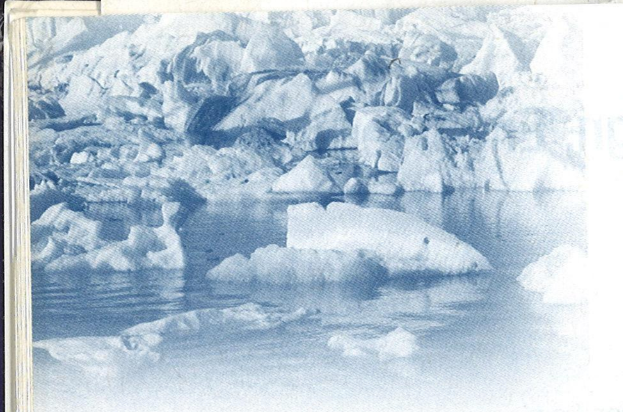


1.1 Background: Evolution from Environmental Protection to Sustainability

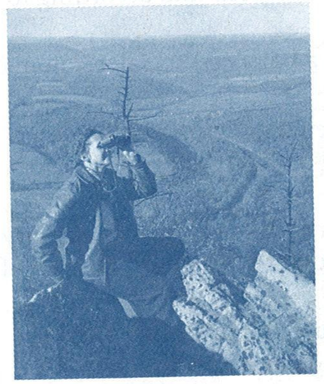
In 1962, Rachel Carson (Application 1.1) published *Silent Spring*, establishing the case that there may be reason to be concerned about the impacts of pesticides and environmental pollution on natural systems and human health. Though as early as 1948, there was an industrial air pollution smog release in the milltown of Donora (Pennsylvania) that killed 20 and injured thousands, it was later, in the late 1960s and early 1970s, that numerous clear and startling visual realities of human impacts on the environment took place. This included smog episodes in Los Angeles that obscured visibility, the Cuyahoga River (Ohio) catching on fire in 1969, and the toxic waste and subsequent health effects in neighborhoods such as Love Canal in Niagara Falls, New York.

Through a shared societal value and a growing environmental social movement, the **Environmental Protection Agency (EPA)** was created in 1972. This consolidated in one agency a variety of federal research, monitoring, standard-setting, and enforcement activities with the mission of "protecting human health and the environment." During this same time, Congress passed many of the fundamental and critical environmental regulations, such as the National Environmental Protection Act (NEPA), the Clean Air Act, the Water Pollution Control Act, Wilderness Protection Act, and the Endangered Species Act.

The Environmental Protection Agency (EPA) is an agency of the U.S. federal government that was created for the purpose of protecting human health and the environment by writing and enforcing regulations based on laws passed by Congress (Application 1.2). Its administrator, who is appointed by the president and approved by Congress, leads the agency.

The EPA has its headquarters in Washington, D.C., regional offices for each of the agency's 10 regions (Figure 1.1) and 27 research laboratories. EPA is organized into a number of central program offices as well as regional offices and laboratories, each with its own

Application / 1.1 Rachel Carson and the Modern Environmental Movement



Rachel Carson at Hawk Mountain, Pennsylvania photograph taken ca. 1945 by Shirley Briggs. (Provided courtesy of the Linda Lear Center for Special Collections and Archives, Connecticut College).

Rachel Carson is considered one of the leaders of the modern environmental movement. She was born 15 miles northeast of Pittsburgh in the year 1907. Educated at the undergraduate and graduate levels in science and zoology, she first worked for the government agency that eventually became the U.S. Fish and Wildlife Service. As a scientist, she excelled at communicating complex scientific concepts to the public through clear and accurate writing. She wrote several books, including *The Sea Around Us* (first published in 1951) and *Silent Spring* (first published in 1962).

Silent Spring was a commercial success soon after its publication. It visually captured the fact that songbirds were facing reproductive failure and early death because of manufacturing and prolific use of chemicals such as DDT that had bioaccumulated in their small bodies. Some historians believe that *Silent Spring* was the initial catalyst that led to the creation of the modern environmental movement in the United States along with the U.S. Environmental Protection Agency (EPA).

