EPA) to establish regulations. Do greenhouse gases fall into this category? In the U.S. in 2006, they did not. On April 2, 2007, the U.S. Supreme Court ruled that the EPA must regulate greenhouse gases if they pose a threat to human health. In December 2009, the EPA found that they do. See how important the judicial branch of government is? Judges' decisions set precedents that accumulate over time to form the Common Law upon which property rights are based. The EPA is part of the executive branch and they implement *statutes*—laws and acts—passed by Congress—the legislative branch.

So at this point you're likely scratching your head and canceling your plans to go to law school. That's fine (we have enough lawyers), as my purpose has been to raise questions rather than to provide answers. Institutional economics is about understanding how specific definitions of property rights to natural resources and the environment and specific public policies affect the incentives, the carrots and sticks, to which resource owners and users respond. One set of property rights or policies may lead to long-term sustainability while another may lead to a chaotic race to exploit natural resources before someone else does. We will certainly want to know the difference, so let's dig in.

The Tragedy of the Commons

Let's begin with the famous "The Tragedy of the Commons" that, in 1968, catalyzed an ongoing debate on how the functioning of social and economic structures, what the essay's author Garrett Hardin called "the remorseless working of things," lay at the heart of problems of natural resource depletion and environmental degradation. Hardin described a common pasture open to anyone who wanted to graze cows on it. What would happen, he asked? Everyone can profit from more meat and milk from their cows, so each villager puts a few more cows on the pasture. Soon the grass is gone, and all the cows starve. Moreover, the soil erodes away, making it difficult to ever restore a fertile pasture. We have a tragedy of the commons. This metaphor remains potent as an explanation for some problems of overconsumption of resources, such as the collapse of fisheries or overpumping of groundwater, that are held as a common pool.

Let's go back to the pizza slices in Chapter 6. What if a dozen slices of good, hot pizza were simply laid on a table outside the lecture hall with a sign saying "first come, first served"? They'd disappear in seconds, perhaps with a few landing facedown on the floor (the 5-second rule only applies if the slice lands crust-down and no one steps on it!). This kind of free-for-all will generally lead to rapid resource depletion, and it can also lead to overuse of environmental sinks for waste absorption, like a watershed's capacity to process nitrogen fertilizer, or the atmosphere's capacity to cycle carbon emissions. It's like a trash can at an outdoor concert or fair that gets overfilled and spills all over. In this way, two of our most intractable environmental pollution problems—polluted runoff and climate change—can be usefully conceived as tragedies of the commons. Garrett Hardin lives on; "The Tragedy of the Commons" is the most often cited paper in natural resource and environmental economics.

As influential as Hardin's thesis has become, however, it is also flawed. Hardin's pasture was not really a commons, it was a free-for-all, open-access, *res nullius*, like air. A better example of a commons is the course you are currently taking and the classroom it meets in. It is not a free-for-all because you have to enroll and pay tuition—others are excluded from participating. The classroom has rules of conduct—no disruptive chatting and cell phone use, raise your hand to be called upon for comments and questions, engage with what's being presented (after all you're paying for it and other's aren't). A commons is a shared resource with rules governing its use to prevent a "tragedy." Hardin's thesis is therefore better thought of as the following logical if-then statement:

If:

- a resource is open-access,
- benefits derived from using the resource are private property,
- and the resource has a limited carrying capacity,

Then:

- self-interested users will over use the resource,
- and the long-term carrying capacity of the resource may decline.

If open-access resources are such a dilemma, then why not make them all private property and allocate them through markets, which neoclassical economics purport work so well? The problem is that many environmental resources are *common-pool*—once they have been created by society or by nature, it is difficult to deny their use to anyone in the affected geographical area. You can put a fence around your land, but can you put one around your clean air? Once money is spent to improve the quality of the air, everyone simply breaths it, whether they contributed to the clear air fund or not. No one is standing at the cash register, collecting tickets at the door, or calling names from a class list of those who have registered and paid tuition. Once wetlands are restored, everyone on the floodplain downstream has less flood risk and better water quality. Once carbon emissions are reduced or sequestration accelerated, everyone suffers fewer impacts of climate change. These services are *non-excludable*.

The average, slightly selfish, person might reason, if I'm going to get it whether I pay for it or not, why not just keep my money? Many of you have probably behaved this way with respect to internet sites and software. Economists call this person a*free rider*. The counter measure to the free rider problem is—you guessed it—taxes. Government forces everyone to pay for a share of what everyone enjoys—national defense, roads, public schools. These are called *public goods*. If privatization often leads to inequality, however, with a few owning much and most owning little, increasing governmental control of common-pool environmental resources often leads to resource mismanagement borne of bureaucratic detachment from local ecological realities. They just don't get it like those who have lived there all their lives. So Hardin's remedies for the tragedy of the commons —privatizing the commons or have government take over and ration its use—have their own problems.

Nobel prize-winning political scientist Elinor Ostrom has been a leader in arguing that local, self-organized common property institutions can often be the best solution to managing natural resources. The most cited example is the Maine lobster fishery where a community of trappers actively discourage new fisherman and collectively manage the available resources in a sustainable manner. But common-property solutions don't always work either. An effective commons requires a number of key elements; by identifying these, we learn a bit more about real-world problems of natural resource sustainability.

1. There is an appropriate *geographical* definition of the common-pool resource being governed, from the global atmosphere to small-scale watersheds and grazing, fishing, or hunting grounds.
2. There is a *scientific capacity* to observe and measure changing resource conditions on an ongoing basis so that answers are known to questions like: How many fish are in the lake or deer in the national forest? At what depth does the water table now lie? What is the nitrate concentration in the water? What is the current atmospheric concentration of carbon dioxide? How fast is sea level rising? Where are visitors to the national park going?
3. *Social capital*—interpersonal relationships in which trust develops over time through collaboration—among resource users is strong enough to enable community members to develop and support their own rules for resource monitoring and use and thereby view these rules as legitimate and help to enforce them against outsiders and selfish renegades (e.g., free-riders) within the group. There is a sense of "our" resources, shared by "us," but not by "them."
4. Larger-scale institutions such as governments and

corporations *support and legitimize* these rules and institutions rather than supplant them with bureaucratic approaches or exploitive takeovers.

5. There is a system for imposing *appropriate sanctions* for violations, from a "slap on the wrist" or a hint from an elder for minor infractions, to fines or a loss of reputation for moderate ones, to arrest or social ostracism for severe infractions. Procedures for *conflict resolution*, especially those short of lawsuits (litigation), are established.
6. *Outside influences*, especially global economic driving forces and technological advances, are understood, and management of the common-pool resource can adapt to them.
7. Governance institutions utilize a *variety of mechanisms*—such as quotas, time and space restrictions on use, fees, or tradable permits—to prevent resource use from exceeding the carrying capacity and are able to raise revenue as needed through such means as taxes, user fees, or voluntary contributions.

Clearly, building institutions that contain each of these elements is a steep challenge; in fact, rarely are all of these conditions fully met. This makes the real world of local resource management institutions a very complex one with a range of successes, failures, and partial successes struggling to become more fully successful. More than in the U.S., where legal and market institutions dominate, it is in developing countries that Ostrom-like local common-property institutions proliferate. Hundreds of thousands of local groups have formed worldwide since the early 1990s for the management of watersheds, irrigation, forestry, and agricultural production.

The Problem of Externalities

Let's return to the legal issues of land ownership raised above. Exercising his or her property rights as a landowner, a corn farmer's eroded soil, fertilizer, and pesticides run off the land, polluting the water downstream, with a resultant loss of ecosystem service values and an increase in water treatment costs. The farmer does not pay these costs—society does. This is an example of a *negative externality*—these water pollution costs are not part of the farmer's cost of production for growing corn.

Another farmer preserves or restores wetlands on the lowest-lying third of his or her farm. These wetlands absorb eroded soil, fertilizers, pesticides, flood waters, and atmospheric carbon, and provide wildlife habitat. The farmer doesn't sell these ecosystem services, however. They are *positive externalities*—benefits produced but not compensated.

The economic result is that, relative to the level of production that maximizes net benefits, goods with negative externalities are overproduced and those with positive externalities are under-provided. This is not the efficient and sustainable outcome we'd want from markets. One answer is to impose pollution fees and offer ecosystem service credits to correct *market failure*.

Given this discussion of institutional economics, why are ecosystem services declining? The answer lies in what my colleagues and I have termed, following on Hardin, the "tragedy of ecosystem services." Let's proceed like a doctor from diagnosis to potential remedy.

The Diagnosis: Why Ecosystem Services are Declining

The findings of the Millennium Ecosystem Assessment and the 2019 United Nations study on biodiversity and ecosystem services discussed in Chapter 4 show that services that are derived from private property and result in goods that are bought and sold in markets (e.g., crops, livestock, aquaculture fish) are increasing—this is called economic growth. When the natural capital from which the services are derived lacks clearly defined property rights, however, services are decreasing. This includes provisioning services such as fish caught from the ocean and other wild foods, fuel wood, genetic resources, and fresh water. Most nonmarketed, regulating services are also declining: air quality, regional and local climate, erosion, pest, and natural hazard regulation, water purification, and pollination. So even though the neoclassical "economy" is growing, the "ecological-economy" may be shrinking, at least in some places.

In diagnosing this disease, let's think through the way different kinds of natural resources are used—their *utilization regime* across the column headings of Table 9.1. *Private goods* (Column 1), such as barrels of crude oil or bushels of corn, are *rival*; once someone has "consumed" the good, it is not available for another person. Private goods are also *excludable*; it is possible to prevent those who have not purchased the good from having access to it. In contrast, *public goods*, such as improvements in air and water quality, are *non-excludable*; it is not possible to prevent people from having access to the good once it is provided. For some of these goods, like the psychological enjoyment of knowing that millions of species, the Grand Canyon, and other natural wonders still exist, utilization has no effect at all on the natural resources remaining. For others, like breathing oxygen, it does, but the supply so overwhelms the demand that we can ignore the effects of consumption. For these, utilization is *non-rival* (Column 3). For other non-excludable goods, utilization is *congestible*—it becomes rival when the carrying capacity is approached. The course you are taking, theater and sports arena seating, roads, parks, and bridges are congestible common pools. Among natural resources, so also are water in rivers and environmental pollution sinks (Column 2).

Table 9.1. Likely outcomes for management of natural capital under various property rights and resource utilization regimes. Adapted from Lant et al., 2008.

	Utilization Regime		
Property Rights Regime	1 – Private Goods Rival or Consumptive and Excludable	2-Public Goods Congestible Utilization of Non-excludable Common Pool	3-Public Goods Non-Rival Utilization of Non-excludable Common Pool
A. Private Property	1A. Potentially efficient level of production Ex: most goods produced in competitive markets	2A. Under-provision Ex: wetland restoration for nutrient removal and carbon sequestration	3A. Under-provision Ex: ecological restoration for biodiversity and aesthetic values

B. Public Property	1B. Perverse subsidies often lead to over-utilization Ex: subsidized mining and grazing on public lands, use of public waters for irrigation, production of timber from national forests	2B. Common public goods provided by governments Ex: parks, roads, sewage treatment plants	3B. Pure public goods provided by governments Ex: national defense, air quality regulation
C. Common Property	1C. Potentially sustainable levels of consumption	2C. Potentially sustainable utilization Ex: Maine lobster fishery	3C. Generally sustainable utilization
D. Open-Access	1D. Unsustainable over-consumption Ex: rule of capture for fish, wildlife	2D. Unsustainable over-utilization Ex: greenhouse gas accumulation, fertilizer runoff leading to eutrophication	3D. Free and sustainable utilization Ex: use of atmospheric oxygen, aesthetic values

Now let's scan down the row headings on the left-hand side of Table 9.1. Here we see four different types of property – private (owned by individuals and firms), public (owned by national, state, and local governments), common (owned by groups) and open-access (owned by no one). We must recognize that, to a property lawyer, these would be just four points along a complex continuum. What are the market outcomes and governmental responses in the resulting dozen boxes?

Neoclassical economic analysis of markets is primarily focused on Box 1A where we saw how well it allocates pizza slices but also cars, houses, and most of the goods we buy in stores or online that are rival and excludable. Hardin's tragedy of open-access, one example of market failure, takes place in Boxes 1D for harvestable resources like fish and 2D for overused environmental sinks. See if you can figure out why.

In Box 2A and 3A, however, the market under-provides public goods like ecosystem services because they are non-excludable and therefore vulnerable to free riders. The producer is unable to take full advantage of their value by charging for them. Rather, potential users have free access to these common-pool resources. This is the case for roads or scientific research, for example, but, unlike ecosystem services, massive institutions provide these public goods.

Similarly, owners of natural capital such as land have the potential to provide ecosystem services, but it is difficult to charge the beneficiaries for them. The landowner usually has no financial incentive to continue providing them and so rarely does, except incidentally. Few invest in improving Hardin's pasture. Few restore fish habitat or wetlands. Few sequester carbon. This is true even if the value to society of the ecosystem services that could be produced exceeds their economic costs to the landowner because *most ecosystem services are positive externalities*.

There is also a legal dimension to this tragedy of ecosystem services that seals the deal. Those who benefit from ecosystem services generated on other's land have no legal recourse if these are no longer provided. If you depend on pollinators harbored in your neighbor's forest, tough luck if (s)he cuts it down for grazing land or housing and your crops don't mature. If you depend on coastal wetlands to absorb storm surges, tough luck if they disappear and your house is flooded in a hurricane. If you tried to sue, a lawyer would say you don't have a case because you had no right to those services in the first place. Moreover, few counterbalancing measures have arisen to enable or require property owners to protect or enhance the continued flow of essential services from ecosystems on their properties. As a result, floodplains, wetlands, and forests that provide carbon storage, wildlife habitat, pollination, water purification, and flood control services are too often drained, cleared, and planted to crops, converted to pasture for livestock, harvested for timber, or urbanized.

So now we have a diagnosis of the disease. Are there available cures?

Government's Environmental Policy Toolbox

When the market systematically fails to allocate natural resources efficiently, equitably, and sustainably, when there is a market failure such as the tragedy of the commons, under-provision of ecosystem services, or externalities, government can step in and alter the rules of the game. Consider an example from my favorite sport of basketball. In the 1950s, when Wilt Chamberlain and Bill Russell started guarding the rim and blocking every shot, the goaltending rule was imposed—you can only block shots on the way up near the shooter, not on the way down toward the hoop. A half-century later this insightful rule change is still in effect because it prevented basketball from becoming a contest of tall guys swatting away every shot with their hand in front of the rim. Natural resource sustainability is a lot more important than basketball, so let's see if policy can modify the rules to produce a more sustainable game of natural resource use. Just like the basketball gurus, who have a set of rules they can modify to solve problems that emerge in the process of competition, so governments have a set of policy tools they can hone to address natural resources management problems that arise as technology and the nature of capitalist competition evolve.

The first tool set is*voluntary measures*, such as information dissemination, public service campaigns, technical assistance, and, not to be underestimated, getting people together in a room to talk about it (best if food is served). These light-handed approaches can sometimes be effective over time, such as in encouraging conservation tillage by farmers, reducing cigarette smoking, and replacing littering with recycling. They generally only work, however, if it is in the recipient's self-interest to make the asked-for changes and they are empowered to make them.

The second set is*positive economic incentives*, such as government purchasing of recycled paper or tax credits for electric vehicles or solar panels. Government-sponsored research and development into subjects such as energy efficiency, new energy sources, and refrigerants to replace ozone-depleting CFCs is another example. Governments can also invest in public transit or in pollution control infrastructure such as water and wastewater treatment plants. They can provide subsidies for best management practices. An example of this policy tool is the Conservation Reserve Program where farmers are paid to retire highly erodible or streamside land from crop production to control soil erosion and enhance ecosystem services. Resource users usually support these types of measures, but they are financed by taxpayer dollars. They also assume that resource users are not required by law or by the structure of their property rights to conduct the activities government is paying them to implement. Paying for carbon sequestration is a new policy of this type now under consideration.

A third set is *negative economic incentives*, such as pollution fees or tradable pollution permits as we explored in Chapter 6. A variant is cross-compliance where, in order to remain eligible for government subsidies, farmers must not drain wetlands or allow soil to erode at excessive rates. When these tools are used, taxpayers do not pay the bill, resource users do, which often leads to their opposition unless the incentives are replacing more expensive direct regulations. It also assumes that the activities being charged for fall outside the realm of property rights.

A fourth set is what we usually think of first—*direct regulation* of practices and technologies. This is government telling resource users what they cannot or must do when using public resources, especially air and water as pollution sinks. The Clean Air Act, Clean Water Act, Endangered Species Act, Resource Conservation and Recovery Act, Superfund, and other environmental laws you may be familiar with are primarily regulatory. Resource users often claim that this policy tool is bureaucratic, limits firms' freedom of action, and imposes high costs that make their products less competitive—all legitimate complaints. Analyses such as cost-benefit analysis have generally shown, however, that the costs are less than expected and the resulting environmental improvements or avoided degradation are enormously valuable. Still, the economist's argument that negative economic incentives can accomplish many environmental goals more cost-effectively than direct regulation deserves careful consideration.

With our environmental policy toolbox now partially filled with hammers, screwdrivers, wrenches, and saws, let's take a closer look at how these tools can be applied to overcome declining ecosystem services.

Policy Tools to Address the Tragedy of Ecosystem Services

The diagnosis presented above identified under-provision of ecosystem services from private land as a critical problem. While there is no one cure, potentially effective remedies lie in (1) the evolution of the common law of property, (2) reforming economic incentives, and (3) the development of ecosystem service districts.

The common law of property currently discourages ecosystem services, but, through judges' decisions, on a case-by-case basis, the law is always changing. When a high court—the Supreme Court for Federal law and the state supreme courts in those respective states—decides a case, lower courts are bound to implement those precedents. This is how the common law evolves.

The natural resource, environmental, and ecological economics literature is rich with suggested policy reforms that would encourage cost-effective provision of ecosystem services. Some of the most pertinent examples that we will explore in depth in Chapter 15 include:

1. Tradable pollution permits, especially for carbon emissions and sequestration, not only to discourage emissions, but to motivate private landowners to store additional carbon on their lands rather than in the atmosphere.
2. Switching from crop production-based agricultural subsidies to ecosystem service-based subsidies in order to increase provision of carbon storage, water purification, soil conservation, and wildlife habitat on private rural land.
3. Incrementally shifting taxation from income to pollution fees and resource consumption and reducing or eliminating subsidies for natural resource production and consumption. This makes it more expensive to exploit natural resources or pollute, thus discouraging them.

Ecosystem service districts—similar to school, fire, and other local service districts—are in their infancy. While not perfect, watersheds, perhaps as modified by state boundaries, are the best bet for geographically defining ecosystem service districts because they are nested at multiple spatial scales based on tributaries. Moreover, the provision of four key ecosystem services—water supply, water purification, flood control, and aquatic and wetland habitats—occurs within the geographical definition of watersheds, and a fifth and sixth—soil erosion control and carbon storage—can also be managed well at watershed scales.

For these reasons, New Zealand has restructured environmental administration along watershed lines. Closer to home, New York City demonstrated how natural capital can provide the essential service of water purification at lower cost than manufactured capital when they spent $1.5 billion on improving water quality in the Catskills watershed, thus avoided $10 billion in construction costs for a water filtration plant.

Given the diversity in ecosystem services and the manner in which they benefit people, the political challenge of overcoming the tragedy of ecosystem services lies in bringing these strategies to bear in the best possible manner for each unique situation.

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CHAPTER 10: POLITICAL ECOLOGY

What is *political ecology* and what can it tell us about natural resources sustainability? Definitions vary, but essentially political ecology is about how society structures access of different groups of people to natural resources, especially land, and how economic processes and public policies generate environmental and natural resource problems. It is not really a school of economics, and, in fact, rejects the notion that one can study the economy separate from society and nature as a whole. It is a distant relative of Marxism, also sometimes referred to as *political economy*, with its emphasis on inequality rooted in differences in political and economic power among groups of people. While neoclassical economics supports capitalism, political ecology critiques it. It is a very different lens that sees a fundamentally unfair world. To taste it's flavor, try viewing the narrative cartoon *The Story of Stuff*.

How many oil fields or mineral deposits do you own? Do you own any agricultural or forestry land? I own 0.4 acres with some nice trees and flowers on it, and I'm considering reducing the area of grass I have to mow in favor of some nice xeriscaping. That may be more ownership of natural resources than most readers of this text possess. Yet, if you are a middle- or even working-class American, you are a “have” in a world of haves and have-nots. Even if you don’t own mineral resources or land, you probably have the spending power to acquire food, water, raw materials, and energy sufficient to meet your needs, if not your every desire. Unfortunately, billions of people do not have sufficient access to natural resources to meet their basic needs. Nearly a billion are underfed while even more are overweight, partly because of the low-quality carbohydrate-rich, cheap food that is available to them—if in large quantities. Over a billion lack access to safe drinking water and as a result suffer from deadly diseases that are completely preventable. Nearly two billion do not have access to electricity, even occasionally. Over two billion lack access to basic water sanitation like toilets and sewers. Most farmers do not own the land they till. Meanwhile, a fortunate few own or control the majority of natural resources and the economic benefits from them. They benefit from excellent ecosystem services while others live amidst environmental degradation and health risks from pollution or natural hazards. These are issues of environmental justice and natural resource allocation, and they greatly affect progress toward natural resource sustainability.

We’ll begin this discussion of political ecology with a look at the globe as a single economic system with an affluent core and an impoverished periphery. A critical look at globalization will follow by uncovering how natural resource consumption in one region can result in unsustainable resource exploitation in another. Problems of natural resource sustainability in the periphery differ in many ways from those in the core. The central issue is often land and water degradation borne of inequality, economic change imposed from outside the region, and population pressure, with population growth itself being a symptom of poverty as we explored in Chapter 5. We'll then compare two case studies of wildlife conservation in East Africa and Alaska. In both cases, the issue is conservation for whom? We'll finish by proceeding from diagnosis to possible cure by examining the Millennium Development Goals and progress toward achieving them.

The Global Economic System of Core and Periphery

Long before the rapid globalization of the last generation, the world was becoming a single economic system based on Western (that is, Western European and American) capitalism. Capitalism first developed in Northwest Europe, especially the Netherlands, followed by England and then France, in the 16th–18th centuries to slowly replace feudalism. It began to spread throughout western Europe and then overseas, partly through emigrant populations from Europe that pushed aside indigenous populations in the Americas, Australia, and

Siberia, and partly through colonialism forced upon African and Asian populations by Europeans.

The early capitalist system enriched Europe, while impoverishing other regions, such as sub-Saharan Africa. Millions of West Africans were captured and forced into slavery in the Americas in the 17th and 18th centuries. In the 19th century, Europeans divided up Africa into colonial spheres of influence. In fact, the modern borders of Africa's 54 nations were largely determined by the Treaty of Berlin (Germany) in 1885. The 17th–19th Century Triangular Trade system of the North Atlantic worked to the advantage of Europe while Africa's economic development was actively undermined. Latin America, as well as the early American South, became a land of haciendas—large plantations owned by Europeans and worked by Africans or Native Americans. Viewed in this way, the American Revolution not only replaced monarchy with democracy, it also helped the American colonies escape the economic fate of many of Europe's other overseas colonies—becoming a periphery.

A similar story can be told in Asia where Indonesia was the Dutch East Indies, Vietnam, Cambodia, and Laos were French Indochina, the Philippines were a Spanish and then briefly an American colony, and British India included all of South Asia. There is clear evidence that the industrial revolution in 18th–19th Century Britain in fact deindustrialized India, whose prosperous cottage industries in cotton clothing and other trades eroded away in the face of mass-produced cotton textiles from Britain. China was an open door to all imperialists where, in the Opium Wars of the 1840s and 50s, the British fired cannons at coastal cities to force the Chinese to accept imports of opium from India. Even in the 21st century, the legacy of colonialism smolders throughout the developing world.

I provide this very brief review of history so that we can understand why some regions of the world—North America, Europe, the Pacific rim of Asia and Australia-New Zealand—are "developed," while others on the wrong end of historical colonialism—Latin America, Africa, the rest of Asia, are "developing." Acknowledging that political and economic power flow largely from a capitalist core in North America, Europe, and, more recently, Northeast Asia, political economists like Immanuel Wallerstein, father of world-systems theory, refer to the*core*, *periphery*, and *semi-periphery* of the world system. These are mapped in Figure 10.1, but we must remember that the map changes on a decadal time scale. For example, South Korea and former Soviet satellites of Eastern Europe that have now joined the European Union have only recently graduated to core status after centuries as semi-periphery countries with elements of industrialization, but markedly lower standards of living than in the core. Eastern China graduated from periphery to semi-periphery on the back of rapid industrialization in the late 20th Century and is currently approaching core status, even while rural backwaters of that vast country remain in the periphery. Russia today is a semi-periphery country.

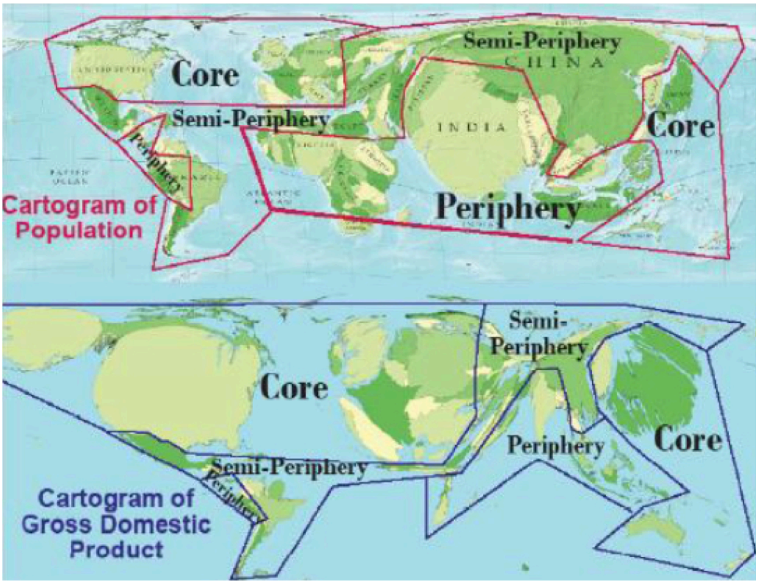

Figure 10.1. A cartogram shows the size of each country proportionate to a specific variable, rather than area. The core, periphery, and semi-periphery of the world economic system as of 2014 on a cartogram of population (top) and gross domestic product (bottom). Note how the periphery looms large in human terms but small in economic terms.

It is easy to document the differences in human welfare between core, semi-periphery, and periphery. A visually interesting way to do this is to compare cartograms of world population (top of Figure 10.1) with gross domestic product (bottom of Figure 10.1). The latter is a map of the world economy, where the core looms large, and even populous peripheries in Latin America, Africa and South Asia shrink. Life expectancy, literacy rates, access to doctors, scientific productivity, and any number of other measures show similar geographical patterns of inequality. Despite the preponderance of people in the periphery, natural resources flow predominantly from the periphery to the core.

Zooming in on a region in, say, Brazil, Costa Rica, or Ivory Coast, we would find that most of the best agricultural land is owned by a small local elite with a European ancestry or historic ties to colonialists or by agribusiness corporations headquartered in the U.S. or Western Europe. How many food and drink products did you consume this week that come from tropical plantations: coffee, tea, chocolate, bananas, mangoes, pineapples? Do these plantations occupy land that could be growing food crops that would better nourish the local population? Are they economic colonies of the core in the tropical periphery?

Once the better lands are taken, land-hungry *peasants* (this means a small-scale subsistence farmer) scramble to find enough land to feed their families. Often they are left with less fertile or more erodible lands. They clear the forest from the hillsides; they graze cattle, camels, sheep, and goats on the margins of the desert; they farm the flood-prone lands alongside the river and the newly deposited mud at the rim of the river delta and become sitting ducks for the next typhoon. They have been *marginalized*; their basic needs are low on the capitalist priority list.

Globalization and Natural Resources Sustainability

Globalization has brought about a steady increase in the volume of natural resources traded among regions of the world. Does trade enhance or undermine sustainability? Let's consider an example from forestry. Today, densely populated, affluent Japan enjoys 74 percent forest cover which provides a variety of ecosystem services locally in Japan—flood protection, soil binding, wildlife habitat, recreation, aesthetics and so on. However, Japan is the world's leading importer of wood products with over 20 million tonnes per year reaching Japanese ports. Domestic production is only a fourth as high. The tropical forests of Malaysia and Indonesia over 1,000 miles to the south have long been a leading source. As a result, in the 1990s Indonesia lost nearly 4,000 square miles of rainforest per year in a region second only to the Amazon for species diversity. Massive fires consuming trees and soil peat and releasing millions of tons of carbon dioxide to the atmosphere have become a periodic disaster in the large Indonesian Islands of Sumatra and Borneo.

By importing most of its forest products, Japan gains the provisioning ecosystem services of Indonesian and Malaysian forests while simultaneously preserving the ecosystem regulation and cultural services provided by its domestic forests. Indonesia's gain in foreign exchange from Japan comes at the expense of large costs in future natural resource and ecosystem service benefits from its depreciating natural capital endowment. In this way, trade redistributes the benefits of both natural resource use and services from ecosystems.

Closer to home, the forested New England landscape was largely cleared for agriculture in the 18th and early 19th centuries. The region developed a manufacturing economy in the late 19th and early 20th centuries, then de-industrialized in the late 20th century as it gained a prominent position in the global service economy. For the last century, New England has witnessed the most extensive reforestation on the globe, primarily due to natural succession on abandoned farmlands, and is now regarded as the least polluted region in the U.S.

Like the Japanese, however, New Englanders have the economic and political power to choose to base their economy on service industries that do not require large-scale exploitation of local natural resources. Also like the Japanese, they have the purchasing power to acquire natural resources from other regions – oil from the Middle East, Canadian, and Venezuelan oil sands and fracked oil and gas shale fields in the U.S., meat and grain products from the Midwest Corn Belt, metals from Africa and Australia, and so forth. The environmental degradation associated with production of these natural resources occurs in the regions exporting them, not New England. Even pollution associated with consuming these resources, such as greenhouse gas emissions from vehicles and power plants, has environmental effects that are felt largely outside of New England. Meanwhile, New Englanders have succeeded in lobbying for legislation to limit sulfur dioxide emissions from coal-fired power plants in the Midwest that cause acid rain in New England and are actively blocking, on aesthetic grounds, wind power projects that would reduce greenhouse gas emissions from the region. Yet these greenhouse gas emissions affect the entire globe, not just New England.

The point here is not to pick on New England, a charming region that I encourage you all to visit in October when the fall foliage (borne of that reforestation trend) is in full color, but to illustrate how interregional trade in natural resources redraws the map of environmental quality—usually to the benefit of the wealthy. Core status in the global economic system sometimes allows a region to have its ecosystem service cake and eat its natural resource consumption too. Political ecologists have called this phenomenon *ecologically unequal exchange* and point out that *environmental justice* is a critical issue.

Moreover, as periphery regions increasingly specialize in natural capital-intensive industries (e.g., mining and processing of ores, petroleum production and refining, paper products, intensive agriculture), they forgo the development of human, social, and intellectual capital that accompanies growth in advanced manufacturing and services industries. Some have called this the *natural resources curse*.

Every locality thus has a history of natural capital appreciation and depreciation that reflects both its physical geography and its changing role in local, regional, and global economies. Globalization intensifies this dynamism by making the natural capital of each locality accessible to global markets, bringing to bear a global search for low-cost minerals, timber, crops, and energy supplies. Small-scale, locally oriented production is frequently abandoned. Traditional economies that rely heavily upon local mechanisms of social reproduction and ecosystem service provision are replaced with commodity trade at the periphery of the world economy. Often, the result is rapid depreciation of the local natural capital endowment. We call it soil erosion, land degradation, deforestation, desertification, and loss of biodiversity.

The World Trade Organization (WTO) regulates world trade, usually in the name of free trade, which we ordinarily associate with minimizing tariffs on exports and other protectionist measures that favor domestic over foreign producers. Nations of the world differ markedly, however, in labor laws and wages and in environmental protections. At its worst, free trade can become a race to the bottom, where the countries with the lowest wages and laxest regulations can produce goods the cheapest. They thereby get more foreign direct investment from multinational corporations in new production facilities and increase their exports. Meanwhile manufacturing jobs may flee from unionized regions and nations with strict environmental codes. This economic process clearly undermines sustainability goals.

The issues raised here do not prove that trade and globalization are bad, or good for that matter, for sustainability. Rather they show that trade and globalization have considerable impacts on natural resources sustainability and these impacts need to be a core component of trade agreements and negotiations, where the devil often resides in the details.

The Political Ecology of Land Degradation

Following on the earlier book *The Political Economy of Soil Erosion in Developing Countries*, in a classic 1987 study, *Land Degradation and Society*, British political ecologist Piers Blaikie and Australian geographer Harold Brookfield investigated the causes of land degradation in several localities around the globe. They found that causes are remarkably specific to the place and time of their occurrence, and so they use the term *regional political ecology*.

Why are lands degrading? Is it population pressure on land-based resources? Surprisingly, they found that land degradation is often more serious in sparsely populated than in densely populated regions. Why? Population growth generates economic demand for agricultural products, which must be produced somewhere, placing pressure on the land at a global scale. Populous fertile regions— like the plains and river valleys of eastern China, the deltas of southeast Asia, the Gangetic plain of northern India, the north European plain, or the American Midwest—have, through the centuries, evolved systems of intensive agriculture on lands and soils that are resilient. They can support continuous farming, if the right long-term investments in land management are implemented. To some extent, terraces, rice paddies, drainage ditches, and irrigation canals have been constructed and are maintained; manure is heavily applied; and conservation tillage has been adopted. The high population densities make abundant labor available to implement conservation measures, such as terrace construction and maintenance, which requires enormous effort. Moreover, farmland is expensive, and therefore is highly valued and degradation is guarded against.

As population and economic growth increase demand, new lands are brought under cultivation where soils may not be as resilient; in fact these may be areas where agriculture has been attempted in the past, but was not sustainable, so they reverted back to forest or grassland. This is especially true in the tropics and subtropics, where humus and nutrients are rapidly cycled into plant biomass and do not accumulate below ground in the soil like they do in temperate climates. It is also true in drier regions, as we saw with the Dust Bowl disaster in Chapter 2, where droughts leave the soil unprotected from the wind—and the rain when it finally does come in a downpour. It is also true in steep areas, where running water gains the momentum and power to strip soils away if they are not completely protected by vegetation.

These more sparsely populated areas are agriculturally *marginal*; they are mediocre lands brought into cultivation only after the better lands are fully developed. Usually, they are more vulnerable to land degradation. For this reason, increases in cropped area do not yield corresponding increases in harvest, because the best lands are farmed first and expansion occurs on less fertile and less resilient soils.

Looking closer, every locality has unique circumstances, not only of land characteristics and climate but of human characteristics of population, culture, and the social and economic relationships between landowners, land managers, and the land itself. The Midwestern model of the individual farmer who owns the moderate-sized farm (s)he tills does not even characterize the U.S. Midwest, where most farmers own only a minority of the land they work, renting the rest from non-farmers who may or may not live in that county. A farmer has a greater incentive to maintain the natural capital of soil on their own land than on land they rent from others.

In developing countries, some farmers are sharecroppers, giving a proportion of the harvest to the landowner as payment for use of their natural capital. In other areas, farmers may till a particular small field as a family unit but share construction and maintenance of irrigation and terracing systems, or livestock herds, with the village as a unit, where local elders dominate the group decision-making process. In other areas, young men leave for months at a time to work in mines hundreds of miles away, provide military service, or take jobs in a neighboring core country while women do almost all of the farming in the fields and pastures surrounding the village. In other areas, agriculture is export oriented, focusing on cotton, coffee, tea, or bananas and under the control of transnational corporations. In other areas, the export crop is opium or cocaine under the control of illegal cartels who may dominate the local political scene rather than the weak government in the national capital that is under pressure from the United States to pursue the losing battle to crush the drug export industry. In other areas, rapid population growth leads to the division of farms into smaller and smaller pieces until they become incapable of supporting the food, fiber, and fuel needs of a family. Sometimes, as in Rwanda, this can lead to tribal warfare over the natural resources needed for survival. In other areas, it leads to ecocide, where desperately hungry people knowingly overwork the land because the alternative is starvation.

Each of these ways in which society organizes the hard work and the application of knowledge in agricultural production greatly influences the implementation of soil conservation and other natural resource management techniques. Given this complexity and diversity, it is easy to see why Blaikie and Brookfield found that when agricultural specialists or soil scientists from core countries diagnose the problem, outline the solution, and leave, expecting their recommendations to be implemented by local farmers, the results almost universally failed. Political ecology can thus be an intricate field of study that never runs out of new situations to try to understand and hopefully improve.

The Political Ecology of Wildlife Conservation: Two Case Studies

If I were to ask you where you would find the greatest resources of wild charismatic megafauna—big exciting animals you'd like to see—two answers I'd expect to hear are the safari lands of Kenya and the wild arctic lands of Alaska. Let's see how political ecology would view these great wildlife resources.

Kenya's Wildlife

Every American kid, even those few who missed *Lion King* (or its remake using updated animation technology), knows the wildlife of the East African savannas—elephants and lions, hippos and rhinos, hyenas and zebras, and a variety of antelope, like the wildebeest. No doubt conserving these precious wildlife species is a noble endeavor consistent with natural resources sustainability. But it's not that simple.

Figure 10.2. Map of Kenya showing national parks in green.

John Akama, a native Kisii of Kenya, studied the political ecology of wildlife conservation in Kenya's national parks as his dissertation under my direction in 1996. By interviewing local agricultural peoples on the borders of two parks, he was able to unravel a thorny conflict of interest that threatened to undermine efforts at wildlife conservation. International organizations such as the World Wildlife Fund help keep the flow of ecotourists from North America and Europe coming and praise Kenya's conservation efforts. Meanwhile, only a third of the rapidly growing population bordering the parks grows enough food to feed their families. There is an urgent need for more agricultural land, but the parks take up 10 percent of Kenya's land (Figure 10.2.) Wildlife frequently wander out of the parks and damage crops, kill livestock, and injure and occasionally even kill local people. Yet they are forbidden from using force against them, and receive no compensation for damages done. Even when an overpopulated elephant herd was culled by park rangers, local people were denied the meat in the midst of drought and food shortages. Less than three percent of local people earned income from the parks. Local agriculturalists who entered the parks were arrested or shot at by rangers, always imported from another tribe in Kenya. An elderly Kamba man living on the border of Tsavo, Kenya's largest national park in the Serengeti Plain on the Tanzania border, summarized the local feelings:

> Whether they [the government] like it or not, we are going to occupy this wilderness. This land used to belong to our forefathers and since our present population has increased tremendously, the wilderness should now be opened for agricultural production (Akama et al., 1996, p. 133).

Only 10 percent of local residents surveyed felt that the park is an asset to local people, 17 percent felt the relationship between the local people and the park is good, and 12 percent felt that wildlife conservation is the most appropriate use of the park land. A majority thought the park should be abolished. These attitudes obviously run counter to those of park officials, the Kenyan government, and ecotourists.

Ecotourism was and remains Kenya's largest source of foreign exchange, funding the modernization of Nairobi, supporting the government bureaucracy, and providing steady jobs for park personnel, some of whose primary job is to keep local farmers and herders out. Science is also at issue. Zoologists from around the world have studied the dietary, health, and reproductive requirements of East Africa's wildlife, but few are studying how to improve agricultural productivity in savanna soils, or where best to place wells to provide safe drinking water for villagers.

Are local Africans then against conserving these wonderful wildlife species? No. Not only do they consistently assert the animals' right to live on the land, but the tremendous herds that early European explorers found in East Africa are proof that African approaches to wildlife management were sustainable, even when they involved hunting. This was the way of life of people such as the Walianguru, whose livelihood was criminalized when the British occupied Kenya, while opening the herds up to western big game hunters including President Teddy Roosevelt, renowned as a conservationist. Perhaps the issue is not pro- vs. anti-conservation. It is conservation for whom?

Alaskan Subsistence

For Americans from the Lower 48, Alaska represents a great northern frontier, a place where the human imprint is evident, but nature, both nurturing and harsh, is dominant. It is a place where the landscape of temperate rainforest, taiga, marshland, arctic tundra, and glaciers has not been transformed into the cities and farms that dominate the Lower 48. As a result, charismatic megafauna—brown and polar bears, caribou, moose, salmon—still live in abundance in natural breeding and predator-prey relationships. Those same wildlife and landscapes draw hunters and anglers seeking optimal recreational experiences as well as tourists who just want to take it all in.

Like arctic communities elsewhere, harvesting of terrestrial and marine wildlife is a fundamental part of many Alaskan's lives, both for food and materials and as a part of long-standing cultural traditions that establish individual and group identities. In rural Alaska, it has been estimated that the average person catches and eats an annual harvest of 120–370 pounds of fish and 80–250 pounds of birds and mammals. Because it is fundamental to people's lives, access to Alaska's wildlife is contested, and the laws governing such access are a core part of the social structure of the state for both Native peoples and for more recent Euro-American immigrants, especially for the quarter of Alaskans who reside in the vastness of rural Alaska beyond Anchorage, Fairbanks, and Juneau.

This case study explores the political ecology of consumptive access to Alaskan fish and wildlife.

Like elsewhere in the arctic, biological productivity and biodiversity are generally low in Alaskan ecosystems. Food chains are simple and subject to cascading effects from the harvest of a single species. Most animals are migratory. Populations fluctuate wildly. Nevertheless, Alaskan ecosystems remain vibrant. The northwestern Alaska caribou herd varies from one-half to one million animals. Salmon runs in Alaskan rivers have not declined substantially from pre-European times. Traditional subsistence and even recreational hunters and anglers are often the staunchest of conservationists, not only because their culture, livelihood, or cherished hobby is dependent upon the continued availability of wildlife but also because they have spent considerable time and energy in a direct relationship with nature that, while consumptive, is generally sustainable rather than exploitive. Demand for wild species creates a demand for wild lands that are their habitat and a resistance to urban, agricultural, and industrial development. Harvest of wild species is also less energy-intensive than agriculture, especially for the production of protein.

Harvest of Alaskan fish and wildlife is divided into dangerously fuzzy legal sets: “commercial,” “recreational/ sport,” and “subsistence” (living off the land). Of all fish and game harvested in Alaska, 4 percent is subsistence, 1 percent is sport, and fully 95 percent is commercial, with a focus on the prodigious fisheries of the shallow Bering Sea that supply a majority of all fish caught in U.S. waters. There is a great deal about subsistence use of fish and wildlife in Alaska that is not recorded because of the predominance of oral tradition and because subsistence practices are extremely localized and varied, reflecting differences in both ecology and culture. For example, among ten rural Alaska communities, there are ten different wild species that rank as the most important food source: chum, sockeye, and coho salmon, whitefish, herring, halibut, caribou, moose, deer, and bowhead whale. If the top ten food sources for each of these communities are listed, 172 species appear.

The history of Native-White relationships in Alaska contains elements of the tragic history of disease, conquering, establishment of reservations, and failed assimilation that characterizes the Lower 48, but it is also different in important ways. In contrast to Great Plains Indians, for example, who no longer hunt bison because White buffalo hunters nearly exterminated them, Alaskan Natives have been partially successful in their struggle to maintain wildlife harvesting in the places their ancestors lived, while also pursuing cash incomes to supplement subsistence hunting and fishing.

The case of the Tlingit is particularly instructive. The richness of the salmon runs of southeast Alaska allowed a sedentary existence for the Tlingit and the consequent formation of social hierarchies at increasing scales from persons to houses to clans to moieties to kwaans. Clans maintained use rights to critical natural capital—salmon streams, halibut banks, hunting grounds, sealing rocks, berrying grounds, shellfish beds, canoe-landing beaches—and clan names reflect an association with a sacred geography. In their own language, they are "beings of" or "possessed by" the location where they live.

Through the Central Council of Tlingit and Haida Tribes of Alaska, these tribes have been able to respond to White encroachment on fishing grounds and historic native lands by empowering traditional kwaans with functions similar to municipalities, thus gaining common property control over fishing and hunting grounds and reversing the earlier forced trend toward private ownership of farm-sized plots of land. The Alaskan Federation of Natives (AFN), formed in 1967, has acquired considerable political standing and has made protection of subsistence rights a major issue. Native Americans have struggled to assert their rights with regard to cultural survival, protection and retention of land, self-government, and to avoid the welfare state of too many of their cousins in the Lower 48. Subsistence rights to fish and wildlife are critical to all of these goals.

Nevertheless, relationships between Native Americans, Euro-Americans, and wildlife in Alaska remain as complex and contentious as anywhere in the Arctic, and laws granting priority to *subsistence* hunting and fishing divides the Alaskan electorate like no other issue. White urban Alaskans, 80 percent of the state population, also cherish consumptive access to fish and wildlife. While not dependent on consumption of wildlife for a livelihood or food, many residents of Anchorage, Fairbanks, and Juneau value hunting and fishing as part of being an Alaskan and as a reason for living in Alaska despite its bad weather, extreme variations in length of daylight, and remoteness. They have invested considerably in boats, guns, tackle, even airplanes in order to get out there where their game live. Represented by groups like the Alaska Outdoor Council, urban-based hunters and anglers often oppose subsistence rights and are a major force in state politics. Recreational hunting and fishing by ecotourists is also growing and the economic value of game taken for sport is particularly high. For the millions of hunters and anglers in the Lower 48, Alaska represents a peak once-in-a-lifetime experience in the remote wilderness. Many will pay top dollar for guided access to trophy hunting for caribou and brown bear or to fly-fish for abundant salmon and trout that will not reject flies their distant Lower 48 cousins have seen again and again.

ANCSA and ANILCA. In 1971 Congress, without strong support from Alaskan natives, passed the Alaska Native Claims Settlement Act (ANCSA) establishing 12 regional Native American for-profit corporations and granting control of 11.6 percent of Alaskan lands, plus $962.5 million, while eliminating Native claims to the remaining 88.4 percent of Alaska. For example, 16,000 Tlingits enrolled as shareholders in Sealaska Corporation received $250 million. ANCSA states:

"All aboriginal titles, if any, and claims of aboriginal title in Alaska based on aboriginal use and occupancy . . . including any aboriginal hunting or fishing rights that may exist, are hereby extinguished."

ANCSA was followed in 1980 by the Alaska National Interest Lands Conservation Act (ANILCA) that divided federally-owned lands in Alaska totaling over 200 million acres, more than 60 percent of the state, among the Bureau of Land Management (24 percent of the state), the Fish and Wildlife Service (19 percent), the National Park Service (15 percent), and the National Forest Service (6 percent). The State of Alaska manages 24 percent of the state's land, and Native Corporations manage 10 percent, with only one percent of the land privately owned. Beyond settling the division of land management responsibilities, ANILCA also established subsistence rights to harvest wildlife as a priority over commercial and recreational uses, giving preference to rural Alaskans but no preference to native Alaskans, some of whom have urban addresses.

Sport hunting and fishing interests attempted in 1982 to have the subsistence provisions of ANILCA repealed, but urban majorities overwhelmingly supported ANILCA at the polls. In December 1989, amid controversies over the meaning of "rural," the Alaska Supreme Court invalidated ANILCA because it explicitly grants priority to rural residents and in so doing violates the state constitution's rule of equal access. As a result of this and the state legislature's failure to remedy the problem, in 1992 for wildlife and in 2000 for fish, the federal government took over jurisdiction of subsistence activities on 60 percent of Alaskan lands under federal jurisdiction. They formed a six-member Federal Subsistence Board tasked with determining annual hunting and fishing regulations and customary and traditional uses. Individual bag limits and seasons that constitute the nuts and bolts of Euro-American hunting and fishing regulations have frequently been found to be incompatible with native patterns of communal harvest at key stages in wildlife migrations.

Recreational use has come into direct competition with subsistence use of fish and game in ways that reflect a certain incompatibility between rural subsistence traditions derived from a hunting and gathering lifestyle and a growing Euro-American, urban-based culture with a sporting tradition that values excitement in the catch, taking home trophies, traveling long distances, and buying expensive equipment and guides. For example, urban Alaskans and tourist hunters spend enormous sums for guided trophy brown bear hunts, leave the meat behind as inedible, and take the skulls and skins to be displayed as evidence of their prowess. Natives hunt brown bear as they emerge from their dens in the spring for meat to be shared. The skins are left at the kill site pointed in a particular direction that carries spiritual meaning and no mention is made of the hunt lest the bears overhear the conversation. Bear hunting clearly means different things to these two cultures.