Application / 1.2 The Basics of EPA Related Laws and Regulations

The EPA has many tools to protect human health and the environment, including partnerships, educational programs, and grants. However, the most significant tool is writing **regulations**, which are mandatory requirements that can be relevant to individuals, businesses, state or local governments, nonprofit organizations, or others.

The **regulatory process** begins with Congress passing a law and then authorizing the EPA to help put that law into effect by creating and enforcing regulations. Of course, there are many checks and balances along the path from law to regulation, including public disclosure of intent to write or modify a regulation, and a public comment period where those potentially affected by the regulation have an opportunity to offer input to the process.

Draft and final federal regulations are published in the **Code of Federal Regulations** (CFR). The number 40 that is associated with environmental regulations (i.e., 40CFR) indicates the section of the CFR related to the environment.

SOURCE: http://www.epa.gov/lawsregs/basics.html

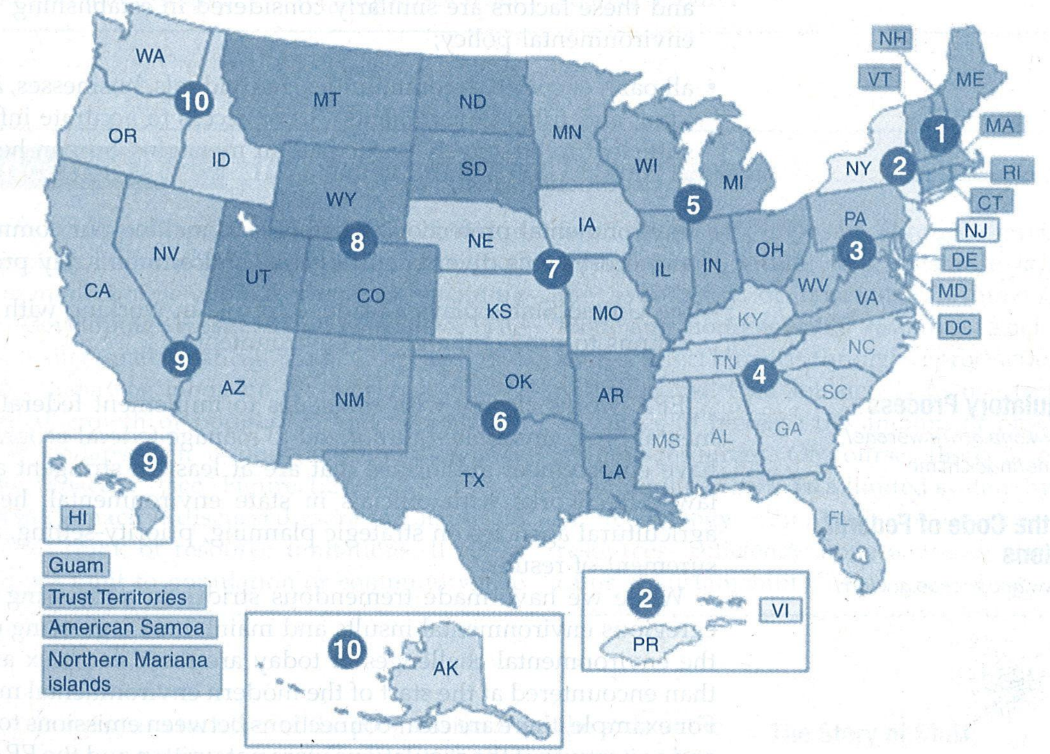


Figure / 1.1 **The EPA's Ten Regions** Each region has its own regional administrator and other critical functions for carrying out the mission of protecting human health and the environment. EPA headquarters are located in Washington, D.C.

(Adapted from EPA).

regulatory, research, and/or enforcement mandate. The agency conducts environmental assessment, research, and education. It has the responsibility of maintaining and enforcing national standards under a variety of environmental laws, in consultation with state, tribal, and local governments. It delegates some permitting, monitoring, and enforcement responsibility to U.S. states and Native American tribes. EPA enforcement powers include fines, sanctions, and other measures. The agency also works with industries and all levels of government in a wide variety of voluntary pollution prevention programs and energy conservation efforts.

The mission of EPA is to protect human health and the environment. EPA's purpose is to ensure that:

- all Americans are protected from significant risks to human health and the environment where they live, learn, and work;
- national efforts to reduce environmental risk are based on the best available scientific information;
- federal laws protecting human health and the environment are enforced fairly and effectively;
- environmental protection is an integral consideration in U.S. policies concerning natural resources, human health, economic growth, energy, transportation, agriculture, industry, and international trade, and these factors are similarly considered in establishing environmental policy;
- all parts of society—communities, individuals, businesses, and state, local, and tribal governments—have access to accurate information sufficient to effectively participate in managing human health and environmental risks;
- environmental protection contributes to making our communities and ecosystems diverse, sustainable, and economically productive;
- the United States plays a leadership role in working with other nations to protect the global environment.

The Regulatory Process
http://www.epa.gov/lawsregs/regulations/index.html

Access the Code of Federal Regulations
http://www.gpoaccess.gov/cfr/

EPA works closely with the states to implement federal environmental programs. States authorized to manage federal programs must have enforcement authorities that are at least as stringent as federal law. EPA works with officials in state environmental, health, and agricultural agencies on strategic planning, priority-setting, and measurement of results.

While we have made tremendous strides in addressing the most egregious environmental insults and maintained a growing economy, the environmental challenges of today are more complex and subtle than encountered at the start of the modern environmental movement. For example, there are clear connections between emissions to air, land, and water even if the regulations were not written and the EPA was not organized with these considerations.

Furthermore, air and water emissions come from many distributed sources (referred to as **nonpoint source emissions**), so it is much more difficult to identify a specific source that can be regulated and monitored. We also have a much higher level of understanding of the linkages among society, the economy, and the environment. These are recognized as the three **pillars of sustainability** and require that we consider them simultaneously, looking for synergies to achieve mutual benefits. That is, we must create and maintain a prosperous society with high quality of life without the negative impacts that have historically harmed our environment and communities in the name of development. And all of this must be performed while maintaining a sufficient stock of natural resources for current and future generations to maintain an increasing population with an improving quality of life.

Global Environmental Outlook
http://www.unep.org/GEO

Class Discussion
Is it better to live within a determined limit by accepting some restrictions on consumption-fueled growth?

Application/1.3 Tragedy of the Commons

The **Tragedy of the Commons** describes the relationship where individuals or organizations consume shared resources (e.g., air, freshwater; fish from the ocean) and then return their wastes back into the shared resource (e.g., air, land). In this way, the individual or organization receives all of the benefit of the shared resource but distributes the cost across anyone who also uses that resource. The tragedy arises when each individual or organization fails to recognize that every individual and organization is acting in the same way. It is this logic that has led to the current situation in ocean fisheries, the Amazon rain forest, and global climate change. In each case, the consumptive behavior of a few has led to a significant impact on the many and the destruction of the integrity of the shared resource.

Application/1.4 *The Limits to Growth* and Carrying Capacity

The Limits to Growth, published in 1972, warned of the limitations of the world's resources and pointed out there might not be enough resources remaining for the developing world to industrialize. The authors, using mathematical models, argued that "the basic behavior mode of the world system is exponential growth of population and capital, followed by collapse" in a phenomenon known as "carrying capacity." (see Figure 1.2)

Carrying capacity (discussed more in Chapter 5) is a way to think of resource limitations. It refers to the upper limit to population or community size (e.g., biomass) imposed through environmental resistance. In nature, this resistance is related to the availability of renewable resources, such as food, and nonrenewable resources, such as space, as they affect biomass through reproduction, growth, and survival. One solution is to use technological advances to increase the amount of prosperity per unit of resources. Of course, there is a risk that maintaining growth in a limited system by advances in technology can lead to overuse of finite resources—efficiency alone is not an effective indicator of sustainability.