Difficult issues remain on the table. Rural re-determination is particularly controversial because, not unlike congressional redistricting, it draws lines on a map around urban areas demarcating populations that are not eligible for subsistence use rights and can harvest fish and game only within normal seasons and established limits of the kind that most Americans find familiar, even if they are a Native and even if their great-grandfather practiced subsistence hunting or fishing. Meanwhile, their next-door neighbor on the rural side of the line who moved to Alaska last year to take a white-collar job has subsistence rights and is allowed, for example, to catch 30 halibut per day and sell $400 of this catch per year. With many rural Alaskans maintaining post office box addresses in town, and with many urban recreational hunters and anglers looking for loopholes, determining the identity of those with and without subsistence rights is an ongoing headache for state and federal personnel.

On Prince of Wales Island, the largest and by far the most ecologically productive island in the Tongass National Forest of the southeast Alaskan archipelago, the harvesting of timber occurs at an economic loss due to high transportation costs and other factors. With recreation and tourism on the rise, the potentially negative effect of clear-cutting on scenic and ecological values adds to the argument against cutting. But it's not that simple.

Tlingit interests on Prince of Wales Island claim that recreational hunters are allowed too large a harvest of black-tailed deer, thereby undermining their most important source of subsistence and their priority rights under ANILCA. Most deer are taken by hunters along logging roads, not only because of the greater access but because old -growth forest is poor deer habitat while timber lands recovering from harvests that took place in the last 30 years make ideal habitat because of the diversity of leafy, woody plants growing at a height that deer can reach. Coordinating forest cutting with deer habitat requirements, and thus subsistence needs and recreational hunting demands, not to mention employment and revenue considerations, therefore represents a challenge for managing timber and wildlife resources jointly and sustainably. Moreover, few reliable data are available on basic characteristics of the ecosystems being managed, such as how many deer there are, how many deer are harvested for subsistence and by recreational hunters, and how large a proportion of the Tlingit diet consists of venison.

This political ecological analysis of consumptive wildlife use rights in Alaska helps to illustrate principles of natural resource sustainability. When consumptive use of specific wildlife species is open-access, and when the food, fur, or other products are sold in global markets, depletion and collapse are the likely result. While an improvement over the tragedy of open access, maximum sustainable yield (see Chapter 7) enforced through regulations can also fail because it results in standing stocks less than half of natural levels with cascading ecological effects and because ecosystems exhibit chaotic and unpredictable variations in fish and wildlife populations, making it impossible to identify the sustainable yield beforehand.

The Alaskan economy remains heavily dependent on natural resources, though with a shift from consumptive harvesting of timber and fish to less consumptive ecotourism. Who will ultimately benefit from this new economy is still being determined.

Getting Started on the Sustainable Development Path

Jeffrey Sachs is a development economist at the Earth Institute at Columbia University rather than a political ecologist, but I am including a discussion of his excellent and inspiring 2005 book *The End of Poverty: Economic Possibilities for Our Time* in this chapter, partly as an antidote. Political ecology can be very insightful in diagnosing problems as we have seen, especially of environmental injustice and inequality in access to natural resources, but it is perhaps less skilled at identifying solutions. Sachs also uses the medical metaphor of "diagnosis," but fortunately, he also provides prescriptions for a cure of many problems of natural resource degradation and poverty in the global economic periphery.

Like the human body, a society, part of which we can think of as an economy, is a complex system where different components are dependent upon one another. Your digestive, nervous, circulatory, immune, and skeletal systems, for example, can only function if the other systems are also functioning. Similarly, agriculture, water supplies, transportation, health care, education, and so forth are interdependent systems in a community. Just as the symptom of a fever can be caused by many different ailments, so poverty is a symptom that requires a differential diagnosis. In medicine, one must treat a patient in the context of their family and home environment. Similarly, poverty or prosperity rarely occurs in one person, or even in one household; it is a characteristic of an entire community. In medicine, the doctor must frequently monitor the patient's condition, such as their temperature, cholesterol, or blood sugar levels. Similarly, monitoring and evaluation are critical in staying on the pathway of sustainable development. Did the new road really open up urban or even international markets for local farmers? Is the distribution of pesticide-laden bed nets really decreasing cases of malaria? How much have crop yields increased due to new fertilizers? Are people actually drinking the cleaner water from the new tube wells or are there unforeseen social barriers to using it? Each locality is poor for a different reason, and each requires a different remedy. Each is also at a different level on the ladder of development and needs a different treatment to climb the next rung.

As we saw in the case of land degradation, poverty lays at the heart of a number of land-use-based natural resources problems. These can become part of the poverty trap, alongside high rates of disease and child mortality, consequent rapid population growth (remember descendant insurance from Chapter 5), climatic fluctuations such as drought, and a loss of revenue when a single key natural resource export loses its market.

Poverty is often localized where basic infrastructures like roads, water and sanitation, electrical power, and telecommunications are lacking. It can occur in very densely populated urban slums, densely populated fertile valleys and plains, or in sparsely populated grazing regions where it is prohibitively expensive to provide infrastructure and connectivity. This kind of rural isolation is especially evident in Africa, where a dispersed population lacks a spatial node such as a port city from which economic development derived from foreign direct investment can spread. Here the problem is that globalization has thus far passed it by.

Disease ecology is also a critical factor in the poverty trap. While you have likely heard a great deal about how AIDS (Acquired Immuno- Deficiency Syndrome) is most virulent in Africa, malaria, a debilitating fever spread by mosquitoes, is at least as great a threat to human life.

Sachs is a tireless advocate of foreign aid. His argument is that, properly allocated, it can be an investment that sets a locality on a pathway of sustainable development. So what should aid be spent on? Sachs argues that there are four key investments that can break the vicious cycle of poverty if carefully allocated as a package:

1. agricultural productivity focused on high-yielding seeds, irrigation water, and fertilizer inputs;
2. basic health care, including family planning and combating environmental diseases like malaria and water-borne pathogens;
3. education with an emphasis on universal primary education;
4. and basic infrastructure such as water and sanitation, roads, electricity, and telecommunications.

The purpose of these investments is to meet the Millennium Development Goals established by the United Nations:

1. Eradicate extreme poverty and hunger by halving the proportion of people living on less than a dollar a day and suffering from hunger.
2. Achieve universal primary education.
3. Promote gender equity and empower women.
4. Reduce child mortality by two-thirds.
5. Reduce maternal mortality by three-quarters.
6. Combat HIV/AIDS, malaria, and other diseases.
7. Ensure environmental sustainability, including halving the proportion of people lacking access to safe drinking water and basic sanitation.

8. Develop a global partnership for development.

It is particularly encouraging to witness the recent increase in global efforts to shrink the malaria map. Since 1946, malaria has been essentially eliminated from the U.S., Europe, southern Brazil, northern China, and North Africa, but it remains pandemic in many tropical areas. It is especially virulent in tropical Africa where 90 percent of world cases occur—over 200 million per year, resulting in over 400,000 deaths, 70 percent of which are in children under five years old. With economic costs of at least $12 billion per year, it is one of the primary factors holding back sustainable development in Africa. A number of international efforts—including the Roll Back Malaria campaign, the Gates Foundation, and the President's Malaria Initiative begun in 2005—are focusing on the free distribution of long-lasting insecticidal bed nets, antimalarial drugs such as artemisinin to replace chloroquine, and research toward a vaccine, where substantial progress was made in 2013. There is reason to be optimistic that the malaria map is about to be rolled back. Nevertheless, global commitments to meet the Millennium Development Goals continue to lag far behind the needs.

In contrast to many political ecologists, however, Sachs contends that globalization and trade has greatly reduced poverty and thereby has advanced the Millennium Development Goals, especially in regions like eastern China and urban India where it has been most active. What the low-income periphery countries of sub-Saharan Africa and parts of Asia lack is the foreign direct investment that globalization brings.

On this question of globalization and sustainable development, I find myself siding with Sachs. What is needed is a more progressive approach to globalization where poverty is ameliorated directly through targeted foreign aid rather than only as a side-effect of capitalist economic development, as powerful as that force can sometimes be for human progress. What is needed is a globalization where environmental and labor standards are actively advanced by organizations such as the World Trade Organization. In this manner, the 21st Century may see natural resources sustainability and the end of poverty achieved simultaneously—partly because each depends on the other.

Conclusion

In contrast to the neoclassical, ecological, and institutional schools of economics, political ecology focuses on diagnosing the political roots of environmental injustice and unequal distribution of the benefits of natural resources. While applicable to the U.S. and other developed countries, its particular focus is the problems of poverty and degradation of land-based resources in the world economic periphery. Managing natural resources for environmental sustainability is necessary but not sufficient. They must also be managed for the sustainability of human capital by meeting the basic needs for food, water, energy, and health of all humans.

With our quadfocals now placed securely on our noses, we are ready to proceed into a resource-by-resource analysis of sustainability in the management of land, water, minerals, and energy in Part III of this text.

Further Reading

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PART IV

PART V: MOVING TOWARD NATURAL RESOURCES SUSTAINABILITY

11.

CHAPTER 15: POLICIES FOR NATURAL RESOURCES SUSTAINABILITY

I aspire to be an environmental policy "wonk." Likely, you don't. Yet even if you don't watch the *PBS News Hour* or *Global Public Square* or read the *Washington Post* or the *New York Times*—some of the best ways to stay informed about what's going in the United States and the world—you can't have completely missed the debates over climate change or fracking that have made environmental policy front page news. But there are a lot, an awful lot, of important developments and policies being made that don't register on the radar screen of even in-depth reporting, no less the popular cable TV news and viral Internet stories, which are perhaps better thought of as "news-ertainment." Before we launch into insider topics, let's start at the beginning. What is policy and how is it made?

The Policy Process

Policy is a decision made by an institution that has authority over employees, products, citizens, or other entities. Companies and corporations make policies as do colleges and universities. Your instructor makes policies over how your grade will be determined and your college makes policies governing what courses you need to pass to earn a specific degree. The primary purpose of governments is to make policies, some of which can be described as laws. The purpose of the legislative branch, the House of Representatives and Senate at the national level and similar bodies at the state level, is to write *statutes*, but it doesn't stop there.

The judicial branch decides cases that serve as precedent in subsequent cases and in so doing builds the *common law*. The executive branch also has an important role to play in making policy as well as the lead role in implementing it. The U.S. Environmental Protection Agency (EPA), for example, is charged with implementing the Clean Air Act, the Clean Water Act, and a dozen other environmental statutes that both houses of Congress have passed and the president has signed into law. Often, the statutes passed by Congress omit many of the important details for implementation, leaving to executive branch agencies like the EPA, the U.S. Department of Agriculture, or the Department of Interior the task of *rulemaking*, of writing the actual regulations that the country must follow. State and local governments operate similarly, creating a complex web of environmental policy across three branches of government and at least three geographic levels—a system of shared responsibility referred to as*federalism*.

Do you remember the lesson from social studies class on how a bill becomes a law? Using an important example, bills to regulate greenhouse gas emissions, let's walk through this process. In 2007 Senators Lieberman and Warner, or more accurately the young legal staff that work for them, prepared the *America's Climate Security Act of 2007*. Initial projections by party leaders (it's the whip's job to keep track of straw polling on upcoming bills) indicated that a slight majority in both the House and the Senate would support it, especially Democrats who held a majority in both houses at the time and therefore controlled which bills come to the floor for debate and vote. Then-President Bush, a Republican, however, indicated that he would veto the bill, and it takes a two-thirds majority in both houses to override a presidential veto. Seeing this obstacle as insurmountable, Democratic leaders decided to *table* the bill—lay it aside for later with the hopes that the Democratic candidate, Barack Obama (who had indicated his support for the legislation), would win the 2008 election over Republican candidate John McCain.

In 2009, with President Obama in office and a Democratic majority in both houses, the issue came up again. The Waxman-Markey *American Clean Energy and Security Act of 2009* came to the floor of the House in June 2009, passing by a narrow 219–212 vote. The similar *Clean Energy Jobs and*

American Power Act, authored by Democratic Senators Kerry and Boxer, was then prepared for consideration by the Senate. But the Senate takes its sweet time. A minority of 41 of 100 Senators can block a bill from coming up for vote by engaging in a *filibuster* (endless debate) and it takes 60 votes to enact *cloture* ending debate and forcing a vote. The remainder of 2009 was taken up with Senate debate over the Affordable Care Act as the Obama Administration and Democratic leaders in the Senate worked to gain 60 votes in order to override a filibuster threatened by Republican Senators. The election of Republican Scott Brown of Massachusetts to take over the Senate seat vacated by Democrat Ted Kenney's death strengthened their hand.

When the historic Affordable Care Act was passed in early 2010 by a legislative maneuver that made an end-run around the Senate filibuster, the Kerry-Boxer cap-and-trade bill was next in line and faced a very similar legislative fight. With the mid-term elections coming up in November 2010, and with very little Republican support, the Democrats decided to table the bill again, likely on the calculation that a second historic legislative battle would cost them even more votes in November. So the bill went into limbo, and was set aside when the Republicans took a majority in the House in the 2010 mid-term elections.

Control of greenhouse gases, however, has a second legal angle residing in the judicial and executive branches. In 2007, in *Massachusetts v. EPA*, the U.S. Supreme Court decided that the EPA administrator must determine whether greenhouse gases pose a danger to public health, and if they do, regulate emissions. On April 17, 2009, EPA issued a preliminary statement finding that they do after considering 380,000 comments received from the public in the *notice and comment* informal rulemaking process. After considering these comments, the EPA issued its final finding on December 7, 2009: greenhouse gas emissions pose a threat to human health and welfare. This finding requires the EPA to regulate greenhouse gases under the Clean Air Act.

The next step is for EPA to write the regulations following the Administrative Procedure Act. Through the rulemaking process, the Obama Administration in June 2014 issued notice for a proposed rule called the Clean Power Plan targeted at reducing greenhouse gas emissions from the generation of electricity. After receiving thousands of comments and modifying the rule in response to them, the final rule was issued in August 2015. It was challenged in the courts by a collection of 14 states, however, which placed a stay (a delay in implementation) on it until certain legal issues were worked through. The Trump Administration then issued an *executive order* on March 28, 2017 reviewing the Clean Power Plan. On August 21, 2018, the EPA provided notice of a proposed rule called Affordable Clean Energy that de-emphasized control of greenhouse gas emissions. The final rule was issued on June 19, 2019.

Meanwhile, ten U.S. states (CA, CN, DE, MA, MD, ME, NH, NY, RI, VT) went ahead with their own carbon emission control policies, generally following some form of cap-and-trade.

In 2022, with Democrats holding the White House and very narrow majorities in both houses of Congress, legislation to combat climate change came up again, initially as part of a huge collection of investments termed "Build Back Better." But after several rounds of negotiations, a majority could not be found for this legislation. Instead a much smaller, but still substantial, partisan compromise was found in the form of the Inflation Reduction Act. While the name of this bill is pure political spin, it provides about $400 billion in tax credits for clean energy investments, from huge wind and solar farms to electric vehicles to heat pumps. It's passage onto law reflects that, while a consensus could not be reached on penalizing carbon emissions, a majority do support subsidizing with taxpayer dollars the transition to sustainable energy systems. Rather than internalizing the cost of greenhouse gas emissions—the social cost of carbon—this approach makes low-carbon energy cheaper and thus more economically competitive against fossil fuel-based energy. Sticks-no; carrots-yes.

What this particularly fascinating and relevant example shows is that the lesson in how a bill becomes a law you learned in social studies class is like learning that, in chess, a bishop moves diagonally and a rook moves straight. When actual policy decisions come along, however, it becomes a matter of actually playing chess—to win—in a power struggle among groups whose interests and philosophies may be in conflict.

In the regulation of greenhouse gas emissions example, some interest groups are naturally in opposition; the fossil fuel and automobile industries come first to mind but also many average citizens who are concerned about increasing prices for electricity and gasoline. How do these groups stack up against the coalition in favor of the legislation: people who are concerned about climate change impacts, the renewable and nuclear energy industries, the property insurance industry who doesn't want to keep paying for the natural disasters climate change brings forth, and so on. And there are a lot of tactics at play, especially the efforts by the former groups to cast doubt on the science of climate change and to argue that controlling greenhouse gas emissions will ruin the economy. Like all policy, environmental policy is politics. As in a football or basketball game, it's a power struggle structured by rules. The heart of the political process is attempts to gain the leverage to structure rules that give your interests a competitive advantage. Sometimes one team wins and the other team loses, though neither victories nor defeats are ever permanent because the season never ends.

Like many, perhaps most, Americans, I find much to critique in this policy-making process. The two dominant political parties play too much against one another and too little for the American people, no less the environment. Money, through campaign contributions that fund media propaganda in ever-lengthening, perhaps even permanent election seasons, has too much influence on who gets elected and the policies they favor once in office. Special interest groups—banks, insurance companies, oil companies, retired people—who can afford the best lobbyists have undue influence and even seem sometimes to be writing the laws and regulations for their own benefit. The media, often owned by these same interests, consistently misses the bigger picture and instead focuses on emotion-grabbing conflicts, vexing improprieties that scrape against our sense of moral and ethical behavior, details of celebrity's personal lives, and sentimental human interest stories. That gets ratings and ratings determine how much advertisers have to pay, which determines whether the news show makes a profit. Meanwhile, the important things that are really going on in the world sometimes receive little attention—unless you consciously look for it beyond the bounds of cable TV news, talk radio, and Internet noise. There is indeed a lot to complain about U.S. democracy, perhaps more than there has been in a century.

In my limited interactions with the political system, however, I've found that it is less corrupt than the cynical public believes and conspiracy theories hold little water. Rather what we have is a battle of interests and a struggle of interpretations founded in beliefs and cultural identities, with unequal capacities to advance these interests and interpretations. Participate in this flawed system and you'll win some battles and lose the rest. Opt out and you'll lose them all by default.

Principles of Sustainable Policies

The often-stated three normative goals for policy making are *efficiency, equity*, and *sustainability*. Neoclassical economics, which we studied in Chapter 6, focuses on efficiency, on maximizing net benefits and cost-effectiveness. As we saw in Chapter 10, political ecology, with its emphasis on social and environmental justice, focuses on equity—fair, if not necessarily equal, outcomes, equal opportunity, and a fair application of the law and rules of the game. Let's review, especially from Chapter 7 on ecological economics, what sustainability requires. Natural capital must be preserved, and perhaps even restored, so that ecosystem services can continue to benefit people and species can be saved from extinction. This means fewer withdrawals from natural capital in the form of resource extractions and waste emissions and greater investments in ecological restoration and resource use efficiencies.

From these three criteria of policy evaluation we can derive some secondary principles. One is *polluter pays*. This is a way of preventing the true social and environmental costs of production from being externalized—of making someone else pay for it in the form of degraded ecosystems, destabilized climate and, as was the focus of the popular movie *Avatar*, undermined indigenous cultures. This is a central principle in pursuing a policy for greenhouse gas emissions, for example. The flip side is *provider gets*. Ecosystem service provision should be compensated so that it is encouraged.

The *precautionary principle* states that, when there is uncertainty over the outcome, the policy that minimizes the consequences of the worst case scenario should be adopted. This principle has played a prominent role in limiting nuclear power development and is often raised against development of new chemicals, nanotechnologies, and genetically modified organisms.

Other principles relate to the decision-making process. *Subsidiarity* calls for policies to be made at as local a level as possible. Local control allows managers to respond to ecological uniqueness and emerging situations rather than be held to rules made thousands of miles away by bureaucrats who know little of local circumstances. Local control can also foster inclusivity and *public participation*. People are much more likely to follow and consider legitimate rules they helped make or that were developed by their neighbors, rather than distant bureaucrats, whether these are governmental or corporate.

With these means of policy evaluation in hand, it's time to examine some specific policies that would foster natural resources sustainability. From the long list of possibilities, we'll focus here on three that are particularly relevant: (1) putting a price on carbon, (2) incentives for sustainable energy, and (3) the Waters of the United States rule governing wetlands.

Putting a Price on Carbon

Whether a substance constitutes pollution is dependent on its context and concentration. Regulations are the dominant form of environ-mental policy when dealing with toxic pollutants like dioxin, DDT, mercury, or lead. Sulfur is a naturally occurring and fairly common element essential to life but it causes respiratory problems and acid rain at high atmospheric concentrations. Carbon dioxide is similarly an essential part of the atmosphere that fuels photosynthesis and helps maintain Earth's temperature but it becomes the most important component of climate change when concentrations climb.

For pollutants like sulfur and carbon dioxide that are only harmful in excess, and where complete elimination is extremely expensive or not called for on environmental grounds, economic incentives have substantial merit as a flexible form of environmental regulation. As we reviewed in Chapter 6, environmental economists have made a strong argument that emission fees and tradable pollution permits can be more cost-effective in attaining a pollution control goal than can regulations that have dominated environmental policy for decades. These policy mechanisms can achieve a specific politically determined pollution control or ecosystem service provision goal at less cost than other forms of regulation.

Reviewing from Chapter 6, it is nearly always the case that firms in an industry or group of industries that emit a particular pollutant have different marginal abatement costs. Greenhouse gas emissions, for example, come from several sectors of the economy, including electrical power plants, vehicles, and the landscape. Reducing emissions will have different costs in each situation by, say, closing down a coal-fired power plant in favor of wind or solar, switching to a plug-in hybrid car, or planting trees on a cattle pasture.

Emission fees or taxes can achieve equimarginality and thus cost-effectiveness in a straight-forward way. If each firm has to pay a set fee of, say, $25 for each ton of carbon emissions, each will abate pollution where marginal costs are less than $25/ton and pay fees for more expensive reductions.

Moreover, both tradable permits and emission fees give firms an incentive to reduce more pollution than regulations require and to develop technological or institutional means to control emissions at less cost because, by doing so, they can sell permits or avoid buying permits or paying fees.

For these reasons, emission fees and tradable pollution permits have been promoted by environmental economists. These policy mechanisms are also winning adherents within an environmental community that is increasingly coming to the realization that environmental improvements must be made by changing private sector behavior within a competitive capitalist framework. We cannot regulate our way to sustainability. What we will see, however, is that in practice it gets one whole heck of a lot more complex than even this subtle argument would suggest. Nevertheless, it is worth working through the complexities because market-based policy mechanisms such as pollution fees and tradable permits are a critical and increasingly important component of natural resources sustainability.

The U.S. Experience with Cap-and-Trade

Let's first examine Title IV of the 1990 Clean Air Act amendments governing emissions of sulfur dioxide from coal-fired power plants. The statute set a cap on total sulfur dioxide emissions from coal-fired power plants, distributed initial allowances at a rate of 2.5 pounds per million btu (1.2 pounds after 2000 in Phase II), and allows firms to trade and to bank these allowances. The allowance trading zone is the 48 contiguous states. Phase I (1995–1999) applied to the dirtiest 261 electric power-generating units and Phase II (2000–2010) applied to most fossil fuel units of 25 megawatts or greater.

Did this first major experiment with *cap-and-trade* work? There has been 100 percent compliance reducing emissions from 8.7 to 4.4 million tons. In fact, affected facilities overcomplied in Phase I in order to bank 11 million tons of allowances for use in Phase II. Costs of abatement fell from $2 billion to $1 billion with benefits ten times higher. Similarly, emissions have been further reduced by 1.4 million tons in Phase II, leaving only 3.0 millions tons, a 66 percent reduction overall.

The reductions in sulfur dioxide emissions and abatement costs came largely from utilities switching from high-sulfur to low-sulfur coal, especially from Wyoming. Within utilities, responsibility for buying and selling allowances has shifted from engineers to financial officers responsible for fuel purchases. Initial transaction costs of 30–40 percent of the value of allowances fell to about 1 percent as participation in the program became embraced and routine. Title IV of the Clean Air Act amendments thus serves as the best model of successful real-world application of tradable pollution permits (i.e., cap-and-trade). More recent shifts from coal to other sources of electricity have reduced sulfur emissions even further.

Later attempts to utilize the cap-and-trade approach have not been as successful, however, and it's important to see why. The Clean Water Act distinguishes between *point-source* pollution, pipes and other outflows that are directly regulated under the National Pollutant Discharge Elimination System, and *nonpoint-source* pollution, which is not, but is subject to Total Maximum Daily Load requirements that are focused on ambient water quality in watersheds rather than on discrete emitters.

Since the 1970s, the Clean Water Act, largely through subsidies to construct wastewater treatment facilities, has done a very good job of controlling point sources but not nonpoint sources. For this reason, it is widely believed that nonpoint sources of nutrients, mostly from agriculture, have lower marginal abatement costs than do point sources, mostly from industry and cities. These circumstances have led to the notion that nutrient trading, especially with point sources as allowance buyers and nonpoint sources as allowance sellers, has the potential to achieve positive economic and environmental results such as those achieved with sulfur. Eighteen states have passed legislation allowing the formation of water pollution trading districts for nitrogen and phosphorus and 37 trading districts were formed. As of 2007, however, only 8 districts had conducted any trading, and the total number of trades in the U.S. was a paltry 13. Moreover, only one of these trades involved a nonpoint source. Trades that have occurred are approved by U.S. EPA on a case-by-case basis; no open-market trading has occurred. Why has water quality trading failed where sulfur trading succeeded? We can identify six reasons.

1. Equity. Regulated point-source emitters such as sewage treatment plants see as unfair a system where non-point emitters such as farms are not regulated.

2. Unregulated nonpoint sources deliver the vast majority of nutrient pollution. How can allowances purchased by point sources do more than scratch the surface of nonpoint runoff?
3. Immeasurability. While point-source emissions flowing out a pipe can be easily measured, nonpoint runoff of nutrients from a specific area of land is very difficult to accurately measure. It is dependent on a multitude of factors such as weather, soil type, the location of drainage tiles, the juxtaposition of cropped fields, vegetative filter strips, surface water channels, and groundwater recharge zones. Because of this uncertainty, trading ratios of 2:1, 3:1, or higher were introduced to make sure that a trade does not result in an increase in ambient nutrient concentrations. But with a ratio of 3:1, marginal costs of nonpoint reductions must be less than one-third as high as point source reductions to facilitate a win-win trade, even without considering transaction costs.
4. Additions from a baseline. Land use changes that are used to create a nutrient reduction credit may have been undertaken anyway. For example, a farmer may plant soybeans instead of corn and sell a nutrient credit but (s)he would have planted soybeans anyway. So there is a problem of baseline nutrient runoff to which must be applied the principle of *additionality*—what additional nutrient reductions can be attributed specifically to the

land management changes associated with the allowance sold?

5. Transaction costs are extremely high because EPA must approve each trade and because farmers and other nonpoint emitters do not normally participate in pollution trading.
6. Geography. While the location of sulfur emissions does matter at a regional scale, the specific location of nutrient runoff or emissions is absolutely critical. Trading nutrient pollution reductions in one watershed for increases in another is unsound since the ecological effects of the nutrients are specific to the location in which they occur. For this reason, the spatial extent of pollution trading must be defined by relatively small watersheds that generally do not contain a critical mass of potential traders.

Cap-and-Trade or a Carbon Tax?

Either cap-and-trade or a carbon tax would force us to buy our carbon footprint while driving greenhouse gas emission abatement toward equimarginality and thus cost-effectiveness. The next question is which is better? The tradability in permit systems facilitates relationships both among polluting firms and between them and sequestration projects. The cap in a cap-and-trade system can require emissions to be reduced at a predetermined rate. For example, the bills that have been proposed in Congress have caps that decline linearly from levels in the year the law takes effect to a 75–80 percent reduction in 2050. This can lead, however, to volatile prices for permits on the carbon market.

The alternative to a decreasing emissions cap is an escalating carbon tax that starts at, say, $20/ton and steadily climbs to perhaps $100/ton in 2050. While this makes the price of carbon predictable, it is difficult to know how rapidly emissions would be reduced as a result. It would also fail to build a direct transactional relationship between carbon emitters and sequestration and storage projects, for better or worse. In fact, a separate carbon credit program, perhaps organized by the U.S. Department of Agriculture, would be required.

When I weigh these pros and cons in the cap-and-trade vs. carbon tax/fee debate, I come out with a practical solution: either is far preferable to a situation where greenhouse gas emissions are unregulated and emitted for free. A carbon tax does have a strong element in its favor, though. A cap-and-trade system anchors emissions while making costs volatile. A tax anchors costs, but it allows emissions to vary. The latter may be preferable because implementation of the long-term, capital-intensive projects that would effectively reduce carbon emissions require certainty of costs. That way companies and investors can place many millions of dollars on the line for a solar or wind farm instead of a coal or gas-fired power plant knowing that the planned carbon taxes—high for coal, moderate for gas, zero for solar or wind—make solar or wind the best investment. With cap-and-trade there's too much uncertainty over permit prices to make this kind of calculation with any confidence. Moreover, carbon taxes can be redistributed to all Americans as a dividend (how about on Black Friday?), potentially making the policy a popular one on election day.

Incentives for Sustainable Energy

As we saw in Chapter 14, sustainable energy is on the march in the U.S. and elsewhere. Even in the absence of strict limits on greenhouse gas emissions, policies have helped this revolution along. Here we will focus on three primary policies: renewable portfolio standards, tax credits, and net metering.

Renewable portfolio standards. RPS originated in Iowa in 1983 as a way to promote ethanol from corn. By 2000, 11 states had passed RPS, and by 2022, 31 states had passed regulations that set goals for a certain percentage of energy produced or consumed in that state to come from designated renewable sources by a target year. Statistically, states with RPS have greater production of wind power, all other things being equal, than states without, so RPS standards can be viewed on the whole as fostering natural resources sustainability. But we must ask, what is *renewable* energy?

In Chapter 7 on Ecological Economics, we defined resources based on their renewability ratio: the rate of creation divided by the rate of consumption. These are low for fossil fuels, making them fall into the nonrenewable category, and high for solar energy and its direct derivatives like wind and hydroelectricity, placing them in the renewable category. Two other important energy sources, however, are more problematic. Nuclear energy relies on uranium or other radioactive elements like thorium that have large supplies relative to the very slow rate at which they are used, and perhaps consumed, in nuclear fission reactors. Does that make nuclear energy renewable? Biofuels rely on photosynthesis and compete for it with the food supply and habitat for biodiversity. So is it renewable? By standard definitions founded in the renewability ratio, it must be, but is it sustainable?

Let's go back to the analysis presented in Chapter 13 where we found that fossil fuels are actually quite abundant on Earth with reserve-to-production ratios that climb to truly high levels if we consider the vast volumes of lower quality fossil fuels like oil sands, gas and oil shale, and coal. We concluded that it is peak emissions of carbon rather than peak oil that is the salient issue.

If running out of nonrenewable resources like fossil fuels is not the issue, then why define energy sources on their renewability rather than their sustainability with respect to carbon emissions and other sustainability indicators? This makes biofuels renewable but perhaps not sustainable, given their high footprints for water, nutrients, even carbon, and their effects on land use and therefore food supplies and biodiversity. It leaves nuclear energy in a very ambiguous position and hydroelectricity less clearly sustainable than it is renewable. Wind and solar energy come out as clearly both renewable, due to their reliance on never-ending streams of radiation from the sun, and sustainable, due to their very low footprints, including for water and nutrients as well as carbon. This analysis makes questionable the crediting of biofuels toward RPS or the subsidization of biofuel production.

Also, energy never consumed is even more sustainable than wind and solar power, so *megawatts* and other indicators of energy avoidance should count. I'd still support RPS for the push they've given to wind power, and likely are also starting to do so for solar, but also argue that it is time to change the concept from *renewable* to *sustainable* energy standards.

Tax Credits. Originating in the Energy Policy Act of 1992, the Production Tax Credit provides producers of wind, solar, and bioenergy with a substantial reduction in taxes for investing in new production capacity. Congress has a history of allowing the Production Tax Credit to expire, such as in 1999, 2001, and 2003 and with last-minute extensions in other years. In modified form, it was extended by the Inflation Reduction Act in 2022. When the history of U.S. wind power installation is compared with the history of the Production Tax Credit, it is clear that companies are holding back in years when it is not in effect, hoping it will be renewed, and then going forward with huge investments when it does come back into effect.

The parallel Solar Investment Tax Credit started in 2006 and was renewed in 2015, providing a 30 percent tax credit on new solar installations, both for utilities and roof-top solar projects. It was also extended by the Inflation Reduction Act. These tax credits have had a huge impact in jump-starting wind and solar energy in the U.S. by improving the rate of return on these energy investments to the point where they make good financial sense. They are thus central to the sustainable energy revolution the U.S. has been enjoying. This can be viewed as justified on the grounds that wind and solar do not produce the negative environmental externalities of fossil fuel-based energy.

Another argument is based on the idea of *infant industries*. New technologies are never as cost-effective as older more established ones that have enjoyed decades of tweaking and optimization under competitive capitalist conditions. Yet, if given the opportunity to gain some momentum, new technologies like wind and solar power can reduce costs and eventually become cost-competitive with older fossil fuel-based technologies. The same is true of electric cars, which receive similar tax credits of up to $7,500. In several years, electric vehicles may be cheaper than internal combustion engine vehicles and these subsidies will have done their job of transforming the auto industry.

This jump start for infant industries is exactly what has happened, with the cost of wind and solar falling to the level of coal and gas in the late 2010s. Therefore, the phasing out of these tax credits may not have a disastrous impact on the sustainable energy revolution. Still, if wind and solar lack the environmental impacts of fossil fuels, the polluter pays principle demands that either greenhouse gases are taxed or sustainable energy is subsidized in order to maintain a level playing field in the competition among these technologies and the companies that seek to profit from implementing them.

Net metering. Millions of American homes, including my own, have placed solar panels on their roofs. When I mention this to friends or neighbors, often the next question is "are you off the grid?" My answer is "if I'm off the grid, I can't use the grid to my advantage."

Net metering allows producers of solar energy to sell their surplus power production—say on sunny days that aren't hot enough for air conditioning—back to the grid, turning their meters backward and only paying for the net electricity they consume. As long as they aren't a net power producer on an annual basis, the electric utility has to credit the solar output they're supplying to the grid. Remember that solar (and wind) are intermittent. That means that, unless you also invest in a great deal of electricity storage, a solar home still needs electricity from the grid, especially after the sun sinks westward or when the rooftop solar panels are buried in winter snow. It also needs a market for its surpluses. So net metering allows solar producers to utilize all the power they produce to offset electricity purchases by using the grid to their advantage.

Of course, from an electric utility's standpoint, net metering forces them to buy all the products their competitors are making. This is a difficult business model, so they are pushing back. Moreover, a solar producer who has little or no electricity consumption from the utility isn't paying for the grid's overall infrastructure, passing that cost onto the nonsolar customers.

The outcome of this tug-of-war is different in every state, with 33 states offering net metering as of 2022. Net metering rules is an active field for modifying laws and regulations in many states.

Taken together, renewable portfolio standards, the production and solar investment tax credits, and net metering for rooftop solar have countered the lack of restrictions on greenhouse gas emissions to facilitate the sustainable electricity revolution we explored in Chapter 14. Together with the steady decline in costs for wind and the precipitous fall in costs for solar, due to technological advances, all of these policies have helped make wind and solar power financially sound investments. That is the key to inducing people, from homeowners to utility company executives, to build them. So, perhaps it was worth slogging through Chapters 6 though 9 on economics after all! Becoming an environmental policy wonk is partly about understanding how policies affect economic incentives, carrots and sticks, and therefore natural resource sustainability outcomes.

The Waters of the U.S. (WOTUS) Rule Governing Wetlands

As we saw in Chapter 7 on Ecological Economics, wetlands are the landscape's best ecosystem service factories, producing biodiversity, carbon storage, nutrient filtration, and water storage to mitigate floods. These services have quite large economic values, though often they do not accrue to the landowner, in what we described in Chapter 9 as a tragedy of ecosystem services. Because of this mismatch in incentives to landowners, some kind of policy is needed to protect wetlands from being converted into shopping malls or, much more commonly, crop fields. Otherwise, the public stands to lose the ecosystem services wetlands are providing for them.

While wetlands have been converted for uses like subdivisions at a steady rate since the 1950s, they were converted, usually drained, for crop fields at a very rapid rate from 1955 to 1974 (Figure 15.1). In that 18-year timespan, there was a net loss of 8.2 million acres of wetlands, an area the size of Maryland. Loss of *palustrine* wetlands (valuable marshes, swamps, and bogs) was even larger, with most of the additions coming in the form of farm ponds (non-vegetated in Figure 15.1). Fortunately, this rate declined from 458,000 acres per year to 290,000 in the 1975–1985 time frame and then declined further to only 58,000 in 1986–1997, a net gain of

32,000 acres per year in 1998–2004, and a slow loss of 13,800 in 2005–2009, when the last wetland inventory was taken. What policies are responsible for slowing down the wetland drainage train?

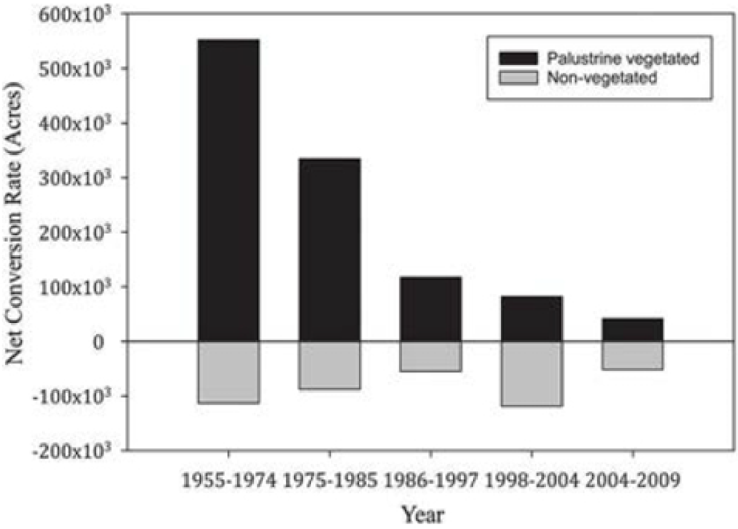

Figure 15.1. The acreage of wetlands in the contiguous U.S. that have been converted to agricultural and other uses annually based on data from the National Wetland Inventory.

The legal definition of wetlands has been one of the most tortuous legal footballs in U.S. natural resources policy. As we know from Chapters 11 on land and 12 on water, most land in the U.S. is owned privately while water is fundamentally public. But where does the land end and the water begin? The answer is usually in a wetland. So who owns the wetlands, private landowners or the public, and who manages them on the public's behalf? You can imagine that more than a few lawyers and politicians have wrestled with this thorny question! So has the U.S. Supreme Court in a series of cases that have drawn and redrawn the boundary between private land and public wetlands time and time again.

The Clean Water Act of 1972 Section 404 is the primary bone of contention. Through the legal doctrine of *navigation servitude*, the U.S. Army Corps of Engineers (Corps) has jurisdiction over navigable waters like the Mississippi River that often cross state boundaries. It also, therefore, regulates dredging and filling in these waters. The 1975 case *Natural Resources Defense Council v. Callaway* established that Clean Water Act Section 404 gives the Corps jurisdiction over "Waters of the United States." The 1985 case *United States v. Riverside Bayview Homes Inc.* established that wetlands adjacent to navigable waters are also under Corps jurisdiction. But what about a marsh in a farmer's field? The 2006 case *Rapanos v. United States* and other cases established that a "significant hydrologic nexus" to navigable waters must exist for a wetland to come under the Corps' Section 404 authority. That includes a swamp along the Mississippi but excludes the marsh in that farmer's field. Each of these court decisions based on a logical test radically alters the map of Waters of the U.S., and therefore of protected wetlands, by tens of millions of acres. In the case of *Rapanos*, it also leaves so much ambiguity that a map cannot be drawn.

In an attempt to remedy this ambiguity, on October 3, 2022, the U.S. Supreme Court heard the case *Sackett v. Environmental Protection Agency*. Some time in early 2023 we will all hear what a wetland is, or more precisely, an answer to the critical legal question, where beyond the water's edge does federal jurisdiction under the Clean Water Act extend? Will Justices Alito, Gorsuch and Thomas identify a rule that greatly limits federal jurisdiction? Will Justices Jackson, Kagan and Sotomayor take EPA's perspective? Or, more likely, will Justices Barrett, Cavanaugh and Roberts identify a compromise rule that can be applied on the ground so that my friends who do GIS can produce a map of the Waters of the United States?

Conclusion

So you still don't want to be an environmental policy wonk. I understand. Nevertheless, what I hope you've learned from this chapter is that environmental policy is important because it creates a decision environment in which natural resources sustainability is nurtured or discouraged, rewarded or ignored. It is also hotly contested and unabashedly political.

Sustainability is not going to come from Washington or from state capitals but the decisions made there set the landscape in which the bike ride to natural resources sustainability is either a downhill coast or a standing-on-the-pedals, thigh-burning uphill pump. If all environmental policy does is put people on the flat terrain and get out of the way, I'm optimistic that they can pedal to sustainability at a steady clip. Better yet would be a decision-environment in which polluters pay and ecosystem service providers get paid. We're a long way from that landscape but every progressive change gets more people, ordinary people who don't compete in the Tour de France, on their bikes riding toward natural resources sustainability.

Further Reading

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12.

CHAPTER 16: ENVISIONING A SUSTAINABLE AMERICAN WAY OF LIFE

So now we've studied, sometimes through economic quadrifocals (neoclassical, ecological, and institutional economics plus political ecology), topics as critical and diverse as accelerating climate change, balancing the electrical grid with sustainable energy, irrigation efficiency, managing nutrient runoff from agricultural watersheds, and even living within the Earth's photosynthetic capacity. We've seen how maintaining natural capital conserves bio-diversity and ecosystem service provision. These are the pragmatic issues of natural resources sustainability in the present. What kind of place would your hometown and the surrounding countryside become in the process of resolving these natural resources sustainability issues? Would it be substantially different than it is today? Would you want to live there?

Change is a difficult thing to achieve. Machiavelli, the great

Italian master of realpolitik, said centuries ago in his masterpiece *The Prince*:

> It ought to be remembered that there is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in introducing a new order of things, because the innovator has for enemies all those who have done well under the old conditions, and lukewarm defenders in those who may do well under the new. This coolness comes partly from fear of the opponents—who have the laws on their side—and partly from the incredulity of men, who do not readily believe in new things until they have had long experience of them.

So with Machiavelli's warning in mind, let's paint a picture, a realistic vision, of a more sustainable America in the mid-21st century that can earn more than lukewarm defenders, perhaps even steadfast advocates, by attempting to overcome your incredulity. Remember, it's not a choice between the present and this or some other vision of the future because, as we have seen, the way things are now cannot be sustained. Rather, it's a choice between a sustainable vision and a degraded version of the present where the sea is flooding coastal cities, damaging extreme weather events have become the norm, water tables are dropping, freshwater bodies and coastal waters are filling with nutrients. More commonly beyond the borders of the U.S., forests are receding, deserts are advancing, and species are going extinct. To quote Confucius, "if we're not careful, we'll end up where we're going." We need a vision, if not a rigid plan. To quote another of my favorite philosophers, Yogi Berra, “if you don’t know where you’re going, you end up someplace else.” So let’s start developing a sense of where we’re going by getting in a time machine and dropping in on your hometown—in 2050.

Your Hometown, 2050

Nobody drives anymore, except recreationally in the beautiful countryside. Then it’s in an electric car, usually rented and self-driven. No, people are not crowded into buses and uncomfortable commuter trains, though the bigger cities do have heavily used subway systems. Rather, the narrow tree-lined streets are abuzz with little one-seater electric robot taxis (Figure 16.1) ferrying folks around town. It’s so simple; you just click your cellphone app and in less than a minute a robot taxi greets you and asks where you’re going, then zips through town and drops you off at your destination. Tailgating and tight traffic is no problem for these well-programmed robots, so they pack the streets, slipping elegantly past one another at the traffic circles that dot the center of town; after all, why would a robot taxi stop at a busy intersection when there’s no reason to? The only time they stop is when they’re picking up and dropping off their passenger or when they’re re-charging because, after all, they are an integral part of the electrical grid, storing electricity, providing it during peak demand, and driving on sunshine or powered by the breeze when they have a passenger to deliver.

Figure 16.1. A one-seater robot car.

When robot taxis were first introduced in the 2020s by Uber and Lyft, it was tricky integrating small, responsive robot cars and big sluggish driver cars, but by the 2030s, most urban dwellers had come to the conclusion that battling traffic behind the wheel was a dangerous, stressful, and expensive waste of time and money, so robot taxis became the norm. By the 2040s, most cities and towns had banned gas-powered driver cars from their central, most densely populated sections so they could capture the substantial advantages of redesigning the streets and sidewalks to eliminate parking and pack the robot taxis closer together. It made downtown an even more fun place to be.

A lot of folks are strolling and chatting on the sidewalks and the cute little footbridges that get pedestrians across these robot taxi packed streets. Others are on electric scooters, segways, or bikes. With internal combustion engines only remaining in a few rural areas, the streets aren't silent but sound more like a swoosh than a roar, even when the robot trucks go by delivering goods with a bigger swoosh. Conversations on the sidewalks and footbridges and drinking and dining in the sidewalk cafes are not interrupted by the sound of engines. Air pollution is also becoming a thing of the past.

Figure 16.2. A LEED Platinum building.

Millennials started the process of taking back the city and making it a great place to live but GenZers have nearly all taken up abode there, mostly in nicely outfitted apartments and condos in quaint two-to-four story, energy-efficient buildings near the center of town, sometimes upstairs from sidewalk-level businesses. These abodes are packed with all the latest electronics plus an essential new appliance—the delivery elevator from the robot car drop-off that brings every restaurant, pub, and store in town to your kitchen or living room. The apartments feature little individual gardens, decks, and patios adjacent to larger community gardens and parks shared by the buildings surrounding them. Since about 2030, most new buildings use geothermal heating and cooling systems replacing electrically powered AC units and cutting drastically the use of natural gas in basement furnaces. Due to passive solar design, heat-rejecting windows, daylighting, and excellent insulation, gas furnaces need only be turned on in the coldest weather (Figure 16.2). In the newest buildings there is no natural gas use at all, with heating provided by solar hot-water units. While some still feel that a suburban house with a large yard is necessary to raise a family, many have abandoned garages and driveways in favor of little robot taxi pickup spots. Most parents feel that kids over ten are OK to take the robot taxi to the park or to meet their friends, so no one remembers old phrases like “soccer mom” and “minivan.”

Figure 16.3. Concept for a Hyperloop station.

The robot taxi traffic is especially busy around the Hyperloop stations (Figure 16.3). The first hyperloops opened in the mid-2020s, one serving all of Germany from its major cargo port at Hamburg, and one connecting passengers between Mumbai and Pune in western India. By the 2030s, hyperloops were becoming the primary mode of medium-to-long distance transportation for both people and cargo in the U.S.

Figure 16.4. A Hyperloop pod.

Elon Musk's original 2013 concept combines magnetic-levitation rail technology, already widespread at the time, with a vacuum tube to produce nearly frictionless, highly energy-efficient transport in small, comfortable 4–16-seater pods (Figure 16.4). Traveling at jet airline speeds in underground or aboveground tubes, passengers can simply grab the next available pod from the Hyperloop station—like they have done with subways for over a century. Their cell phones give them all the information they need to get on the right car at the right time while also handling all the billing, so there are no awkward lines to make sure people have a ticket. What even the most optimistic projections didn't realize is how much Americans would enjoy coasting along at 300–600 miles per hour while drinking good coffee and eating sandwiches, pizza, or Chinese food as they use the wireless Internet, chat on the cell phone or with the person sitting next to them, or take a nap. Unlike in Europe and Asia, passenger rail never caught on in the U.S. outside a few of the largest urban areas. Yet the Hyperloop has not only replaced all 20th century-style passenger and freight rail, it has also replaced most flights of less than 1,000 miles with their annoying security lines, massive petroleum consumption, and poorly designed air-to-land connectivity. In comparison, Hyperloop stations are located in city centers and downtown so Hyperloop-to-robot taxi connections are a snap. With a national ridership of over 10 million passengers each day, most of the thousand or so Hyperloop stations have become commercial hubs, monitored by a cop on a segway, bustling with restaurants, shops, hotels, and nightlife, replacing the fast-food joints and gas stations at interstate exits and the overpriced captured markets at airports.

Running on electricity and hyper-efficient in their frictionless environments, the Hyperloops are powered by solar, wind, and modern nuclear electricity and so, like the robot taxis, are essentially emission-free. In 2050 Hyperloop lines serve most of the connections that the interstate (really inter-metro) highways had served in the 20th and early 21st centuries, but the build-out continues as Hyperloop lines evolve into Hyperloop networks across the U.S. map and into Canada and Mexico. Most people remember traffic jams and car crashes, which at the beginning of the 21st century killed a horrific 30,000 Americans each year and maimed several times that many, but no one remembers them fondly. With most businesses and homes using advanced video-conferencing technology on big screens that makes you feel like you're there, long trips are also less needed than they once were.

Throughout the U.S., it is the Age of the City, some smallish, some very large, but suburban blight is a problem. Car-oriented development has, unfortunately, outlasted the car it was designed to serve, and so the sprawl remains, even as it slowly empties of people. Outlying towns and villages with lovely natural surroundings have their charms for many, but largely empty highways serving largely empty box stores and malls charm no one. For them, the theme is "the future has arrived, but it's unevenly distributed."

Figure 16.5. An advanced greenhouse.

Fortunately, some of what had been suburbs has taken on a new role in agriculture. For high-quality fruits, vegetables, nuts, herbs, and so forth, which make up much of people's diets, farming has moved indoors. CRISPR and other gene-editing techniques have produced super-crops that have high yields and nutritional value and taste delicious. These are grown in advanced greenhouses (Figure 16.5) with controlled environments that make climate almost irrelevant. Plants photosynthesize from the red and blue portions of the light spectrum, so that's what LED lights provide—24 hours a day, 365 days a year—at the perfect temperature and humidity and with elevated carbon dioxide levels. So not only are the crops genetically engineered, they are engineered to optimally utilize the optimized environments in which they grow year-round.

Water circulates within the greenhouse, so there is no water consumption, while only the nutrients contained in the food leave the greenhouse. These are obtained locally from sewage treatment plants, dairies, and chicken-egg farms. No nutrients run off or evaporate as pollution. With robots doing the picking, harvesting, and loading, and small electric robot trucks delivering to local grocery stores and restaurants, most of the jobs in agriculture have become doing all this engineering, matching supply and demand over time so that everything is fresh, and making sure it's all done at a profit.

Figure 16.6. A cattle feedlot.

Out in the countryside, especially in fertile belts of the Midwest, you still find amber fields of grain – under the wind turbines. These fields supply staples like wheat as well as corn and soybeans for the many medium-size pig and chicken-egg farms, as well as hay for dairies. These compete with plant-based, high-protein foods, first introduced as *Beyond Beef* and the *Impossible Burger* around 2020. Cotton also grows now in the fertile Midwest due to the warmer climate, and corn and soybeans can be grown across Minnesota and the Dakotas and on into Canada. Beef feedlots (Figure 16.6) have been phased out, however, along with giant pig and chicken feedlots, with livestock raised in smaller, more humane environments. The outlawing of antibiotic use for livestock in order to preserve their essential germ-killing power for humans, the elimination of subsidies, regulations to restrict greenhouse gas and nutrient pollution, and a slow decline in consumer preferences for meat forced livestock raising into new, more integrative modes that produce a better product in a more sustainable way. Beef cattle have returned to pastures and rangelands where new grazing techniques, like planting tannin-containing legumes, make finishing—force-feeding corn to cattle to quickly double their weight before they perish from it—unnecessary. Biofuels are also a thing of the past, along with the gasoline they were once mixed with.

These shifts in the U.S agricultural system have allowed two other goals to be pursued more vigorously. First, climate change has wreaked havoc on agricultural systems around the world, but this has opened up even greater opportunities for U.S exports to fill the ever-widening shortfalls. So corn, wheat, soybeans, and other major crops that were once used to produce ethanol for gasoline or force-fed to cattle are now exported at a profit to a hungrier, but more affluent, Asia and Africa. Second, the U.S. agricultural landscape has blossomed with ecosystem services like carbon storage, wildlife habitat (including for pollinators like bees), floodwater storage, and water filtration. This has been accomplished through policies to incentivize wetland and soil restoration and the integration of semi-wild land uses with crop production. Coastal folks who once referred to the U.S. agricultural heartland as “fly-over states” now sometimes take the Hyperloop there on vacation to see the bucolic farmscapes dotted with wind farms and vibrant towns.

The year 2050 marks two seemingly paradoxical outcomes; it is the year the U.S. finally achieved zero net carbon emissions at the same time that the world witnessed the Year of Peak Warming. Globally, greenhouse gas emissions peaked in the 2020s (they peaked in the U.S. in 2008) and then started a brisk decline, but the climate system has lags. The most important one is the vast amounts of heat energy, many times more than the atmosphere can contain, that are stored ever-deeper in the oceans. So even after emissions peaked, declining emissions were still sufficient to warm the atmosphere, which continued to warm the oceans. Then the oceans started their decades-long process of releasing that excess heat back into the atmosphere, guaranteeing a warmed climate well into the 22nd century. Still, by rapidly reducing emissions through the 2020s, 2030s, and 2040s, the 2050 temperature peak nudged just over the goal of 1.5oC in warming. This enormous achievement reduced climate change from the existential threat to modern civilization it could have been had high emissions continued, to a difficult, expensive, ever-present but ultimately manageable problem. In the U.S., the most profound adaptations have occurred in coastal cities. New Orleans and Miami simply aren't where they used to be. Boston, New York, Washington, Baltimore, Norfolk, Houston, and dozens of smaller coastal cities have had to retreat from their coastlines through carefully laid redevelopment plans. Florida had to be entirely re-thought as the Atlantic and Gulf of Mexico swallowed the beaches and delivered even more severe hurricanes.

As we saw above, specific crops are now grown in different states than they were at the start of the century. Once the leader in corn and soybean production, Illinois now leads in cotton while North Dakota and Minnesota lead in corn and soybeans. People take hurricane, wildfire, and heat wave alerts very seriously. But it all could have been far worse had mitigation not worked.

The U.S. greenhouse gas mitigation strategy has four major components. The first two are *decarbonize the grid and electrify transportation*. We've seen how wind and solar power, complemented by natural gas until electricity storage, modular nuclear power, and smart grid technologies catch up, was able to eliminate the vast majority of carbon dioxide emissions from the electricity sector. By then transitioning nearly all transportation to run on electricity, gasoline, diesel, and biofuels were phased out as well. In 2050 natural gas is still an important fuel for heating older buildings, but this is balanced by making the American landscape a net carbon sink, resulting in, for the first time in 2050, zero net carbon emissions.

We saw how the growth of forests in the eastern U.S. offset 11 percent of U.S. carbon emissions in the 2010s. This principle of *let the forests grow* with trees getting bigger and bigger, and covering more and more acres in the warmer, wetter, carbon dioxide-rich climate, is augmented by other carbon-absorbing tools: restore the wetlands and restore the soil. The final card is *cull the herd*. Reduced methane emissions from cattle and changes in land use from growing feed to growing ecosystems reduced emissions sufficiently to make the American landscape as a whole a carbon sink substantial enough to offset all remaining emissions from remnant fossil fuel use.

Together, these land management strategies also improved the health and beauty of the landscape and the prosperity of rural areas. Americans mostly live in the cities, but they see the countryside as a big playground and are willing to pay rural landowners substantially sums to make it one. While growing crops remains essential, most rural landowners, farmers, and ranchers now make more money on wind and solar energy projects, reimbursed carbon storage, and recreational use fees and easements than they ever made on timber or livestock grazing, so they see city folks as their market and allies more than as opponents.

Conclusion

So, would you want to live in this American town in 2050? Taking a lesson from Machiavelli, I find that a viable pathway to a more sustainable way of life doesn't, and really can't, involve *sacrifices*. People just aren't willing to give up the things they love having, eating, and doing for a distant, collective goal—especially in this era of political polarization and leaderlessness, of disinformation and noise that drowns out the signal. Rather their response is the one Machiavelli illustrated. Their incredulity takes over and they defend their lifestyle against the theories of some pointy-headed intellectuals, mocked by social media.

Instead of sacrifices, the pathway to sustainability asks for a *willingness to change for your own sake*. Our lifestyles will actually be better, not worse, in this Hometown in 2050 than they are today. People will be healthier, safer, and have more fun things to do. The picture I've painted is not at all a back-to-the-land exercise in reminiscing about the world of our great-grandparents and returning to the good old days. Rather it's very technological, full of cell phone apps, robots, the instantaneous, silent acceleration of electric vehicles, the elegant swooshing of giant three-bladed wind turbines, and the magic that turns sunshine into electricity. It accepts globalization as the inevitable stage in the progress of human civilization in which we now live. It's driven by the private sector, with government, local as much as national, mostly playing the role of a fair referee enforcing well-thought-out, widely agreed-upon rules and providing some strategic carrots and sticks. So the pathway to sustainability isn't alien; it's American. And, as we've seen with reductions in water consumption, the decarbonizing of the economy, the sustainable energy revolution, and other already-achieved trends through which we are getting more with less, we're already on the pathway to sustainability. We just need to see it more clearly, pave it with yellow bricks, so we can follow it faster and more directly.

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PART V

PART IV: RESOURCE-BY-RESOURCE

13.

CHAPTER 11: USING LAND SUSTAINABLY

Land. What does it mean? If we start with the entire Earth, land means the interface between the atmosphere and the lithosphere, where the sky touches the ground. While the biosphere extends into the lower atmosphere, the Earth's crust, and the deep wide oceans, its two hearts are the land surface and the shallow fresh and salt waters near its shores. Clearly, this is the tiny portion of the planet humans care most about. Land is human habitat and for this reason we are territorial creatures, defending *our* land against trespassers, *our* house against intruders, *our* nation against invaders. Land is our home.

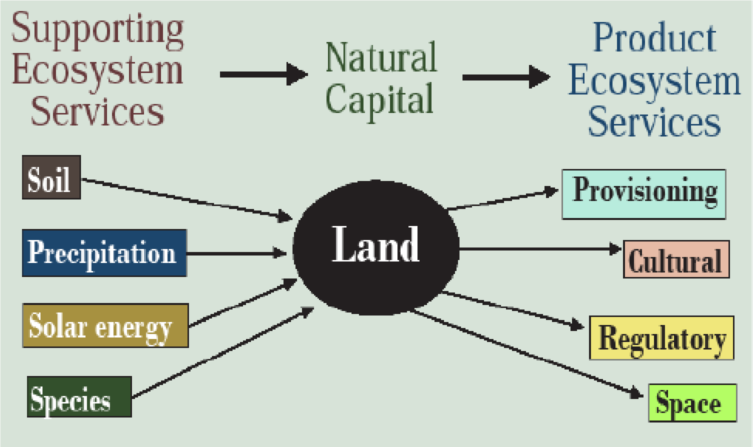

Figure 11.1. What is land as a natural resource? We can think of it as natural capital, generated by a package of supporting ecosystem services. It is capable of producing provisioning, cultural, and regulatory services as well as developable space.

From a natural resource and ecological perspective, land is a package of supporting ecosystem services such as physical space, the soil covering it (if there is any), a place for precipitation and solar energy to interface with the soil, and the species of plants, animals, and microorganisms that inhabit that space (Figure 11.1). Collectively, these form natural capital in the sense we discussed that concept in Chapter 7 on ecological economics. As a unit of natural capital, land is capable of producing provisioning, cultural, and regulatory ecosystem services. Not all lands were created equal, however. The cold, nearly soilless northern Canadian Shield or the desert basins of Utah and Nevada, for example, have far less value as natural capital than the prime farmlands surrounding the Chicago metropolitan area or the scenic seacoasts of California's climatic paradise. We obviously need to identify the factors that make land more or less valuable as a natural resource.

Three of these factors are the mantra of real estate traders: location, location, location. For example, commercial establishments prefer high traffic areas in attractive parts of town or interstate exits. For industries, adjacency to transportation facilities and proximity to raw materials and markets are key geographic factors. For homes, proximity to schools, churches, restaurants, shopping, and other nice homes is key along with a lack of pollution, crime, and visual blights like warehouses, rail yards, and interstate highways. We will not dwell here, however, on these geographic factors of urban land development where the primary service land provides is developable space. Instead, our focus will be on the agricultural and ecological value of rural lands, over 95 percent of all lands on Earth as well as in the U.S., as units of natural capital. Are these lands being managed in a manner that sustains their capacity to produce ecosystem services for human welfare, including the majority of humanity that lives in towns and cities? If not, what needs to change?

The Acquisition and Disposition of Land in the U.S.

The United States of America is a large country and this did not happen by accident; the 84 years from 1783 to 1867 witnessed a national territorial expansion equal to any other in world history. From thirteen British colonies hugging the Atlantic, the Treaty of Paris with Britain in 1783 established the new country's boundaries from the Great Lakes and St. Lawrence River in the north to then-Spanish Florida in the south, west to the Mississippi River (Figure 11.2). Yet, west of the Alleghenies (a prominent ridge in the Appalachian chain), the land was "Indian Country" being steadily encroached upon by settlers. Only 20 years later in 1803, Ambassador Robert Livinstone reported to President Jefferson that Napoleon of France, indebted by war and withdrawing from American colonial ambitions, was interested in selling all of France's North America lands west of the Mississippi, not just the mouth of the Mississippi in Louisiana. Despite constitutional reservations, the U.S. took the sweet deal. Then in 1818 the U.S. compromised with Britain on the 49th parallel, rather than the divide demarcating the Mississippi watershed, and in 1819 leveraged Florida from Spain.

Figure 11.2. The Territorial Acquisitions of the U.S.

The next round of territorial acquisition came in the 1840s when the U.S. observed that newly-independent Mexico's hold on its northern lands was tenuous. Annexation of the briefly independent Republic of Texas and the Mexican session followed a short brutal war initiated by the U.S. imperialist claim to "manifest destiny." Another war with Britain was avoided by the Oregon Compromise of 1846 that extended the northern border along the 49th parallel to the Pacific. Finally, the U.S. purchased Alaska on the cheap from Tsarist Russia in 1867. Some territorial changes have occurred since 1867 but all Americans living today have enjoyed these stable national borders.

Whether annexed, purchased or otherwise acquired from European and North American powers, all of these lands were wrested from indigenous peoples, usually following a similar process. Treaties were negotiated between the U.S. government and the various Indian tribes guaranteeing protection of native lands. Settlers ignored them and encroached on whatever lands they wanted and thought they could defend from Indian counter-attack. Democratically elected governments refused to enforce the treaties they had signed, bending to popular pressure, making these encroachments an on-the-ground fact. Indian peoples moved west or became marginalized.

In perhaps the most tragic episode of all, in 1830 President Jackson signed the "Indian Removal Act" forcing the Creek, Cherokee, Chickasaw and other indigenous peoples to march along the "Trail of Tears" from their historic homelands in the southeast to their "permanent" new home in Oklahoma. Yet on April 22, 1889, 50,000 "sooners" rushed in to claim these native lands. The march west continued through the end of the 19th Century by which time the few hundred Indian Reservations occupying 2.3 percent of U.S. area had been established.

With the exception of the Republic of Texas, in each of these episodes of territorial acquisition, native lands fell into the hands of the U.S. government with Congress busily debating what to do with them. and the courts attempting to resolve an onslaught of disputes Securing these newly acquired lands permanently and developing the country required encouraging pioneers to settle the western frontier and, when the time came, to admit new states into the union on an equal basis with the original states. By 1912 the 48 conterminous states had been admitted to the union: Alaska and Hawaii were added in 1959.

Throughout the 19th century, the U.S. government was focused on "disposing" the recently acquired lands to private individuals and companies who would form the new states. The process was chaotic and rife with corruption, yet it was also rapid and effective, with the frontier "closing" in the 1890s. Policies governing mineral, wildlife, timber, water and other resources encouraged a race to the west to be the first to lay claim to these resources that lay within the new lands that had been precisely laid out into square mile sections and townships. The Homestead Act rapidly established a farming-oriented white population throughout the ecologically productive and fertile Midwest but, west of the 100th meridian, which runs through the center of the 48 states, aridity made 160-acre rainfed homesteader farms unviable due to lower ecological productivity.

John Wesley Powell, the daring explorer of the Colorado River and father of the U.S. Geological Survey, argued that Midwestern-style homesteads would not work in the arid and mountainous West. Rather, with a few exceptions such as the fertile Williamette Valley of Oregon, destination of the Oregon Trail, a viable farm needed perhaps 40 acres of communally organized, highly productive irrigated cropland joined, except in the Central Valley of California, to several square miles of ecologically unproductive rangeland. Since water was the limiting factor in human development in the West, states should be organized on the basis of river basins. Had Congress taken Powell’s advice, western states would be named “Columbia,” “Snake,” “Sacramento,” “North Colorado,” South Colorado,” “Rio Grande,” and “Great Basin.” The stories of the wild west, rife with lawlessness and conflict borne of desperation, would have been much tamer.

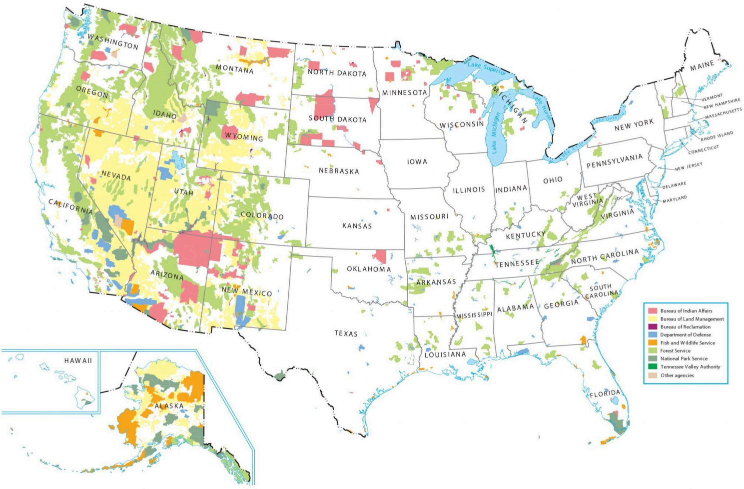

Figure 11.3. The U.S. Federal Lands and Indian Reservation system.

While the scattered agriculturally viable lands of the West were “disposed” as they were east of the Rocky Mountains, most lands could not be settled with substantial rural populations and the majority therefore remained in federal hands. Today, Federal Lands occupy 28 percent of the U.S., divided among the Bureau of Land Management (BLM), National Parks and Fish and Wildlife Refuges (all in the Department of Interior), and National Forests in the Department of Agriculture (Figure 11.3). Yet these percentages vary from 80 percent in Nevada, 46 percent in the 11 western states as a whole and 61 percent in Alaska. In contrast, federal lands are no more than 14 percent of any state east of the Rockies and less then 2 percent in 13 eastern states.

In 1872 Yellowstone became the first of 63 National Parks, the gems of the federal land system managed by the National Park Service for preservation balanced with managing ever-multiplying visitors that reached a record 300 million in 2021. First established in 1891 to protect mountain watersheds from excessive deforestation and erosion, the 154 National Forests are managed for recreation alongside grazing and timber supply, among other uses prescribed in the Multiple-Use Sustained-Yield Act of 1960. The first of 550 National Wildlife Refuges was established in 1903; they are not concentrated in the west and span every habitat type but emphasize wetlands with their high biodiversity.

While the largest in area, Bureau of Land Management lands are ‘leftovers’ from the original federal domain that aren’t suitable as national parks, forests, or wildlife refuges and were not claimed by 19th Century settlers. On these vast semi-arid to arid lands, including two-thirds of Nevada, the BLM balances often-competing recreational uses with natural resource extraction, from sparse grazing to intensive mining and, more recently, renewable energy development.

Our concept of property, and the evolution of that essential legal idea, is based fundamentally on land. Urban development and agricultural production occur overwhelmingly on private land where investments sown create the right to reap. Yet much of what happens on land affects neighbors, communities, ecosystems, watersheds, even the planet, in ways that are essentially public. How the U.S. came to acquire and then divide its lands into private and public spheres is thus a building block of a deeper understanding of land as a resource.

Land Cover and Land Use

Figure 11.4. Satellite image of the contiguous U.S.

Figure 11.4 shows what a satellite sees when it looks at the contiguous 48 U.S. states. The interesting technical field of *remote sensing* is the art and science of rigorously analyzing the raw data that generate a satellite image to determine what is actually on the ground, often to place it into a category of land cover. It can be a challenge to, say, determine which field has corn and which has soybeans, which grassy place is a cattle pasture and which is a backyard. Remote sensing images can also be used to detect changes in land cover due to urbanization, deforestation or reforestation, changes in agriculture or climate.

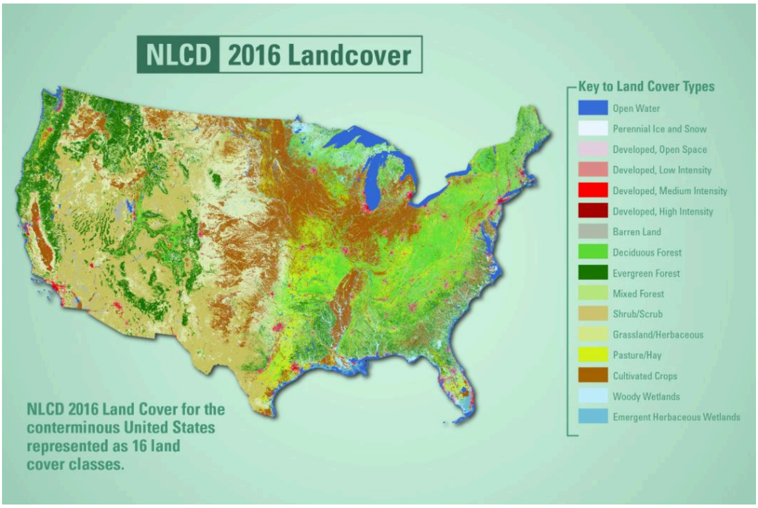

Figure 11.5. Land cover map of the continuous 48 states in 2016.

Using satellite image analysis methods, a land cover map of the U.S. was generated by the U.S. Geological Survey, as shown in Figure 11.5. Note how vegetation, the first trophic level and foundation of ecosystems, is the primary criterion for classifying land cover. Figure 11.6 adds up the land uses in each of eight categories in the form of a pie chart. Note that the development of these categories involves judgment calls, for example, how many different categories of forest should there be? Even after the categories have been decided, how many trees does it take to turn a grassland into a forest? Are the lily pads along the fringe of the lake freshwater or wetlands? More critically, is the landscape really divided into clearly urban and clearly rural locations? These questions have to be decided by reasonable rules of thumb but they always entails oversimplifications that can distort our understanding of the real world they portray. Data on land use change, such as rates of urbanization or tropical deforestation, are based on these agreed-upon rules as to what constitutes land in one or another category in a world that, on the ground, contains every shade of ambiguous gray.

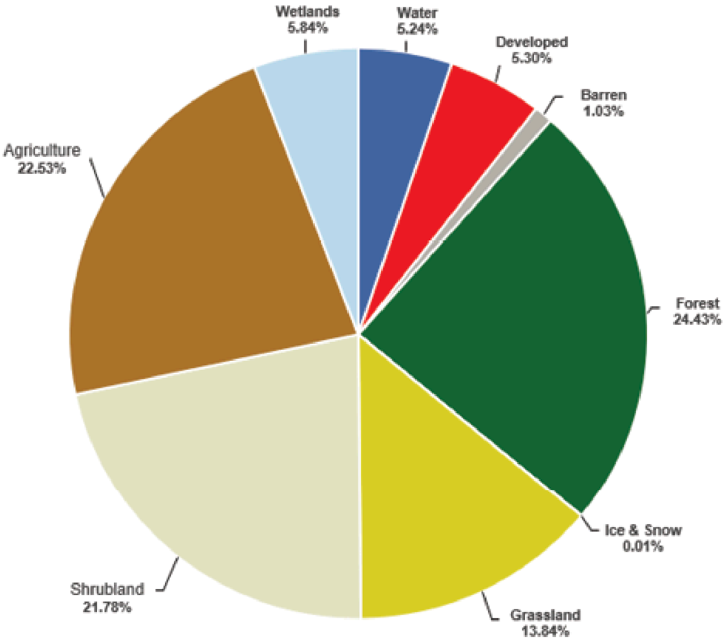

Figure 11.6. Major land uses in the United States, 2016.

Having provided these caveats and clarifications, you may be surprised to find that one of the largest categories of land cover in the contiguous U.S. is shrub/scrub at 22 percent. This represents the large areas of the western U.S that are semiarid sagebrush and arid cactus country. Cultivated crops cover 16 percent, especially in the Midwest; together with pastures, agriculture occupies a critical 22.5 percent of U.S. land. Grasslands, dominant in the Great Plains, occupying 14 percent. About a quarter is forest, with mostly evergreen or coniferous common in the western mountains and the sandy southeastern coastal plains while rural areas of the eastern U.S. that are too hilly or infertile for crops are mostly deciduous forest.

Developed land is about 5 percent but 3 percent of this is open space—backyards, parks, and grassy areas intermixed with 1.5 percent of low-density development; we call it the suburbs. Medium density, the city, is 0.7 percent, and only 0.25 percent is high intensity development that you would find on Manhattan Island in New York, the Chicago Loop, or other big city downtown areas.

Land use is conceptually different from *land cover*. It's not just the vegetation, rooftops, or other things we see from above but the purpose to which the land is being put. By far the most prevalent land use is agriculture, occupying about half of all land when grazing and crops are summed, both globally and in the U.S. Agriculture in its many forms is therefore front and center in a discussion of land as a natural resource and is a central focus of this chapter. Forests also occupy one-fourth of the land surface, so forestry is our secondary focus. Agricultural and forest lands each generate both provisioning ecosystem services—food, fiber, and fuel—as well as cultural and regulatory ecosystem services. The mix among these, and the maintenance of natural capital so that ecosystem services can be provided in perpetuity, are the central issues in using land sustainably.

Forms of Agricultural Land Use

We've had several rendezvous with agriculture already, especially in Chapter 2 on Lessons from Environmental History. Agriculture is the deliberate manipulation of ecosystems to produce goods and provisioning services for humans, especially food but also fiber (e.g., cotton, flax, wool, wood) and fuel (e.g., wood, biofuels). Not coincidentally, the geographic distribution of cultivated areas (Figure 11.6 top map) matches well, but not perfectly, with the distribution of people on Earth. With some exceptions, land that can support agriculture defines the human habitat on Earth. Pastures and rangelands used for livestock (Figure 11.7 bottom) tend to lie in less densely populated regions that are not suitable for crop production due to aridity or soil infertility, yet they occupy even more land in total.

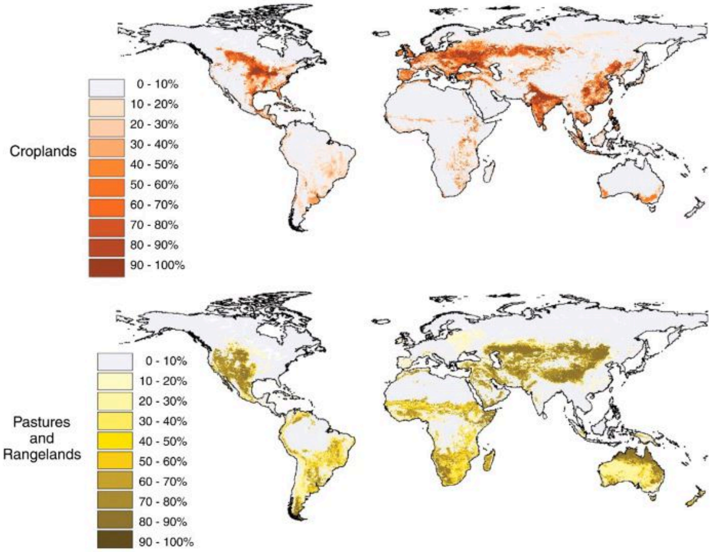

Figure 11.7. Global map of cropland area and pastures and rangelands used for livestock grazing. Grazing generally occurs on lands that are less suitable for crop production due to aridity, high slopes, or low fertility.

There are many forms of agricultural production. Here we simply need to identify some of the most important. First, we must describe two dichotomies. Commercial agriculture focuses on sale of commodities in markets. Subsistence agriculture produces food for local consumption. *Intensive* agriculture applies considerable labor and capital to achieve high yields per acre on highly fertile land. *Extensive* agriculture applies large areas of less fertile land to achieve more modest outputs per acre. With these dichotomies in mind, let's briefly run down the legend in Figure 11.8.

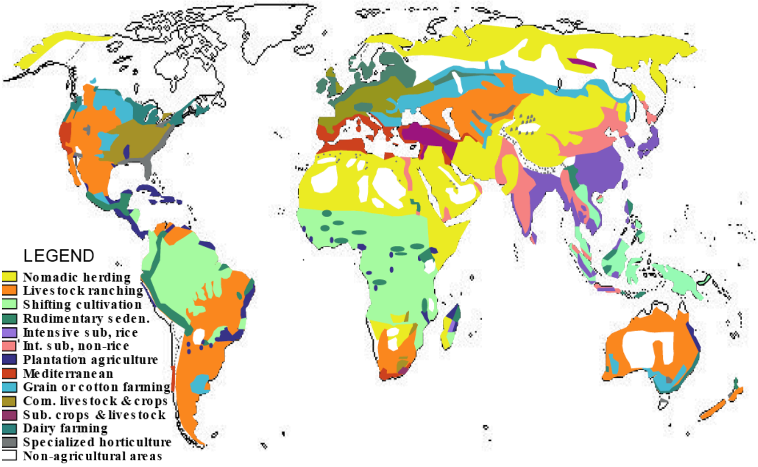

Figure 11.8. Geographic distribution of major forms of agricultural production.

Nomadic herding occurs in arid and semiarid areas where sheep, goats, cattle, camels, or, in the sub-arctic, reindeer are moved frequently in search of greener pastures. It is an ancient but shrinking subsistence-oriented way of life in the Middle East and North Africa, Central Asia, Mongolia, and Siberia.

Livestock ranching occurs in similar environments, but on privately owned ranches, providing goods for commercial markets. It is common in drier grassland and shrubland areas of the western U.S., Latin America, Australia, and Kazakhstan.

Shifting cultivation uses the infertile soils but warm climates of wet tropical regions by periodically burning vegetation to release its nutrients into the soil as ash. It is extensive, usually subsistence in orientation, and seminomadic as farmers must move to new fields every few years as soil fertility declines. It releases enormous quantities of carbon and other pollutants to the atmosphere through forest burning. Shifting cultivation can be sustainable in tropical forests if population densities are low and fallow periods are long but it is becoming less and less viable as population pressure forces farmers to adopt more intensive approaches.

Rudimentary sedentary agriculture can replace shifting cultivation to meet food needs in developing countries in areas where soils will support permanent cultivation.

Intensive subsistence tillage employs hundreds of millions and feeds billions in the populous regions of South and East Asia. Rice, a very productive subtropical grain native to marshes, is dominant where growing seasons are long and water is abundant for flooding the paddies, such as in southeastern China, eastern India and Bangladesh, southeast Asia, the Indonesian island of Java, and the few flat valleys of southern Japan. Drier or cooler areas of Asia, such as western and northern India and northeastern China, often focus on wheat production in combination with a multitude of vegetable crops.

Plantation agriculture often focuses on tropical crops such as coffee, tea, cocoa, and bananas for export to temperate countries. Mediterranean crops such as grapes, olives, and avocados utilize the wet winters and dry summers of that region as well as of California.

Crop farming, in its commercial form, is common in subhumid temperate regions such as the wheat belts of the

North American Great Plains, along the Russia-Kazakhstan border, the Pampas of Argentina, and southeast Australia.

Commercial livestock is the focus of crop farming in areas that have sufficient rainfall and soil fertility to support corn (called "maize" outside North America), often planted in rotation with soybeans. Most of the crop harvest is fed to cattle, pigs, and chickens with meat as the primary product, though increasingly corn is used for biofuels. This form of farming is very familiar to inhabitants of the Midwestern Corn Belt centered on Illinois and Iowa, as well as in Europe from France through Germany to Poland.

Dairy farming, where female cattle are fed from pastures, hay, and "silage" corn that has too short of a growing season to mature into grain, occurs to the north of commercial livestock areas both in Europe (the British Isles and Scandinavia) and North America (the Northeastern and upper Great Lakes states and southeastern Canada).

Specialized horticulture, common along the U.S. Atlantic coast and in parts of California, focuses mainly on fruit orchards and vegetables, often on small, productive farms near urban markets for fresh produce. It is a small percentage of agricultural land, but it produces some of the highest quality food products.

The Challenge of Agricultural Sustainability

A 2011 paper on "Solutions for a Cultivated Planet" in the prestigious journal *Nature* summarizes the challenge of agricultural sustainability well:

> Increasing population and consumption are placing unprecedented demands on agriculture and natural resources. Today, approximately a billion people are chronically malnourished while our agricultural systems are concurrently degrading land, water, biodiversity and climate on a global scale. To meet the world's future food security and sustainability needs, food production must grow substantially while, at the same time, agriculture's environmental footprint must shrink dramatically.

Increase food production and decrease the resources used to produce food at the same time? This seems like quite a trick to pull off! Yet there are reasons to think it is quite possible by following some straightforward strategies as we will see below.

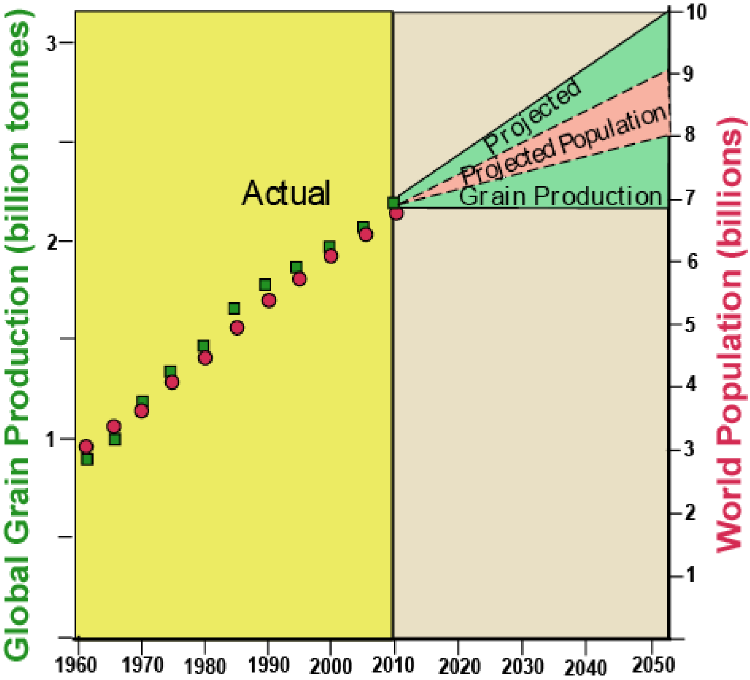

Figure 11.9. The race between global human population (red circles) and grain production (green squares), 1960–2010. How will these figures project to 2050?

First, let's look at the food-population balance and how it has been evolving. Population was rapidly increasing, doubling from about 3 to 6 billion in the period 1960–2000 but has slowed in the 21st century, as we explored in Chapter 5, to reach 8 billion in 2022. Has global food production kept pace? If we focus on grains (rice, wheat, and corn provide 60 percent of human calories), we can see from Figure 11.9 that it slightly more than doubled from 0.9 to 2.2 billion tonnes from 1960–2010 and was 2.3 billion tonnes in 2021.

How was this enormous increase in grain production achieved? Did the area in crops expand? It turns out that cropland area since 1960 has been very stable in Eurasia and North America though it has expanded in Africa and South America. Eastern South America in particular represents the planet's agricultural margin, reflecting the overall supply-demand balance. Even during the most rapid increase in human population in history, only in Brazil has substantial new cropland been brought into production. This tells us that the world's farmers have already found the fertile and resilient lands and few remain open for agricultural expansion. What does remain is primarily tropical forest, a great storehouse of biodiversity and carbon that many would wish to conserve.

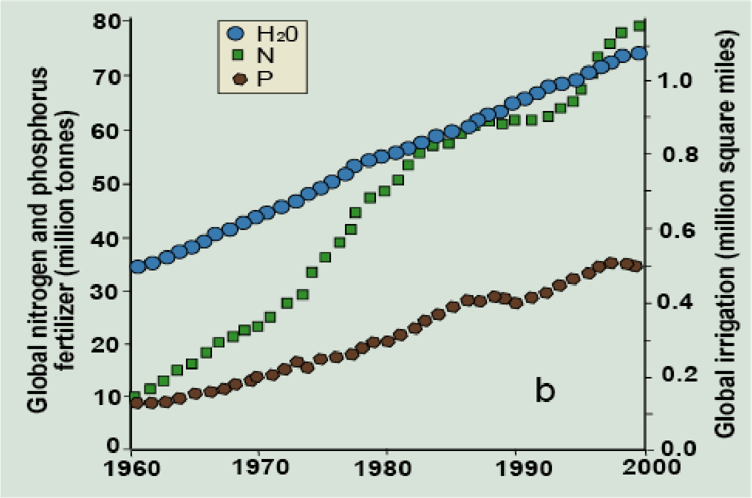

Figure 11.10. a. Global cereal (grain) yields 1960–2000. b. Worldwide use of nitrogen and phosphorus fertilizers and area irrigated 1960–2000.

Fortunately, yields on cropland doubled from 1960–2000 as shown in Figure 11.10a. How was this achieved? Iowan Norman Borlaug is often called the father of the *Green Revolution*. He witnessed how the use of higher-yield varieties of grain and the application of chemical fertilizers, especially nitrogen, and irrigation water in drier regions could greatly increase crop yields. He made it his life mission to bring these benefits to developing countries in order to combat world hunger and won the Nobel Peace Prize for these efforts. Figure 11.10b shows how an 8-fold increase from 10 to 80 million tonnes in nitrogen fertilizer, a tripling in phosphorus application from 10 to 30 million tonnes, and a doubling in area irrigated from 0.14 to 0.28 billion hectares (540,000 to 1,080,000 square miles) resulted in a doubling of grain yields from about 14,000 to 28,000 hectogram per hectare (3.8 to 7.6 tons per acre). The doubling of crop production that occurred from 1960 to 2000 was due 71 percent to increases in yields and only 21 percent from expansion of area cropped. The remaining 6 percent was due to more double-cropping. It seems as though Borlaug's formula has worked.

Unfortunately, it's not that simple. First of all, political ecologists and others have argued that it is primarily the larger commercial farmers that have achieved the higher yields because they are the ones who can afford the fertilizers, irrigation developments and cutting-edge seeds. Smaller subsistence farmers have often lost their market and ultimately their land in the process. So even if there is more food produced, there are also more desperately poor people in rural areas who can't afford to buy it. Often these hungry economic refugees end up swelling the slums and shantytowns surrounding many cities in periphery countries.

There is also an ecological critique. As we explored in the context of ecological limiting factors, crops can only absorb so much fertilizer and water. In 1960 every pound of nitrogen fertilizer applied yielded 80 additional pounds of grain. By 1980 this had fallen to 20 pounds, where it has remained. Once adequate nitrogen and phosphorus fertilizer has been applied, adding more fertilizer does not increase crop yields appreciably. In fact, less than half of global fertilizer applications are taken up by crops. The rest pollutes water as we explored in Chapter 3. Irrigation water increases yields only to a point as well and, as we will explore in the next chapter, many areas are running very short of fresh water. These watersheds and aquifers may not be able to maintain the quantities now used for irrigation, no less expand them. So, Borlaug's Green Revolution seems to have largely played itself out. Except in sub-Saharan Africa, we cannot expect additional inputs of fertilizer and irrigation water to increase crop production at anywhere near the rate achieved over the past half-century. Worse, fertilizers have become the most widespread source of water pollution on Earth, and nitrogen fertilizers can evaporate to form nitrous oxide, a powerful greenhouse gas and a contributor to acid rain. Moreover, irrigation places far more strains on freshwater resources than any other use. Rice paddy agriculture and livestock are the leading sources of atmospheric emissions of methane, the second leading greenhouse gas.

There are other constraints to increasing agricultural yields as well. The health of crops can often only be maintained through an ongoing technological race against the biological process of natural selection. New hybrids of corn, rice, and wheat must be developed every few years to maintain resistance against fungal and other diseases. Weeds develop resistance to herbicides in a decade or two. More antibiotics are fed to livestock than to humans, yet resistant strains of bacteria usually develop in one to three years. This threatens the ability of antibiotics to control bacterial infections in humans as well, an enormous public health issue. Increasing agricultural production emerges as a natural resources sustainability dilemma of enormous proportions.

It gets even more challenging when we more fully consider pesticides, an umbrella term that includes herbicides (weed killers), insecticides, and fungicides. As Rachel Carson pointed out in her 1962 classic *Silent Spring*, many pesticides are *persistent*, meaning that normal ecological processes do not quickly break down these chemicals into ordinary harmless forms; they are not biodegradable. Worse, many also *bioaccumulate*; they become more and more concentrated as they move up the food chain. This tends to occur with chemicals that are fat-soluble because most of the fat that occurs in nature is in animal's bodies, such as polar bears and humans. While some good work has been done to reduce pesticide's risk to human health, their use remains widespread. Pesticides pose health risks in the form of cancer, neurological problems, and endocrine disruption, including birth defects, retarded brain development in children, and reproductive problems. In fact, sperm counts in human males have been substantially reduced worldwide. Pesticide exposure may play a role.

Climate change is now clearly slowly the rate at which crop yields are increasing. Heat waves are as devastating to most crops as they are to isolated elderly people lacking air-conditioning. Moreover, rainfall patterns are becoming more erratic and growing seasons increasingly misfit the life cycles of crops where they are currently being grown, necessitating substantial geographic shifts as an essential adaptation.

Yet, while the rate at which crop yields have increased has slowed in the 21st century, at about one percent per year it still exceeds the rate of population growth. A second revolution in genetically modified organisms (GMOs) has enabled more direct manipulation of crop characteristics to improve yield and other characteristics like resistance to bad weather and pests. This more knowledge-intensive, rather than input-intensive, approach has enabled, for example, U.S. corn yields to continue their upward climb at a rate of about 1.5 bu/ac/year to increase from about 120 bu/ac in 2000 to 150 bu/ac in 2017.

Going forward, even more radical genetic techniques like CRISPR, or gene editing, lie on the horizon to continue to drive yields upward while controlling desired quality attributes.

New approaches using high-tech greenhouses may produce another revolution in yields, as well as in food quality. Gene editing can combine with LED lights calibrated to the best wavelengths for photosynthesis, temperature control, and carbon dioxide fertilization to produce yields far greater than those achieved in outdoor fields. Moreover, water is recycled within the greenhouse, eliminating evapotranspiration losses, and the only nutrients that leave the greenhouse are in the crops themselves. This is a hyper-intensive, more urban and industrial approach to farming, which may sound to some like one more step in our alienation from nature. To others, such as in the Netherlands where it is widely practiced today, it is a way to meet human nutrition and sustainability goals while releasing millions of acres of land from the plow and the cow.

This technology vs. population race must be won in the face of climate changes. And it must be won in a manner that reduces water, nutrient, and carbon footprints as well as ecological impacts captured by measures like HANPP that we explored in Chapter 8. Now the agricultural sustainability challenge begins to look as steep as the Wasatch Front.

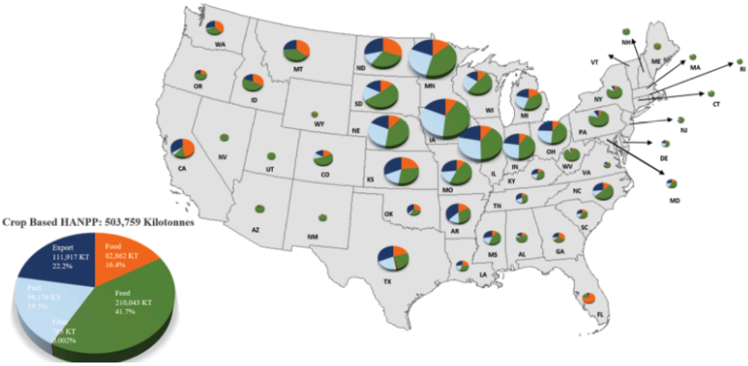

Figure 11.11. Allocations of crops in the conterminous U.S. to food, feed, fuel and exports in 2012.

The notion that farming is environmentally and ecologically benign is widespread. It seems to harken back to an earlier, simpler era of our grandparents and great-grandparents when life was less complicated and people “lived off the land.” Certainly organic farming and local food have their merits in rebuilding some of what has been lost in the relationships food builds between people and their local environment and community. Yet in the U.S. three-fourths of all cropland grows only five crops: corn, soybeans, wheat, hay, and cotton. Of these, only wheat is used primarily for food. Figure 11.11 shows that in the U.S., livestock feed at 42 percent, exports at 22 percent, and biofuel at 20 percent all exceed food at 16 percent for allocation of crops. This is especially the case in the highly fertile Midwest, where food, mostly wheat, is an orange sliver in the large crop pies in Figure 11.11. These figures compare to 67 percent allocation to food globally. It has been calculated that shifting crop production and allocation from feed and fuel could produce food for 4 billion people. So local food markets, where I buy my fruits and vegetables when they are locally in season, are a good thing but only focus on one narrow slice of the agricultural land use pie. Clearly one way to reduce the footprint of crop production is to focus more on food.

When we use footprint analysis to measure the commitment of land and water, nitrogen, phosphorus, and carbon sinks to the agricultural enterprise, we get a picture of agriculture as a dominant consumer of renewable resources and waste sinks. The majority of grassland and savanna ecosystems worldwide have been converted to agriculture as well as nearly half of temperate deciduous forests. Over a fourth, and climbing, of tropical forests have been cleared for agriculture.

So we need to think a little harder about how to meet the challenge of agricultural sustainability. The "Solutions for a Cultivated Planet" article cited above provides five strategies, in addition to using genetic and other technologies to continue to increase yields, that can drive a more sustainable agricultural enterprise worldwide and for the U.S.

1) *Stop expanding agriculture*. Land clearing is the single greatest threat to biodiversity and also releases large quantities of carbon to the atmosphere that had been contained in plants and soil. Given that the most productive agricultural lands have been in production for generations, and the margin for expansion in tropical forests is both lower-productivity and high in ecosystem services and biodiversity conservation value, a clear case can be made that expanding agricultural area works against sustainability. The drainage of wetlands, our best ecosystem services packages, for crop production furthers this case against adding more land to crop production.

2) *Close yield gaps*. Crop yields, such as for corn in the U.S. as we saw above, have continued their remarkable climb. This is not true worldwide, however, where crop yields vary greatly. Nutrient and water limitations, lack of advanced seeds, poor management, and other factors limit yields in much of the world, especially in developing regions of Africa, parts of Latin America, and Eastern Europe. Closing the gap between possible and actual yields would reduce rural poverty and make more world regions self-sufficient.

3) *Increase agricultural resource efficiency*. The topic of

irrigation efficiency tends not to come up in casual conversation at social gatherings. Yet getting "more crop for the drop" is an issue central to natural resource sustainability. In Chapter 3, we defined evapotranspiration as the sum of evaporation and transpiration but evaporation does nothing to produce food while transpiration is essential to power photosynthesis. Modern irrigation systems, such as drip irrigation, often led by Israeli technology, use small underground pipes to delivery water drop by drop into the root zone of crops below ground so that evaporation is minimized. Satellites and drones can monitor the greenness of crop fields over both space and time to target areas needing irrigation water and fertilizer.

Yet there are enormous efficiency gaps. Central pivot irrigation makes the Great Plains appear as a pattern of giant circles from an airplane window but is much more efficient on a calm night than on a hot windy afternoon. From there it gets worse. Unlined canals, flood irrigation over uneven fields, and other wasteful practices are surprisingly common. In the next chapter focusing on water, we'll see how sometimes there is no incentive for farmers to invest in efficient irrigation systems.

Fertilizer applications are critical to achieving near-optimal yields, yet excessive applications are the leading source of polluted runoff. So this is a problem of getting it just right. Unfortunately, Gulf Hypoxia resulting from nitrogen runoff from the Mississippi River is not the only case of a "dead zone"; the problem is escalating worldwide, with hypoxic conditions appearing along the northern coast of Europe, in the Mediterranean, the Bay of Bengal, along the East Asian coast, and elsewhere.

Fertilizer runoff is an example of a negative externality overwhelming the denitrification capacity of watersheds, a clear case of a tragedy of the commons as we explored in Chapter 9. Providing technical assistance, eliminating subsidies for fertilizers, or even taxing or regulating them, emerge as policy tools to address this acute problem of agricultural sustainability.