Figure 1.3 provides a timeline of the progression from the start of the domestic environmental movement in the 1960s through the progression to recent major international sustainability activities. Based on the events on the timeline, there is a clear progression from initial regulatory responses to egregious environmental assaults to a more proactive, systematic international dialogue about a broad sustainability agenda

The Story of Stuff
http://www.storyofstuff.com

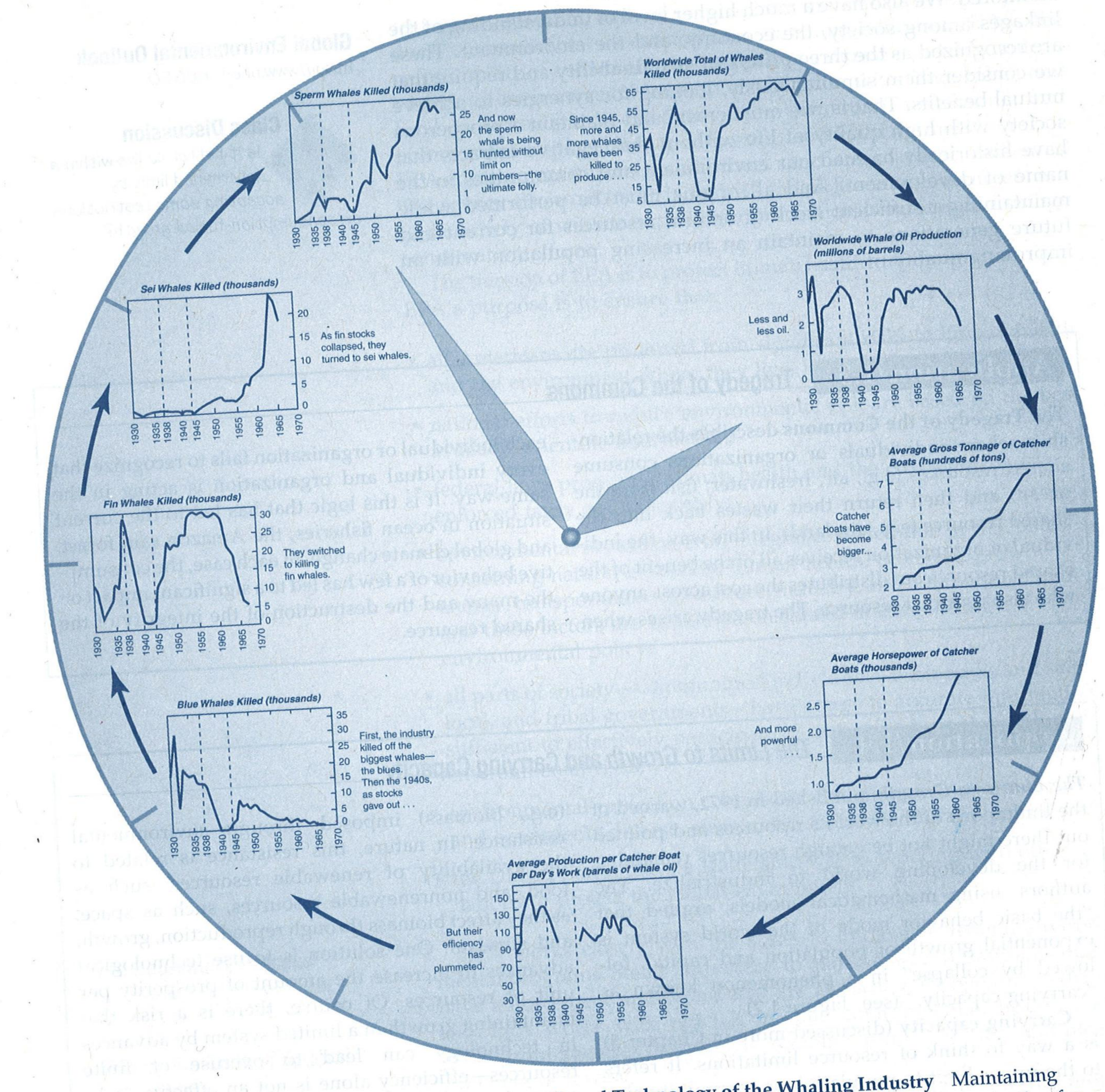
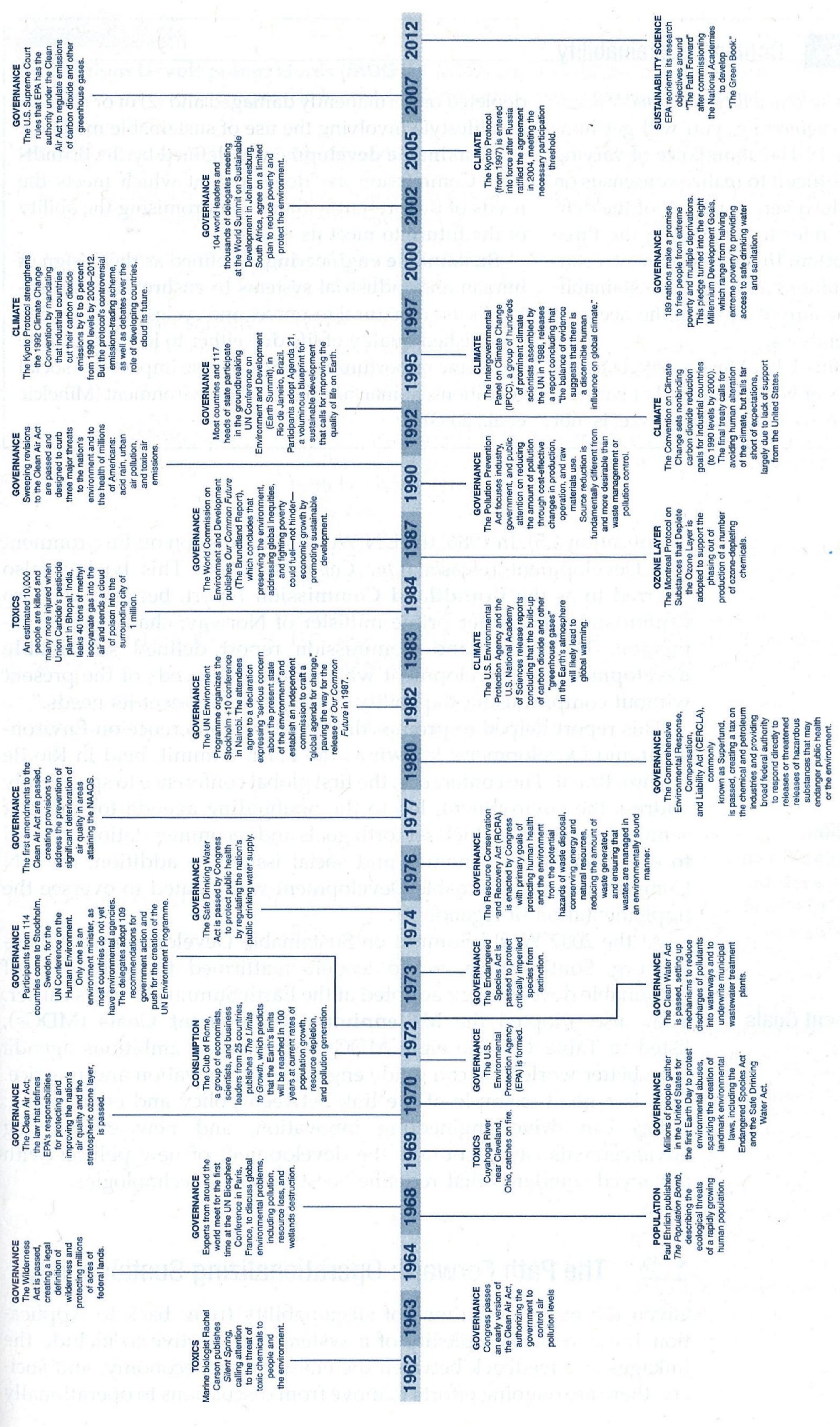