4) *Reducing waste*. Czech-Canadian environmental scientist Vaclav Smil has analyzed the energy content of the food system and finds that less than half the calories harvested from the field are consumed by people. For every 100 calories harvested worldwide, 13 are lost postharvest, largely to pests. Another 37 are fed to livestock, with only 11 regained as meat and dairy products. An additional 17 are lost in the distribution system and households, leaving only 44 that are actually eaten by people. In the U.S., losses are even higher than the worldwide figures due to an emphasis on biofuels and livestock and high rates of food waste. Grocery stores often discard perfectly edible, but imperfect, produce that customers pass over. Expiration dates on meat and dairy products are usually too stringent encouraging households to throw away perfectly good food. Restaurants are another source of waste. We are certainly not running a tight ship even though all food carries with it a water, carbon, nitrogen and phosphorus footprint

that serves no purpose if the food is not eaten . . . or is overeaten.

5). While we associate agriculture or farming with producing food for people, this is only partly true. Much agricultural land is devoted to producing feed for livestock, fiber products like cotton, or biofuels. In 2018, fully 40 percent of all corn grown in the U.S. was used for ethanol in gasoline, and most of the rest feeds livestock. Corn's rotational partner, soybeans, is also largely sent to feedlots, as is the hay grown on less fertile lands.

Livestock production is a central sustainability concern. Livestock constitute over 60 percent of mammalian and a similar fraction of bird biomass on Earth. Feeding them utilizes three-fourths of global agricultural land. Cattle are specifically at issue, requiring 28 times more land, 11 times more irrigation water, 6 times more reactive nitrogen, and 5 times more greenhouse gas emissions than other forms of animal-based calories. Shifting from beef to chicken and pork could release crops sufficient to feed 357 million people; further shifting to dairy and eggs could feed 815 million people.

What I am arguing here is not that cattle are evil, but that they are qwerty. What does that mean? Look at your keyboard and on the upper left you will see this "word" spelled out. It's not at all an efficient way to place the 26 letters of the alphabet on a keyboard—in fact, it is just the opposite. A century ago, though, this deliberately inefficient layout was used to slow down typists who would otherwise jam the keys on old typewriters. Yet when the whole world switched to computer keyboards, cellphone texting pads, and everything else we now write on in the 21st century, this layout of the letters came along for the ride as technological lock-in. It makes no sense but it's hard to change because every day our fingers and nervous systems are getting tied into that layout as the powerful form of human capital known as habits.

Similarly, cattle were an essential tool of survival when the American frontier was extended west of the Mississippi River through the Louisiana Purchase, Mexican Cession, and Oregon Compromise. The majority of this newly acquired land is grassland with a net primary productivity that humans found a way to appropriate. While humans can't eat grass, they can eat cattle and drink their milk and, as ruminants, cattle can eat grass. So cattle became the great tool to HANPP or colonize vast grasslands and in that context they remain a valuable and potentially sustainable element of agricultural productivity. The problems come in when the Green Revolution generated an enormous surplus of grain, especially Midwestern corn, with no obvious market. So cattle, the livestock species that was most familiar, in fact ubiquitous, became the means through which to dispose of these massive corn surpluses to produce a salable product in the form of ever more beef production. The U.S. beef cow population grew four-fold between 1939 and 1979 from 10 million to over 40 million head as hamburgers became a staple food for

Americans. Notice that cattle, large animals on the order of 1,000 pounds, have a high feed conversion ratio of around 8 and up to 15 as harvested. So one cow can dispose of up to 15,000 pounds of surplus corn! This is as deliberately inefficient as the qwerty keyboard layout and has become just as locked-in.

A similar story could be told about coal, which enabled the 18th and 19th-century industrial revolution. Without coal, human civilization would not have progressed in anything approaching the rapidity that it has and, without cattle, the Western U.S., and much of South America as well, would never have been settled and brought under the influence of modern times. Anything that has been central to survival and progress for a couple of centuries is inevitably going to become a cultural icon—like the coal miner, the cowboy, the hamburger, and the beefsteak.

Yet traditional virtues such as hard work and self-reliance are not embedded in cattle and coal any more than inspired creative writing is embedded in the typewriter. An equally important virtue is to embrace a better way of doing things. So I don't look forward to the last cow disappearing from the American farmscape, especially from uncroppable grasslands where they belong so much more than in Confined Animal Feedlot Operations (CAFOs), but I do look forward to the day when we can look back at "peak cattle" decades into the phasing out of this unsustainable practice, just as we can already look back upon "peak coal," which occurred in 2009 (perhaps).

What is Sustainable Agriculture?

Fortunately, there are sustainable alternatives to the current system of agrochemical-intense crop production, overgrazing of grasslands, and CAFOs that globally has left 800 million people under-nourished but a billion overweight. Michael Pollan, in his widely-read critique of the U.S. agricultural and food delivery system, *The Omnivore's Dilemma*, describes the Polyface Farm in Virginia, run by Joel Salatin. This grass-based farm is pastoral (rather than industrial) and biological (rather than mechanical), based on perennial (rather than annual) crop species. It is a polyculture (rather than a monoculture) relying on solar energy (rather than fossil fuels) to produce a diversified (rather than a specialized) set of products for the local (rather than the global) market. At its heart is the utilization of ecological interactions among the farm's various species of plants and animals.

It seems the chickens eschew fresh manure so Joel Salatin waits three or four days before bringing them in—but not a day longer. That's because the fly larvae in the manure are on a four-day cycle, he explained. "Three days is ideal. That gives the grubs a chance to fatten up nicely, the way the hens like them, but not quite long enough to hatch into flies. . . . The hens picked at the grasses, especially the clover, but mainly they were all over the cowpats, doing this frantic backward-stepping break dance with their claws to scratch apart the caked manure and expose the meaty morsels within." . . . This is what Joel means when he says the animals do the real work around here. "I'm just the orchestra conductor, making sure everybody's in the right place at the right time" (Pollan 2005: 212).

And make no mistake, the Polyface Farm produces a great deal of high-quality protein-rich food and does it in a manner that is cost-effective, employs somewhat more labor, and regenerates natural capital such as fertile soil rather than depleting it.

By the end of the season, Salatin's grasses will have been transformed by his animals into some 25,000 pounds of beef, 50,000 pounds of pork, 12,000 broiler chickens, 800 turkeys, 500 rabbits, and 30,000 dozen eggs. This is an astounding cornucopia of food to draw from 100 acres of pasture, yet what is perhaps still more astounding is the fact that this pasture will be in no way diminished by the process—in fact, it will be the better for it, lusher, more fertile, even springier underfoot. Salatin's audacious bet is that feeding ourselves from nature need not be a zero-sum proposition, one in which if there is more for us at the end of the season then there must be less for nature—less topsoil, less fertility, less life (Pollan 2005: 126).

The audacious bet of sustainable agriculture is that we are not necessarily faced with a trade-off between (a) maintaining the natural capital that makes agriculture and ecosystem services from rural landscapes possible and (b) meeting the food needs of a growing human population. We can have our cake and eat it too but only if agriculture undergoes a process of change that goes by various names like *ecological intensification* and *permaculture*. Likely, this change will only occur if the economic incentives farmers and ranchers face favor sustainable agriculture as the most profitable form of farming and if a learning culture matures where master farmers like Joel Salatin inform other farmers willing to innovate.

There are two contrasting ways of viewing this challenge. The first is an impact approach that views agriculture as a major source of pollution and a land use that removes nature. The second is a public goods approach that sees agriculture as a multifunctional enterprise that produces ecosystem services alongside food and fiber goods. These views are embedded in the structure of property rights to land and to the water that falls upon and runs through that land. The former suggests a regulatory or polluter-pays approach similar to environmental laws imposed upon other industries that use public water and air resources for waste disposal. The latter suggests a system of compensating farmers for the ecosystem services that they choose to produce from their land.

The Conservation Title of the 1985 U.S. Farm Bill set historic precedents in recognizing the importance of ecosystem services from rural landscapes. The Conservation Reserve

Program (CRP) offers farmers annual payments, often in the range of $50–100 per acre per year, to replace crop production with permanent vegetative cover on highly erodible and other environmentally sensitive lands to, in essence, produce ecosystem services instead of crops. CRP has resulted in enormous reductions in soil erosion and water pollution while increasing wildlife habitat and carbon storage in soils. The program at one time had 40 million acres enrolled, an area the size of Iowa or New York, but as of this writing stands at 24 million acres as farmers have allowed their contracts to expire to take advantage of high crop prices, partly induced by biofuel subsidies. CRP thus, in a sense, leases ecosystem service provision from farmers.

The Wetland Reserve Program, initiated in the 1990 Farm Bill, offers farmers a lump sum payment in the neighborhood of $1,000 per acre to restore wetlands on cropland. As of this writing there are over two million acres enrolled in WRP. Lands damaged by major floods have been a particular focus of the program.

Organic farming exemplifies the co-production of food and ecosystem services. Separate, usually higher-priced markets for organic food have made organic farming profitable but they have also introduced a bureaucratic approach to defining what food products can legally claim the organic label, focusing on the absence of chemical fertilizers and pesticides. Note that agriculture does not need to be organic to be sustainable. In particular, modest applications of nitrogen fertilizer can increase yields without generating water quality or other problems.

These initial efforts to build programs to increase ecosystem service provision from agricultural lands are a good start. The dominant form of agricultural production in the U.S., however, remains very chemical-intensive and CAFOs continue to increase their central role in an agricultural system that is dominated by mass production of livestock and a short list of non-food crops.

Sustainable Forestry

Forests are an icon of environmentalists, some-times called “greens” for the color of tree leaves. Their opponents often refer to them derogatorily as “tree-huggers.” Some of us, myself included, enjoy spending time in the woods; others find it a lonely or even scary place.

Forests are second only to agricultural lands as a land-based resource and they share many of the same issues. Like soil, forests are natural capital that can produce provisioning services—wood as a raw material for construction, the feedstock for paper, and fuel—as well as supporting, cultural, and regulatory ecosystem services. For this reason, the primary law governing forest management in the U.S. is called the Multiple Use Sustained Yield Act. We will see that many of the dilemmas of sustainable forestry boil down to answering the question "what set of ecosystem services does the public want and how can the forest deliver them?" Or, asked differently, "among the sets of ecosystem services the forest is capable of producing, which set does the public want the most?"

Unlike agricultural lands, which are almost entirely managed privately, forests in the U.S. are more evenly split between public and private management. The U.S. Forest Service, founded by Gifford Pinchot in 1905 under the direction of President Teddy Roosevelt, manages 193 million acres, an area larger than Texas. While not all of this area is covered by trees, most of the area of the western mountain ranges is in national forests as are many of the steepest lands of the sprawling Appalachian chain. Of the 751 million acres of forest in the U.S., 44 percent is in national forests and other public lands, but the majority, 56 percent, occurs on private land.

Timber can be considered a crop but one with a long rotation of decades rather than a growing season, making it less profitable than annual crops on land where these can be grown. Forests usually generate a more abundant package of supporting, cultural, and regulatory ecosystem services than agricultural land. While soil erosion presents an ever-present danger to the value of agricultural natural capital, fire is the greatest threat to forests. Both share a concern that invasive species, pests and diseases will take over, crowding out the crops or the timber managers are trying to produce. Both also share a concern that climate change will alter the ecology to which managers have become accustomed.

Agricultural lands are not natural ecosystems; they are cultivated for specific human benefits. So also are some forests such as orchards and ornamental trees on front lawns. Forests range along a continuum of human intervention from cultivated, through managed commercial forests, through natural forests managed for fire suppression, to true wilderness.

Unlike in the tropics, the area covered by forests in the U.S. has been slowly increasing for a century. Why is this the case? Where precipitation exceeds potential evapotranspiration, as it does in the eastern half of the U.S., in the Pacific Northwest, and in the high Rocky Mountains, forests will naturally grow wherever plows, bulldozers, and fires fail to prevent it. Therefore, in humid climates, rural land that is not used for crops or grazing is nearly always forest. As the agricultural margin retreats, forests advance. Think of this historically. The pioneers headed west for land. East of the Mississippi River, most was forested land from which they would cut and burn out a farm. Many of these farms are still producing crops or livestock today but on hilly, infertile, and erosion-prone lands, the farms failed the ecological test of resiliency and the economic test of profitability. As soon as farmers stopped clearing and planting, the forests began to return. Thus the increase in forest has occurred largely due to a process of abandonment of marginal farms and natural succession. Along with forests that have been cut for timber in the past, it is often called second-growth forest in contrast to virgin or old growth forest that has not been cut in historic times. In much of the Eastern U.S., these second-growth forests continue to grow; the volume of standing timber doubled between 1960 and 2010 in an unheralded example of natural capital accumulation.

Economics of a Stored Natural Resource

Following the logic in Part II, let us consider forests first from a neoclassical economic perspective where the primary forest product is wood as a raw material. Every year that goes by, the trees are growing, adding more wood to the natural capital stock. At some point in time, however, we need to call in the lumberjacks and harvest the wood. When is the best time to do this? Figure 11.12 shows a typical growth curve over a century for trees to be used for timber. Yellow pines in the southeast may grow faster than this and Douglas firs in the northwest may grow slower but each will start off as saplings that add wood gradually, and then surge in height and girth as they mature. As they age, however, their rate of growth will slow until the maximum wood-storing capacity of an acre of forest is reached. Marketable timber is always less than the full mass of wood because twigs, roots, small branches (called 'slash') are not suitable for use.

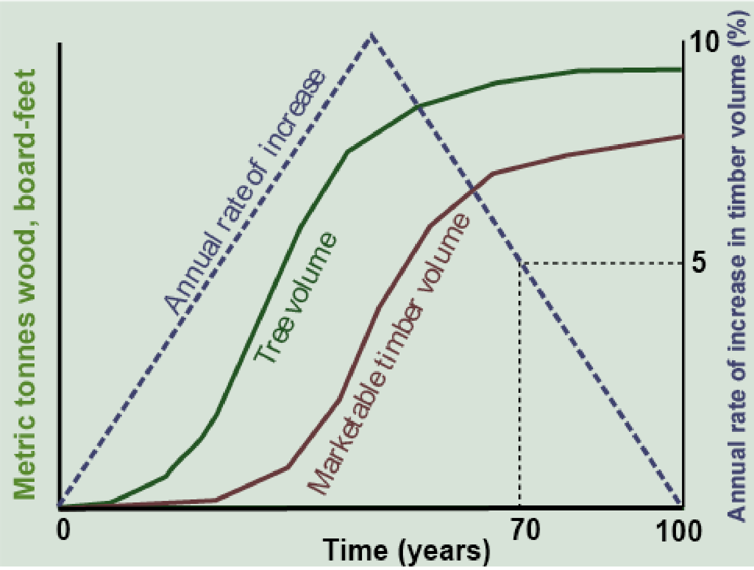

Figure 11.12. A typical pattern of tree growth and timber volume over a century. Note that the optimal time of harvest (70 years in this example) occurs when the annual rate of growth drops to the overall rate of return on investments in the market (5 percent in this example).

You may think that the best time to cut is when the full volume of marketable timber is reached, at 100 years in Figure 11.12 but this is not the case. If the volume of timber is increasing at a slower rate than the investment market could return, say a 5 percent annual rate of return, it is more profitable to harvest the timber and invest the profits. The optimal time to cut then becomes 70 years—30 years sooner. This also gives the next generation of trees a 30-year head start.

Over a larger area, a few tracts are being harvested while the rest continue to grow. As long as the overall increase in tree volume through growth is equal to or greater than the rate of cutting, then we can say the resource is being managed sustainably—at or below maximum sustainable yield. It's not that simple, however, because the trees may not survive for 70 years.

The Management of Fire and other Ecological Threats

Forest fires are frightening and destructive, as an increasing number of breaking news stories has shown us. Despite expenditures of one to two billion dollars each year, forest fires on federal lands (mostly national forests) increased from an area about the size of Connecticut in 1960 to New Jersey in 2002 to larger than Maryland in 2017, including the Camp Fire that turned Paradise, CA into ashes, killing 85 people and destroying over $16 billion in property. The perception that wildfires are growing worse is clearly based in reality. A new record for a creage burned was set in 2020.

Fire is a defining characteristic of forest ecosystems. Natural fires started by lightning have always been present. Native Americans were great advocates of burning the forest to clear land for crops, to chase prey into hunters' traps and to encourage grasslands as habitat for their prey, such as bison. Today, humans start about 90 percent of wildfires either accidentally or deliberately. Except for the wettest rainforests, such as those found along the Pacific coast north of California, most forests have a fire history that in some way has controlled their development. Pine and oak, two of the most common tree genera in the U.S., are well adapted to fire. Some pine species have seeds that only open and germinate during or after fire. Most oak saplings cannot grow in the shade of their parents; they need fire to clear a sunny spot in which they can thrive.

As a forest grows and matures, dead trees and fallen limbs on the forest floor are particularly apt to accelerate a fire started during drought conditions. Fuel gradually accumulates and, with it, the fire risk. Small ground fires can usefully remove this debris, helping to prevent large destructive fires in the future. But fire is precarious; it's hard to predict when a change in the wind, weather, topography, or the distribution of fuel will turn a small, useful fire into a conflagration that destroys hundreds of square miles of forest or people's homes.

Fire suppression has always been the most important mission of the U.S. Forest Service but the question of when fire is a good thing has never been settled. For most of the 20th century, the policy was to put out all forest fires as quickly as possible. This led to the accumulation of fuel, however, increasing fire risks. In recent decades, the pendulum has swung toward seeing fire as an essential tool of ecological management but when summer homes and rural residences start penetrating the forest, protecting people and their property take precedence over ecological management. Fire also releases vast quantities of carbon dioxide that are better kept out of the atmosphere, stored in wood.

Beyond fire, windstorms, invasive species, and pest outbreaks pose a danger to forests, often one that is heightened by climate change. For example, milder winters have facilitated the spread of bark beetles into the forests of the Alaskan coast, killing untold thousands of valuable spruce and cedar trees, leaving a landscape vulnerable to fire in their wake. Kudzu and Asian bittersweet vines strangle forests in the southeast. Controlling these biological invasions is often a losing battle. Fungal plagues of Asian origin wiped out two wonderful deciduous trees species—the American chestnut and the Dutch elm. Due to all of these ecological risks, the nice S-shaped growth curve presented in Figure 11.12 may never play out.

Ecosystem Services from Forests

So far, we have only been considering forests as a risky place to try to grow a sustainable supply of wood. A forest is an ecosystem that produces many other services as well. In fact, only wetlands generally produce greater ecosystem services than forests on an acre-by-acre basis. In increasing recognition of these competing demands from forests, the concept of ecosystem management was born. That is, forests need to be managed for the full suite of ecosystem services rather than wood supply alone. Table 11.1 lists these services under the four categories of supporting, provisioning, cultural, and regulatory adopted by the Millennium Ecosystem Assessment.

Table 11.1. Typical ecosystem services provided by forests.

Supporting	**Provisioning**	**Cultural**	**Regulatory**
photosynthesis/ primary productivity	timber supply	landscape aesthetics	flood control
maintenance of biodiversity	pulp for paper	recreation	water purification
soil formation and binding	game	spiritual values	carbon storage
nutrient cycling	biofuel feedstock	hunting and gathering	pollination

So do we have to choose only one ecosystem service from this list? Of course not, because many of them are complementary—provide one and others come along with it.

Can we have them all? No, because some of them are competitive—they form a trade-off. In particular, you are perhaps thinking that maximizing the timber, biofuel, and paper pulp supply competes with all the rest. That's why we need to protect the forests. But it's not that simple. Its a complex problem of, first, determining what ecosystem services the public wants, essentially a political exercise, and then figuring out how best to deliver them over time from the forest ecosystem, essentially a scientific and management exercise. Let's penetrate this idea a bit deeper through some controversial resource management problems in our national forests. In each of these, look for how the problem boils down to the question: What ecosystem services does the public want and how can the forest deliver them?

The Shawnee National Forest, which contains most of the public land in Illinois, is a hunter's paradise with waterfowl, wild turkey, and large white-tailed deer that grow fat on acorns and hickory nuts. Beneath the 80–120-foot-tall oaks and hickories, one finds slowly growing maples and beech that can tolerate the shade. In time, however, the oaks and hickories will die off, taking the mast of acorns and hickory nuts with them, leaving a maple-beech forest that is even more beautiful in the fall but that lacks the abundance of food for the game that hunters and naturalists now enjoy. In other areas, yellow pine was planted in rows decades ago, leaving a bounty of potential two-by-fours but less wildlife habitat.

Under natural conditions, raging fires opened up areas for restoration of oak and hickory, but today, such fires are suppressed to protect the significant rural population that enjoys their homes in the woods. If a return of the natural fire regime necessary to maintain the oak-hickory forest is too risky, a replacement mechanism is clear-cutting and replanting with acorns and hickory nuts. This would simulate the natural fire regime while providing high-quality wood and establishing oak and hickory forests for the rest of the century. Deer would flourish 5–20 years after the cut when abundant tree leaves are within reach. However, clear-cutting is, understandably, opposed by local environmental groups, who find the current forest structure highly aesthetic for recreational activities such as horseback riding and have a gut reaction against cutting—especially when, in the Shawnee, it generally doesn't turn a profit. What's your solution to the problem of what ecosystem services does the public want and how can the forest deliver them?

The most well-known forest controversy in the U.S. is the management of the northwestern forests. The issue is often painted as a conflict between jobs for lumberjacks harvesting the most profitable timber supply in the national forest system vs. the endangered northern spotted owl of the old growth forest. Is that the issue? Or is it a tug-of-war between different sets of ecosystem services?

The harvesting of old-growth timber in the once stupendous forests of the Northwest is nearly complete—only about ten percent remains—while most of the region is blanketed with second-growth forests that will start to reach maturity in coming decades. A similar cycle of the "great cut" of large old-growth trees, followed by regeneration and more sustainable management of second growth, occurred in earlier centuries in the eastern and lake states. Only now we have the Endangered Species Act that forbids federal actions that would lead to the loss of habitat of listed species.

Dependent on the old-growth environment that includes large dead trees called snags, northern spotted owls are a fine bird species that we wouldn't want to lose to the abyss of extinction. But are they the real issue or just the point at which the teeth in the Endangered Species Act bite? Ecological studies revealed 312 plant, 149 invertebrate, 90 terrestrial vertebrate, 112 anadromous fish, and 4 resident fish species that are also dependent on the old-growth ecosystem. So the issue is far larger than the endangered northern spotted owl: it is the preservation of the forest-based natural capital that generates a suite of ecosystem services listed in Table 11.1. Of particular interest are naturally spawning salmon and a mountainous forested landscape that is second to none for its beauty and recreational opportunities. Salmon and this grand landscape symbolize the Northwest, a region many Americans have deliberately migrated to, despite the endless drizzle, just to soak it all in. The northern spotted owl doesn't particularly symbolize these values, rather the Endangered Species Act is the most effective legal lever that people who value this suite of ecosystem services can use to protect them—and the owl is the best species to engage that law.

On the other side of the debate, timber cutting generates jobs and income and helps maintain low prices for lumber. When timber is exported as raw logs rather than as finished wood products, however, many potential jobs in wood-based industries are actualized overseas.

With these issues boiling over, the Clinton Administration negotiated the Northwest Forest Plan in 1994 applying to national forests in northern California, western Oregon, and Washington. Among other elements, the plan called for protection of old-growth forests that contain endangered species and protection of riparian corridors along streams, while vigorous timber-cutting programs of over one billion board feet per year were to continue.

Unfortunately, most observers are disappointed with the progress made under the plan. Rather, the legal requirements of the Endangered Species Act have held sway in court. There has been little active management to control fire risks or to thin maturing forests to accelerate their development of old-growth characteristics. Timber cutting and associated jobs have plummeted in a sea of red tape while profitable, value-added, wood-based industries have not developed. This disagreement over forest resource management has failed to ask, no less answer, the question "what ecosystem services does the public want and how can the forest deliver them?"

Ecosystem Services over Space and Time

Not only timber cutting, but other ecosystem services have a time and space dimension. Figure 11.13 uses the same axes as Figure 11.12 but charts how certain ecosystem services develop as the forest grows. Forests are excellent at filtering water as it seeps through the leaves, stems, and roots, and at controlling floods by transpiring and storing water. These services become available early on, as soon as the forest forms a dense canopy of saplings. Different forest wildlife species thrive at different periods. The northern spotted owl is a creature of old growth but deer enjoy the early phase when more leaves grow within reach. (Recall the example of the Tongass National Forest from Chapter 10.) Most people find mature and old-growth forests with large trees and limited undergrowth more aesthetically pleasing, even cathedral-like, than the dense, nearly impenetrable brush of a newly restored forest. So as a forest matures, its suite of ecosystem services evolves with it.

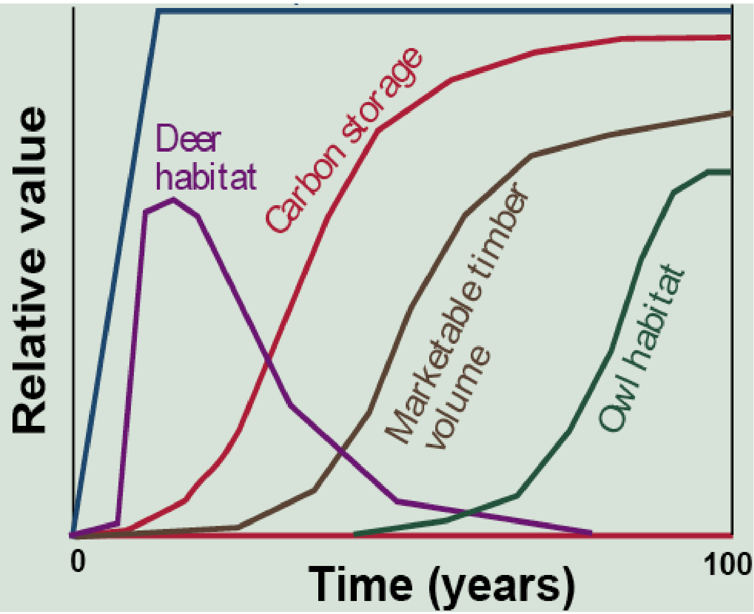

Figure 11.13. An example of the development of ecosystem service values over time in a forest.

Carbon storage, an increasingly critical forest service, is coincident with the volume of wood in the growing forest, about 45 percent by weight in trunks and leaves alike. Researchers from Woods Hole Research Center in Massachusetts showed that, prior to 1945, the U.S. landscape was a source of carbon emissions but that, since 1945, it has become a substantial carbon sink. Largely due to fire suppression and forest growth on abandoned farmlands, growing U.S. forests are offsetting over 10 percent of U.S. carbon emissions from fossil fuels. This lends another angle to the long debate over fire suppression since the accumulation of woody debris removes carbon from the atmosphere, while burning releases it, as does decay. Perhaps deadwood could be collected from forest floors to replace a bit of coal, thus killing the renewable energy, fire management, and climate change birds with one stone.

Space also matters. The services of water purification and flood control are best provided by forests hugging streams—the riparian zone. Biodiversity can be maximized by interspersing forest tracts of different ages, thus providing a variety of habitats but some species require large contiguous tracts of old growth. All of these intersecting goals calls for a new paradigm.

Ecosystem Management

Ecosystem management is a concept developed in the 1990s by a coalition of scientists from academia and federal agencies, with special reference to management of public lands and forests. It arose partly from the failure of management focused on wood supply and fire suppression on the one hand, restrained by the Endangered Species Act (which only kicks in when species are about to disappear) on the other. Done properly, ecosystem management is a process to answer the question we have posed: "What ecosystem services does the public want and how can the forest (or landscape) deliver them?" It also acknowledges how difficult that can be. First, different segments of the public want different things. Some want to buy wood cheap, others want to protect their favorite recreational spot, others want to save species from extinction or preserve the aesthetics of the forest in its natural state. Working this all out is a terribly difficult, though not impossible, political and economic task.

Second, ecosystems are complex systems that are unpredictable and only partly understood. Fires, floods, droughts, pest outbreaks, wind-storms, exotic species invasions, human mismanagement—these disturbances all occur, and the ecosystem must be able to either resist them, or more likely be resilient to them.

For this reason, *resilience* is a critical concept in ecosystem management. What does it mean? If I say that you are resilient, it means that when a hardship comes—illness, injury, loss of a loved one, financial loss, a damaging addiction—you are able to rebound in a way that maintains your vigor and positive direction. For an ecosystem, it means that it can withstand disturbance or *exogenous shocks* and still maintain its fundamental ecosystem functions and dynamics—though it will never return to its original state. Ecologists are still working out what makes an ecosystem resilient but biodiversity almost certainly helps because if one species suffers a major setback, another can take its place in the food web and in the performance of essential functions like decomposition or nutrient cycling. Ecological resilience, and therefore biodiversity, is thus central to natural resources sustainability.

All of this entails a measure of humility as well. We only partly understand the complexity of ecosystems and cannot always predict how they will respond if humans do X or Y. Like in medicine, we can at least record the management measures that were taken and the results that occurred. Then we can adjust the treatment, if necessary, and again record the results. In the natural resources field, this is called *adaptive management*. It is distinct from *planning* because to develop and implement a plan, two prerequisites must be present: the planner has the political authority to implement the plan and the results of management actions are predictable. Yet these two prerequisites are rarely met. Adaptive management—learning as you go through observation and experimentation—thus goes hand-in-hand with ecosystem management as the best ideas we currently have for managing our forests and other landscapes sustainably.

Analyzing Ecosystem Services from Rural Landscapes

On largely privately-owned rural landscapes, the most common type in the U.S., especially between the Rocky Mountains and the eastern seaboard cities, agricultural production co-mingles with semi-natural land uses. Aggregately, these landscapes generate both private provisioning and public ecosystem services. An example will help illustrate.

The land that forms Big Creek, near my former home at Southern Illinois University, is divided into a large number of privately-held land units or farms. In selecting land uses, say between crops, pasture and forest, each farmer responds not to the watershed-scale performance, but to the performance of his or her own farm, given the characteristics of the land they have to work with and the policies and economic conditions that apply to it.

Figure 11.14a, for example, shows that, in humid climates where crops and forests will grow without irrigation, we find that crops are most profitable on flat, fertile, well-drained land. Producing crops is expensive, however, and profits fall toward zero on marginal land that may be less fertile, a bit hilly, or frequently flooded. These lands are better suited to pasture, which is less profitable, but also less costly. On even less productive land—hilly, infertile, rocky, or perennially wet—forests remain or are allowed to regenerate. So the land use map of a watershed tends to be well-organized with crops on the most fertile, forests on the least fertile, and pastures on the intermediate land from the standpoint of agricultural productivity. This occurs not by a central plan, like on a National Forest, but by each farmer or landowner doing what they see as best on their own parcels. In more densely populated countries, such as many in Asia, farmers will push crop production onto even more marginal land using terraces and other labor-intensive practices—usually at the expense of forests. This also occurs in the U.S., as shown in Figure 11.14b, when crop prices are high, such as when large volumes of corn are used to produce ethanol.

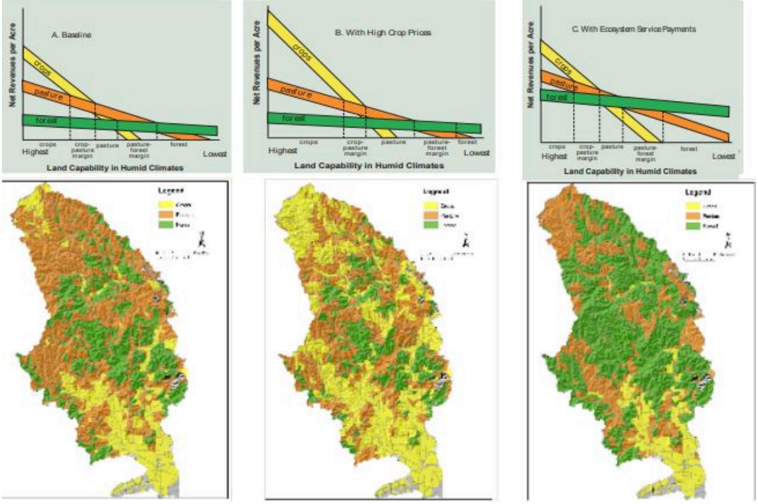

Figure 11.14. The effect of economic incentives on land use. A. In the baseline case, in humid climates, crops yield the highest net revenues on high capability land, but profits decline rapidly as land capability lessens. Forests yield the lowest net revenues on high capability lands, but profits fall only slowly with declining land capability. Pastures are intermediate. This results in crops being grown on the most productive rural lands, pastures on the moderately capable lands, and forests on the least capable. B. If crop prices rise, crops push into the crop-pasture margin. C. With ecosystem service payments, net revenues for crops rise only slightly, pastures moderately, and forests greatly. This results in pastures pushing into marginal cropland, and forests pushing into pasture.

Forests produce greater ecosystem services per acre than pasture; pasture produces more than cropland. If farmers were actually paid for these services, say through the Conservation Reserve Program or carbon credits, it would increase the profitability of forests the most and crops the least. This would encourage forests on what had been pastures and pastures on what had been cropland (Figure 11.14c). Crop food production would decrease a bit but ecosystem service provision would increase greatly on an evolving land use map.

In the more arid landscapes characteristic of much of the western U.S., where rainfall is insufficient to support crops or forests, we instead have a landscape of irrigated crops, on the most fertile lands where water can be obtained, and rangeland where it cannot. Where rainfall is insufficient to maintain even grazing, there is the nonagricultural desert.

As we view the rural landscape from our windshield while driving, aerial photographs, or satellite images, we are looking at a system that is organized from below—parcel-by-parcel—rather than from above in accordance with a plan. This can leave the rural landscape fragmented. Large blocks of forest are broken up by roads and farms. Large areas of wetlands or riparian ribbons along rivers are broken into remnants. This impacts biodiversity greatly, favoring edge species and species that adapt well to human-modified environments over wild species that require large areas of undisturbed forest or other natural habitats.

Land use and land cover change has rapidly emerged as a science, where changes can not only be monitored through technologies like remote sensing but even predicted using spatial and economic models. In this manner, the changes in the landscape of, say, an increase in demand for biofuels, or a shift away from eating meat, or a market for carbon, can be understood. The implications of this new map on ecosystem service provision and biodiversity can also be examined, if rarely predicted with precision. In this way, a signal can be found connecting, say, the consumption of burgers at fast food restaurants, with the fate of endangered species in the Amazon, or, as we saw in Chapter 8 on industrial ecology, subsidies for the production of biofuels for cars with the storage of carbon in forests and soils.

This discussion of land resources and how to manage them sustainably has now become the longest chapter in this text, and yet we've only scratched the surface. Consider it an appetizer, one that brings you to the table for the main course.

Further Reading

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14.

CHAPTER 12: WATER RESOURCE SUSTAINABILITY

Like fire, people are mesmerized by water. A babbling brook, a placid tree-lined lake, the foam of crashing waves on the seashore—people can't take their eyes off it. Water is my favorite resource to study because it intersects closely with other important resources like land and agriculture as well as energy, while it is, at the same time, a critical part of the environment, even if the "life blood" metaphor has become hackneyed. We have already taken a look at the hydrologic cycle in Chapter 3. Here we will study how humans utilize water, especially the small proportion of it that is fresh rather than salt, and how it can be used sustainably.

In the resource taxonomy illustrated in Chapter 7 and Figure 7.6, water is a flow resource. The hydrologic cycle is driven by solar energy, which is perpetual; as long as the sun shines, water will continue to be evaporated and distilled from the ocean, transported over land, and fall as precipitation, the fundamental form of freshwater resource available to a region.

That's the good news. Precipitation is less reliable than sunshine or even wind, however, and this raises the issue of storing water from prior precipitation for later use. The slowly melting snowpack on a mountain range serves this purpose admirably for free. The water flowing quickly to the sea in streams and rivers usually represents precipitation that fell in the last week or month. The soil also stores water for weeks to months for crops and other plants as we saw in Chapter 3. The water in a reservoir formed by a dam on that river or a natural lake may contain somewhat older precipitation on the order of years. Groundwater, on the other hand, may be water that originally fell as rain centuries, even millennia, in the past. If an aquifer recharges every year from infiltration and percolation, then we can still think of it as a renewable reservoir, but if the recharge rate is slower than the rate at which it is pumped, water can be as nonrenewable as oil. The water itself is not destroyed when it is pumped and applied, say, as irrigation for crops, but it re-enters the hydrologic cycle either by evaporating or transpiring to fall as rain, likely on the salty sea, or runs rapidly down rivers to the same destination. It is in this sense that the measure of *water consumption* is *evapotranspiration*.

As a natural resource, then, fresh water is similar in some ways to forests, which we discussed in Chapter 11. It is renewable but only at a finite and variable rate defined by natural processes. For this reason, we need to carefully manage the limited reservoir available for future use, just as we do the stock of standing timber. Also like forests, which can be destroyed by fire or land clearing, the usefulness of water can be destroyed by pollution. While water does not reproduce biologically like forests, fossil groundwater is as irreplaceable as ancient redwoods and sequoias—on a human time scale, these are stock resources. Unlike forests, however, water can sometimes be overabundant. Among natural hazards, flooding is the leading cause of property damage, even though earthquakes can claim more lives.

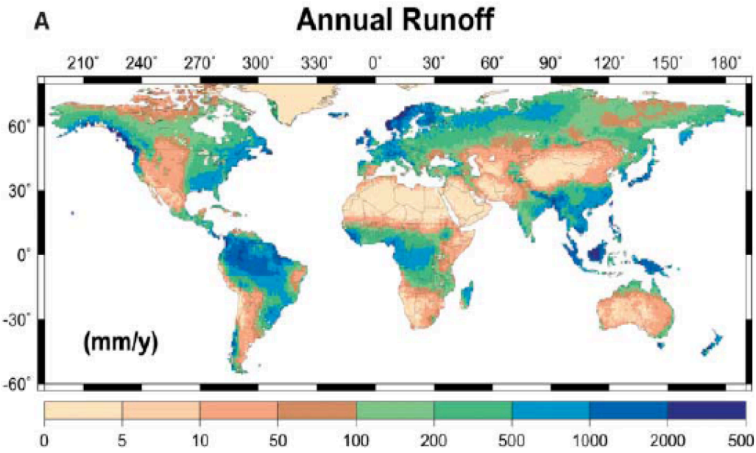


Figure 12.1. The geographic variation in mean annual surface runoff in millimeters per year.

On average, freshwater is relatively abundant but on average doesn’t help us much more than you having enough oxygen to breath on average. Figure 12.1, repeated from Chapter 3, demonstrates the great geographic variation in freshwater runoff from precipitation—the part of the hydrologic cycle that can be captured by humans and put to work. Note again that the scale in millimeters per year is logarithmic, meaning that the areas in dark blue have 1,000 times as much water as the areas in light tan. It is again worth pointing out that nearly the entire human race lives in areas with between 50-1,000 mm/y (about 2–40 inches) of annual runoff. You could rebut that the blue areas with surplus runoff of over 1,000 mm/y could give the extra water to the brown areas with less than, say 100 mm/y. Massive transportation of water rarely works out, however, because, even in the 21st century, rivers can't be rerouted in a practical manner (with a few amazing exceptions and grandiose plans, such as one to reroute much of the flow of the Yangtze River in China north to the desiccated Yellow). As a bulky, heavy substance with a low value per unit weight, it is not economical to transport huge quantities of water long distances. So water resources are tied to specific geographical areas usually defined by watersheds.

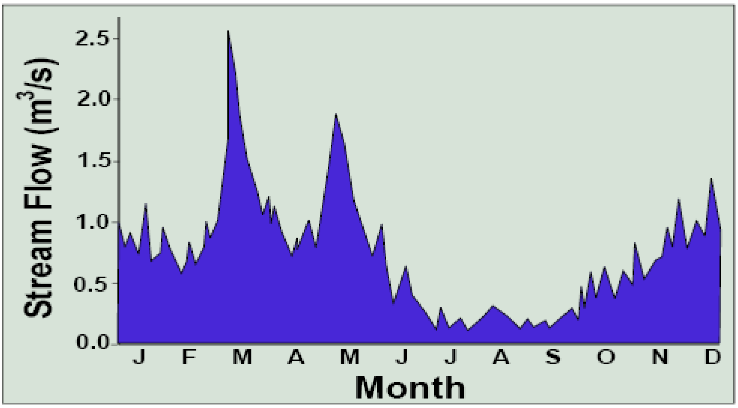


Figure 12.2. A hydrograph showing a variation in flow from 0.1 to 2.6 m^3/s.

The availability of freshwater also varies greatly over time. Repeating the hydrograph shown in Figure 3.4 as Figure 12.2 shows the flow of a stream varying 26-fold. In arid regions, stream flow varies even more, from nothing most of the time to deadly torrents upon occasion. Storing these torrents behind dams for later use can be very helpful, but reservoirs encourage losses to evaporation and can run dry during extended droughts. Getting the right amount of water at the right quality to the right use in the right place at the right time is the ever-present dilemma in water resources management.

How Humans Use Water

Go ahead, take a drink; that's the most fundamental, and the most important, use of water because, well, it keeps us alive. But it isn't even the tip of the iceberg of human uses of water. Let's begin with what likely comes to mind next, after drinking—the use of water in homes and buildings in such everyday ways as the kitchen faucet for cooking and cleaning, the bathroom for showering and the toilet, and water-using appliances such as dishwashers and clothes washing machines. The average American uses 30 gallons per day in this manner, the most of any country, though it has declined considerably due to efficiency improvements. Add in outdoor water uses, mostly from the hose nozzle—watering the lawn and garden, filling the swimming pool, washing the car, even clearing the sidewalk—and we're up to 59 gallons per person per day, though the regional and seasonal variation of outdoor uses is much greater than for more essential indoor uses.

Now let's consider commercial water use—water fountains and restrooms in schools and other public buildings, restaurant kitchens, hospitals, and so forth. Then we add in industrial water used in light manufacturing plus outdoor water use in all these to keep that nice green grass and shrubbery look that attracts customers and makes things look legit.

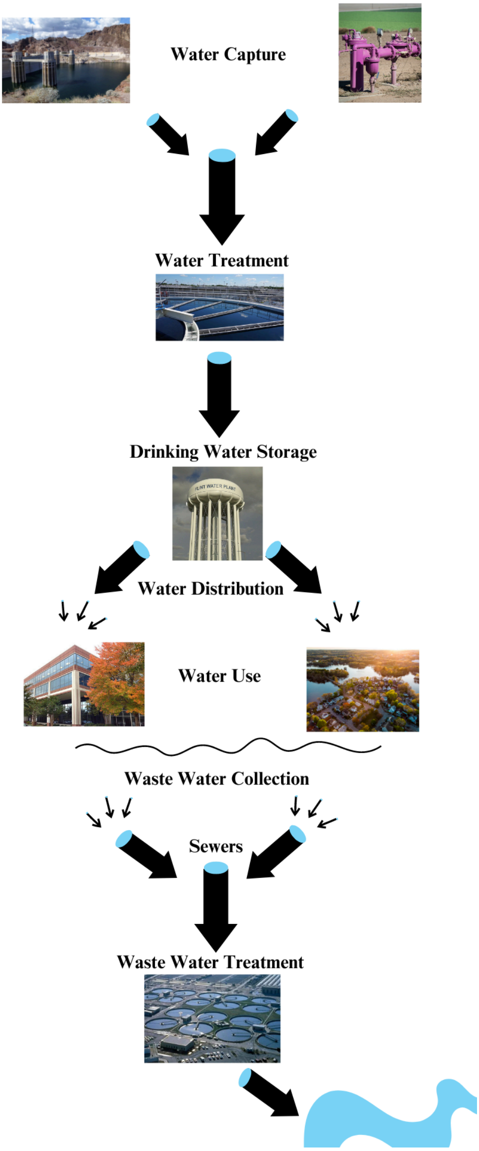


Figure 12.3. Diagram of a typical urban water supply system.

In most cases, all of these uses are supplied by *municipal water supply systems*, one of the most fundamental and critical infrastructures that makes modern life possible. Figure 12.3 diagrams the essential elements in a municipal water supply system. First comes the capturing of water from a natural source: wells for groundwater and usually dams to store the erratic flows of surface water in reservoirs. The water is then piped to the water treatment plant where raw water is purified according to the specifications of the Safe Drinking Water Act. Chlorine is added to kill algae, bacteria and viruses that are always present in water, even in pristine wilderness brooks. A flocculent is also sometimes added to get the suspended clay particles to coalesce and sink to the bottom, clarifying the water.

By and large, public water supplies in the U.S. are safe to drink, at least as safe as expensive bottled water, though problems can arise, especially from trace chemicals that can very slightly increase the risk of cancer and other health problems. The last major outbreaks of waterborne illness in the U.S. occurred in Milwaukee in 1993 when cryptosporidium, a form of bacteria from livestock manure, infected the public water supply, sickening 403,000 people and killing over 100. In 2014 Flint, Michigan switched its water supply from Lake Huron to the Flint River and failed to add chemicals needed to prevent it from leaching lead from the interior of old pipes. As was reported in the national news, over 100,000 residents, many of them children, suffered from lead poisoning, whose effects on their nervous systems may be lifelong. Many think Flint is the tip of an iceberg made of old lead pipes.

Here's where the water supply system gets really interesting from an engineering standpoint. Consider the circulatory system in your body, starting at your beating heart, which provides pressure. Blood rushes from the heart through the aorta, then through arteries to innumerable capillaries. Similarly, the water tower or mountainside reservoir, being higher in elevation than the faucets, provides pressure to connected water mains and smaller pipes to every faucet, shower, and toilet in the city—hundreds of thousands of them in even a small city. When you open the tap, water is forced out by gravity manifested as hydrostatic pressure. Moreover, dirty, untreated water can't get into the piping system because the pressure pushes it out. This ingenious system for delivering high-quality water to an entire town or city was invented by the Romans for their capital city with its famous ancient aqueducts and is now used worldwide in various forms. At least one billion people do not have access to treated, piped water, however, a humanitarian and development issue we will explore below.

Once the water is used, there is a physically separated wastewater system analogous to the veins that lead back to the heart. Water goes down the drain or toilet to the wastewater system. In urbanized contexts, the wastewater pipes from homes and buildings funnel into sewers which feed downhill to the wastewater treatment plant. At the plant, primary treatment screens and filters the water to remove large objects which are then land-filled or incinerated. The remaining water undergoes secondary treatment where activated sludge—bacteria whose reproduction is stimulated by extra oxygen—essentially eat up organic matter in the water. The fertile, but possibly contaminated, sludge is used in land reclamation, such as on coal-mined lands or to establish golf courses. It can also be used to grow algae for biofuels.

In most cases, the water is then released to nature—usually a stream or river, but sometimes a lake or the ocean. In other cases, it undergoes tertiary treatment, sometimes in natural or created wetlands or in sandy filters leading to aquifers, where nutrients (N, P) and other pollutants are reduced. The resulting water is not fit to drink, though it is possible to feed it into the drinking water plant in a recycling system. Most people are a bit "woozy," however, about drinking recycled sewage. Even if the wastewater treatment plant outflow is not fed into the drinking water treatment plant directly, *reclaimed wastewater* can still be put to industrial, agricultural, or landscaping uses. In arid regions, this is an important part of the non-potable water supply of cities. As small, separate wastewater systems, many rural homes and buildings use septic tanks and drainage fields to seep the water back to nature after bacteria eat up most of the nasty organic wastes.

Because cities have so much impervious surface—roofs, roads, and parking lots where rain runs right off without infiltrating to groundwater or transpiring—they also require *stormwater systems*. We often see these as gaps under the curb in low-lying areas along the street where the rainwater seems to disappear down the storm drain. In many cities these stormwater systems join with the sewer lines to end up at the wastewater treatment plant. During a heavy rainstorm, however, the plants can be overwhelmed with water and the sewage can pass through untreated. In other cities, the stormwater system empties directly into a stream, river, lake, or the ocean untreated. Some cities are beginning to use a more green approach, feeding storm water into wetlands and ponds where nature can begin a purification process while encouraging infiltration and evapotranspiration. Others are using pervious pavements in parking lots so the water can infiltrate rather than run straight down to streams to generate an urban flash flood. As is often the case with natural resource management problems, stormwater management seems mundane, but it is an important wrinkle in sustainable water resource management, and intensifying rainfall events due to climate change are making it even more essential.

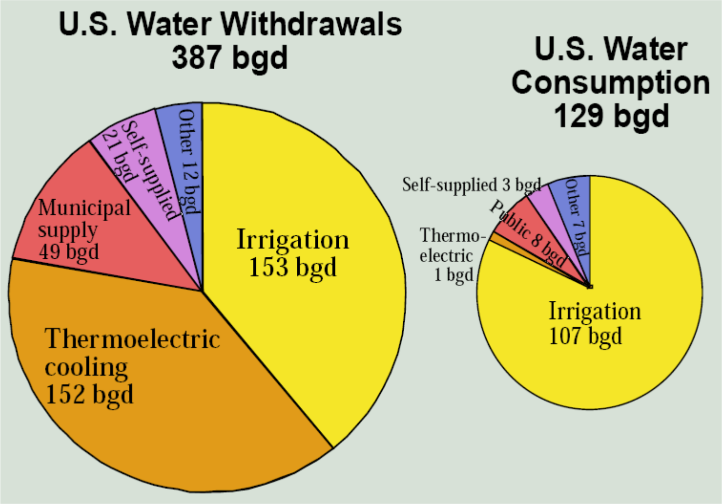


Figure 12.4. U.S. water withdrawals and consumption in billions of gallons per day (bgd). Source of data: U.S. Geological Survey.

We've now discussed a lot of uses of water, but we're still only getting started. Large industrial facilities like paper mills and food processing plants usually have separate water systems not hooked into the municipal supply system. Thermoelectric (coal, gas, and nuclear) power plants are especially large users of water for cooling. In the U.S., withdrawals of water for this purpose are three times higher than for all municipal supply purposes put together. Power plants are neck-and-neck with irrigation as the largest source of U.S. water withdrawals (Figure 12.4). In fact, power plants are built adjacent to water supplies rather than fuel supplies to minimize the distance huge quantities of water have to be pumped and piped.

Fortunately, salt water serves as well as far more scarce fresh water for this purpose, explaining why many power plants are built along the coast. Before 1960, 80 percent of power plants built once-through cooling systems where about 99 percent of the water returns to its source—several degrees warmer. Since 1980, 80 percent have constructed cooling towers; these reduce water withdrawals by up to 95 percent but result in much more loss through evaporation. If we also consider the water passing through hydroelectric dams and evaporating from their reservoirs, as well as water needed to produce biofuels and fossil fuels, it is clear that much of the water we use goes to produce our energy supply. This is often called the *water-energy nexus* and it also includes the energy needed to pump and treat water.

We've still only covered the tip of the iceberg, however, because *food production is the largest use of water*. This comes in two primary forms: irrigation and rainfed agriculture. Irrigation is the deliberate application of water to plants, especially crops, to encourage their growth. In arid and semiarid regions, irrigation is required to make crops grow, though water resources are limited. In wetter climates, supplemental irrigation can counteract the effects of drought. In the U.S., irrigation is roughly tied with thermoelectric cooling in withdrawals but leads in withdrawals of fresh water since salt water kills crops. Because most thermoelectric withdrawals are quickly returned to the source, irrigation is by far the leading source of water consumption, with 83 percent of the U.S. total of 129 billion gallons per day (bgd) (Figure 12.4). This is even more the case globally; 87 percent of water consumption is for irrigation.

All of the human uses described above require water to be withdrawn (i.e., pumped) from a natural source—a reservoir, lake, river, or aquifer. When human water uses are characterized and measured, such as by the U.S. Geological Survey, we measure *water withdrawals*; these total 387 billion gallons per day (Figure 12.4) for the U.S. The second measure is *water consumption*—the amount of water that evaporate or transpires away into the atmospheric component of the hydrologic cycle. Swedish scholar Malin Falkenmark makes the case that this presents only a partial view of water use, what she terms*blue water*. First, if food production is the dominant use of water, why count water applied to crops as irrigation and not also count water that falls as rain on crops? Rainwater, which is drawn from the soil and transpired by crops as an essential element in their growth, is called *green water*. Green water use in the U.S. has been estimated at 357 bgd, nearly as much as all withdrawals and about three times higher than all other sources of water consumption. Factoring in green water drives home the point that the dominant human use of water is agriculture, and it explodes the average American's daily water use to 1,794 gallons.

Table 12.1. Water used to produce everyday items and mass ratio of common agricultural products.

Everyday item	**Liters to produce**	**Agricultural product**	**Mass ratio (weight of water/weight of product)**
glass of beer	75	rice	2,291
cup of coffee	140	wheat	1,394
glass of orange juice	170	soybeans	1,789
bag of potato chips	185	chicken	3,918
hamburger	2,400	cotton lint	8,242
cotton t-shirt	4,100	beef	15,497
leather shoes	8,000	coffee	20,682

Table 12.1 shows how much water it takes to produce a variety of everyday items and common agricultural products. (Remember that a liter is very close to a quart or a fourth of a gallon and weighs a kilogram, 2.2 pounds.) The primary reason these numbers are so high is the huge amount of water that is transpired by crops, including those eaten by livestock.

So the majority of the water content in the products listed in Table 12.1 is green water, rain used by crops, rather than blue water withdrawn from natural sources.

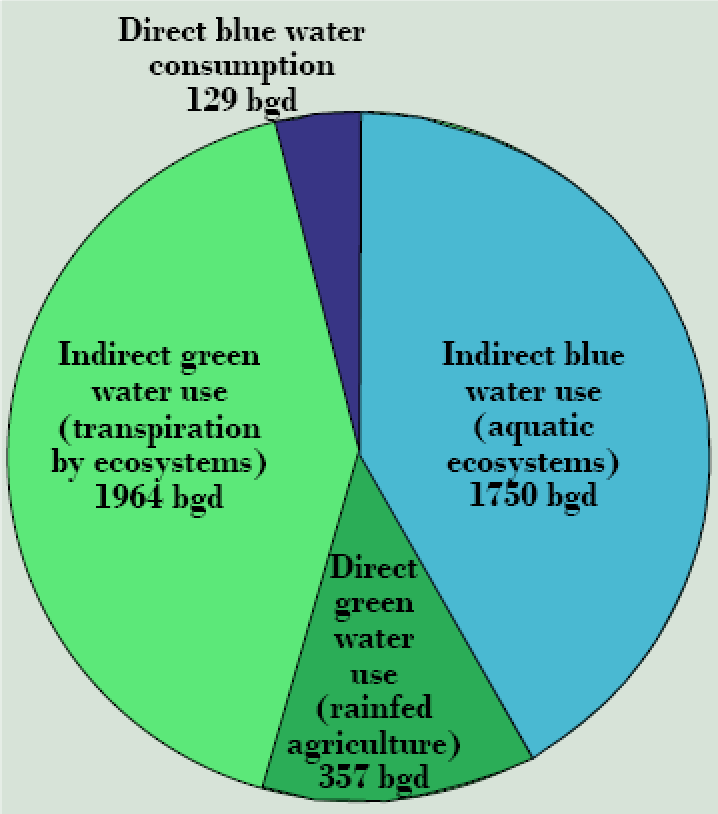


Figure 12.5. U.S. blue and green, direct and indirect water use. Total precipitation is 4,200 bgd.

We've now covered human uses of water for provisioning ecosystem services as a factor of production in the economy, but what about supporting, cultural, and regulatory services, all of which require water? We'll term this *indirect water use*. Indirect green water use of 1,964 bgd is transpired by natural ecosystems—forests, wetlands, and grasslands. When we benefit from the services these ecosystem provide, we are indirectly using the precipitation that fell on them and was then transpired back to the atmosphere. Indirect blue water use of 1,750 bgd is precipitation that flows into lakes, streams, rivers, and on down to the ocean, making aquatic ecosystems—and the services they provide—possible. These include hydroelectricity, navigation, fishing, recreation (in-stream uses), nutrient cycling, maintenance of biodiversity, and just gazing at it – a luxury that places a substantial premium on waterside homes. So, in one way or the other, we use the entire endowment of 4,200 bgd of precipitation that falls on the United States annually (Figure 12.5).

It is encouraging that blue water consumption is, for the U.S. as a whole, only about three percent of the rain and snow that falls from the sky. That number is also not very meaningful or helpful, however. To see why, let's explore perhaps the most scenic river basin in the U.S.—the Colorado River, author of the Grand Canyon.

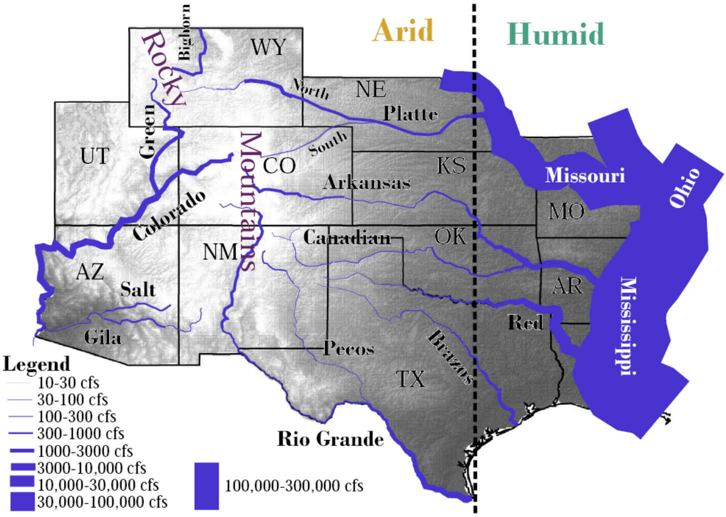


Figure 12.6. Rivers of the Southwestern U.S. with mean discharge in cubic feet per second (cfs) shown. Note that the actual flow is proportionate to the square of the line width (think of the lines as two-dimensional pipes), making real differences in water availability between the arid West and humid East even greater than appears in the map. Note how many rivers reach maximum discharge as they emerge from the Rocky Mountains and lose flow downstream. Portions of the Arkansas, Canadian, Colorado, Gila, Salt, and South Platte rivers have a median flow of 0 cfs—they are usually dry beds. Source of data: U.S. Geological Survey.

The Colorado River (Figure 12.6) runs from the Continental Divide in the Colorado Rockies westward, where it joins the Green River—flowing south from southwestern Wyoming—in eastern Utah at Canyonlands National Park. Flowing southwest, the Glen Canyon Dam at the Utah-

Arizona border forms Lake Powell, the terminus of the upper basin. It then bends west, enters the Grand Canyon (a marvel you simply must see despite the crowds from all over the world) reaching Lake Mead, held back by the Hoover Dam along the Nevada border. From there, the river heads south to form the Arizona-California border until it crosses into Mexico and ends its 1,450 mile journey at the Gulf of California.

Except that the Colorado does not end there because only rarely does any water reach the Gulf. The rest is used, and consumed, along the way by irrigation farmers—from Wyoming to southern California—and by Las Vegas, Phoenix, Tucson, Los Angeles, San Diego, and other cities, all of whom pipe water uphill from the Colorado River. Some water is even tunneled beneath the Continental Divide to the cities of the Colorado Front Range and beneath the Wasatch range to Salt Lake City in interbasin transfers. The river ends in a thousand irrigated fields and dozens of water treatment plants. It's used up. The delta, once perhaps the most vibrant ecosystem in the region, is barren desert.

The Colorado is not alone in this fate (Figure 12.6). The Rio Grande brings water from the Sangre De Cristo Range in southern Colorado to Albuquerque and El Paso as well as irrigation farmers in the valley—then dries up. The Rio Grande then re-emerges further east where its tributary, the Rio Conchos. arrives from Mexico.

The Arkansas River flows east from the Sangre de Cristo, but it barely enters Kansas before it runs dry, only to reappear in eastern Kansas where rainfall is great enough to produce perennial streams. It's not just surface water that is being consumed. Recall from Chapter 2 that water tables in the Ogallala Aquifer are dropping from western Kansas to north Texas. The same is occurring in parts of California where the land is subsiding above dewatered aquifers. Most of the southwestern United States is using all its available water, and climate models predict the region to grow considerably drier. This is the region—the Sunbelt—that Americans are flocking to!

It is no consolation that the Great Lakes are the world's second greatest storehouse of liquid, fresh water (mile-deep Lake Baikal in Russia is first) or that the Mississippi is the most voluminous river in North America. Even if the states possessing these vast resources were to allow it to be exported, which they will never do, the cost of engineering schemes to transport the water would be in the tens to hundreds of billions of dollars. For California, desalinating ocean water is an option, but an expensive and energy-intensive one that only the affluent city of Santa Barbara has taken, and they regret the expenditure. At a cost of \$0.50–\$1.00 per cubic meter, or about \$600–\$1,200 per acre-foot, desalinated water is not cost competitive with leasing water from irrigators and is too expensive for use in agriculture.

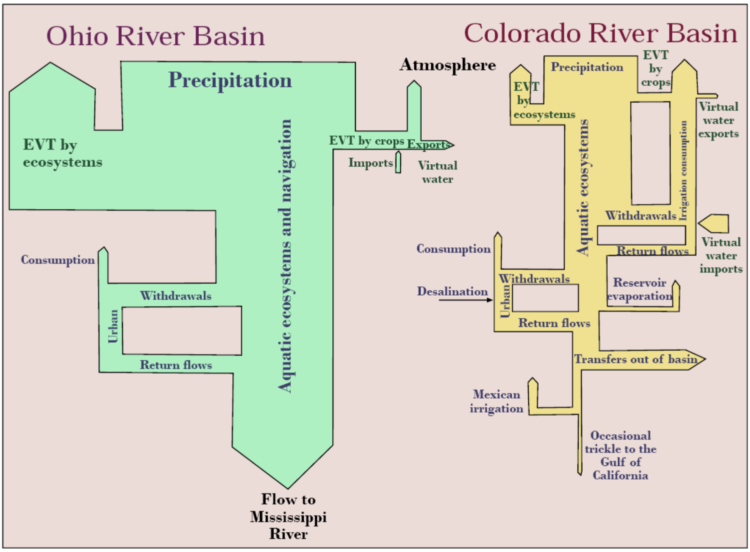


Figure 12.7. The flow of water through human uses for an important eastern (Ohio) and western (Colorado) river basin. Width of arrows is roughly proportional to water volume. EVT is evapotranspiration.

One way of integrating these issues for a specific river basin, and comparing it to others, is through a water flow diagram such as shown in Figure 12.7. On the left, a prominent eastern river basin, the Ohio, averages over 40″ of annual precipitation. There is almost no irrigation in the basin, though rainfed agriculture is important. The basin exports more virtual water than it imports (we'll explore the concept of *virtual water* below). The greatest source of withdrawals is for thermoelectric cooling with high rates of return flow. The Ohio and its tributaries support abundant aquatic ecosystems beneath the high volume of barge traffic. Huge quantities of water discharge to the Mississippi, of which it is the largest tributary.

Using the same technique, the somewhat larger Colorado River watershed appears very different. Far more scant precipitation is transpired by ecosystems, withdrawn and consumed by irrigation, evaporates from reservoirs, is transferred out of the basin, or is consumed by urban and industrial uses. The small volume reaching Mexico is consumed for irrigation there, leaving only an occasional trickle of water to reach the Gulf of California. The basin imports more virtual water than it exports, and it utilizes small quantities of expensive desalinated water. Water managers consider removing scant riparian vegetation to conserve water transpired by ecosystems. No water is left unspoken for; an increase in any water use implies a decrease in some other use.

With your mind's eye, you can perhaps imagine these diagrams in motion, expanding following snowmelt and rainstorms and contracting during droughts. A similar water use flow diagram could be developed for any river basin, and comparing them would reveal a great deal about the water resources challenges they face.

The answers for the Colorado and other river basins in the American Southwest do not lie in increasing water supplies; they must lie elsewhere. One option, of course, is water conservation or demand management. Low-flow toilets, shower-heads, and "water sense" appliances make a big difference if the majority of the population is employing them.

These nonconsumptive water uses deliver water to the wastewater system, however, where it can potentially be recycled. An even bigger dent can be made through *xeriscaping*—replacing the green grass, shrubbery, and big shade tree look with attractive, desert-like landscaping that requires several times less water. Through these and other techniques, municipal water use has fallen from 100 gallons per capita per day in the 1990s to 59 in 2017, an enormous accomplishment in improving water use efficiency, even though the water mains in many older cities are over a century old and leak chronically.

Water can be harvested in barrels and cisterns from occasional rains falling on the roof. Better yet is using aquifers, which are not open to evaporative losses, rather than surface reservoirs for water supply storage. Increasing the price of water reduces the amount used, especially if prices per gallon increase as more gallons are used.

We must remember that conservation, reductions in use, must come from where the water is now going—predominantly agriculture. It also makes more sense to conserve on less valuable and more consumptive uses of water such as irrigation rather than more valuable and less consumptive uses occurring indoors. Irrigation efficiency, a topic that at first seems mundane, suddenly rises toward the top of the list in water resource sustainability. It's time to start talking about acre-feet—the amount of water needed to cover one acre of cropland one foot deep in water: 325,851 gallons.

There are a number of levels of irrigation efficiency. The first is "more crop for the drop." Flooding an uneven field from an unlined ditch does work—farmers have been doing it for thousands of years—but it is not an efficient approach to maximizing the bushels produced per acre-foot of water applied. Overhead sprinklers are not only more efficient, but the commonly-used central-pivot system makes lovely circles on the landscape that amaze airline passengers gazing out window seats as they traverse the Great Plains. More efficient yet is drip irrigation where small, perforated pipes in the soil deliver water, sometimes with fertilizer mixed in, directly to crop roots one drop at a time. As water use efficiency goes up, however, so does the cost of investing in irrigation equipment. This can only be paid for with the value of the water conserved. Water is generally subsidized and underpriced, or even free, even in arid regions, undermining the economic incentives needed to encourage purchase and installation of efficient irrigation equipment. As we concluded in Chapter 6 on neoclassical economics, "that which is cheap gets wasted; that which is expensive gets conserved."

Table 12.2. Application rates, yields, and revenues for irrigated crops in the
environmental uses. Values are for illustrations purposes only, but within
water costs $600-$1200 per acre-foot using current

Water use	a. Acre-feet/ Acre (depth in feet)	b. Increase in Yield per acre (tons)	c. ($
flood-irrigated pasture grass	3	8	5
alfalfa hay irrigated with sprinklers	4	6	20
flood-irrigation of rice	6	2	20
sprinkler-irrigated soybeans	3	1	33
sprinkler-irrigated corn	3	3	14
drip-irrigated vegetables	3	3	40
urban: municipal water supply			
environmental: in-stream flow			di

The second level of irrigation efficiency could be called "crops that drink fewer drops." Table 12.2 shows typical amounts of water used per acre for a variety of crops, typical yields per acre, and typical revenues by multiplying by price. Dividing the revenue by the water use produces a measure of economic value per unit of water applied. We can clearly see that water used to irrigate pastures or grow alfalfa for cattle produces little revenue. It's not the highest and best use. Drip irrigation on vegetables produces many more dollars per acre-foot. Economics would dictate that scarce resources be reallocated from lower-value to higher-value uses. A higher price for water would also make low value uses uneconomic. For example, at a price of $100 per acre-foot, irrigating pasture, alfalfa, and rice produces an economic loss. This price would reallocate water now used for these crops to other more valuable uses, not only corn, soybean, and vegetable production but municipal water supplies, and possibly leaving the water in the stream to support fish and other aquatic life, though it is very difficult to measure a per acre-foot dollar value to aquatic ecosystem services.

The third level of irrigation efficiency is called virtual water, but "virtual" anything always requires an explanation. Let's say southern California phases out irrigation of 10,000 acres of corn, saving 30,000 acre-feet of water, half for environmental uses like in-stream flow, and half for urban uses where the 15,000 acre-feet are worth $10,500,000. Instead they import or buy the 60,000 tons of corn the irrigation would have produced from Iowa for $3,600,000, saving $6,900,000 with improved aquatic ecosystems as a bonus. This corn required 30,000 acre-feet of rain falling in Iowa to grow and was sent to California on a train instead of being sent to an ethanol plant. In an important sense, southern California is gaining access to these 30,000 acre-feet of Iowa rain and coming out ahead because the urban and environmental uses of the water are more valuable to California than the corn it is no longer producing. It is also a better solution than transporting the 41 million tons of water from Iowa because the corn weighs only about 41 thousand tons, 1,000 times less, than the water used to grow it. Iowa also benefits by gaining an additional export market for their abundant harvest of rainfed corn. In this way, water-surplus regions can make money by selling water-intensive products like crops and livestock to water-deficit regions. This allows the latter to reallocate their scarce water supplies away from consumptive, low-value irrigation to less-consumptive, higher-value urban and environmental uses.

Virtual water is an example of what economists call *comparative advantage*. Regions are better off using their best endowments to produce a surplus for export while importing goods and services for which they lack resources. It runs against the notion of local self-sufficiency, however, and therein lies a few caveats. Using the virtual water strategy makes arid regions dependent on humid regions for their food supply and undermines local agricultural economies. Now only the most paranoid person would worry that Iowans are going to embargo food from Californians, but on a global scale, food security is a limitation on virtual water trade. The Middle East is the world's most water-deficit region and North America the greatest exporter of virtual water. Would that region trust North Americans with their essential food supply any more than Americans trust Middle Eastern countries with their essential oil supply? In fact, they do.

Table 12.3. Mean annual virtual water imports to and exports from major world regions, 1995–1999 (billions of gallons per day).

Virtual Water Imports	Bgd	Rank	Virtual Water Exports	Bgd
Central and South Asia	142	1	North America	162
Western Europe	76	2	South America	50
North Africa	36	3	Southeast Asia	49
Middle East	30	4	Central America	28
Southeast Asia	29	5	Central and South Asia	22
Central America	24	6	Oceania	22
South America	15	7	Western Europe	20
North America	13	8	Former Soviet Union	13
Eastern Europe	8	9	Eastern Europe	9
Former Soviet Union	6	10	Middle East	8

Southern Africa	6	11	North Africa	4
Central Africa	2	12	Southern Africa	3
Oceania	1	13	Central Africa	1
Source: Chapagain and Hoekstra, UNESCO 2004.				

A 2004 global study of virtual water trade by UNESCO shows some fascinating patterns (Table 12.3). The U.S. exports 131 bgd, about the same as total withdrawals or the flow of the Ohio River, with net exports of 108 bgd. North America is by far the leading virtual water exporting region at 162 bgd with net exports of 149 bgd. South America (35 bgd), Oceania (22 bgd) Southeast Asia (20 bgd), former Soviet Union (7 bgd), Central America (4 bgd), and Eastern Europe (1 bgd) are also net exporters. The leading net importing region is Central and South Asia at 120 bgd, followed by Western Europe (56 bdg), North Africa (32 bgd), Middle East (22 bgd), Southern Africa (3 bgd), and Central Africa (1 bgd).

What underlies these patterns? Virtual water net importing regions are those that struggle for food self-sufficiency either because they lack rainfall (North Africa, Middle East, Southern Africa, part of South and Central Asia) or they are very densely populated (South Asia) or both densely populated and affluent enough to afford huge supplies of food and raw material imports (Western Europe). Net exporting regions have modest population densities relative to their endowment of crop-producing soil and rainfall (e.g., South and North America). Through virtual water, the New World feeds, and thereby indirectly waters, the Old. In a similar manner, can the Eastern U.S. water the Western U.S. by selling it food, cotton, lumber, paper, and other water-intensive products? This would reallocate scarce western water from low-value irrigation to higher value urban uses as neoclassical economics would indicate and to ecosystem service provision as ecological economics would indicate. To unravel why these seemingly sensible schemes to reallocate western water are not as straightforward as one might wish, we need to take a journey into the dilemma of prior appropriation, the legal system for allocating the use of water in the western states.

The Dilemma of Prior Appropriation

Imagine yourself as a pioneer in the mid-1800s heading west to the lands the U.S. bought from Napoleon (the Louisiana Purchase), more recently split with British Canada (the Oregon Territory), annexed from the Mexicans (the Southwest), or took from the Native Americans (all of the above). The U.S. government is encouraging you to go because, if these vast lands are not occupied quickly, they could be lost to their former owners. The mountains and canyons are breathtaking but, as the explorer John Wesley Powell pointed out again and again to anyone who would listen, the land is too arid to support the standard homesteader approach of establishing a rainfed farm on a few hundred acres.

Given this limitation, your first option for establishing a livelihood is mining, especially for that pretty yellow metal that's worth a lot of money. The best way to get at it is through hydraulic mining—blasting the streamsides with a fire hose to release the rock and sediments. Then you're ready to pan for gold. Your second option is farming to feed all those miners, but this requires irrigation. Either way, you need water and there's not much of it to go around. So you establish a mining operation by diverting water from a stream and you have enough success to make a living in this grand new country where the sky is not cloudy all day.

A decade later, another party of pioneers arrives and, seeing how success in this dry country depends on access to water, settle upstream of you so they can divert the stream for an irrigated farm. But that leaves you without enough water to continue mining. Rather than challenging them to a duel, you decide to take a safer route and call upon the county judge. Smart move, because the judge decides "*first in time, first in right*." The *prior appropriation* of water—your senior and continuing mining operation—has precedence over junior (more recent) appropriations of water. The judge orders the newcomers to cease and desist in diverting water from the stream to their farm. Subsequent cases use this precedent, western states pass statutes codifying the system, and prior appropriation is established.

In this hypothetical case, the judge was right. If he had decided in favor of the late-coming irrigators, new pioneers could simply leapfrog one another up the valley to get at the water upstream of earlier users, in the process inciting innumerable conflicts. Moreover, by protecting your right to use the water in your mining operation, you are rewarded for heading west early, despite the hardships of the frontier, with a perpetual right to use water that your heirs can inherit. You have helped establish an economically viable American presence on the land, so long as you keep putting that water to a beneficial use and don't move on or give up mining to become a guitar player or a judge. *Use it or lose it*. Not every valley has gold, however, and in other valleys, irrigation farmers and ranchers made first claim to most of the water.

Now let's fast-forward to 2020. Los Angeles is the second biggest city in the country and California is the most populous state. Denver, Las Vegas, Phoenix, Sacramento, Salt Lake, San Diego, and San Francisco-Oakland-San Jose are big enough to have pro sports teams. Albuquerque, El Paso, and Tucson may soon get there as well. These cities want the water the old pioneers have locked up in farming and obsolete mining operations, and they're willing to buy it at prices ranging from \$300–\$800 per acre-foot that would be difficult to refuse (see Table 12.2). Environmental groups are also making offers to leave the water in the river to protect endangered fish species.

Sporting groups are making offers to improve dynamite trout streams and white-water rafting rivers. But little water gets sold from lower to higher value uses. Why?

That's a terribly complicated and frustrating question to answer, but I'll take a stab at it, even if I'm not a lawyer. First, you have to *own* something before you can sell it. The pioneers' heirs don't own the water any more than I own my office at Utah State University. The state owns the water and Utah State owns my office. They, and I, have a right to use it, for a specific purpose, so long as we keep using it *for that purpose*. (Writing this text qualifies as a beneficial use of my office!) These are *usufructuary* rights, not real property. Second, did anybody ever go to the state engineer's office and write it all down? Where? When? For what use? Using what method? With what result? Third, how much water are we talking about? 62.384 acre-feet per year? Unless the watershed has been *adjudicated*—an expensive process of identifying and quantifying all the water rights in a river basin—nobody has ever accurately measured it. So how can I sell something I really don't own and I don't know how much of it there is? Moreover, like my office, if I try to sell it, that just shows that I'm not using it anymore and the state will give it away to the next person in line—a junior appropriator—just like my department will give my office to someone who can make better use of it if I stop writing and teaching.

Fourth, water flows down streams to rivers to the sea (or an interior basin like Great Salt Lake). Where is the buyer relative to the seller in this system? Is there a third party in between whose water rights would be harmed by a transfer? Fifth, what if someone invents a better way to mine gold that uses a lot less water? If I adopt it, I lose my water right. The same is true for farmers who are contemplating more efficient irrigation practices or giving up on something as wasteful as watering pastures to raise of few extra cows. Neither has any more incentive to conserve than I have to use only half my office. And leaving the water in the stream for fish is not on the list of beneficial uses. I guess that old 19th century judge never took ecological economics and learned about ecosystem services. We're in one heck of a legal mess here but this problem illustrates how important the institutional economic approach, which examines how the law structures carrots and sticks, can be.

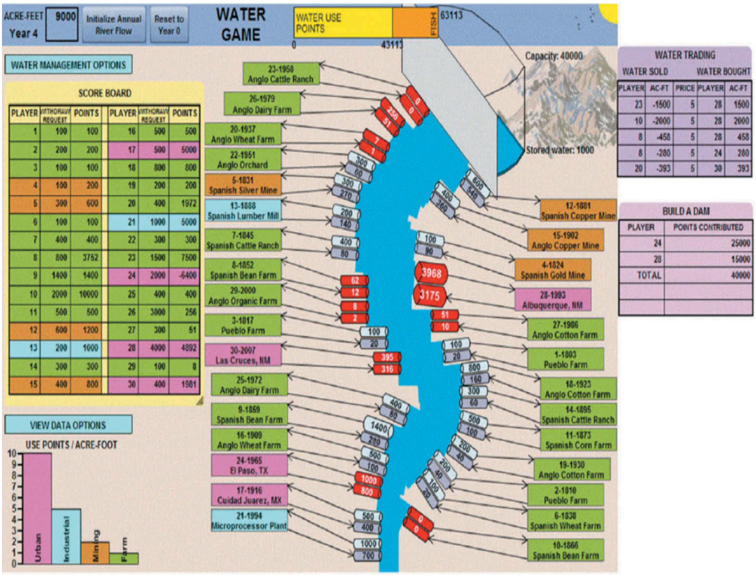
Some western states, especially California, are making progress through the legal minefield of prior appropriation. In the droughts of the 1990s, they established *water banks*. Very few people who have a right to use water in perpetuity are willing to give that up, so the focus is on *leasing* the right for a season rather than selling the right permanently. Second, rather than individuals buying and selling to each other, the state engineer serves as the clearinghouse. Those pioneers' heirs can lease mining and irrigation water to the state for a rental fee—say \$200–\$400 per acre-foot—and the cities buy them up. The state keeps a small portion of the water to leave in the streams (a water tax) and does a complex geographical and hydraulic analysis to determine how best to move the water from all the sellers to all the buyers along existing streams, rivers, canals, and pipelines. Since the state is the buyer, sellers are immune to the use it or lose it snag. Water banking can work in other western states as well.

With southwestern cities growing in population relentlessly, with no undeveloped water around to increase supplies, with enough water to maintain habitat for endangered species of fish required by law, with climate change making the Southwest ever drier and melting the mountain snows earlier in the spring, water banking and similar quasi-market arrangements for reallocating water must work. The future of the American West depends upon conserving and reallocating its increasingly scarce freshwater resources in a sustainable manner, and water conservation and reallocation is the only sustainable approach.

Now combine water reallocation with virtual water. Let's say dry western states import more basic food commodities like corn, soybeans, wheat, and hay from the Midwest, where these crops are in surplus and grown using green water. This could come, for example, from corn now destined for biofuels. Western farmers then lease or sell some of their water rights to cities and for environmental purposes at a profit. By taking greater advantage of these regional comparative advantages, the Western prior appropriation states greatly alleviate their water scarcity problems. Virtual water becomes real water through trade and reallocation. Is this a sustainable solution? I think it's the best idea now on the table.

The Water Simulation

Based on prior appropriation rules and set in the New Mexico section of the Rio Grande Basin, the water simulation serves well as a classroom exercise and/or an individual assignment. Figure 12.8 shows the simulation user interface. The game is initiated by a quantity of water, drawn randomly from a range from 5,000–20,000 acre-feet, flowing from the Sangre de Cristo Mountains of Colorado at the river's headwaters. Thirty water users lie long the river, each with a water demand, a consumption vs. return flow percentage, a water use (urban, industrial, mining, farming) that determines user points, and a date that determines their priority. Water is allocated from the oldest (most senior) to the youngest (most junior) priority until, except in the wettest years, it is exhausted. This often leaves junior water users as critical as Albuquerque with no or insufficient water and the riverbed dry and devoid of fish.



SCORE BOARD

PLAYER	WITHDRAW REQUEST	POINTS	PLAYER	WITHDRAW REQUEST	POINTS
1	100	100	16	500	500
2	200	200	17	500	5000
3	100	100	18	800	800
4	100	200	19	200	200
5	300	600	20	400	1972
6	100	100	21	1000	5000
7	400	400	22	300	300
8	800	3752	23	1500	7500
9	1400	1400	24	2000	-6400
10	2000	10000	25	400	400
11	500	500	26	3000	256
12	600	1200	27	300	51
13	200	1000	28	4000	4892
14	300	300	29	100	8
15	400	800	30	400	1981

WATER TRADING

WATER SOLD			WATER BOUGHT	
PLAYER	AC-FT	PRICE	PLAYER	AC-FT
23	-1500	5	28	1500
10	-2000	5	28	2000
8	-458	5	28	458
8	-280	5	24	280
20	-393	5	30	393

BUILD A DAM

PLAYER	POINTS CONTRIBUTED
24	25000
28	15000
TOTAL	40000

Figure 12.8. The interface for the water simulation. Thirty water users are spaced along the river resembling the Rio Grande. Each can earn water use points through, in decreasing return per unit water applied, urban, industrial, mining, and farming. Management options include minimum flow requirements, water trading, and building a dam. Basin-wide water use points are the sum of player points plus fish points based on minimum flows achieved.

Players can address this unacceptable situation through three management options: (1) setting a minimum flow requirement for fish, (2) trading or leasing water among users at agreed-upon prices, and (3) building a dam to store water from wet years for subsequent dry years. While each player's goal is to maximize their own water points, the overall goal is to maximize river-wide water use plus fish habitat points. The randomness of water flows, the many possibilities for trading, and the interaction among management options capture some of the essential complexities and dilemmas of allocating scarce water resources under the prior appropriation doctrine. The simulations is available at Weidong's Projects Homepage. Enjoy!

The Mississippi Watershed and the Problem of Polluted Runoff

Climate change, Amazon deforestation, endangered charismatic species like polar bears, and natural disasters like major hurricanes and wildfires seem to get all the attention. Meanwhile, more subtle, but no less urgent, environmental problems like polluted runoff grind on right under our very nose. America's signature river, the Mississippi, the fascination of Mark Twain and whose name kids use when counting seconds, is its greatest example. The Mississippi River has a problem of too little sediment and too much nitrogen.

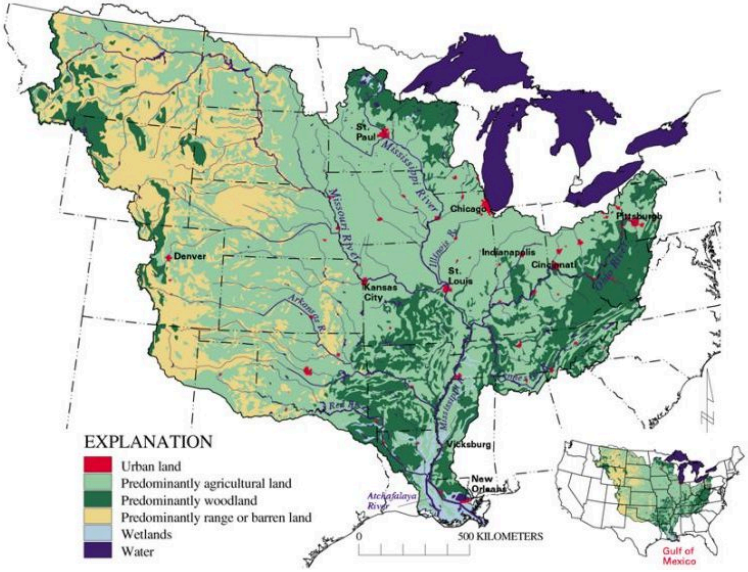


Figure 12.9. The Mississippi watershed showing land use patterns and the hypoxic zone in the Gulf of Mexico.

East to west, the Mississippi watershed stretches from the Appalachian crest from New York to Georgia to the continental divide from Montana to New Mexico. North to south it reaches from Alberta to its delta in Louisiana (Figure 12.9).

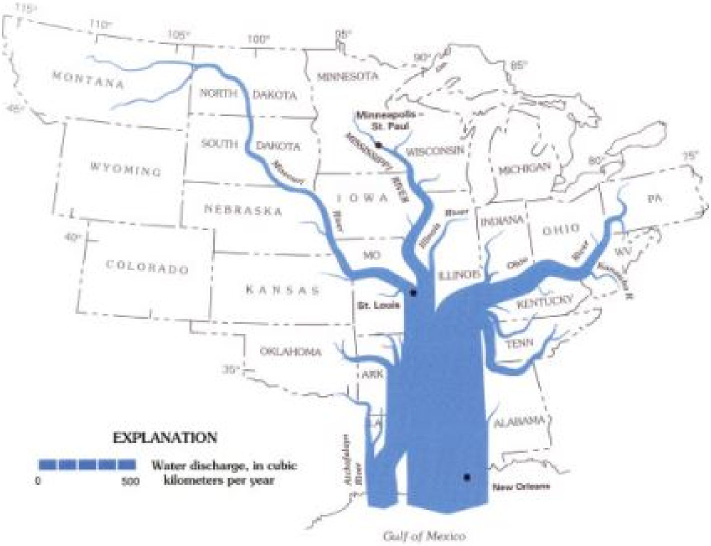


Figure 12.10. Diagram of water flow in the Mississippi and its tributaries and distributaries.

The basin contains America's agricultural heartland as well as substantial areas of forest in the eastern portion and dry rangeland in the western portion. It has many cities, though on the whole is somewhat less densely populated than the U.S. average. Its largest tributary basin by land area is the Missouri, but its largest tributary river by volume of water is the Ohio. Its largest distributary (when they reach the delta, rivers usually divide into multiple channels) is the Atchafalaya (see water flow diagram in Figure 12.10), which would likely become the primary pathway to the sea, by-passing New Orleans, were it not for the Old River Control Structure preventing this with millions of tons of concrete.

The Mississippi and its major tributaries are barge superhighways carrying vast tonnages of coal, grain, timber, and other products from as far upstream as Sioux City, Iowa, on the Missouri, Minneapolis on the Upper Mississippi, and Pittsburgh (where the Allegheny and the Monongahela join to form the Ohio) to the port of New Orleans, and from there to the world and back again.

All rivers carry not only water but vast quantities of sediment to the ocean. This process slowly erodes away the land while nourishing the ocean and building a delta where the sediment drops out as the current wanes. The river system that Lewis and Clark traveled two centuries ago from Pittsburgh to the Continental Divide featured a clear Ohio, with its forested watershed holding the soil and filtering sediments. When they turned north and upstream, they encountered a muddy Middle Mississippi, though the turbidity disappeared as they gazed up the clear Upper Mississippi north of the Missouri River junction near St. Louis.

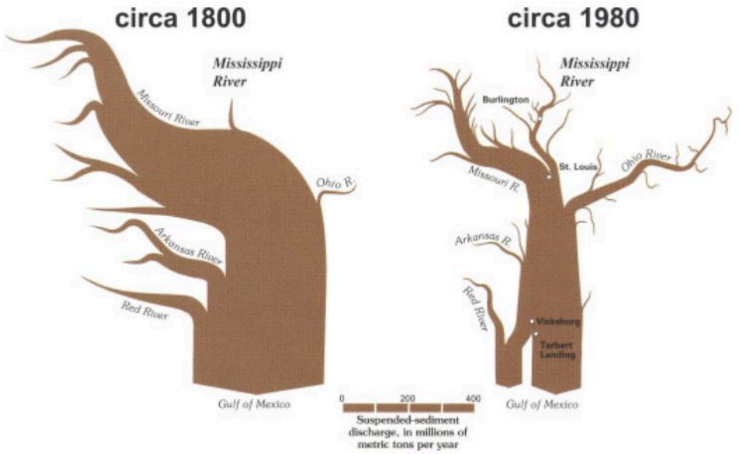


Diagram of sediment flux in the Mississippi River basin circa 1700 on the left and 1980-1990 on the right.

Getting started up the Missouri, they found a river too thin to plow and too thick to drink. Like the Yellow River in China, the Missouri carried an enormous sediment load borne from natural erosion on the glacial loess soils of Iowa and Nebraska and from the Great Plains—too dry to completely cover the land in a protective blanket of vegetation, yet regularly experiences intense erosive downpours. Other Great Plains tributaries like the Platte, Arkansas, and Red also contributed to the stupendous sediment load of 400 million tonnes per year (Figure 12.11). These sediments built most of Louisiana as the delta wetlands growing upon them stretched farther and farther into the Gulf of Mexico, protecting New Orleans from the storm surges of periodic hurricanes.

Human use of the river basin was to change the patterns of that sediment flux. Soil erosion resulting from agricultural development in the Ohio and Mississippi watersheds increased sediment loads from low to moderate. In the Missouri Basin, the Fork Peck, Garrison, Oahe, Big Bend, Fort Randall, and Gavins Point Dams were constructed by the Army Corps of Engineers between 1937 and 1963, ostensibly to provide water supply, control flooding, and improve navigation of the river by barges.

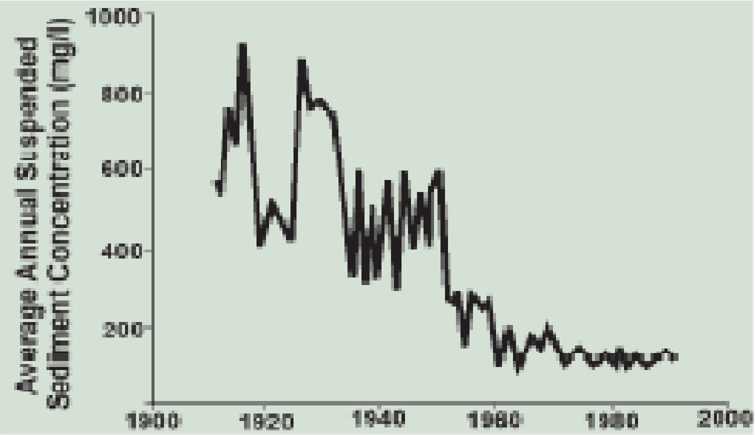


Figure 12.12. Suspended sediment concentrations in the Mississippi River at New Orleans over the course of the 20th century. Adapted from National Academy Press, 2008.

With the closures of the Garrison, Fort Randall, and Gavins Point dams in 1954 and 1955, the river's enormous sediment loads immediately began to fill up these reservoirs with silt, while the river's sediment load was reduced by at least three-fourths (Figure 12.12). The effects were felt locally as the hungry Missouri began to dig deeper into the loess and, in so doing, forcing all of its tributaries to do likewise, thereby producing a landscape of biologically impoverished entrenched streams undermining bridges across western Iowa and eastern Nebraska. The effects of reservoir sedimentation were also felt all the way to New Orleans as the river's sediment load plunged. With the river contained within levees to facilitate navigation, what sediment remained was deposited 100 miles southeast of New Orleans, bypassing the delta almost altogether. With sea levels beginning to rise due to climate change, and oil and gas extraction accelerating natural subsidence, the sediment-starved delta began to sink and erode away—rapidly. It is estimated that since 1950 Louisiana has lost 1,900 square miles, an area about the size of Delaware (Figure 12.12). Moreover, this loss of protective wetlands has left New Orleans extraordinarily vulnerable to storm surge impacts of hurricanes as was tragically witnessed in 2005 with Hurricane Katrina.

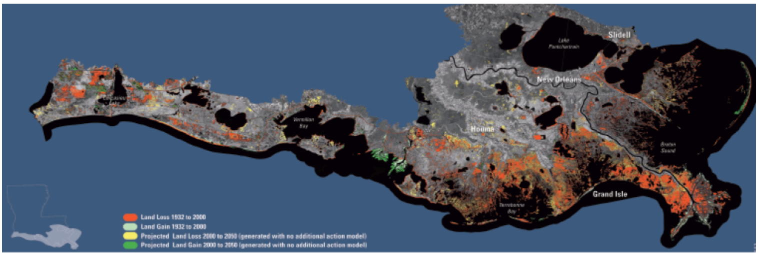


Figure 12.13. Land loss in southern Louisiana, 1933–2000. Source: U.S. Geological Survey.

In response, new ideas are being placed on the table. One is to build storm surge barriers east and south of New Orleans to block the sea from again invading the city. The first $1.1 billion phase of a $14.7 billion Army Corps of Engineers project is complete—a 2-mile-long seawall 10 miles east of New Orleans. Another idea works more closely with nature—redistribute the sediment to rebuild the delta. Even with its reduced sediment load, well-planned breaks in the levees containing the Mississippi to create new distributaries could accumulate lobes of silt, reversing the erosion process and creating new wetland environments. It would take decades, however, before New Orleans was again protected from hurricanes by a restored delta. Removing a Missouri River dam—especially the farthest downstream one at Gavins Point—to release more silt could also help. Restoring the Mississippi delta is an opportunity to practice adaptive management—learn by doing—while making its habitation more sustainable.

And then there's the problem of too much nitrogen. As we've seen, nitrogen causes eutrophication by fertilizing algae, which consume oxygen when they die, creating hypoxic conditions. Oxygen-breathing creatures such as fish either die or move on. The Gulf hypoxic zone set a record area the size of Maryland in 2019, but the majority of streams and rivers feeding the Mississippi are also eutrophic, as is that great river itself.

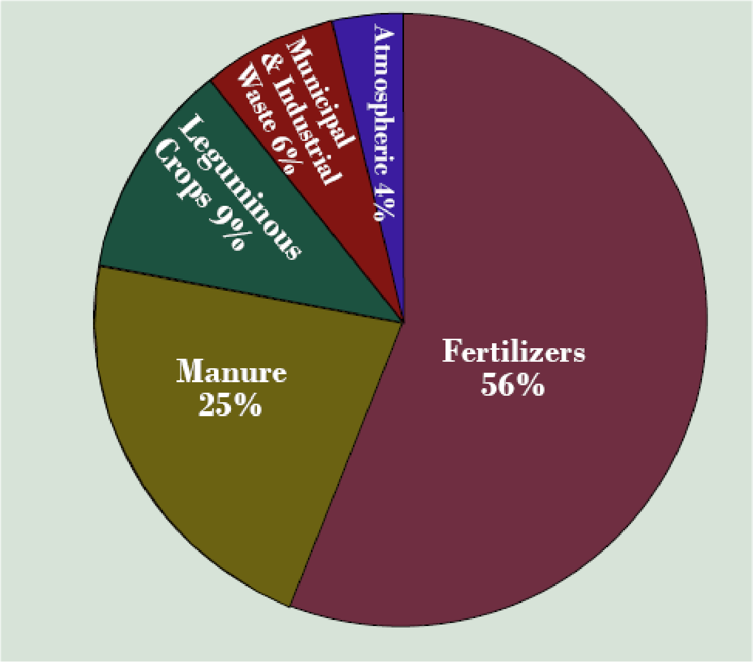


Figure 12.14. Sources of nitrogen load in the Mississippi River.

Where does all that nitrogen come from? The 2008 National Research Council study identifies fertilizers as the source of over half, followed by manure contributing one-fourth (Figure 12.14). Leguminous crops like soybeans are the third leading source. It's mostly coming from Midwestern agriculture.

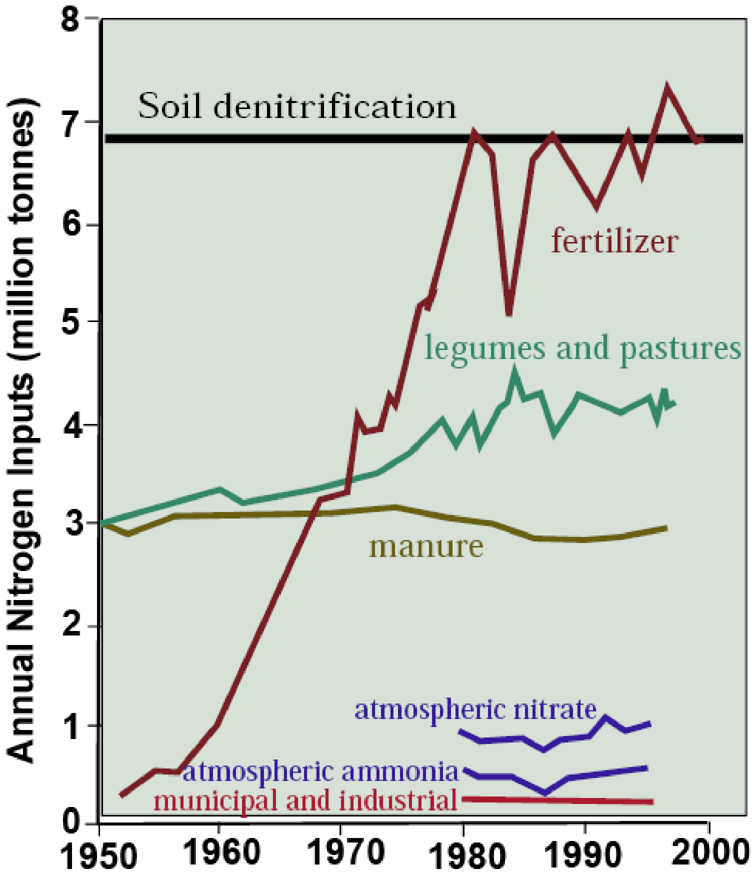


Figure 12.15. Sources of nitrogen to the Mississippi River, 1960–2000.