Figure / 1.2 Limits to Growth and Technology of the Whaling Industry Maintaining growth in a limited system by advances in technology will eventually result in extinction for both whales and the whaling industry. As wild pods of whales are destroyed, finding the survivors has become more difficult and has required more effort. As larger whales are killed off, smaller species are exploited to keep the industry alive. Without species limits, large whales are always taken wherever and whenever encountered. Thus, small whales subsidize the extermination of large ones.

(Based on Payne, R. 1968. "Among Wild Whales." *New York Zoological Society Newsletter* (November)).



TOXICS
Marine biologist Rachel Carson publishes *Silent Spring*, calling attention to the threat of toxic chemicals to people and the environment.

GOVERNANCE
Congress passes an early version of the Clean Air Act, authorizing the government to control air pollution levels

GOVERNANCE
The Wilderness Act is passed, creating a legal definition of wilderness and protecting millions of acres of federal lands.

GOVERNANCE
Experts from around the world meet for the first time at the UN Biosphere Conference in Paris, France, to discuss global environmental problems, including pollution, resource loss, and wetlands destruction.

POPULATION
Paul Ehrlich publishes *The Population Bomb*, describing the ecological threats of a rapidly growing human population.

TOXICS
Cuyahoga River near Cleveland, Ohio, catches on fire.

GOVERNANCE
The Clean Air Act, the law that defines EPA's responsibilities for protecting and improving the nation's air quality and the stratospheric ozone layer, is passed.

GOVERNANCE
The U.S. Environmental Protection Agency (EPA) is formed.

GOVERNANCE
Millions of people gather in the United States for the first Earth Day to protest environmental abuses, sparking the creation of landmark environmental laws, including the Endangered Species Act and the Safe Drinking Water Act.

GOVERNANCE
Participants from 114 countries come to Stockholm, Sweden, for the UN Conference on the Human Environment. Only one is an environment minister, as most countries do not yet have environmental agencies. The delegates adopt 109 recommendations for government action and push for the creation of the UN Environment Programme.

CONSUMPTION
The Club of Rome, a group of economists, scientists, and business leaders from 25 countries, publishes *The Limits to Growth*, which predicts that the Earth's limits will be reached in 100 years at current rates of population growth, resource depletion, and pollution generation.

GOVERNANCE
The Clean Water Act is passed, setting up mechanisms to reduce discharges of pollutants into waterways and to underwrite municipal wastewater treatment plants.

GOVERNANCE
The Endangered Species Act is passed to protect critically imperiled species from extinction.

GOVERNANCE
The Safe Drinking Water Act is passed by Congress to protect public health by regulating the nation's public drinking water supply.

GOVERNANCE
The Resource Conservation and Recovery Act (RCRA) is enacted by Congress with primary goals of protecting human health and the environment from the potential hazards of waste disposal, conserving energy and natural resources, reducing the amount of waste generated, and ensuring that wastes are managed in an environmentally sound manner.

GOVERNANCE
The first amendments to the Clean Air Act are passed, creating provisions to address the prevention of significant deterioration of air quality in areas attaining the NAAQS.

GOVERNANCE
The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), commonly known as Superfund, is passed, creating a tax on the chemical and petroleum industries and providing broad federal authority to respond directly to releases or threatened releases of hazardous substances that may endanger public health or the environment.

GOVERNANCE
The UN Environment Programme organizes the Stockholm +10 conference in Nairobi. The attendees agree to a declaration expressing "serious concern about the present state of the environment" and establish an independent commission to craft a "global agenda for change," paving the way for the release of *Our Common Future* in 1987.

CLIMATE
The U.S. Environmental Protection Agency and the U.S. National Academy of Sciences release reports concluding that the build-up of carbon dioxide and other "greenhouse gases" in the Earth's atmosphere will likely lead to global warming.

TOXICS
An estimated 10,000 people are killed and many more injured when Union Carbide's pesticide plant in Bhopal, India, leaks 40 tons of methyl isocyanate gas into the air and sends a cloud of poison into the surrounding city of 1 million.

GOVERNANCE
The World Commission on Environment and Development publishes *Our Common Future* (The Brundtland Report), which concludes that preserving the environment, addressing global inequities, and fighting poverty could fuel—not hinder—economic growth by promoting sustainable development.

OZONE LAYER
The Montreal Protocol on Substances that Deplete the Ozone Layer is adopted to support the phasing out of production of a number of ozone-depleting chemicals.

GOVERNANCE
Sweeping revisions to the Clean Air Act are passed and designed to curb three major threats to the nation's environment and to the health of millions of Americans: acid rain, urban air pollution, and toxic air emissions.