In 1950 manure, legumes, atmospheric, and industrial sources of nitrogen roughly balanced (at about 7 million tonnes per year) soil mineralization—the denitrification that anaerobic bacteria provide as an ecosystem service, mostly in wetlands. Since 1950, however, fertilizer runoff has climbed from almost nothing to about 7 million tonnes (Figure 12.15), doubling the input of nitrogen and overwhelming the denitrification process. The result is nitrogen overload and the undermining of aquatic and marine ecosystems.

Why is this happening? Just like the atmosphere can be overused as an open-access sink for carbon, the Mississippi watershed is being overused as an open-access sink for nitrogen. Farmers and feedlot managers do not pay a fee to use the watershed as the dump for their excess nitrogen, nor are there limits or caps on how much they can allow to run off. So, as in Hardin's tragedy of the commons, this congestible resource is overused. Moreover, wetlands, as nature's kidneys, encourage denitrification. Except through the Wetland Reserve Program mentioned in Chapter 11, no one gets paid to convert low-lying cropland to wetlands to provide this ecosystem service. So, in the tragedy of ecosystem services, it isn't provided in sufficient quantity. In fact, over three-fourths of the wetlands in the Mississippi Basin have been drained, largely to expand agriculture.

Moreover, each state is responsible for the quality of water in their streams and rivers and submit lists of those requiring pollution reductions to the Environmental Protection Agency's Total Maximum Daily Load (TMDL) program. Unfortunately, the Mississippi River forms state borders from Minnesota-Wisconsin to Louisiana-Mississippi, so it's an orphan in the state-based TMDL process. Here we see again how a legal and institutional economic approach reveals a pattern of incentives that generates a problem rather than resolving it.

In the nitrogen simulation described in Chapter 3, you can utilize two potential solutions to Gulf hypoxia, fertilizer reductions and wetland restoration, to attempt to eliminate or minimize the hypoxic zone within a set budget. See how well you can do.

Two Global Water Issues Critical to Water Resources Sustainability

It is often stated that at least one billion people on Earth do not have access to safe drinking water through a treatment system such as we described above. About twice that number lack access to basic water sanitation—a septic or sewer system. Most Americans cannot imagine the human cost of this lack of water resources development. Over two million babies and young children die every year from diarrheal diseases from drinking contaminated water. Many other diseases of the poor, especially in the tropics, are water-related: cholera, typhoid, schistosomiasis, and guinea worm (a dreadful disease former President Carter's Center is determined to eliminate). If these diseases could be prevented, infant and child mortality would plummet, and with it, the fertility rate (remember descendant insurance from Chapter 5). From there, economic development could gain a foothold, bringing the world's poorest into a life of security and dignity. It has often been said that the best way to improve the world is to bring safe drinking water to those who don't have it. It turns out that this is likely true.

There is a silver lining: it used to be worse. In 1970 only 30 percent of people in developing countries had access to safe drinking water and only 23 percent had working sanitation systems. By 2000, 53 percent had sanitation and fully 80 percent had access to treated drinking water. This represents one of the great untold success stories in sustainable resources management. The problem is never a lack of water; as we saw above, water for drinking and sanitation is a tiny fraction of water use. A mere 50 liters, about 12 gallons per person per day, can make the difference. Some have claimed that this should be a human right.

The problem is a lack of infrastructure along the lines shown in Figure 12.3, expensive water treatment and distribution infrastructure that nearly all Americans have enjoyed for about a century. Given the momentum generated over the past 50 years and the enormous benefits in controlling disease, it seems that delivering safe drinking water to nearly everyone is a goal that is both achievable and worthwhile. I put it first on the to-do list for sustainable water resources management.

Even if this goal is achieved, however, it still does not feed everyone. When green water is included, meat-rich and sometimes overabundant North America diets require about 1,200–1,300 gallons per day to produce. Largely vegetarian and sometimes inadequate African and Asian diets require about half as much. Where is this water going to come from in a world with an increasing population that is transitioning to diets that require much more water to produce? In much of tropical Africa, the problem is developing the water resources they do have for municipal supplies and irrigation. In the virtual water-importing regions stretching from North Africa, through the Middle East, South and Central Asia to North China, in contrast, the problem is lack of water resources to expand, or even maintain, irrigation.

In *Pillar of Sand*, Sandra Postel told how the Green Revolution, including the great expansion of irrigation, was the key to expanding food supplies to keep up with population growth in the populous continent of Asia over the past half-century. Like in the Colorado River Basin, however, in watershed after watershed, freshwater supplies have been fully developed. We examined the catastrophe of the Aral Sea in Chapter 2. The Yellow River of North China now sees intervals of months where not a drop of water flows to the Yellow Sea. The capital of Beijing is threatened with an inadequate water supply. China's response has been a multi-billion-dollar plan to build canals transferring a substantial portion of the voluminous Yangtze River northward to the Yellow basin.

Groundwater tables are dropping in north China and western India. The sources of the Indus River in Indian Kashmir, lifeline of arid Pakistan, are a lightning rod of conflict between India and Pakistan. Management of the Brahmaputra-Ganges has generated conflict between India and Bangladesh, management of the Mekong among the nations of Southeast Asia. Climate change is worsening the situation by melting the massive glaciers of the high Himalayas and Tibet that serve as the summer supply for all of these rivers. The water situation is even more severe in the even drier Middle East where Turkey, Syria, and Iraq have struggled over the waters of the Euphrates. Jordan, Israel, and Palestine share the trickle of water known as the Jordan River and aquifers along it.

These are the most pressing issues in water resources sustainability, but, as we discussed with reference to the American Southwest, there are solutions in more crop for the drop, crops that drink fewer drops, virtual water, and water reallocation. As in the dilemma of prior appropriation in the Western U.S., there are social, political, and economic barriers unique to each country and watershed to feeding more people with less water. The key is to diagnose what these barriers are and to overcome them. Who would have thought in 1970 that 30 years later 80 percent of people in developing countries would have access to safe drinking water? Who would have thought in 1980 that by 2020 total U.S. water withdrawals would have declined? Resignation is the enemy of the solution. Patient persistence is its friend.

The Ecological-Economic Value of Water

Fresh water has so many uses. Managing it consists of evaluating those uses relative to the resources available, in terms of both quantity and quality, over time and across space. The idea from neoclassical economics that scarce resources should be allocated to their highest and best use is sound, but in making that determination we need to work our way through market failures that provide the wrong incentives to managers and users. We also need to fully incorporate ecosystem services into the equation. The market value of water to users—usually as a factor of production of crops, energy, or a clean and healthy home, business of facility—represents what they are willing to pay for it. There are two more critical values of water, however, that escape neoclassical economic analysis. The first 50 liters of safe drinking water per capita per day, the water lifeline, is essential to public health and thus saves lives, especially babies and small children. It thus has a huge value to people, preserving human capital, whether it generates an "economic" value or not. Finally, water in its natural settings, in lakes, streams, wetlands, and so forth, is, as we have seen, the most critical factor of production of ecosystem services. In fact, ecosystems defined by fresh or shallow salt water (e.g., estuaries, wetlands, aquatic) have the greatest ecosystem service value per unit area.

What is the opportunity cost of using water for one purpose rather than another? The costs of supplying water that a user must pay for include the cost of building the water supply system we described above, plus operation and maintenance of that system. That excludes any charge for the water itself, however, especially the value of the alterative use that could have been made of it. It also excludes economic externalities such as the degradation in the quality of the water that inhibits other uses. It is in this sense that neoclassical economists have argued that water is underpriced—all the costs for using it are not paid for by the user. In ecological economics, this argument goes even further because when water is consumed or degraded in quality, the ecosystem services that water could have generated are lost. Except in conditions of flood, there is, at the margin, an ecological-economic opportunity cost. Water used to irrigate crops is water no longer available for salmon spawning, as in the case of the Klamath River, or the survival of an endangered fish species, as in the case of the Rio Grande, or for denitrification and bird habitat in wetlands, as in the case of the desiccated Colorado River Delta.

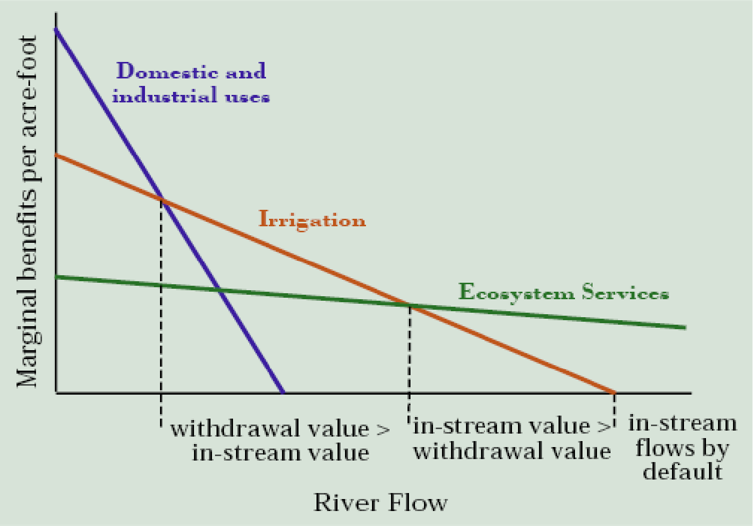


Figure 12.16. The ecological-economic allocation of scarce water between off-stream withdrawals for domestic and industrial uses as well as for irrigation versus in-stream use for ecosystem services.

Figure 12.16 analyzes these trade-offs for a hypothetic western river. The marginal benefits, the ecological-economic value of one more acre-foot, is shown on the y-axis. On the x-axis is the flow of the river from the first trickle on the left to bank-full flow on the right. The value of domestic and industrial uses is high, but these diminish quickly as needs are met. Irrigation values are not as high, but they diminish more slowly as land less and less suitable for irrigated agriculture and less and less valuable crops are brought into production. For the first acre-foot of water, ecosystem service values are probably not quite as high, but every acre-foot counts, expanding the services that can be delivered from streams, wetlands, and riparian zones.

Highest and best use represents the highest value use at each level of river flow. For the first increment of river flow, this is domestic and industrial uses that keep people healthy and generate large numbers of jobs. Once these needs are met, additional river flow can be allocated to either irrigation or left in the natural watercourse for ecosystem services. If the value of the latter is excluded, farmers will use water until its marginal value is zero, leaving limited in-stream flows only when they can't earn additional income from the remaining water. But water left in the stream or reservoir for ecosystem services can exceed values for irrigation. A point is reached where the highest and best use is in-stream flows. In fact, when the long-term viability of a species or salmon run is at stake, the value of an acre-foot in the stream may exceed any possible value in irrigation. When ecosystem service values are not considered, too much water is withdrawn from the stream and the highest and best use of scarce water is not realized. This is unsustainable as well as inefficient. Virtual water can play an important role here by trading food from water-abundant regions, where irrigation and ecosystem services are not in competition for scarce water, to water-deficit regions so that the latter can maintain in-stream flows, aquatic ecosystems, and their biodiversity and services.

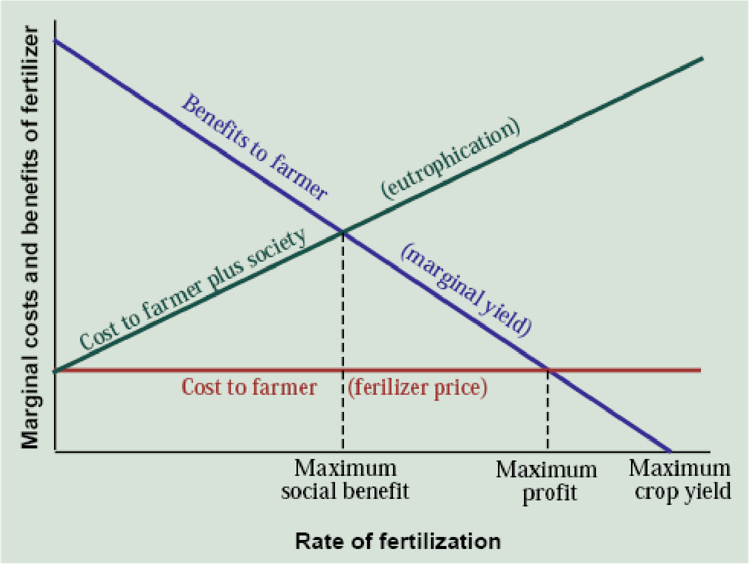


Figure 12.17. Optimal fertilization rates for maximizing yield, profit, or social benefits.

A similar logic applies to water quality, again especially in an agricultural context. Take the nitrogen overload problem in the Mississippi discussed above, which results from heavy rates of fertilization. In Figure 12.17, the marginal costs and benefits of adding more fertilizer to crops are shown on the y-axis and the amount of fertilizer applied along the x-axis. Starting from zero, as fertilizer is added, crop yields, and thus revenue to the farmer, increase, but at a decreasing rate due to diminishing marginal returns. At some point (where the benefits to farmer line crosses the x-axis), crops stop responding to more fertilizer. Farmers wishing to maximize their crop yields would stop adding more fertilizer at this point. Fertilizer must be paid for, however, and its price represents the marginal costs to farmers of adding more. To maximize profits rather than yield, farmers would stop adding fertilizer at the point where the revenues from additional yields fall below the cost of the additional fertilizer.

At this point farmers are still overfertilizing because there is also a social cost to fertilization that comes in the form of eutrophication and the associated loss of ecosystem values. These costs climb as more and more fertilizer is added, overloading the watershed with nitrogen. When this is figured in, the time to stop adding more fertilizer is shown where the marginal cost and benefit curves cross and social benefit is maximized. This lower level of fertilization represents the best balance between food production and protection of aquatic and marine ecosystems. If it were widely employed, the Mississippi River story told above would be a much more sustainable one, and you and I may never have heard of Gulf hypoxia.

From National Water Resources Development to Local Integrated Water Resources Management

Over the years, I have heard frequent calls for a national water policy or to restore the defunct National Water Council. I'm unconvinced. As Massachusetts member of the House of Representatives Tip O'Neil once said of politics, all water issues are local. States own the water within their boundaries. Except for a few communities that have taken the privatization route, local governments provide drinking water and wastewater services for their citizens. Moreover, the nature of water resources management problems is changing in a way that makes localities the playing field even more than in the past.

As told by Marc Reisner in *Cadillac Desert*, for most of the 20th century U.S. water issues focused on water resources development—capturing freshwater, usually with a dam, before it escapes to the sea and bringing it to bear as a factor of production for growing cities, industry, power production, navigation, and agriculture. Dams and levees were constructed to try to contain floods. It was the territory of the civil engineer working for a federal agency such as the Army Corps of Engineers or the Bureau of Reclamation and of members of Congress bringing home the bacon in the form of a federally funded water project.

After the Clean Water Act passed in 1972, the focus shifted to environmental infrastructure, especially the construction of wastewater treatment plants. Civil engineers became environmental engineers, and Congressmen brought home earmarks rather than barrels of pork. In their own fashion, developing countries like Brazil, China, and India are still working through this era of water resources development, and tropical Africa has begun it.

We are now two decades deep into the 21st century and the playing field has changed remarkably. The great era of dam, levee, and drinking and wastewater treatment plant construction is over. Those infrastructures are in place, even if many, especially in the older eastern cities, have suffered from deferred maintenance. The issues of this century revolve around sustainability and working locally with nature to meet human needs. These include irrigation efficiency and institutional mechanisms to reallocate water from low-value uses to other purposes, managing urban water demands, and controlling urbanization of floodplains. Controlling polluted runoff and restoring wetland and aquatic ecosystems that water resources and land development has left in a degraded state are even more locally oriented issues.

The federal agencies of the 20th century—the Army Corps of Engineers and the Bureau of Reclamation—can be helpful here but as occasional consultants and contractors hired by locally-controlled initiatives. Rather than the primary funder of engineering projects, the new, more limited role of the federal government is primarily to gather and disseminate data, to conduct research with shared results, and to provide the right incentives for conservation.

Instead, we need stronger local watershed-based institutions, perhaps resembling school, fire, and other local service districts. In order to be effective, watershed service districts need four characteristics. First, *integrated* watershed management should promote a shift from single-purpose management (e.g., water supply, flood control, wastewater treatment, stormwater control) to managing the watershed as a human ecosystem, where each of these elements interact. Second, the districts may require *powers* other forms of local government possess such as the authority to enact regulations, create economic incentives, administer permits, and conduct public information campaigns. They would also need to be *funded* through traditional means such as taxes, fees, and bonds. Third, they need the *institutional capacity* (e.g., budget, staff, and expertise) to manage a critical natural resource sustainably. This includes carrying out complex scientific and economic analyses and managing regulatory and permit programs. Fourth, they must be perceived as *legitimate* by the local community by holding elections for officers who conduct the public's business in a transparent manner and are held accountable by the public for decisions made.

Summary

Freshwater is a subtle resource because we use it in many ways that slip beneath the radar screen of our popular culture. It is the key component of functioning ecosystems, yet these ends are often subordinated to the needs of energy, agriculture, urban development, navigation, and public health.

Fortunately, as long as the hydrologic cycle keeps bringing rain and snow, we have the opportunity to make water resources management more sustainable by managing human needs within the context of watersheds as human ecosystems. Water teaches us that sustainability is more than just leaving some resources in the bucket for the next generation. It is also about keeping ecosystems—for which water is like blood for our bodies—functioning so that they may serve us in perpetuity.

Further Reading

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15.

CHAPTER 13: WEALTH FROM THE EARTH - MINERAL RESOURCES

While our most essential natural resources come from ecosystems—air, water, forests, soil, and the food that it grows—many important industrial raw materials are mined from beneath the Earth's surface. Fossil fuels, metallic ores, phosphorus for fertilizer and materials for roads, concrete, and bricks are stock resources with a fixed geologic resource base (as defined in Chapter 7 on ecological economics). In thinking about the sustainability of stock resources, we want to consider how large the geologic stock is, the process and rate through which humans use, recycle, or consume that stock, and, through these factors, assess how long the stocks are likely to last.

Figure 13.1 helps us think about that process, which we will explore using an important metallic ore (copper) as an example. The original resource base, the total mass of copper in the Earth's crust occurring as crystals in igneous rocks, has changed little in a billion years, but that doesn't make it easy to estimate how much copper there is. Gordon and colleagues in a 2006 paper on metal stocks and sustainability estimate the world total at 1,600 million tonnes, though other analysts come up with different numbers. For this reason, we call estimates of ore that may someday be found by geologists speculative resources. When, in fact, they are found and measured, they become proven reserves. Since most ore prospectors work for private companies, the actual amount of proven reserves is privileged information that is sometimes overestimated or underestimated based on whether recording reserves is a cost or an asset to the company. Companies also need an economic incentive to invest large amounts of money in resource prospecting. If reserves are large and prices are low, this incentive is lacking.

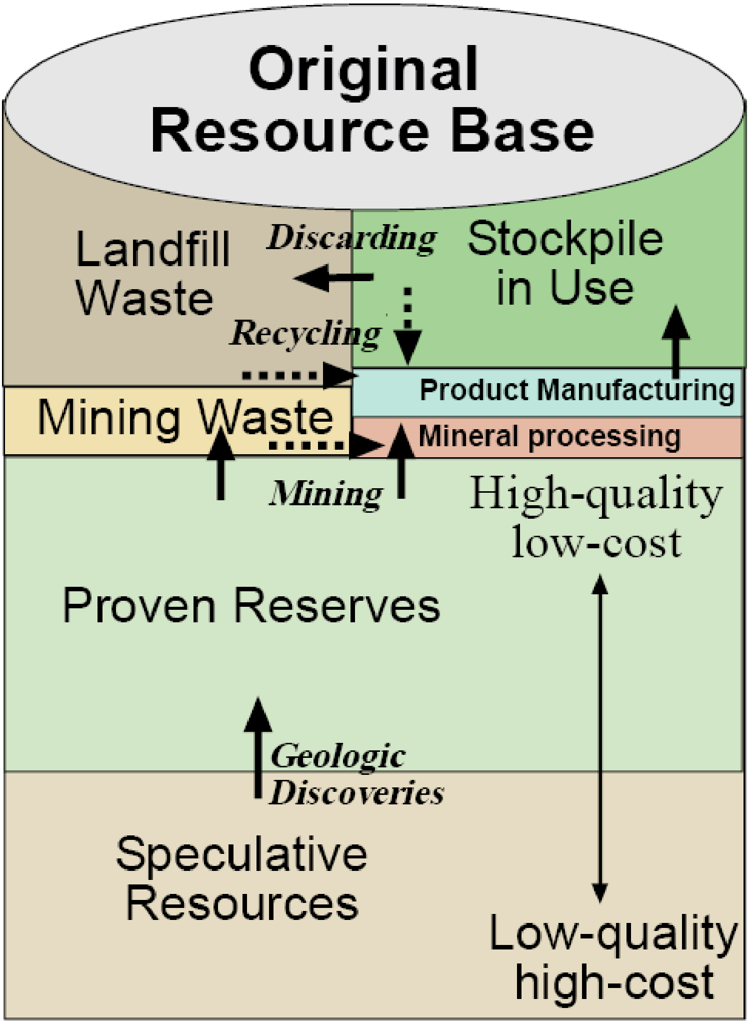

Figure 13.1. Relevant stockpiles of material resources and flows among them.

With these qualifiers, proven reserves for copper are estimated at 590 million tonnes (MT). In comparison, proven reserves of iron ore are 230,000 MT and of aluminum are 28,000 MT, so copper is not an abundant metal, but more so than zinc at 330 MT, lead at 130 MT, nickel at 110 MT, tin at 10 MT, and gold at 0.04 MT, which has reserves roughly 1/10,000,000th of those for iron (Figure 13.2).

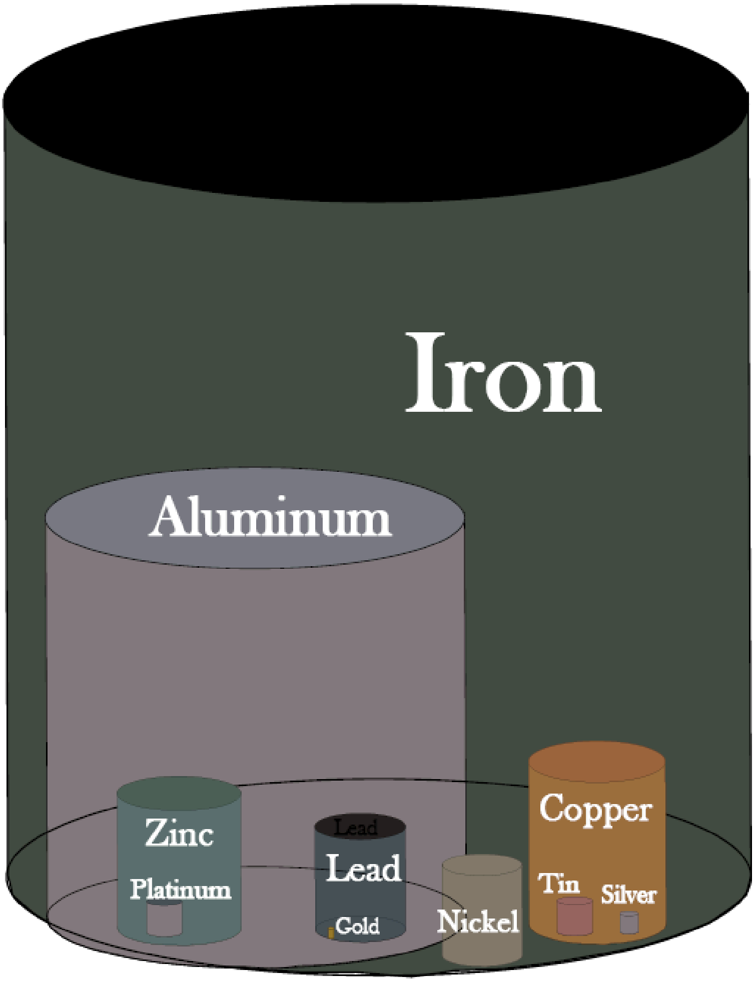

Figure 13.2. Relative mass of reserves for various metals—iron, aluminum, copper, zinc, lead, nickel, tin, platinum, silver, and gold—as comparative volumes of cylinders.

Copper was the first metal to be mined and forged in the bronze age several thousand years ago because it is the easiest of the common metals for smiths to forge into tools and weapons. Nevertheless, in all of human history through 1900, only about 2 MT of the Earth's resource base of 1,600 MT of copper had been extracted. In the 20th century, however, about 400 MT were mined, a quarter of the global resource base, with an additional 590 MT in reserves awaiting mining. This degree of rapid acceleration in global mining over the last century is evident for many other minerals as well.

All mining occurs from reserves, but often only a small fraction of the material mined becomes pure copper metal. Most of the ore is materials other than copper and becomes mine waste and an environmental problem if it is not managed carefully. Even some of the copper crystals never make it out of the smelter to become a raw material for the manufacturing of products.

Once copper enters the economy, it is made into industrial goods that form an *above ground stockpile of resources in use* (Figure 13.1). In the U.S in 1900, this was about 1 pound of copper per person, but in 2000 it was 525 pounds contained in infrastructure (209 pounds), buildings (168 pounds), industrial and domestic equipment (39 pounds), and vehicles (62 pounds). It should amaze you that the amount of copper each American is utilizing multiplied over 500 times in the 20th century. Data for many other countries are similar. This shows us how forceful global industrialization, and its demand on natural resources, is. Globally, 56 percent of all the copper ever mined, 222 MT, is in products now being used while 44 percent or 176 MT has been discarded—someplace. While this copper still exists on the planet, it is in a form that is much more difficult and expensive to recover than the high-quality reserves from whence it came, or from the products it now resides within that could be recycled later. To the extent that copper has been consumed, it is via this one-way ticket from high-quality ore that is mined and processed into metal to make products that are then discarded in a manner that would be very expensive to recover. Perhaps 11 percent (176 out of 1,600 MT) of the Earth's resource base of copper has met this fate so far.

Fossil fuels, on the other hand take a one-way trip from reserves to consumed (except when oil is used to make recyclable plastics, much of which ends up polluting the oceans where it is found in alarming quantities in the digestive tracts of marine animals). Gold, due to its high value and ease of recycling, is never discarded, meaning it has a 100 percent recycling rate!

Currently, 45 percent of new copper produced comes from recycling of old products or, far less often, is recovered from landfills. A higher proportion of copper contained in obsolete products is recovered for remanufacturing, but as long as the above ground stockpile-in-use is growing—as it continues to do as developing countries play catch-up in constructing industrial infrastructures—even 100 percent recycling must be augmented by new mining of reserves.

The process of prospecting for, hopefully discovering, mining, and utilizing minerals is driven largely by economics, following neoclassical rules. When reserves are large relative to rates of use, or prices are low, it doesn't make economic sense to prospect for new deposits. Among proven reserves, the highest quality and cheapest to produce are mined first and not until industrial demand makes it profitable to do so. Industrial demand for specific raw materials depends on specific technologies that utilize it. Copper is an excellent conductor of heat and electricity, and so demand for it has continued to climb as a raw material for industries like motor vehicle electronics and air conditioning. These new and growing uses of copper have offset declines in demand for high-voltage transmission lines (where cheaper aluminum has served as a substitute) telephone lines (which cell phones have made obsolete), and plumbing (where plastic PCV pipe is the new standard). These examples show how *resource substitution through technological change* is an essential factor in the natural resources sustainability equation. For example, the last cryolite mine was closed in 1987, but the mineral is easily replaced by synthetics, so the loss of this natural resource has not been missed.

So how sustainable is our use of copper? A first approximation can be made by looking at reserve-to-production ratios. Given reserves of 590 MT, current production of about 5 MT per year would last 118 years, but I think you can already see the fallacy in using that figure as an estimate of when we will run out of copper. New reserves may be produced through geologic discoveries from the remaining resource base, leaving us a nearly 600-year supply. If we can recycle, say 75 percent of the copper we use, then the supply will last for 2,400 years. Most of the copper that was once in the Earth will accumulate in the above ground stockpile-in-use, which is used again and again.

But then again, current rates of extraction are increasing steadily at 3.3 percent per year, yielding a doubling-time of 21 years. At that rate of increase, all the copper would be mined out and placed in the stockpile in use or discarded in less than a century. Along the way, the availability of copper ore for new products would be steadily declining, but the availability of copper in obsolete products for recycling would be increasing.

Clearly, *recycling replaces mining* as a source of raw materials as we go through this process of transforming the Earth's copper from ore to industrial products. So we will never entirely run out of copper even if remaining resources are so remote or poor in quality that they can't be profitably mined. This is called *economic exhaustion*.

Preventing the dissipation of copper by discarding it is critical in the long run. However, a metal like zinc is harder to recycle than copper because it is mostly used as a thin film on iron-based steel to prevent corrosion and is very difficult to separate for recycling. So the recycling of metals and other materials is tied to the technologies through which they are used and how easily they can be separated out or disassembled from the products that contain them so they can be recovered for recycling. Otherwise, generic junk, such as landfill waste, can be viewed as a low-grade ore.

Economics helps us understand this process as well. As high-quality reserves of copper become scarce, the price of new copper from ore will rise, decreasing the quantity demanded and increasing the incentives to recycle copper. Moreover, rising prices for copper will induce engineers and manufacturers to come up with substitutes—like aluminum or plastic—in various end uses.

Resource substitution is not automatic, however. It must be vigorously pursued by technologists as a response to rising prices, and sometimes compromises must be made. For example, aluminum is not quite as good a conductor of electricity as copper, and I'd rather cook with a copper-bottomed pot than aluminum or iron. History has shown that substitution can almost always be accomplished, given time and the right economic incentives, allowing the economy to shift from use of scarce to more abundant resources (Figure 13.2). So I find myself feeling optimistic about the future availability of copper and many similar industrial raw materials even though they are stock resources.

Technological change can also intensify demand for a scarce resource. Coltan is a rare mineral containing the metals niobium and tantalum used in cellular phones and laptop computers. The rapid rise in demand for it has catalyzed conflict between Congo and Rwanda in East Africa. Rare platinum, with a resource base of only 37 MT, is a key component of current technologies for manufacturing hydrogen fuel cells, a product that may or may not become more important in the future. Demand for lithium is skyrocketing as electric cars using lithium-ion batteries penetrate the automobile market. Critically, resource substitution is usually not a viable option for ecosystem services or biodiversity. Have you got any substitutes for oxygen or the photosynthesis that produces it? How about the blue whale or polar bear if they go extinct? This is referred to as *technological asymmetry*—technologies for making products advance much more quickly than for maintaining nature.

Carroll Ann Hodges of the U.S. Geological Survey makes the case that, with the exception of petroleum that we will explore in depth, "running out" is not the issue with stock resources mined from the Earth, though certain regions and countries can face a problem of dependence on imports. For example, the U.S. is more self-sufficient than all but a few countries, yet it still relies on imports for all of its bauxite (aluminum ore) and manganese, nearly all of its industrial diamonds, platinum, tungsten, chromium, tin, and potash. On the other side of the coin, several developing nations (e.g., Surinam and Jamaica in Latin America; Zambia, Zaire, Guinea, Botswana, Niger, and Liberia in Africa) are economically dependent on minerals as their primary export, yet their overall social and economic progress has lagged so badly that economists refer to the *resource curse*—a far cry from sustainable development.

Closer to home, consider a 1994 sale to a Canadian corporation of 1,800 acres of federal lands in Nevada containing 8–10 billion dollars worth of gold (not counting exploration and production costs) for a mere $9,000! Even more than the prior appropriation system for allocating water, policies such as the Mining Law of 1872 are based on 19th century objectives to provide economic incentives to quickly settle the West by developing its natural resources, not contemporary concerns for natural resources sustainability or a fair return to the taxpayer for resources on public lands.

Mining currently occupies only 1 acre in 400 in the U.S., and only one tenth of that for metals. Nonetheless, its environmental impacts can be devastating—complete destruction of vegetation and soil—and reach beyond the mine site, especially through leakage of toxic heavy metals and sulfur into streams (known as *acid mine drainage*). Fifty-two historic mines are Superfund sites with estimated cleanup bills in the billions of dollars. Fortunately, new U.S. environmental laws have done much to internalize the environmental costs of current mining and to slowly restore past mining sites, one at a time. The greatest problems now occur in developing countries, less from multinational corporations, who have mastered modern environmental protection technologies, than from small local and national companies lacking it.

This brief exploration into nonfuel minerals tells us that stock resources mined from the Earth and used as raw materials can be used sustainably if three requirements are met:

1. As any particular resource becomes scarce, a process is developed for relying increasingly on recycling of materials from above ground stockpiles and for resource substitution to more abundant materials through technological change.
2. The ecological impacts of mining are minimized by mining in suitable sites using modern technology and applying post-mining environmental restoration techniques.
3. Foreign exchange earned through mineral imports is channeled into investments in sustainable development and human capital such as family planning, agricultural improvements, health care, and education.

Now let's look at the nonrecyclable fossil fuel minerals—oil, gas and coal—and assess their sustainability.

Fossil Fuels: Oil

Americans are more dependent upon auto-mobiles for transportation than any other country, but they aren't worth anything if the gas tank is empty. This makes a concern for security of fuel supplies legitimate, yet it still doesn't explain the fascination with, bordering on paranoia about, gasoline. Everyone born before 1965 or so remembers the 1973 OPEC oil embargo when gas stations ran out or offered only a couple of gallons after waiting in line for hours (using up what little gas was left while idling). When news of the September 11, 2001, terrorist attacks hit the airwaves and the Internet, many American's first response was to rush to the gas station to fill up. Concern over vehicle fuel supplies goes even further back. Daniel Yergin in his 1990 Pulitzer Prize-winning book *The Prize: the Epic Quest for Oil, Money, and Power* (updated in 2011) argues that the Allies' superior access to oil, and starving Japan and Nazi Germany of the fuel for their war machine, was a key factor in winning WWII. Oil is clearly the natural resource that has raised the greatest issues of security of supply.

As recently as the first decade of the 21st century, the world's oil reserves were concentrated in the OPEC countries surrounding the Persian Gulf, the sheikhs of oil, and most other countries, including the United States, imported the majority of their oil from this politically volatile region, raising repeated political calls for energy independence to reduce supply vulnerability. Things have changed. Technology has enabled development of two more difficult sources of oil—oil sands and shale oil—increasing world reserves substantially and changing the geography of who's got the oil (Table 13.1). Two countries in the Western Hemisphere that could not be more different politically—Venezuela and Canada—are the new kings of oil sands or heavy oil, while the U.S. has emerged as the king of shale oil through the 21st century technology of fracking. The geography of production is more diversified than it was with Russia and the United States alongside Saudi Arabia as the leading oil producers and with China and Brazil breaking into the top ten.

Table 13.1. Leading countries in oil reserves and production. Source: Energy Information Administration

Country	2017 Oil Reserves (billion barrels)	Rank	Country	2016 Oil Production (billion barrels per year)	2008 Reserve/ Production Ratio
Venezuela	301	1	Russia	3.85	21
Saudi Arabia	266	2	Saudi Arabia	3.82	69
Canada	170	3	United States	3.24	10
Iran	158	4	Iraq	1.62	88
Iraq	143	5	China	1.45	17
Kuwait	102	6	Canada	1.34	126
United Arab Emirates	98	7	United Arab Emirates	1.14	86
Russia	80	8	Kuwait	1.07	95
Libya	48	9	Brazil	0.92	14
Nigeria	37	10	Venezuela	0.83	362

Country	**2017 Oil Reserves (billion barrels)**	**Rank**	**Country**	**2016 Oil Production (billion barrels per year)**	**2008 Reserve/ Production Ratio**
United States	35	11	Nigeria	0.73	51
World	1,727		World	29.43	59

When considering the future availability of oil to run our cars and trucks, a vigorous debate centers around the idea of peak oil. Given that oil is the consummate nonrenewable resource, peak oil asks the question: When will oil production hit its maximum or peak and then start to decline?

Peak Oil?

You've probably never heard of the late American geologist and petroleum engineer M. King Hubbert. He developed a method in 1956 to assess the future lifespan of fossil fuels and used it to predict that U.S. oil production would peak in 1970 and then start a long decline following a bell-shaped curve. If we compare Hubbert's 1956 predictions with actual production of U.S. oil through 2004 (Figure 13.3), it looks to me like he nailed it. Except for some ups and downs associated with the OPEC troubles of the 1970s, the empirical dots fall almost exactly on the theoretical curve! As an experienced scientist, I can tell you that the empirical data rarely fit the theory this cleanly.

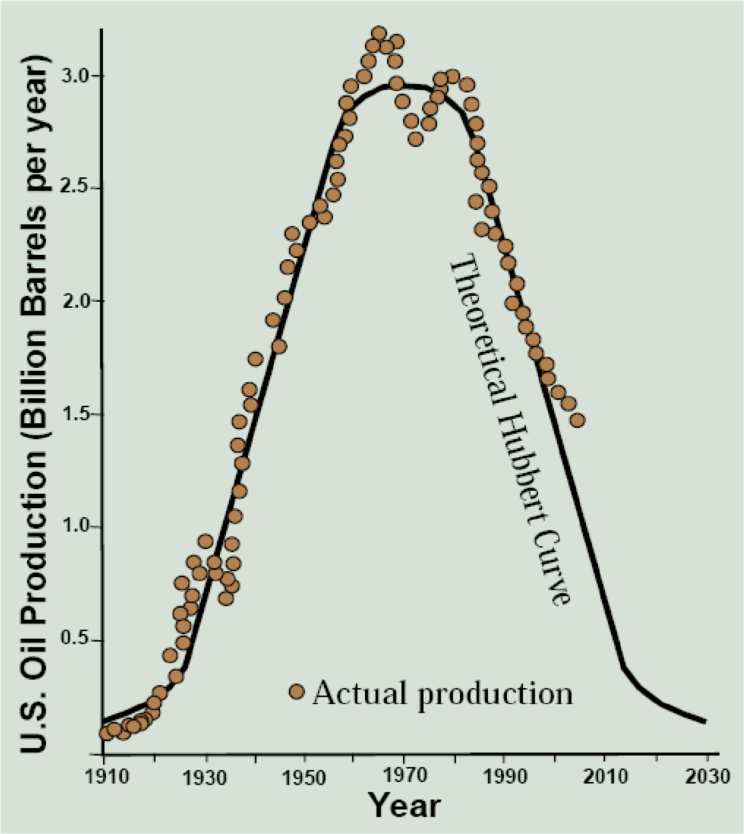

Figure 13.3. Hubbert curve for U.S. oil production with actual production through 2004 shown as dots.

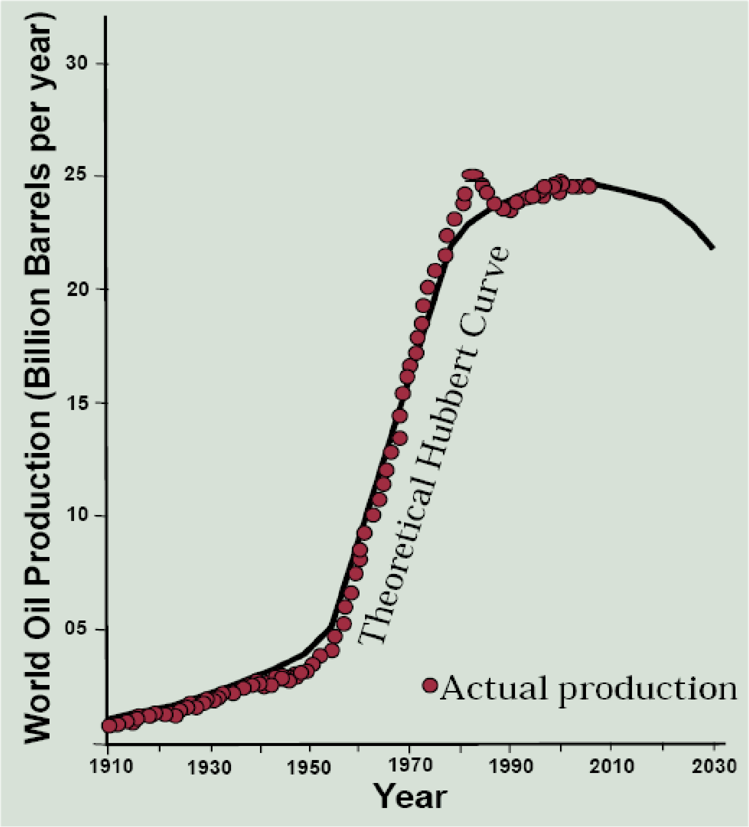

Figure 13.4. Hubbert curve for world oil production with actual production through 2004 shown as red dots.

The question then emerges whether *world* oil production will follow the Hubbert curve, and if so, when is the peak? It turns out that the data fit the Hubbert prediction very well with a minor exception of the 1970s when the oil world industry was spasming from the effects of the OPEC oil embargo and the Iranian Revolution (Figure 13.4). If we take this curve as a prediction, world oil production peaked in 2005 and will fall to half of that peak level in about 50 years!

Stop and think about that. The good news is we won't run out of oil tomorrow, in fact, half of the original resource base of two trillion barrels is still left in the ground and some oil is likely to be produced for the rest of your long life. But think about the economics of the ever-diminishing world production of oil. During the upward slope of the Hubbert curve, world oil production is *demand-driven*—as more countries get more cars, trucks, and airplanes and need more oil, demand increases, driving production up. But on the downward slope, world oil production is *supply-constrained*—there is only so much oil that can be produced and only the highest bidders will get any, even if all of Asia is acquiring automobiles like Americans. You learned in Chapter 6 to know that this means one thing—higher oil and gasoline prices in the long run. Moreover, much of it would be imported from the OPEC countries bordering the Persian Gulf.

To argue that there's a lot more conventional oil out there if we only look for it is to argue that geologists have done a poor job locating oil, and the million or so dry holes that have been drilled are due to their incompetence. This isn't likely. With so much money at stake, some of the best scientific talent and enormous technological resources have been devoted to finding oil fields. The inevitability of global peak oil seems to be reinforced when we examine trends in oil discoveries over the past several decades (Figure 13.5). The big oil fields of the Persian Gulf region were discovered in a few waves of successful exploration between the late 1930s and the mid-1960s. Since the late 1970s, global oil discoveries have been steadily dropping to quite low levels since the early 1990s. Will more oil be discovered? Of course, but for a generation, discoveries have been disappointing despite the most sophisticated natural resource exploration endeavor in human history. So, as the raft of books about peak oil in the first decade of this century foretold, it seems we better get ready for declining oil supplies and spiking gasoline prices!

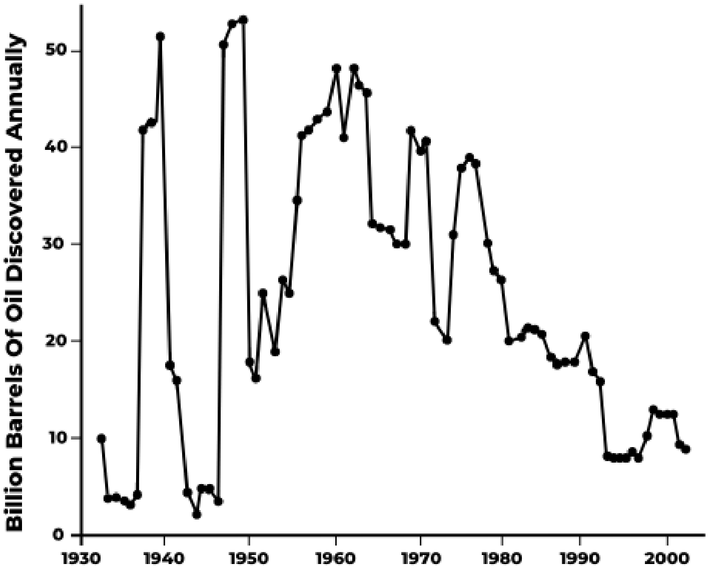

Figure 13.5. Annual global oil discoveries, 1932–2004.

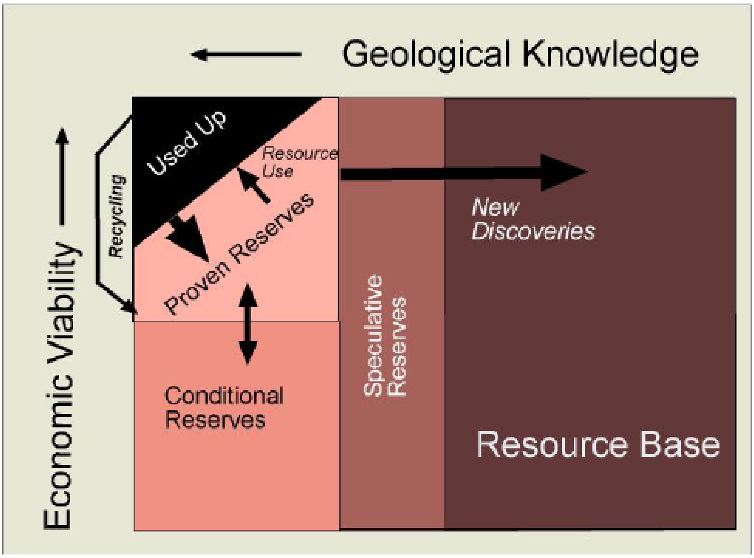

Figure 13.6. The interplay between geologic knowledge, and economic viability in the resource base of a mineral resource.

But that's not what has happened. Let's see why. Figure 13.6 lines up the resource base of a mineral like oil along two axes: geologic knowledge (increasing to the left) and economic viability (increasing to the top). Use comes from proven reserves, and so the portion of the resource base that is consumed comes from the top left and eats into proven reserves from there. This would use up proven reserves, usually in a matter of decades, except that proven reserves grow to the right as speculative resources are more thoroughly evaluated and new geologic discoveries are made. Yet we see from Figure 13.5 that this process has slowed, seeming to indicate that there aren't huge oil fields out there just waiting for an exploratory well to be drilled in the right spot.

Now let's look at economic viability. Less economically viable than proven reserves are *conditional reserves*: well-known resources that are not profitable to produce—under current economic and technological conditions. Economic conditions are always in flux, with higher prices potentially making some conditional reserves profitable and therefore proven reserves. It is the state of technology, however, that changes the game more fundamentally. The 20th century ran automobiles on liquid oil that could be pumped from conventional oil fields. For this low-hanging fruit among petroleum resources in the Earth, the peak oil predictions are probably near the mark. But conventional oil is only the tip of the iceberg of all the fossil fuel resources that it is technologically feasible to turn into gasoline for our vehicles.

First come tar sands, now renamed oil sands as they move from conditional into proven reserves in places like Canada and Venezuela. These are not high quality supplies of oil, which is why they were deliberately left in the ground for most of the 20th century. Rather they are a sticky goop: heavy, carbon-rich oils with a high viscosity. They probably originated as oil that migrated up toward the surface because a geological trap was lacking and then began to evaporate away the lighter portions, leaving the heavy oil behind. They must be mined out of the ground like strip-mining of coal, then elaborately refined with natural gas to reach the right mix of carbon and hydrogen to produce a liquid you can put into a gas tank. As these technologies have progressed, however, this process has become economically viable, if environmentally costly. The Athabaskan oil sand pits of Alberta were an ugly scar on the landscape even before the 2016 Fort McMurray fire, the worst natural disaster in Canadian history. The controversial Keystone XL pipeline would link Alberta's oil sands with refineries in Houston and Louisiana. It seems that your vehicle may be running more and more on oil sands in the future.

Shale oil also has an enormous resource base of perhaps two trillion barrels. It is "uncooked" petroleum occurring as a greasy substance in the thin-layered, brittle sedimentary rock called shale, the rock type where most petroleum originates. Here again, technology changes the game. *Hydraulic fracturing or fracking* (which we will discuss in more depth below in relation to natural gas) is now producing oil shale in large enough quantities to substantially decrease U.S. dependence on oil imports. The Bakken fields of North Dakota have the largest shale oil production to date.

It is also possible to make gasoline from coal through the Fischer-Tropsch process developed and applied by the Nazis during WWII. The process is expensive and emits enormous quantities of carbon dioxide. So oil sands, shale oil, and oil from coal are prominent examples of conditional reserves—well-known resources that only become economically viable when technology improves and/or prices rise.

These unconventional oil sources developed though modern technologies can potentially extend oil's lifespan and broaden the period of peak production as pictured in Figure 13.7. If so, note that as the 21st century proceeds, a larger and larger proportion of oil would have to come from these more economically expensive and environmentally problematic sources, changing the technology and geography of oil production, refining, and use. Note how this scenario is quite different from simply relying on Hubbert's peak oil curve because it takes technology and economics, rather than geology, as the driving factors.

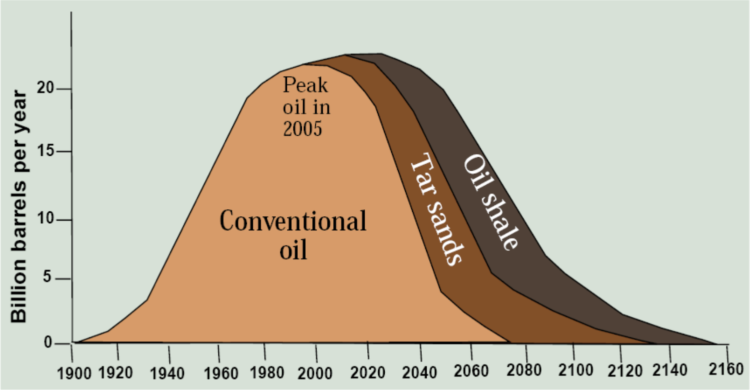

Figure 13.7. The possible effect of tar sands and oil shale on the lifespan of oil using a Hubbert curve.

Will this scenario of high oil production with a shift from conventional oil to oil sands and shale oil materialize? Only if technologies to free automobiles from liquid fuels or to free people from automobiles fail. Only if the world tolerates high levels of greenhouse gas emissions, because there is no feasible way to capture carbon dioxide from a tailpipe. Amory Lovins calls our current scenario the "oil end game" after the game of chess where the players have only a few pieces left and are trying to queen a pawn by getting it to the end row. We win the oil end game by making it obsolete. As the saying goes, the Stone Age didn't end because the world ran out of stones.

I think the 2013 book by Berners-Lee and Clark entitled *The Burning Question: We Can't Burn Half the World's Oil, Coal and Gas. So How Do We Quit?* gets it right. It's not about peak oil; it's about peak emissions. Will we run out of oil, and if so, when? This is not the right question because if we are willing to pay an escalating economic and environment cost there is plenty of oil, perhaps way too much, to put into our cars for the remainder of the century and beyond. Rather the pertinent questions are, when will other transportation technologies supersede gasoline-powered vehicles? And, based largely on the answer to this question, when will carbon emissions from fossil fuel burning peak and start their desperately needed decline? This framing of the issue says that it is not the size of the nonrenewable fossil fuel resource base that is central to sustainability, and this also makes a switch from nonrenewable to renewable energy supplies a secondary issue. Rather it is how we make fossil fuels obsolete or environmentally benign so that the real constraining factor—carbon emissions—can peak sooner rather than later. We will return to this issue at the end of the chapter, after bringing two nearly as important fossil fuels into the picture—gas and coal.

Natural Gas

As we explored in Chapter 3, natural gas is created by the same geological process as oil of slowly cooking ancient organic matter, though at a temperature above the oil window. This is why they are together called petroleum. Natural gas (mostly methane or CH_4) occurs in almost every oil field, but sometimes it also occurs without oil. The geography of gas reserves and production resembles that for oil but with some important differences that reflect oil-rich vs. gas-rich petroleum provinces and the new shale game where gas is more prevalent than oil (Table 13.2). The Persian Gulf is well-represented, but Russia leads the list with enormous reserves in western Siberia. U.S. reserves have climbed in recent years with major shale gas discoveries and leads all countries, slightly topping Russia, in gas production.

Table 13.2. The top ten list for natural gas reserves and production. Source: Global Energy Statistical Yearbook

Country	2018 reserves trillion m^3	Rank	Country	2017 production billion m^3
Russia	47.8	1	United States	767
Iran	33.7	2	Russia	694
Qatar	24.1	3	Iran	209
United States	15.5	4	Canada	184
Saudi Arabia	8.6	5	Qatar	166
Turkmenistan	7.5	6	China	147
U Arab Emirates	6.1	7	Norway	128
Venezuela	5.7	8	Australia	99
Nigeria	5.5	9	Saudi Arabia	98
China	5.4	10	Algeria	95

Natural gas got a later start than oil or coal, with large-scale production only about a century old, because gas is inherently dangerous, and therefore technologically demanding, to store and transport. Within the U.S., high-quality steel pipelines with calibrated pressure controls move natural gas from wells to consumption sites, a complex infrastructure network of which few are even aware. To ship it overseas requires even more sophisticated facilities to cool it to -260°F when it liquifies and can be shipped on specially designed liquified natural gas (LNG) tankers. For this reason, oil, with its ease of transport in supertankers, is more of a global energy commodity while gas is usually consumed within the continent where it is produced.

In the 21st century, gas has continued to climb in importance for two reasons. First, it burns cleaner than oil or coal. This is true with respect to carbon dioxide emissions per unit of energy produced, where it emits about half that of coal. Gas is also relatively free of other pollutants that are a hazard to human health. That's why you can burn it right in your house for the furnace, clothes dryer, or, in the case of the stove, even without ventilation. Second, much natural gas can be found in shale, where the 21st century technology of hydraulic fracturing can be brought to bear. It is to this game changer in the fossil fuel industry that we now turn our attention.

Fracking

It has long been known that natural gas is formed in shale and much of it remains locked within this impermeable rock in a fashion similar to shale oil. In the 20th century, the technology to release it from these shales and bring it to the surface was lacking. In this century, a technology known as fracking has been developed where highly pressurized water is brought to bear on gas-rich shales in order to fracture it, thereby creating permeable pathways for the gas to migrate to a well (Figure

13.8). The fractures are kept open using sand and slick water: water treated with chemicals (often undisclosed) to make it less viscous. This is combined with advances in *horizontal drilling* to capture gas from shale plays that may be rather thin but stretch over long distances removed from the wellhead (Figure 13.9).

Figure 13.8. A typical wellhead used for horizontal drilling and hydraulic fracturing or fracking.

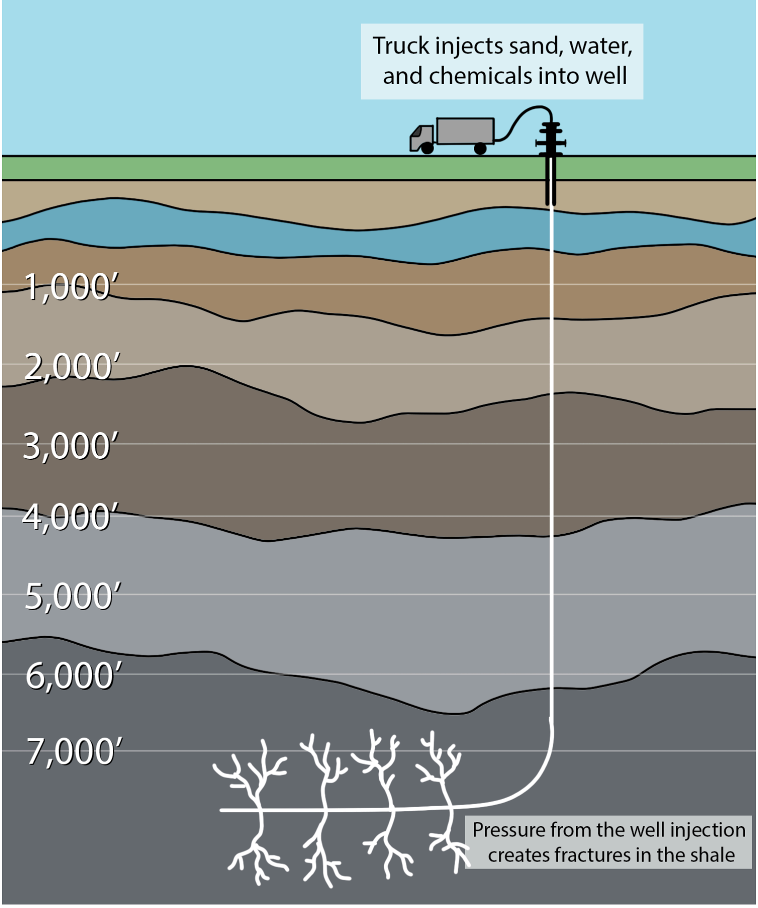

Figure 13.9. Fracking, combined with horizontal drilling technologies have made it possible to produce natural gas from impermeable shale, leading to a gas boom in the U.S.

In the 2010s, shale gas production exploded in the U.S. as fracking has proven to be a successful and profitable technology, though also one with environmental risks. These risks include minor earthquakes generated by the water pressure used to fracture shale, leakage of toxic fracking fluid used to make slick water, leakage of natural gas to groundwater or the atmosphere, and alterations to the geohydrology of aquifers, possibly affecting public drinking water supplies. A loophole in the U.S. Safe Drinking Water Act currently exempts fracking from normal environmental regulation, leaving each state to decide how to allow, regulate, or ban fracking.

The size of this newly available resource of shale gas continues to be assessed, but there is no doubt that it is large. With global conventional natural gas reserves greater than oil on an energy basis, and a later start in producing it leaving a higher proportion still in the ground, gas has a longer lifespan than oil, so no one is yet predicting “peak gas” (Figure 13.10). Shale gas resources promise to extend the lifespan of natural gas through the remaining decades of the 21st century. These developments are interesting, but questions remain. Just how huge is the shale gas resource in the U.S. and globally? How widely distributed is it around the world? How effective is fracking technology at recovering shale gas resources? Is fracking environmentally sound compared to other energy production technologies? Will it be placed under normal environmental regulations? What other energy sources will these new gas resources replace (e.g., coal or wind)?

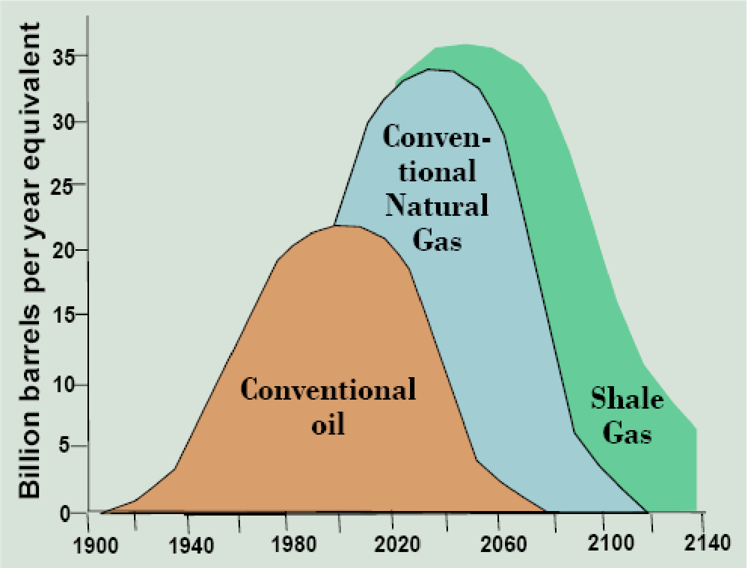

Figure 13.10. A possible Hubbert curve for natural gas with extension for shale gas.

The Coal Phaseout

Whenever oil, gas, or other energy resources are available at reasonable prices, no one wants to use coal. Why? Try putting coal in the gas tank of your car. Airplanes can only run on oil, and while the Titanic ran on coal, all modern military and civilian boats and ships run on oil because it allows higher performance designs. Very few Americans heat their home with coal anymore in favor of cleaner-burning natural gas. For the production of electricity, it does serve well but again with much higher levels of air pollution than for natural gas and far greater environmental costs in mining it compared to conventional oil and gas that can be pumped from wells. So it's an economical and available, but undesirable, source of energy that has a long history of being replaced by something better. As told by Barbara Freese in the 2003 book *Coal: A Human History*, this abundant fossil fuel has cost countless lives from mine accidents and air pollution, but it spurred first the English, then German and American, then Eastern European, then Chinese economies forward in their 18th, 19th, and 20th century industrial revolutions.

Coal has a distinctly different geography than petroleum. Figure 13.11 provides a global map of major coal deposits. The U.S. is the world leader with stupendous reserves of 251 *billion* tonnes, a fourth of the world total, followed by widely distributed countries such as Russia, Australia, China, and India (Table 13.3). Unlike petroleum, there is no Persian Gulf where global resources are concentrated. In coal production, China's coal-based economy is far in front, followed by the U.S. where coal still produces over one-third of all electricity, down from one-half at the turn of the century. Reserve-to-production ratios are high, compared to oil or even gas, in most countries, including the U.S., with reserves to last two centuries at current rates of production.

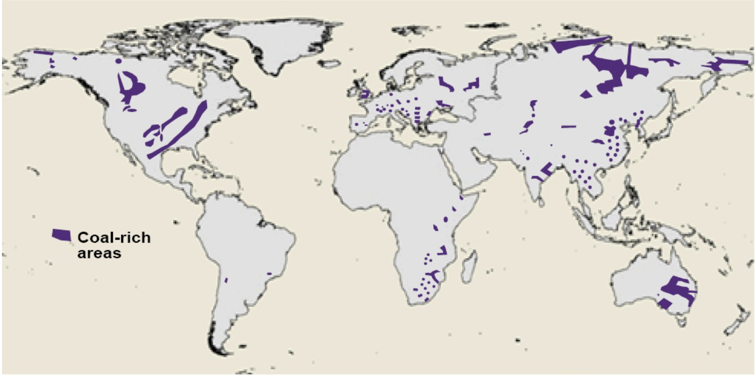

Figure 13.11. Global map of coal-rich areas.

Table 13.3. Countries leading in coal reserves and production. Sources: Reserves and Production

Country	2017 coal reserves (billion tonnes)	Rank	Country	2017 coal production (million tonnes)
United States	251	1	China	3,874
Russia	160	2	United States	907
Australia	149	3	Australia	644
China	139	4	India	538
India	98	5	Indonesia	458

How does the Hubbert curve for coal stack up against oil and gas? The answer looks something like Figure 13.12 where coal gets an earlier start and the total area under the curve is several times larger than for oil and gas, reflecting its much larger original resource base. So there's more than enough coal to go around not only for your lifetime, but for your children's and possibly grandchildren's as well, especially in the U.S. So when the oil and then the gas run out, we just switch over to coal. Right?

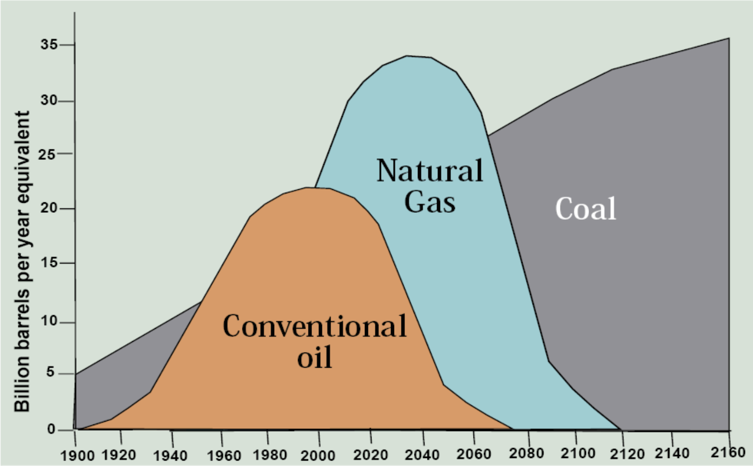

Figure 13.12. A generalized Hubbert curve for coal compared to oil and gas.

I think you can already tell what's missing from this line of argument. The limiting factor in the world's use of coal is not the size of the resource base. It is the atmosphere's capacity to absorb the carbon dioxide and other pollutants emitted by burning it. So it's not about peak oil, peak gas, or peak coal; it's about *peak carbon emissions*.

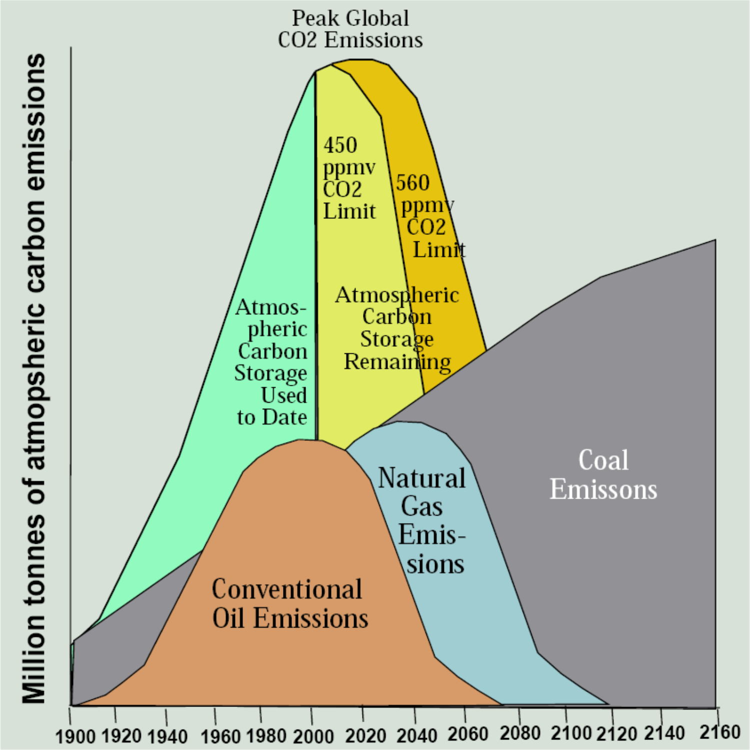

Figure 13.13. A Hubbert Curve for global greenhouse gas emissions compared to the carbon content of reserves for oil, gas, and coal. Conversion factors: Oil; 6.1 million btu per barrel; Natural gas 1,100 btu per cubic foot; coal 20,000,000 btu per ton. Per Quad: oil = 164 million barrels, gas = 1.1 trillion cubic feet, coal = 50 million tons

Let's redraft the Hubbert curve to focus on emissions from burning rather than the size of the resource base of the three fossil fuels (Figure 13.13). As you may recall from Chapter 3, the preindustrial level of carbon dioxide was 280 ppmv, corresponding to an atmospheric carbon pool of 550 million tonnes. The concentration recently passed 400 ppmv corresponding to an atmospheric carbon pool of about 800 billion tonnes, 200 billion tonnes larger. Reflecting a goal of limiting warming to 1.5°C, if we set a limit at 450 ppmv, corresponding to an atmospheric carbon pool of about 884 billion tonnes, the atmosphere can absorb only another 84 billion tonnes from fossil fuel emissions, assuming other atmospheric inputs and outputs of carbon like land use change cancel each other out (which is close to being correct). That means that emissions from burning fossil fuels have already used up nearly 90 percent of the augmented atmospheric carbon sink that can ultimately be tolerated. We can bump that up to the CO_2-doubling scenario that climate modelers frequently utilize of 560 ppmv corresponding to an atmospheric carbon pool of about 1,100 billion tonnes leaving us with 300 billion tonnes to go but with an understanding that climate change effects would be correspondingly more severe with warming in the neighborhood of 2°C.

With this in mind, Figure 13.13 uses the Hubbert approach to show a curve for atmospheric emission of carbon dioxide from all fossil fuels over the same time span as fossil fuel use. Note that the natural gas curve shrinks a bit and the coal curve grows a bit compared to the Hubbert curves for reserves to reflect the relative carbon emissions per unit of energy produced—lowest for gas, highest for coal.

The green section of the curve shows the increase in emissions since 1900 and the area under it reflects the cumulative storage of surplus carbon in the atmosphere, just as the area under the Hubbert curves for fossil fuels reflects cumulative consumption. For any peak level of carbon dioxide concentrations, such as 450 ppmv or 560 ppmv, we can identify a curve of emissions that has a moment of peak emissions in the same way that we are likely now seeing peak production of conventional oil.

When these graphs are compared, the conclusion I reach is that remaining reserves of conventional oil and gas will use up the remaining atmospheric carbon sink—if burned with carbon dioxide emissions vented to the atmosphere. Enormous reserves of coal, oil sands, and oil shale can never be used so long as this results in atmospheric carbon emissions. For this reason, most remaining fossil fuels, especially coal, are useful natural resources only if a way can be found to utilize their energy content without venting carbon to the atmosphere, such as through carbon capture and storage. If this technology never proves to be viable economically, most of the remaining reserves of fossil fuels, especially coal, are *stranded assets*. They're no more valuable than a typewriter factory.

With that thought, let's proceed from mineral resources to a broader discussion of energy sustainability in Chapter 14.

Further Reading

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Gordon, R.B., M. Bertram, and T.E. Graedel, 2006. Metal stocks and sustainability. *Proceedings of the National Academy of Science* 103(5): 1209-1214.

Berners-Lee, M. and D. Clark, 2013. *The Burning Question: We Can't Burn Half the World's Oil, Coal and Gas, so How Do We Quit?* London: Profile Books.

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16.

CHAPTER 14: ENERGY SUSTAINABILITY

The subject of energy has always fascinated me. Not so much the physicist's idea of forms of energy—electromagnetic, nuclear, mechanical, chemical, heat, and so forth—though that comes into the story, but energy as the lynchpin of what we know as modern industrial society and as a key element in natural resources sustainability.

Energy is a quintessentially interdisciplinary topic where technology, economics, and the environment come together in geographical space and historical time. We've known energy is a key sustainability issue since I was kid during the 1973 OPEC oil embargo, then called the "energy crisis," that sent Americans into a panic. Back then, Americans responded to the energy challenge for a while, driving more fuel-efficient cars and foregoing oil as a fuel for electricity production, but as oil prices settled down and supplies seemed to again become reliable, we got complacent. The crisis seemed to go away, and car companies sold us minivans, pickup trucks, and SUVs to drive from our air-conditioned homes to our air-conditioned offices while the number of electrical appliances and electronic devices multiplied. Now, with climate change, we're faced with a historic, long-term energy challenge. How will we meet it?

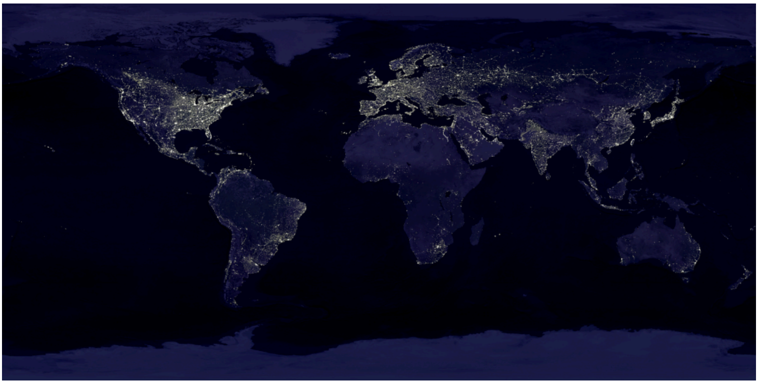


Figure 14.1. This mosaic of the world at night is essentially a map of electricity use. Note how the geographic distribution of both population and wealth are reflected in its spatial patterns.

Figure 14.1 shows the world at night. What we see is essentially a map of electricity consumption, reflecting both population density and level of industrial development. Two centuries ago, the map would have been black. Some of it is still black, not only in uninhabited areas but in poor developing countries, especially in Africa, where most people do not have daily access to electricity.

In exploring the issue of energy, we first need to establish how we use energy to make our lives better. "Energy" is really an umbrella term for three sectors that are often nearly separate: (1) electricity, (2) fuels for vehicles, and (3) heating for buildings and industrial processes. To understand our current energy predicament, a sense of history is critical, and so also is knowledge of where we now stand, because that is where the journey into the energy future begins. So we'll proceed from past to present to future in the fashion of Ebenezer Scrooge in *A Christmas Carol*.

The Ghost of Energy Past

The tiny population of primitive humans in East Africa 100,000 years ago had no more access to energy than any other animal—the sun to keep them warm and the calories in the food they ate. Fire (biomass energy, that is) made it possible for advanced hunters to inhabit cooler climates outside Africa and expand the range of edible foods, among other advantages (Table 14.1). Then came the domestication of draft animals like the ox and the horse in the Fertile Crescent, followed by the use of wind to push ships and pump water in the ancient world. Next came the use of falling water to drive mills in early modern times. Then it was back to fire again, but this time using the enormous storehouse of chemical energy from past photosynthesis in fossil fuels, and the industrial revolution was on. The human population has grown by a factor of perhaps 10^6 (a million) and each person uses perhaps 10^3 (a thousand) times as much energy as primitive humans, for a total human energy use today 10^9 (a billion) times as great as our East

African forebearers were able to muster. Energy use is a key element in human's rise to ecological dominance.

Table 14.1. Energy sources available to humans at different stages of technological development. The bottom shows the exponential growth in population, energy use per capita, and total energy use.

	Stage			
Energy source	**Primitive humans**	**Advanced hunters**	**Agriculturalists**	**Modern industrial**
Food	x	x	x	x
Fire		x	x	x
Animals			x	x
Wind			x	x
Water			x	x
Fossil fuels				x
Population (10^x)	10	4	6	8
Energy use/cap (10^x)	2	3	4	5
Total energy use (10^x)	6	9	12	15

Fossil fuel use is a centerpiece of modern industrialization. The industrial revolution may not have occurred without coal. Coal has also fueled China's mighty industrial revolution of the last few decades. World coal production, including production in China, seems to have peaked, however, in about 2013 and gas has eclipsed coal as the leading source of electricity in the U.S. Environmental concerns, especially climate change, have initiated the phasing out of coal.

Perhaps the best book ever written about energy is Daniel Yergin's *The Prize: The Epic Quest for Oil, Money and Power* which won the Pulitzer Prize in 1992, and was revised and updated in 2011. A 900-page seminal work on world oil history, we will here recount only a few of its themes. Yergin introduces the concept of hydrocarbon man—comparable to earlier epochs of cave man, bronze age man, iron age man—and so forth, to describe the state of 20th century technological progress. You and I use hydrocarbon fuels every day of our lives, for transportation, electricity, and to heat our homes.

The modern transnational corporation was invented by John D. Rockefeller of Standard Oil, the monopolist forerunner of ExxonMobil, Chevron, and other corporate giants. In fact, the game of Monopoly is based partly on Rockefeller and Standard Oil where the game is won by driving all your opponents into bankruptcy.

Calouste Gulbenkian, a Turkish oil trader, opened the door to American and British involvement in Persian Gulf oil fields through his Iraq Petroleum Company, and in linking Middle East oil to Western industrial development, he became the richest man in the world in the 1930s and 1940s.

Oil is an essential tool of modern warfare, to power airplanes, ships, tanks, trucks, jeeps, even missiles. If Nazi Germany and Japan hadn't run out of it, WWII may well have had a different outcome. The Persian Gulf War of 1991–1992 was fought to reverse Saddam Hussein's annexation of Persian Gulf neighbor Kuwait and to prevent Iraq from also attacking Saudi Arabia and gaining control of half of the world's oil reserves. Oil continues to be a major factor in 21st century global geopolitics.

The economic principles we studied in Part II of this text play an important part in the history of oil, and they will play no less a part in its future. It is a nonrenewable resource with a finite life span as we have seen. Inelastic supply and demand give it a volatile price. The real action, however, is a political power struggle over the economic benefits of oil. As oil consumers, you and I want to spend as little as possible for gasoline and other oil products to maximize our consumer surplus, and the governments of the U.S. and other oil importing nations want to minimize money sent abroad for imports.

The Organization of Petroleum Exporting Countries (OPEC) cartel sees things differently. By restricting the supply, they can force the price upward, expanding their export revenues. The economies of Iraq, Iran, Kuwait, Saudi Arabia, Venezuela, and even Russia are dependent on oil revenues and go up and down with the price of a barrel of crude. Americans' ability to conserve oil is limited by the vehicles now on the road, which are replaced on average only every 13 years, and by the geographical patterns of our towns and cities, which are so often designed to facilitate automobile rather than foot or bicycle traffic and lack adequate public transit. We call it *sprawl*.

The present is even more a product of the past in the electricity industry because it is the most capital-intensive sector of the economy. Coal and, even more so, nuclear power plants cost billions of dollars to build and it takes decades of electricity sales to pay off the mortgage. They can't be shut down economically until their useful life of 50 years or more is over. An older plant that is paid off, but still operates in good condition, is very profitable, like living in a house after the mortgage-burning party. Half of U.S. electricity comes from coal and nuclear power plants and hydroelectric dams that are more than 30 years old. The electricity supply for the rest of your life will come from the power plants that are newly built, under construction, and planned for construction in the near future. These, however, are no longer mostly coal, nuclear, and hydro; they are wind, gas, and solar. Decisions like these to construct expensive infrastructure have enormous long-term consequences, both positive and negative, for natural resource use and environmental outcomes.

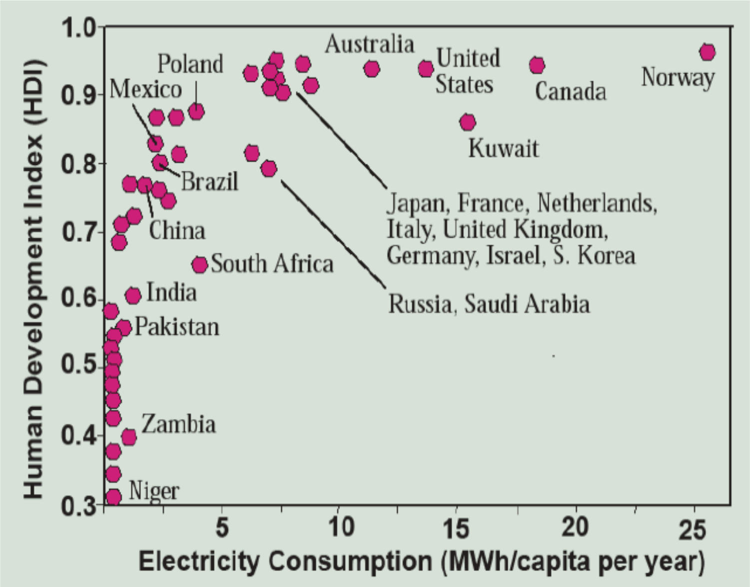


Figure 14.2. The relationship between the human development index and per capita electricity consumption for 43 countries, 2003–2004.

The historical and geographical process of building power plants and distributing electricity to the population, almost always starting with the urban and affluent and proceeding to the rural and poor, is a cornerstone of economic development. Figure 14.2 shows the relationship between the Human Development Index (similar to the Genuine Progress Indicator or Index of Sustainable Economic Welfare we examined in Chapter 7) and electricity consumption for 43 countries in 2003–2004. The majority of people in the poorest countries, an estimated 1.2 billion altogether, lack access to electricity. They have corresponding HDI scores of 0.7 or lower. At the other end of the spectrum, all countries with HDI of 0.9 or greater consume at least 5,000 kilowatt-hours per person per year. Among them there is also a huge range, however, from around 7,000 in affluent Western European and Northeast Asian countries, to twice that in the United States, even more in Canada, and 26,000 kilowatt-hours per person in hydropower-rich Norway. So while reliable access to electricity is a key component of a high-quality middle-class lifestyle, efficient and parsimonious use does not diminish quality of life and excessive use does not improve it.

It is remarkable how inefficient energy use can sometimes be—thereby showing us how much room there is for improvement. In your car, 88 percent of the energy in gasoline is consumed in the engine, driveline, accessories, and idling. Another 6 percent is lost to air and road friction, leaving six percent to move forward, but 5.7 percent moves the heavy car forward. Only 0.3 percent of the energy propels the driver.

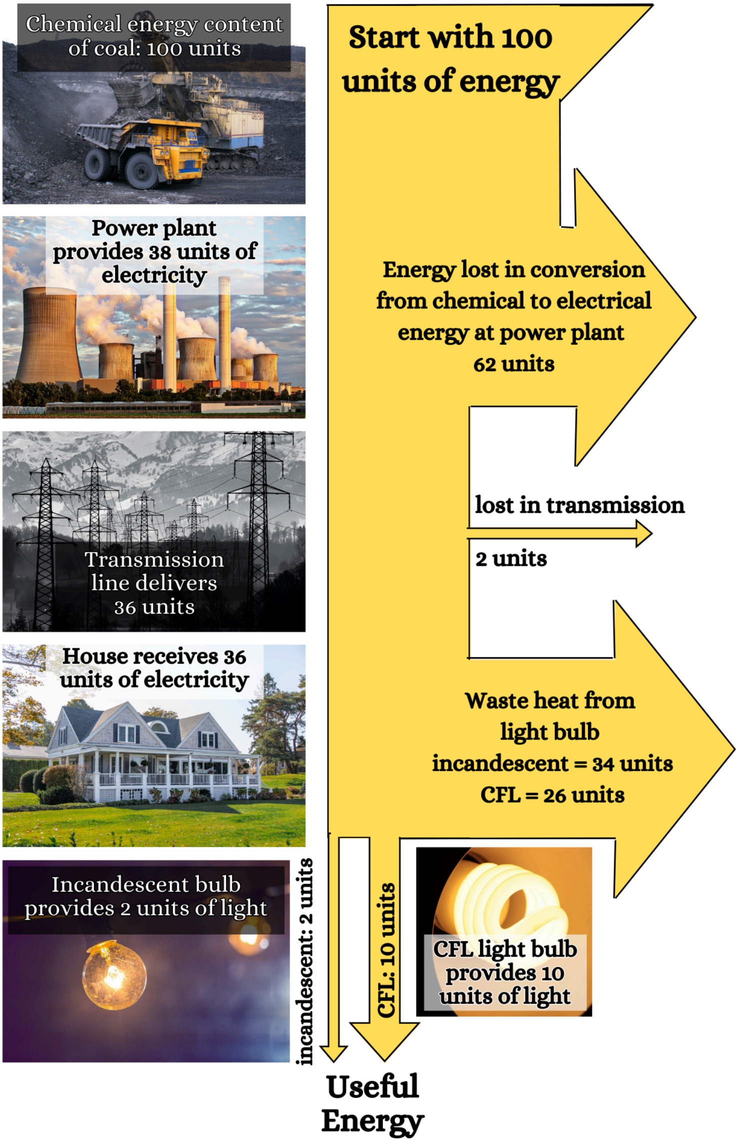


Figure 14.3. The loss of energy from coal to light bulb.

Take a typical, old-fashioned incandescent light bulb (Figure 14.3). The coal delivered to the power plant contains 100 units of chemical energy, but 62 of these are lost in converting it to heat and then to electricity. For this reason, it makes more sense to heat your home by burning a fossil fuel (usually gas) directly than to convert it to electrical resistance heating. Two more are lost along the transmission line, delivering 36 to the light bulb. But 34 of these are lost as heat rather than light, leaving only 2 of 100 units of energy to provide light, with 98 units as waste. Likely, only a small percent of that helps someone see better.

More efficient compact fluorescent lights (CFLs) greatly reduce the loss of electricity as heat. LEDs are even better. Even more energy could be saved with lights that come on only when someone enters a dark room. Nearly everywhere in our economy, we have older items of manufactured capital, from short-lived light bulbs to medium-lived vehicles to long-lived buildings and power plants that were built in an era of energy abundance and climatic bliss and use energy inefficiently. As we move to an era of energy efficiency, we must keep in mind that manufactured items that use energy are replaced one at a time in an ongoing economic process that takes decades. In fact, the average building in the U.S. lasts 70 years, about the same as the average person, so the country rebuilds itself, in terms of both manufactured and human capital, every seven decades or so. Energy efficiency is largely won through this process of replacing inefficient manufactured capital with more efficient technology. How much more energy efficient will the buildings now being designed and constructed be?

The Ghost of Energy Present

Where do Americans now get their energy and what do they use it for? Figure 14.4 gives an overview from the U.S. Energy Information Administration in quads—quadrillion btu. In 2018 our energy supply of 122 quads came from a variety of sources, but with fossil fuels (oil, gas and coal in that order) providing 79 percent of the total, including over 21 quads of imported oil, though there were also 14 quads of oil exports. Net imports were only 3 percent of overall energy supply, the lowest level in decades.

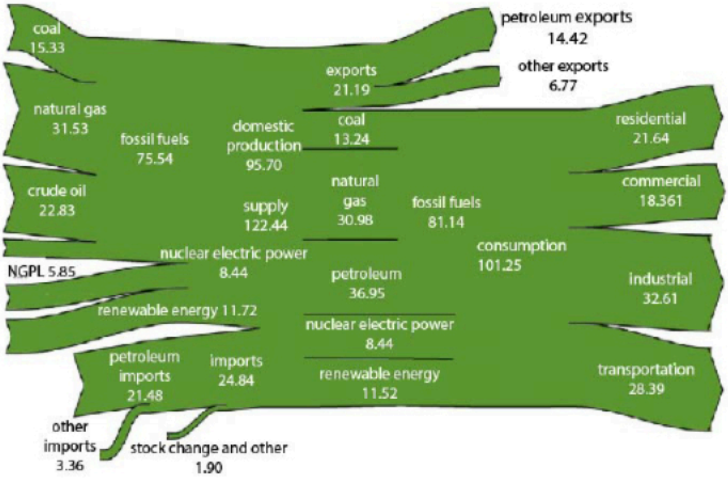


Figure 14.4. The flow of energy through the U.S. in 2018.

Americans consumed 101 quads, 81 from fossil fuels plus 8 as nuclear and 12 as renewable sources of electricity. This energy was distributed among the industrial (32.6 quads), transportation (28.4 quads), residential (21.6 quads), and commercial (18.6 quads) sectors. Transportation is very oil-dependent, but the other sectors largely depend upon natural gas and electricity—which itself comes from various sources that we will explore next.

The flow of energy in 2018 through the U.S. electricity sector is shown in Figure 14.5. Natural gas at 11 quads (29 percent) of the total is neck-and-neck with coal at 12 quads (31 percent). About 100 nuclear power plants provided over 8 quads (22 percent), and renewables, lumped together for the moment, provided 7 quads (17 percent) of electrical energy. You'll quickly notice that 61 percent of the energy consumed is lost in conversion from chemical energy (in hydrocarbon molecules) to heat to electricity, leaving 15 quads of electricity actually produced. Another 9 percent of this is lost in running the plants and distributing electricty through transmission lines, leaving 13.46 Quads of electricity actually consumed. This electricity is divided up into the residential (37 percent), commercial (35 percent), industrial (24 percent), and other sectors.

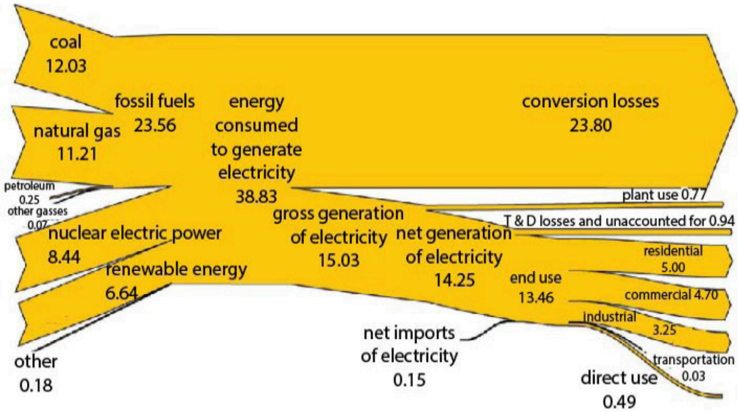


Figure 14.5. Flow of energy in electricity for the U.S. in 2018.

So there's our snapshot of where we get our power, but as Gretchen Bakke in her 2016 book *The Grid: The Fraying Wires Between Americans and Our Energy Future* tells, electricity is a lot more interesting than these percentages. The Eastern Interconnection of the U.S. grid (Figure 14.6) is the biggest machine in the history of the world. Electricity is a generic product—there is no difference between power coming from a coal, nuclear, gas, hydro, wind, or solar power plant. They are all just electrons racing their way back to the nucleus to balance the electrical charge of atoms. They all feed into the grid, which delivers electricity to each of its tens of millions of customers throughout the Eastern, Western, and Texas Interconnections.

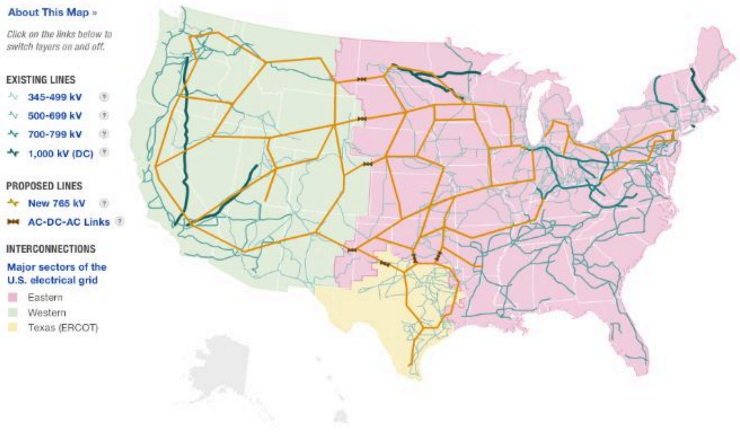


Figure 14.6. Major transmission lines in the U.S. electrical grid.

Unlike any other product, electricity demand is like a crying baby—its needs must be met immediately, on a second-by-second basis, from plants connected to the grid. Expensive to build, but very cheap to fuel and run, nuclear power plants provide base load all of the time, along with less expensive to build and relatively cheap to fuel coal plants (Figure 14.7). On a hot summer afternoon, however, when all of the air conditioners come on, there is a need for peaking power. That's when the smaller, more flexible, and less expensive to build, but more expensive to fuel, natural gas plants get turned on one at a time to continuously balance electricity supply and demand on the grid. Hydroelectricity can also be managed to supply peak load if there is sufficient water in the reservoir. It is important to note that investments in power plants and transmission lines must be sufficient to meet peak, not average, demand, just as roads and bridges are built to accommodate rush hour and parking lots to suffice during the biggest event. That makes the distribution of demand over time an important issue in natural resources sustainability, especially for electricity.

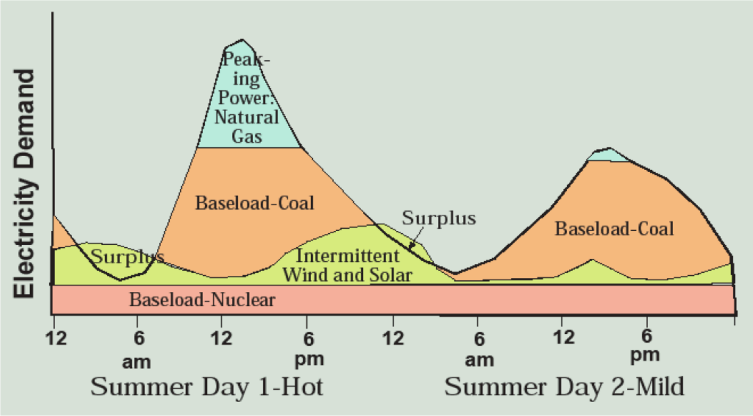


Figure 14.7. How different forms of electricity production meet variable electricity demand on the grid. A small amount of surplus energy can be stored through pumped storage.

Wind and solar power are harder to control since the energy comes from the natural transfer of energy in moving air and sunlight. They are intermittent or variable sources and therefore present problems in managing the grid to meet instantaneous demand.

For water, we solve this problem of supply and demand not matching over time with storage by building dams that form reservoirs. We also store large quantities of oil, in vehicle's gas tanks, oil depots, even the Strategic Petroleum Reserve underground in Louisiana. But for electricity, storage is a major dilemma, one upon which the future of wind and solar energy hinge. How can surplus wind and solar power be stored up to meet peak demands that occur hours or days later (Figure 14.7)?

Let's now proceed to examine options for our energy future on source-by-source basis, with the first source being energy efficiency.

Ghosts of Energy Future: The Sustainable Energy Revolution

An overdue sustainable energy revolution has begun. Even as electric cars start rolling out, the transformation in how that electricity is produced and managed is even more profound. Just look at the difference between where our electricity came from in 2018 (Figure 14.5; coal, gas, nuclear, and renewables, led by hydro) and what was planned for construction in 2019 (Figure 14.8; 46 percent wind, 34 percent gas, and 18 percent solar). The future will be substantially different from the past but there will also be continuity; the present is the beginning of the journey to the future, especially where there's over a trillion dollars worth of infrastructure already in place. With this in mind, let's begin by looking at energy efficiency and only then proceed to energy sources.

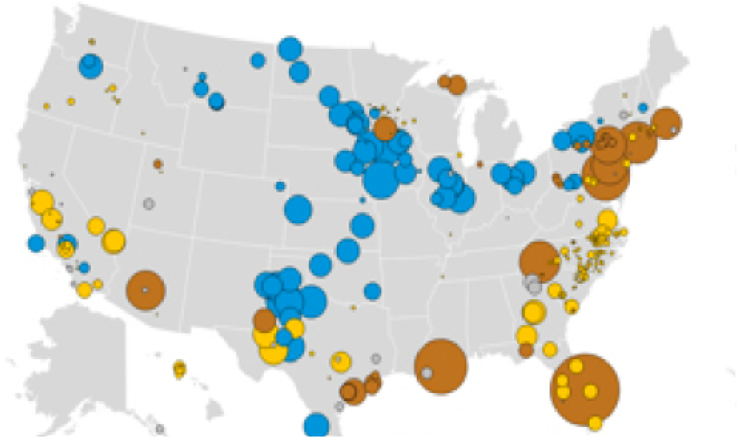


Figure 14.8. Planned additions to U.S. electrical generation capacity in 2019, including 46% wind, 34% gas, and 18% solar.

Efficiency, Efficiency, Efficiency

Both the U.S. and the world have become more energy efficient in the sense that the amount of energy used per dollar of national income produced has been steadily falling. As population and the economy grow, however, total energy use worldwide continues to grow, but it has plateaued in the U.S. since about 2000 at around 100 quads. It's a considerable accomplishment to expand the economy by more than 40 percent without substantially increasing energy consumption; this is a victory for efficiency. In previous chapters, we have discussed how world population can be stabilized and how growth can be uneconomic. Here we will examine ways in which energy use can be reduced without sacrificing basic energy services of mobility, access to electrical technologies, and comfortable indoor temperatures. For this reason, we will use the term *efficiency*—which implies technological progress or behavioral change to deliver more energy services with less energy generation—rather than conservation, which implies foregoing desired energy services. In fact, in developing countries, delivering more energy services is critical to improving human welfare.

We also have to make a distinction between theoretical or best-case energy efficiencies and real-world applications. Demonstration buildings have achieved over 90 percent reductions in energy use, or even become net energy producers, but the entire fleet of buildings in use is becoming more efficient at less than one percent per year. Gasoline-powered cars have been designed to exceed 100 miles per gallon, but only slow progress has been made in the U.S in improving the fuel efficiency of the average vehicle on the road. Customers often prefer, or are convinced they prefer through advertising, other attributes such as size, styling, and performance, and financially stressed auto-makers often advertise SUVs, minivans, and trucks because of their higher profit margins.

The difference between possible and real-world energy efficiency lies in economic incentives, dissemination of new technology, and overcoming on-the-ground problems of implementing change, including customer habits and preferences. For example, despite the marketing power of Toyota, Honda, and Ford, only 2.8 percent of new automobile sales in the U.S. in 2016 were hybrids (2 percent), plug-in hybrids (0.4 percent), or electric vehicles (0.4 percent). The 97 percent of new automobiles that are not hybrids will be using, on average, a gallon of gasoline for every 25 miles through about 2030.

CFL light bulbs save at least 75 percent of the energy used by incandescent light bulbs, last perhaps ten times as long, and are available at reasonable prices in nearly every store, yet their adoption by customers lagged until regulations began phasing out incandescent light bulbs. Rail-based public transit uses less than one-tenth as much energy per passenger mile than the average for automobiles. Yet in 1970, U.S. passenger cars and small trucks provided 2,516 times as many passenger miles and in 2006 this had increased to 4,152 times as many. The energy Titanic turns agonizingly slowly even while the icebergs approach.

There is also a problem of customers misperceiving the economics of energy efficiency investments. For example, an energy efficient refrigerator with the freezer on the bottom may cost $1,500 and consume $50 worth of electricity per year while an inefficient one will cost $1,200 and consume $150 in electricity costs per year. Over ten years, the efficient model costs a total of $2,000 (1,500 + 10×50) while the inefficient model costs $2,700 (1,200 + 10×150). But customers don't make this calculation; they simply buy the refrigerator based on the price tag and how much they like it—and they are used to having the freezer on the side or the top.

In other circumstances, there are split incentives. Landlords don't invest in insulation because renters pay the heating bill, but renters don't invest because they won't stay long enough to reap the efficiency rewards. Or homeowners don't invest in solar panels, ceiling fans, or efficient natural gas furnaces because they don't carry forward into the sales price of the house, which makes banks reluctant to offer home improvement loans for them. A majority of Americans carry consumer debt, such as credit card balances, and have difficulty mustering a capital investment of a few thousand dollars even if it would pay for itself in a few years of reduced energy bills. There's also a lack of informational feedback. When you buy an article of clothing, you take money from your wallet and hand it to the clerk, but when you turn on the air conditioner, the expense disappears into a complicated monthly utility bill you may not even bother to look over. A real-time meter that graphs electricity charges placed next to the thermostat might provide the feedback you need to make solid economic decisions about energy use.

Habits play a role as well. How about turning off unneeded lights or the air conditioner when the heat wave abates? In warm summer weather, you can close windows and curtains in late morning to keep out the hot sunlight and open them in the evening to let in the rapidly cooling air. Unplugging the computer and TV set when leaving town, or the coffee maker when it's done brewing, eliminates electricity waste in stand by mode; this is sometimes called vampire load. Cold water washes most clothes as well as hot. When you need an item at the grocery store, do you check the kitchen for other items that are also needed to save the next trip, or think of another errand that can be accomplished on the way? Differences in driving habits can amount to as much as a 25 percent difference in gasoline mileage in the same vehicle. For example, try keeping plenty of distance between you and the car in front of you so you can limit braking and acceleration. Slow down way back from a red light so it turns green by the time you get there. Of course, maybe you can leave the car in the garage, driveway, or parking lot sometimes. Developing a good habit is an investment, because once it becomes routine, its automatic.

With this introduction, let's explore some of the most important opportunities to improve energy efficiency in major sectors: buildings, industry, and transportation.

Buildings use 39 percent of all energy, mainly for heating, cooling, and electrical devices. A combination of insulation and reducing air infiltration, passive solar design, modern window designs that maximize daylighting, efficient heating and cooling systems, and setting temperatures around 65 in winter and 75 in summer has been shown to reduce energy consumption by up to 90 percent. It is far more difficult, however, to retrofit older buildings than design new ones for energy efficiency. This places the focus on building codes so that as the building stock turns over, it becomes more efficient over a period of decades. In the meantime, periodic energy audits that identify and rectify sources of waste have been demonstrated to reduce energy use by 10–30 percent or more.

Refrigerators are an energy efficiency success story in the U.S. In 1977 they consumed an average of 1,800 kilowatt-hours per year, but by 2002 this fell to only 450 kilowatt-hours. This success was driven by appliance standards first in California and then nationally. TVs and computers could follow suit by minimizing energy use while in standby mode. Appliance standards and building codes are a key tool in achieving electricity efficiency in buildings.

Industry uses 32 percent of all U.S. energy with more than half of this in the energy-intensive industries of iron and steel, aluminum, chemicals, petroleum refining, cement, and pulp and paper. Fortunately, economic incentives to reduce energy use are strong in this sector because it is an expensive factor of production, increasing the likelihood that cost-effective investments will be made. Recycling is the best way to reduce energy use in the metals industry, saving 78 percent of energy use in steel making and more in aluminum.

Transportation uses 28 percent of energy, two-thirds of this for passengers and one-third for freight. Energy use in vehicles can be made more efficient by reducing weight, aerodynamic drag, and tire-rolling resistance. Between 1990 and 2007, average miles-per-gallon in U.S. vehicles actually declined from about 25 mpg to 22 mpg, largely due to the popularity of truck-frame vehicles (SUVs, minivan and pickups) for routine personal transportation that circumvents Corporate Average Fuel Economy (CAFE) standards. In 2012 the Obama Administration issued ambitious fuel-efficiency standards to improve fleet-average levels to 36.6 mpg in 2017 and 54.5 mpg in 2026. Watch to see how this important experiment in improving natural resources sustainability plays out in the policy arena, in the engineering divisions of auto corporations, and on the road.

Much more substantial energy savings, 90 percent of more, can be made by transferring passenger miles from air and automobile to rail. Let's face it, the U.S. has the worst passenger rail system of any industrial country, lagging behind even China and India. It has been well documented that oil and automobile interests actively removed urban public transit systems in the mid-20th century to make Americans more dependent on their products. Simultaneously, this limited access to affordable transportation for the poor, young and elderly, and visually impaired and has greatly encouraged suburban sprawl.

This situation, which forces the average American to drive over 13,000 miles per year, must simply be reversed, but how to do it? Great cities have great subways, like the New York subway, the Washington, DC metro, and the Chicago L trains, and the stations become commercial hubs. Yet, given the mediocrity of urban public transit elsewhere and the nearly complete failure of intercity rail transit in the U.S., maybe technology can provide another model. The seeds of such a system may lie, within the city or town, in small, one-seater autonomous electric vehicles (a.k.a. robot cars) that can be hailed on cell phones on the Uber/Lyft business model. Very fuel-efficient, they would only need to park when recharging, with their batteries providing electricity storage to meet peaking power needs. Expect a development similar to this to become available in larger U.S. cities in the 2020s.

Between cities and for moving freight, the hyperloop shows such great promise that Germany plans on using it to transport freight in and out of the large port at Hamburg, India is planning a passenger route out of Mumbai, and construction has begun in Abu Dhabi. The idea, illustrated in a 2013 white paper authored by Elon Musk, is based on the proven technology of magnetic levitation now used in some high-speed rail. The twist is to overcome the high wind resistance that occurs at high speeds by running the trains in a vacuum tube like the one you may have used at the bank drive-up teller. This technology promises speeds in the range currently achieved by jet airplanes at less than 20 percent of the energy consumption because the trains run in a friction-free environment. Keep your eyes on this exciting development in transportation technology; I'm betting most of those reading this will one day take a hyperloop ride at over 300mph, maybe way over.

Evaluating Energy Sources

What would be the perfect energy source? The economist wants it to be *cheap*. The environmentalist wants it to be *clean and safe*. The politician and the patriot want it to be *domestic*. The resource expert wants a *large, long-term supply*. The engineer wants it to be technologically *well understood* and serve well in two specific energy use contexts—*electricity* and *fuel for vehicles*. Will all the cheap, clean, safe, domestic, well-understood energy sources with a large, long-term supply applicable for electricity and vehicle fuel please stand up! Why is no one standing? Perhaps because we have no perfect energy sources. Instead we have to make choices about which of these ideal characteristics we're willing to trade to get some of the others.

With this in mind, let's evaluate our energy sources like an instructor assigns grades in a course (which almost always involves some degree of subjectivity). Table 14.2 gives my grades on each of these criteria for our major energy sources (coal, hydroelectricity, natural gas, oil, wind, solar, nuclear, biofuels). Note that I've listed them according to the economists' criterion because price is the first test of an energy source in our economic system where the criteria of clean and safe are only partially internalized into the price. If they were fully internalized, we'd have an ecological-economic criterion that serves as a better yardstick in evaluating these energy sources for sustainability. Let's proceed with how I came up with these grades, but you'll have to assign each source a final grade based on how important you think each of the criteria are.

Table 14.2. A grade sheet, based on the author's subjective judgment, for energy sources using eight criteria.

Source	**Cheap**	**Clean**	**Safe**	**Domestic**	**Large, long-term supply**	**Well under stood**	**Usef for elect**
Coal	A	F	B	A	A	A	B
Hydroelectricity	A	C	B	A	C	A	A
Natural Gas	B	B	B	A	B	A	A
Oil	B	C	B	C	C	A	B
Wind	B	A	A	A	A	A	C
Solar	B	A	A	A	A	A	C
Nuclear	C	A	C	A	A	B	B
Biofuels	C	F	A	A	F	B	C

Coal and "Clean" Coal

Coal is by far the most abundant and least expensive fossil fuel with a resource base sufficient to supply current rates of extraction for centuries. Moreover, the United States has about one-fourth of world reserves, 251 billion tons with over half of this in eastern Montana, Wyoming, and southern Illinois, and production each year of about one billion tons. This supplies about one-third of U.S. electricity. These factors account for its As.

Coal gets a B on safety because coal mining remains a dangerous occupation and a C on usefulness in a vehicle because coal can only be used if converted to oil using the Fischer-Tropsch process, which is expensive and results in large greenhouse gas emissions. The problem is that coal gets an F on clean due to (1) atmospheric emissions of carbon dioxide, sulfur oxide, nitrous oxide, mercury, and more radioactivity than most people realize from the smokestack, and (2) scars and acid mine drainage from mining.

Recently, the coal industry has invented the phrase clean coal. Is it another oxymoron? It is possible to gasify coal into methane, which when burned produces only water and carbon dioxide. Another approach is to capture the carbon dioxide in power plant smokestacks and put it back into the Earth in a process known as carbon capture and sequestration. Most people, including myself, are skeptical when they first hear this idea of geological sequestration. I've become more optimistic, however, because carbon dioxide is harmless in the Earth where it can't absorb long-wave radiation and, likely, we can trap it where it will stay put for many thousands of years.

The world emits about 12 billion metric tonnes of carbon dioxide per year from coal combustion with over one billion tonnes coming from the U.S. The InterAcademy Council, in an excellent 2007 publication called *Lighting the Way: Toward a Sustainable Energy Future*, estimates that oil and gas fields can sequester 675–900 billion tonnes globally, enough for several decades. The carbon dioxide increases reservoir pressure, allowing a higher proportion of the oil or gas to be produced. This element makes it more economical to pipeline carbon dioxide from coal-fired power plants to oil and gas fields, but it also results in carbon dioxide emissions from the extra oil and gas produced. Moreover, oil and gas fields are not as easy to secure from carbon dioxide leaks as are other geologic environments because of the production wells that have been drilled through the overlying geologic trap.

The second option is to sequester carbon dioxide in unmineable coal seams to enhance methane production. The third option is to store carbon dioxide in deep saline groundwater, making salty club soda (this is the meaning of a carbonated beverage). The capacity is enormous: 1,000–10,000 billion tonnes. The lower estimate would serve for the remainder of the century and the higher estimate could likely store carbon dioxide from all remaining fossil fuels on Earth. Moreover, these formations are very good traps, making the likelihood of leaks very low. And even if slow leaks were to occur far in the future, the oceans could absorb carbon dioxide emitted at slower rates than are now occurring.

So I'm cautiously optimistic about the sustain-ability of storing huge amounts of carbon dioxide in the Earth. In fact, sequestration is necessary if most of the Earth's remaining coal, and perhaps natural gas, resources are to be used as an energy source without causing unacceptable climatic disruption. Without sequestration, most remaining fossil fuels are standed assets. This addresses the dilemma presented at the end of Chapter 13 where climate change, rather than the resource base size, is the limiting factor in fossil fuel use.

Putting these factors together, I conclude that coal's future will look completely different from its past and declining present. The future could be based on coal gasification with carbon capture and sequestration in a policy environment where carbon emissions are levied a charge or regulated. It will no longer be cheap. It'll take time for the technologies to be perfected and plants to be designed, authorized, and constructed. Don't expect the first truly clean coal power plant to come on line before 2030, if ever, but if successful, it could eventually replace all of the coal-fired electricity generation in the U.S. and provide a more sustainable approach to coal-based electricity for the world, especially China, which is pushing ahead of the U.S. in clean coal technology.

Hydropower

Water falling downhill by the force of gravity can spin a turbine to directly generate electricity. The amount of water and the distance it falls determine how much. In most hydropower projects, a dam is constructed on a large river to store water, thus allowing the amount of water flowing through the turbines to be controlled, and to increase the distance it falls, thus increasing power produced (An interesting exception is Niagara Falls where at night the water is directed through holes drilled in the rock behind the falls).

Nature provides only a relatively small number of locations where large amounts of water fall considerable distances. For example, North America's largest river, the Mississippi, has a low gradient; it falls less than 1,000 feet from its source in Minnesota to the Gulf of Mexico. The Columbia River of the Pacific Northwest has both large water flows and a steep gradient, so it is the leading hydropower producing river in the U.S. This makes electricity rates in Oregon and Washington the cheapest in the U.S. Canada is hydropower-rich, especially in British Columbia in the mountainous west and Quebec and Labrador in the wet and rocky east.

Give hydropower an A for being cheap, domestic, well-understood, and useful for electricity, including as peaking power, and a B for safety because we have yet to see a catastrophic dam break at a hydropower facility.

U.S. hydroelectric development began in earnest in the

1930s with the construction of Hoover Dam on the Colorado River. Development accelerated in the 1960s and 1970s as the Bureau of Reclamation and the Army Corps of Engineers raced to develop the best dam sites. Little development has occurred since 1980, however, for a variety of reasons. First and foremost, the choicest sites accounting for 76 percent of technical capacity were developed first, leaving only inferior leftover sites for further development. Second, federal funding for water resources projects was reduced in the 1980s in favor of local cost sharing. Suddenly, local support of new projects evaporated when they had to pay for them. Third, environmental opposition to dams accelerated as we discussed in Chapter 6. Regret over the drowning of the Hetch Hetchy Valley, a twin of Yosemite Valley in the Sierra Nevada of California, shot dead proposals to place hydroelectric dams in, for example, the Grand Canyon.

The most salient environmental issue in hydropower development involves migratory and anadromous fish such as salmon. Salmon migrations plummeted in the Columbia River basin following hydropower development and have not recovered. Once prodigious salmon species are now on the endangered species list. Fish ladders have proved to be fairly effective in getting adult spawning salmon upstream past the dams, but juvenile salmon struggle to make the downstream journey to the sea, getting lost in large reservoirs, tumbling through turbines, and becoming easy prey. Many millions of dollars have been spent in efforts to reconstruct salmon migration pathways throughout the northwest, with little progress to show for it. Anadromous fish migrations have also been impacted on the Atlantic Coast.

Figure 14.9. The recently completed Three Gorges project on the Yangtze River in China. It is the largest hydroelectric facility in the world.

It is now nearly impossible to get a license to build a new hydropower project in the U.S. In fact, removal of economically unimportant hydropower dams is now occurring, such as two on the Elwha River in the Olympic Peninsula of Washington and two on the Penobscot River in Maine, successfully restoring salmon spawning to the upper reaches of those watersheds. Other regions of the world are rapidly developing a majority of their hydroelectric potential as the U.S. and Europe already have. The gigantic Three Gorges project on the Yangtze River of China (Figure 14.9) epitomizes both the advantages and disadvantages of hydropower. It provides inexpensive, renewable, pollution-free electricity while also storing a water supply for other purposes and providing flood control. It does so by reengineering an entire river system, however, turning rivers into lakes, blocking fish migrations and the flow of silt to the ocean, and inundating populous, agriculturally productive, or scenic valleys. Completed in 2008, the Three Gorges project triggered landslides and forced the migration of over a million people.

Hydropower raises quite different issues from other forms of energy generation and so my grading sheet is more subjective. I'll have to fudge a C for being clean because it is pollution-free but has severe ecological and physical impacts on rivers. It has a long-term, in fact, perpetual supply, but of limited magnitude—another C. And you can't use it to run your car unless it's a plug-in hybrid or an EV—a C.

Wind

Nearly everyone likes wind power, and why shouldn't they? On my grade sheet (Table 14.2) it gets As for being a well-understood, clean, safe, domestic source of energy and Bs for being affordable (if not quite cheap), for having a large perpetual supply, and for being a source of electricity, though an intermittent one. Too bad you can't run your car on it—until you get an electric car.

Starting in the 1980s in California, wind power currently supplies over six percent of U.S. electricity and is expanding rapidly. In 2019 wind will be the leading source of new electrical power capacity constructed. Wind resources are excellent throughout the Great Plains as well as on the east shores (due to prevailing westerly winds) of the Great Lakes, the broad continental shelf of the Mid-Atlantic, and the narrow one along the Pacific Northwest coast (Figure 14.10).

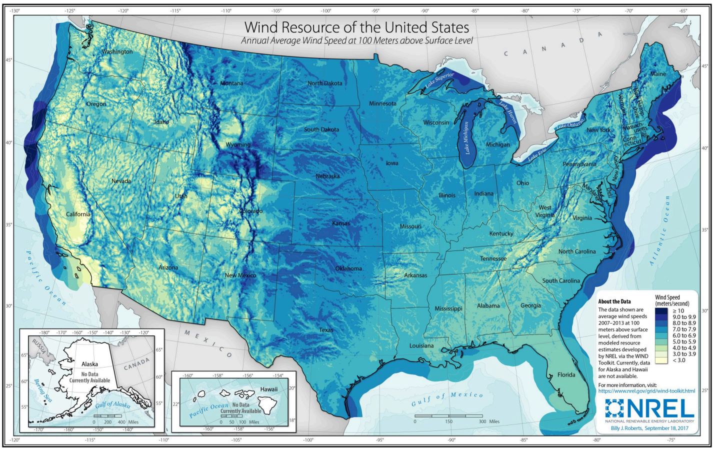


Figure 14.10. Wind energy resources map from the U.S. Department of Energy's National Renewable Energy Laboratory.

Of course, wind power has to be transported by transmission lines to the customer. Existing and planned wind farms are found in locations with better-than-average wind power potential, close to existing transmission lines and railroads or interstate highways and close, but not too close, to population centers. North Texas and the Iowa-Minnesota border have joined the North Sea shores of Europe and northwestern China as the world's wind power capitals. All but a few of the calm southeastern states have some commercial-scale wind power installations. Texas is especially bullish on wind and their state laws for siting wind farms provide no opportunity for local opposition that has at times plagued wind power development in New England and elsewhere in the eastern U.S.

Wind has ushered in a new geography of energy. Figure 14.12 shows all the major electricity power plants in the U.S. categorized by color (green for wind) for the various sources and with the size of the circles proportionate to power output. There are many geographical patterns for all sources of electrical power that can be observed from this excellent use of cartography. How many can you discern?

Figure 14.11. Photographs of an offshore and land-based wind farm. Aesthetics is a key issue in wind farm siting.

Wind is clean because it has no emissions to either air or water. While the turbines occupy a great deal of land, farmers can plant crops or graze livestock right under them, so they consume only enough land for the base and a one-lane gravel road to it—about an acre. The primary impact is visual with fields of turbines as tall as 500 feet (Figure 14.11), though this can be either positive or negative depending on the context and the beholder. For example, four wind projects in New England and one in California have been blocked or long delayed, primarily on aesthetic grounds, but hundreds of projects elsewhere, especially in the agricultural plains of the central

U.S., have gone forward with minimal opposition and often solid local support. It is also quite possible to build wind farms in shallow water where use of riprap or other materials for the base can improve fish habitat. Offshore wind power is just getting started in the U.S., but the potential is enormous, partly because the windiest areas are close to major population centers, especially along the northern Atlantic Coast. It is also possible to build even larger wind turbines in the ocean using ships.

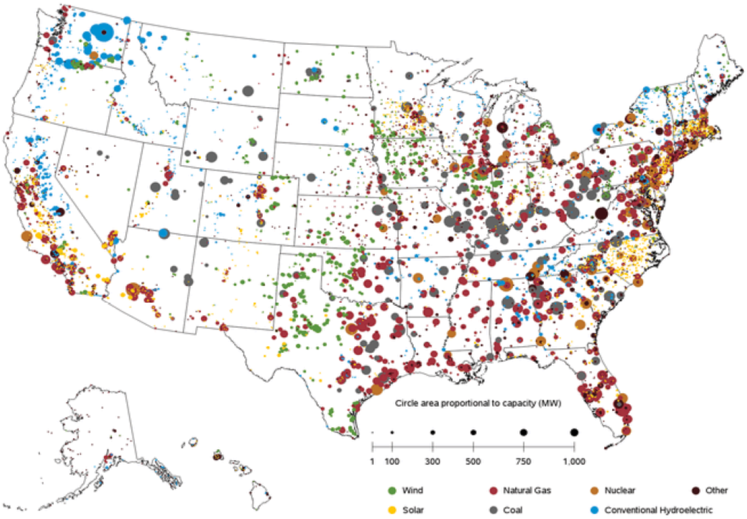


Figure 14.12. The geography power plants in the U.S. in 2018.

Research and development efforts over the last few decades have produced a design for very large 5-megawatt turbine designs that are cost-effective and far less hazardous to birds and bats than earlier, smaller, faster-spinning designs. Wind power is currently only a bit pricier than coal and has intermittently enjoyed a subsidy called a Production Tax Credit, which greatly encourages investors.

Up to this point, it sounds like wind may in fact be the perfect energy source, but there are four issues under debate that we should explore.

First, the wind blows intermittently and with no regard for electricity demand (review Figure 14.7). The greater the proportion of wind (or, to a lesser extent, solar) power, the more difficult it becomes to keep the grid in balance. This requires either storing large amounts of electricity or balancing the grid with a lot of peaking power, likely from natural gas. Currently, the best technology for storing electricity is pumped storage—using surplus power to pump water to an upper reservoir, then regaining the hydroelectricity when needed by flowing it back down through turbines. The need to find other means to store electricity is so keen that underground caves are used to compress air when power is in surplus so that it can be released through turbines to meet peak power demand. Electricity storage is the limiting factor in expanding wind (and solar) power and the new technological holy grail in the electricity field.

The second issue is that the location of the windiest on-land sites is far from electricity customers and existing transmission lines feeding the grid. This means that the cost of wind power must include expensive investments in high-voltage transmission lines (see orange lines in Figure 14.6) connecting concentrations of new wind farms, say in the Dakotas, with concentrations of customers several hundred miles away, say in Kansas City, Minneapolis, Milwaukee, and Chicago.

The third issue is how large a proportion of electricity it could ultimately supply. The data I find most convincing show that it could supply all U.S. electrical needs, but this would require enormous areas of the Great Plains and shallow oceans to have dense swarms of wind turbines, zoning out only areas around towns, bird migration routes, and shipping lanes. It would also require surplus power to be stored, perhaps as hydrogen from splitting water molecules, to balance the grid. You decide whether this is a route you'd like the U.S. to take over the coming decades. Even if using wind for a majority of electricity is problematic, building up to the 20 percent level that the grid can handle in the next decade or two seems to be an essential step in energy sustainability.

A fourth issue is local public acceptability. Some argue that opposing wind farms is a case of NIMBY (Not In My Back Yard) in a selfish form. Others argue that wind turbines destroy the aesthetics of some types of landscapes and that the local community therefore has the right to say no. Others argue that the local community should be in on the income stream from the power sales to offset property taxes or build new schools. Whatever the answer to these questions, if a large wind farm was proposed near my home, I would want a vote, and I would vote yes, especially if it provided economic advantages to the local public sector, but no if it destroyed the aesthetics of the mountain ridge I and others frequently admire.

Natural Gas

When people think of fossil fuels, they think first of oil, then coal, and maybe then they remember natural gas. That's a mistake. Over the next decade or two, natural gas will likely become the most important fossil fuel that pulls us through from our current overreliance on oil and coal to a more distant future reliance on . . . something else.

As we have seen, natural gas is the cleanest fossil fuel (I give it a B) with negligible air pollution emissions other than carbon dioxide and less of that (53 million tonnes per quad) per unit of energy produced than coal (95 million tonnes per quad) or oil (79 million tonnes per quad). As we saw in Chapter 15, its global supply is finite, but resource estimates have been rising with the shale gas boom discussed in Chapter 13 and below (I give it a B). We can anticipate increasing world gas production through at least 2030, while keeping in mind that, while it is not the long-term energy solution, it is a key 21st century transition fuel.

Natural gas gets an A for being well-understood, and an A(+) for its usefulness for electricity because of its flexibility as a source of peaking power. It gets a B for being domestic because North America has substantial reserves, especially as shale gas proves to be abundant. It's safe, but you don't want to go hunting for a gas leak in your basement with a candle or a cigarette lighter.

In 2013, 112,000 automobiles in the U.S. and 14.8 million worldwide ran on natural gas, and there have been no safety problems with storing the gas on board. The biggest challenges in using this cleaner, more abundant fossil fuel is that, even when compressed, it stores less energy per unit volume than gasoline. So the specially designed compressed natural gas tank is more expensive, heavier and larger, yet still delivers a smaller driving range and requires more time to refill. The advantage is that emissions of all air pollutants are substantially reduced and engine life is extended because the fuel is so clean. So natural gas-powered cars and trucks are a viable option, but electricity seems to be beating it out as the successor to gasoline.

Natural gas is currently at the center of an energy and environment controversy over fracking as depicted in the 2012 film *Promised Land*. Early in the 21st century, petroleum engineers working the Barnett Shale around Dallas, Texas, found a way to marry the decades-old technique of fracturing shale using hydraulic pressure to increase permeability in a petroleum field with the new techniques of horizontal drilling. This technological revolution started the shale gas boom, which soon spread to the enormous Marcellus Shale play stretching from New York to Kentucky, with the heart of the action in Pennsylvania. Domestic natural gas supplies increased, reducing prices. Plans for importing liquified natural gas (LNG) were replaced with proposals to export it as reserve estimates sky-rocketed. Is this shale gas boom good or bad for natural resources sustainability?

Environmental groups are opposing fracking due to its demonstrated environmental risks. First is contamination of groundwater with natural gas or fracking fluid, usually from poor, leaky well casings. Second is possible release of methane, a powerful greenhouse gas, into the atmosphere. Third is potential release of fracking fluid into surface water and high rates of water use. Fourth is the uncertainly over earthquakes induced by fracking operations.

On the plus side, natural gas burns cleaner than the coal it is replacing in the electricity market. U.S. greenhouse gas emissions may have peaked, partly due to gas replacing coal. Its peaking power flexibility complements efforts to increase intermittent wind and solar power.

I find myself on the side of tightly regulating, but not banning, fracking because its benefits are essential—every realistic evolution toward energy sustainability I can envision employs gas as a key transition fuel through the mid-21st century. While the environmental risks are real, they are borne of carelessness that can be remedied through thoughtful, strict regulations. This should be federal, by reversing the Halliburton loophole in the Safe Drinking Water Act but is now occurring on a state-by-state basis. Regulation of fracking is an active field of play in environmental policy.

Nuclear Fission

Nuclear power is based on atomic fission, where radioactive elements, in this case uranium, spontaneously emit high-energy neutrons from their nucleus, releasing enormous quantities of energy. These neutrons in turn can split or fission the nuclei of other uranium atoms, causing more neutrons to be emitted, which in turn cause other nuclei to fission in a chain reaction, or positive feedback process. In the 1940s, Robert Oppenheimer led the secret Manhattan Project at Los Alamos, New Mexico, which applied the fission process to produce the nuclear bombs (named *Fat Man and Little Boy*, also the title of an interesting movie about the Manhattan Project) that were dropped on Hiroshima and Nagasaki, Japan in August 1945, killing hundreds of thousands of civilians but also ending WWII. An interesting start for an energy source.

Subsequent scientific research in the 1950s and 1960s found a way to control the chain reaction by absorbing just the right amount of neutrons in graphite rods so that it produces large amounts of heat energy to boil water to spin electrical turbines, without spiraling into a radioactive explosion. The U.S. built about 100 nuclear power plants for several billion dollars each from 1963 to 1983. The plants have performed remarkably well and currently supply 19 percent of U.S. electricity.

On March 28, 1979, the Three Mile Island nuclear power plant near Harrisburg, Pennsylvania, had an accident involving the loss of coolant and small amounts of radioactive gases were released, but still far less than the release of radioactivity from a typical coal-fired power plant. It was a close call. Seven years later on April 26, 1986, the Chernobyl Nuclear Power Plant in Ukraine, then part of the declining Soviet Union, had a far worse accident when the nuclear reaction ran out of control, ironically during a safety test, causing the power plant to explode, killing 56 people. With no containment building to hold in the radioactive gases, the accident released 400 times the radioactive fallout of the Hiroshima bomb over large areas of the Soviet Union and Europe and forced the permanent evacuation of 336,000 people. Estimates vary, but 600,000 people were exposed to radiation and perhaps 4,000 subsequently died of cancer. Following these two incidents, the American public turned against nuclear power and no plants have been built since 1983. The high costs of building nuclear plants and the lack of a solution for disposing of spent nuclear fuels have also contributed to the cessation in nuclear power plant construction.

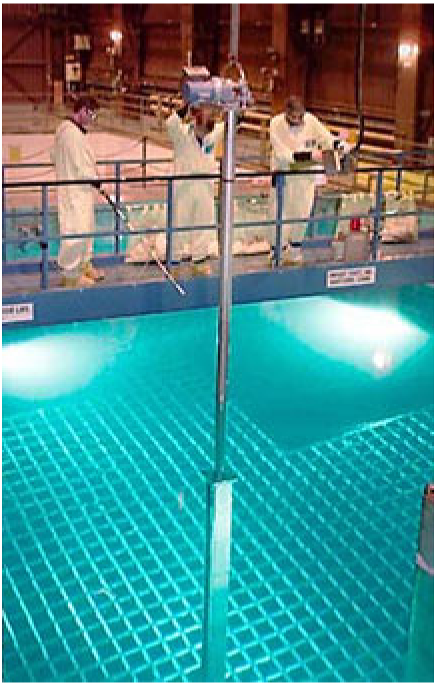


Figure 14.13. Nuclear power plant technician placing spent fuel rod in concrete and steel-lined pool at the power plant.

Spent uranium, control rods, and other materials from the core of nuclear reactors constitute high-level radioactive waste. A nuclear power plant typically produces less than 100 pounds of high-level radioactive waste per year because a uranium pellet the size of the tip of your finger has the energy content of a ton of coal. Currently, most of the 57,000 tons of accumulated waste, enough to cover a football field about five yards deep, is stored at the power plants in steel and concrete-line pools of water (Figure 14.13). Whether for or against nuclear power, most scientists agree that the waste would be more safely stored in a geologic repository after it cools for a few years to a few decades at the power plant sites.

An application to store all this waste below Yucca Mountain, Nevada was submitted by the Department of Energy to the Nuclear Regulatory Commission, but its chances of being approved are nearly zero. It is the #1 NIMBY issue in the U.S. The site is not geologically ideal and lies thousands of miles from most of the existing power plants, which are in the populous Great Lakes, Mid-Atlantic, and Upper South regions near large sources of water for cooling the power plants (Figure 14.12). The distance issue is important because analysis shows that the most dangerous phase in handling nuclear waste occurs during its transport by rail or truck from temporary to permanent disposal.

Some perspective is required here, however. In the Cold War with the Soviet Union, the U.S. produced at least 30,000 nuclear weapons. According to the Department of Energy's Office of Environmental Management, these programs generated more than 1.5 million cubic meters, several million tons, of solid radioactive waste and 88 million gallons of radioactive liquid waste, enough to fill the Superdome in New Orleans. So we have about 100 times as much high-level nuclear waste to deal with from the military as from civilian nuclear power plants. An area larger than Delaware spread among 35 states requires cleanup.

The Office of Environmental Management has safely transported and placed 100,000 containers of high-level radioactive waste 2,000 feet underground in a stable geologic formation at the Waste Isolation Pilot Plant near Carlsbad, New Mexico. Perhaps this and other sites for military nuclear waste disposal present a ready solution to the waste problem from nuclear power. In the meantime, there is room at power plants for a few decades more waste, but it is time to resolve the disposal issue.

So here are my grades on nuclear power: a C for cheap, given the large capital costs for building the plants, despite low fueling costs, a B for clean, given that nuclear plants emit almost no air and water pollutants but do generate toxic waste. A controversial C for safety, given the industry's outstanding safety record (despite the dicey situation at Three Mile Island decades ago), and the potential for a solution to the nuclear waste problem. I'll give it a B for being well-understood, which it is, but it also involves the most complex engineering and safety issues in the energy field. A C because you can only power an electric car with a nuke. It produces electricity but gets a B because nukes cannot be turned on and off flexibly to produce peaking power like gas plants can.

Finally nuclear gets an A for being a domestic source of electricity running on uranium, a mineral with a large reserves-to-production ratio that is potentially recyclable. There is a trade-off here: without reprocessing of nuclear fuel, stocks of uranium are used up faster, but reprocessing and breeder reactors conserve uranium at the expense of producing weapons-grade plutonium. I'd favor using up more uranium to minimize risks of nuclear proliferation.

An intriguing option for nuclear power lies in an element slightly lighter than uranium: thorium. A half-century ago, the U.S. selected the uranium-based over the thorium-based approach to nuclear power because it can help produce nuclear weapons materials—precisely the technology's greatest drawback today. And thorium-based technologies use up rather than generate nuclear waste. A nuclear fission plant in Norway has successfully replaced uranium with thorium. Google "thorium-based nuclear energy" and see whether you think it is a viable option for sustainable energy.

Advanced Small Modular Reactors are another option under development at Idaho National Laboratory and elsewhere. Their modular form provides flexibility in size and location so that power capacity can be added incrementally, reducing financial risk and serving remote locations. Like gas, they can be turned on and off quickly to balance the grid against variable output from wind and solar power plants. They employ passive safety features and may also generate far less nuclear waste. As a carbon-free source of electricity, this technology has the potential to be part of a sustainable energy future.

Oil

Oil has never been an icon of environmental sustainability. Let's remember, however, why oil has been a preferred energy source for a century. It's safe and easy to transport and handle because it's a liquid that doesn't explode and won't kill you if a little splashes on your skin (don't drink a glass of it though). It has a high energy content for its weight and volume so that the two cubic foot gas tank in your car or truck filled with 100 pounds of gasoline sends you 300 miles down the road. This is especially important for airplanes that will need oil as a fuel even after everything else has adapted to doing without it.

About three-fourths of oil use is in vehicles and the remainder is residual fuel oil (what's left of the crude oil after the better parts are made into gasoline, diesel, and jet fuel), which is used in industry and for home heating. So the key to reducing oil use is to design cars and trucks to run more efficiently, to run on something else, or to replace them with a different kind of vehicle.

Electricity has emerged in the last few years as the clear heir apparent to gasoline. Widely available for over a decade, hybrid cars generate electricity on board through braking and store it in a nickel metal hydride or a lithium-ion battery. This augments the power from the gasoline engine, giving the vehicle about a 40 percent boost in gasoline mileage.

Plug-in hybrid vehicles have become common on the market since about 2015. Most use a lithium-ion battery that can power the vehicle for 20–30 miles or complement the gasoline engine increasing gas mileage (and acceleration) substantially. My Toyota Prius Prime is averaging over 80 miles per gallon, including charging it from my solar panels (that's right, I'm drivin' on sunshine). Going to work or running errands around town, it runs completely on electricity obtained by plugging it into a regular outlet in the garage. Tesla made fully electric cars (EVs) popular among those who can afford one by expanding the driving range to over 200 miles and opening charging stations throughout the country. Most major car companies have now released or have made multimillion dollar investments to produce EVs by the early 2020s. Some auto companies have declared EVs the winner and the internal combustion engine the loser in this high-stakes technological race. EVs, we must remember, are only as green as the grid from which they draw their power. As we saw above, the replacement of coal with gas, wind, and solar is steadily achieving the goal of making the grid much greener than oil—and cheaper, with electricity costs averaging about $1/gallon.

Even partial electrification of automobiles has considerable advantages because it expands energy options. Clean coal, hydro, wind, solar, shale gas, and nuclear power can all propel an electric car. None of them can propel your liquid fuel automobile, which can only run on gasoline, perhaps mixed with ethanol from biofuels. It is also possible to capture and store carbon emissions from a power plant but not from a tailpipe.

Solar Energy

Solar energy strikes the Earth at a rate thousands of times greater than humans' current generation of energy, making it an enormous perpetual energy source. Passive solar is an underrated source of energy through efficiency by making better use of sunlight as an environmental service. For example, a large deciduous tree on the south side of a house reduces air conditioning costs in summer by shading the roof, but it allows sunlight through the windows in winter when sun angles are lower and the leaves have fallen. Special heat-rejecting window glazings and daylighting—designing interior spaces and windows to make best use of sunlight—can be worked into architectural designs to eliminate nearly all need for artificial light when the sun is up.

The real solar revolution, however, is in active solar, primarily photovoltaics, which directly transform solar energy into electric current. Like wind but following about a decade on its heels, the rapid reduction in cost of production has been a key to the sustainable energy revolution now underway. The cost per watt of solar photovoltaic energy produced has fallen from $76 in 1977 to $4 in 2000 to $0.25 in 2017. (A book entitled *How Solar Energy Became Cheap* came out in 2019 telling us how this happened). This fact alone should convince you that we are indeed in the midst of a sustainable energy revolution. Thinking back to Chapter 6, this is a rightward shift (i.e., increase) in the supply curve that, reviewing now, has what effects? A decrease in price, an increase in quantity, and an increase in consumer surplus.

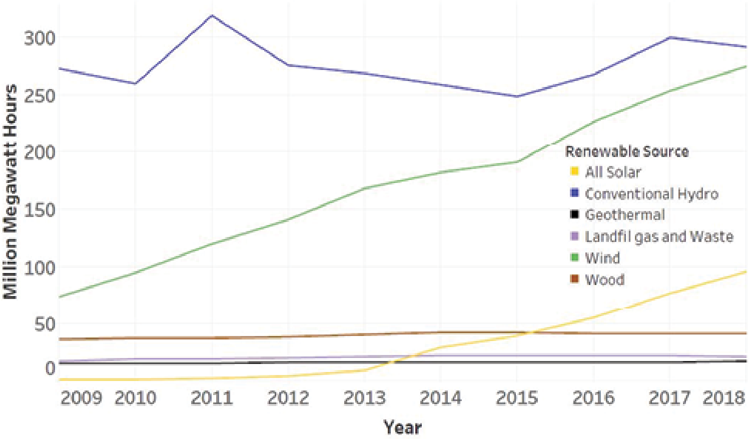
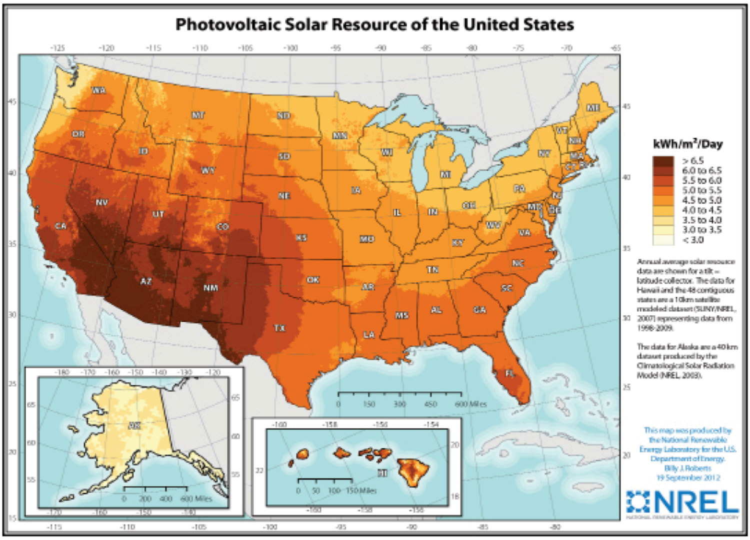


Figure 14.14. Deployment of various sources of renewable electricity in the U.S., 2009–2018.



Photovoltaic Solar Resource of the United States

Annual average solar resource data are shown for a tilt = latitude collector. The data for Hawaii and the 48 contiguous states are a 10km satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2009.

The data for Alaska are a 40 km dataset produced by the Climatological Solar Radiation Model (NREL, 2003).

This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy. Billy J. Roberts 19 September 2012

Figure 14.15. U.S. Geography of potential to produce photovoltaic electricity.

Figure 14.13 shows how different renewable energy technologies have fared over the past de-cade in U.S. electricity production. Hydro, the early leader supplying about six percent of electricity, is not growing but only varying according to how wet the weather is, which governs the amount of water flowing through turbines. Wood, waste, and geothermal collectively produce about one percent of U.S. electricity and are not expanding. In contrast, wind surpassed hydro in about 2019 with a four-fold expansion in the last decade to reach six percent of all electricity produced and doubling every seven years. Wind also accounted for nearly half of all new power capacity constructed in the U.S. in 2019.

Solar achieved two percent in 2018, which seems small but is doubling every three years and is 18 percent of new capacity constructed in 2019. Given the enormous reductions in costs cited above, solar is poised to take over one slice of the electricity pizza, and then another. Keep in mind, however, that both wind and solar potential each have their own geographies as shown in Figure 14.10 for wind potential, Figure 14.14 for solar potential, and Figure 14.12 for capacity constructed by 2018. It makes perfect sense for Iowa to be a wind state and Arizona to be a solar state.

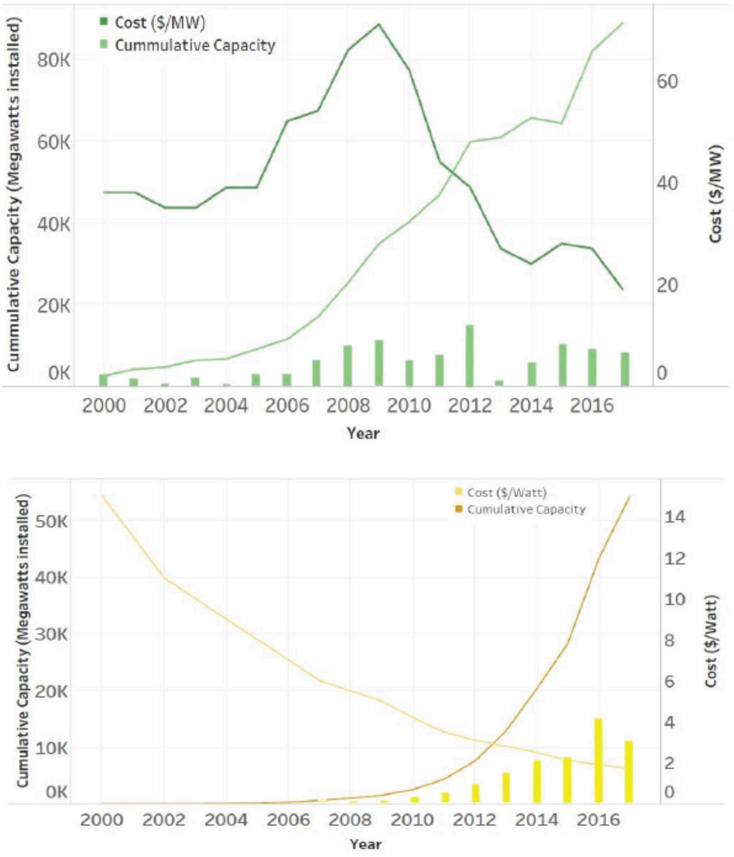


Figure 14.16. The relationship between cost, installation, and cumulative capacity for wind (top) and solar (bottom) electricity.

Figure 14.15 captures the fundamental relationship between the decline in the cost of wind power and then solar power, and how, once they cross a threshold of being cost-competitive with traditional sources like coal and gas, deployment grows exponentially. This is at the heart of the sustainable energy revolution.

Conclusions

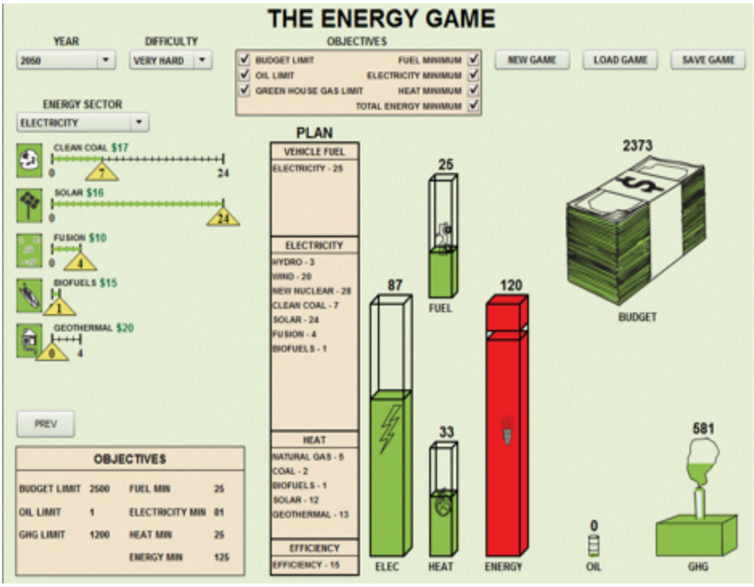
Even a half-dozen years ago, the kind of progress in sustainable energy displayed in Figure 14.15 seemed out of reach. Instead there was a list of hoped-for technological breakthroughs from geothermal to hydrogen gas to cellulosic biofuels to the real sci-fi panacea—nuclear fusion, the source that powers the sun. Yet, the breakthroughs in wind and solar achieved in the last decade, together with the anticipated electrification of vehicles, seem to make these technological drives important but more secondary than they seemed a few years ago. Of course, even after technological problems are solved in an engineering sense, there is still the task of implementation: build and maintain the wind and solar farms, install solar panels, build EVs, and trim the darn trees away from the power lines. But that just means jobs, jobs, jobs.

We fortuitously find ourselves in a much better position relative to achieving energy sustainability than we could have hoped at the turn of the century. Wind and solar are not only essentially free of greenhouse gas emissions, they are free of other air pollutants and, importantly, do not place great demands on water resources. And they can be produced in large quantities in a cost-effective manner, replacing even gasoline in electric vehicles. The primary technological hurdle that remains to be climbed is electricity storage or, more broadly defined, syncopating electricity production with electricity consumption. The better we can solve that problem, the less we need to rely on natural gas, largely obtained through fracking, to keep the grid in constant balance. Meanwhile, gas remains the workhorse of the heating sector and is thus a critical transition fuel.

Of course, there are policy hurdles to be climbed as well if this sustainable energy revolution is to come into force in the next few decades rather than the next several. It is to policy then that we turn our attention in Chapter 15.

The Energy Simulation

The primary goal of the energy simulation is to design an energy plan for the U.S. through 2050 that is able to meet four objectives: (1) supply U.S. energy needs in three sectors (electricity, vehicle fuel, and heating), (2) within a budget, (3) while reducing reliance on oil, and (4) reducing greenhouse gas emissions. Students improve their understanding of where their energy currently comes from, and how, with new possibilities brought about by technology, these sustainability problems can be addressed in the future. The simulation (available at Weidong's Projects Homepage) is played by adding energy options in units of quads (quadrillion British thermal units) to meet future energy needs, within a budget, in 2020, 2030, 2040, and 2050. Each energy option within a sector has a limit on its energy production potential and, therefore, on the number of quads. Additional limits can be placed on oil consumption or greenhouse gas emissions, reflecting climate change mitigation. The simulation is thus a challenge of meeting multiple objectives simultaneously at different levels of difficulty. From very easy through very hard, the budget decreases while the energy requirement increases; thus, the range of energy choices that fulfills the multiple objectives diminishes as difficulty level increases.



YEAR: 2050

DIFFICULTY: VERY HARD

OBJECTIVES

☑ BUDGET LIMIT
☑ OIL LIMIT
☑ GREEN HOUSE GAS LIMIT
FUEL MINIMUM ☑
ELECTRICITY MINIMUM ☑
HEAT MINIMUM ☑
TOTAL ENERGY MINIMUM ☑

ENERGY SECTOR: ELECTRICITY

PLAN

VEHICLE FUEL
ELECTRICITY - 25

ELECTRICITY
HYDRO - 3
WIND - 20
NEW NUCLEAR - 28
CLEAN COAL - 7
SOLAR - 24
FUSION - 4
BIOFUELS - 1

HEAT
NATURAL GAS - 5
COAL - 2
BIOFUELS - 1
SOLAR - 12
GEOTHERMAL - 13

EFFICIENCY
EFFICIENCY - 15

OBJECTIVES

BUDGET LIMIT	2500	FUEL MIN	25
OIL LIMIT	1	ELECTRICITY MIN	81
GHG LIMIT	1200	HEAT MIN	25
		ENERGY MIN	125

Figure 14.17. The energy game user interface. In this example, the year is 2050 at a very hard level of difficulty with all objectives enabled. Some of the measures in the electricity sector are shown. The player has satisfied all objectives except total energy requirement ("Energy min 125" below), where they need 5 more quads without exceeding the 127 remaining in the budget.

Students play the simulation by adding units to energy options within each sector using a slider bar in one quad units up to the capacity constraint. As they do so, all of the graphs on the right-hand side of the user interface (Figure 14.16) change, reflecting impacts on energy produced, money spent, oil consumed, and greenhouse gases (GHGs) emitted. Graphs for satisfied objectives are green whereas those for unsatisfied objectives are red. Students may find that satisfying (turning green) one objective (e.g., total energy or electricity supply) turns another red (e.g., budget or GHG). They then make adjustments until all objectives are satisfied.

Through the simulation, students learn not only the different sources of energy, but their relevance to specific sectors of the energy system. For example, vehicle electrification increases demand for electricity, but the provision of electricity has more options. Students learn that all energy needs must be met but that resource and environmental constraints cannot be violated. And it all must be done in an economical way. Nonetheless, this can be achieved.

Further Reading

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