GOVERNANCE
The Pollution Prevention Act focuses industry, government, and public attention on reducing the amount of pollution through cost-effective changes in production, operation, and raw materials use. Source reduction is fundamentally different from and more desirable than waste management or pollution control.

GOVERNANCE
Most countries and 117 heads of state participate in the groundbreaking UN Conference on Environment and Development (Earth Summit), in Rio de Janeiro, Brazil. Participants adopt Agenda 21, a voluminous blueprint for sustainable development that calls for improving the quality of life on Earth.

CLIMATE
The Convention on Climate Change sets nonbinding carbon dioxide reduction goals for industrial countries (to 1990 levels by 2000). The final treaty calls for avoiding human alteration of the climate, but falls far short of expectations, largely due to lack of support from the United States.

CLIMATE
The Intergovernmental Panel on Climate Change (IPCC), a group of hundreds of prominent climate scientists assembled by the UN in 1988, releases a report concluding that "the balance of evidence suggests that there is a discernible human influence on global climate."

CLIMATE
The Kyoto Protocol strengthens the 1992 Climate Change Convention by mandating that industrial countries cut their carbon dioxide emissions by 6 to 8 percent from 1990 levels by 2008–2012. But the protocol's controversial emissions-trading scheme, as well as debates over the role of developing countries, cloud its future.

GOVERNANCE
189 nations make a promise to free people from extreme poverty and multiple deprivations. This pledge turned into the eight Millennium Development Goals, which range from halving extreme poverty to providing access to safe drinking water and sanitation.

GOVERNANCE
104 world leaders and thousands of delegates meeting at the World Summit on Sustainable Development in Johannesburg, South Africa, agree on a limited plan to reduce poverty and protect the environment.

CLIMATE
The Kyoto Protocol (from 1997) is entered into force after Russia ratified the agreement in 2004, meeting the necessary participation threshold.

GOVERNANCE
The U.S. Supreme Court rules that EPA has the authority under the Clean Air Act to regulate emissions of carbon dioxide and other greenhouse gases.

SUSTAINABILITY SCIENCE
EPA reorients its research objectives around "The Path Forward" after commissioning the National Academies to develop "The Green Book."

Figure / 1.3 Timeline of critical events leading from a mission of environmental protection to a goal of sustainability.

(Events adopted from www.worldwatch.org).

Application / 1.5 Defining Sustainability

If you Google the words *sustainability*, *sustainable development*, and *sustainable engineering*, you will get hundreds of definitions. Try it! The abundance of varying definitions has made it difficult to realize consensus on what sustainability is. However, nearly all of the definitions of sustainability refer to integrating the three elements of the **triple bottom line** (environment, economy, society). Most definitions also extend sustainability criteria to include the aim of meeting the needs of current and future generations.

Sustainability is defined by Merriam-Webster as follows: (1) of, relating to, or being a method of harvesting or using a resource so that the resource is not depleted or permanently damaged and (2) of or relating to a lifestyle involving the use of sustainable methods.

Sustainable development is defined by the Brundtland Commission as "development which meets the needs of the present without compromising the ability of the future to meet its needs."

Sustainable engineering is defined as the design of human and industrial systems to ensure that humankind's use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health, and the environment (Mihelcic et al., 2003).

(Application 1.5). In 1986, the UN World Commission on Environment and Development released *Our Common Future*. This book is also referred to as the **Brundtland Commission** report, because Ms. Gro Brundtland, the former prime minister of Norway, chaired the commission. The Brundtland Commission report defined **sustainable development** as "development which meets the needs of the present without compromising the ability of the future to meet its needs."

This report helped to prompt the 1992 UN Conference on Environment and Development, known as the Earth Summit, held in Rio de Janeiro, Brazil. The conference, the first global conference to specifically address the environment, led to the nonbinding agenda for the 21st century, *Agenda 21*, which set forth goals and recommendations related to environmental, economic, and social issues. In addition, the UN Commission on Sustainable Development was created to oversee the implementation of Agenda 21.

At the 2002 World Summit on Sustainable Development in Johannesburg, South Africa, world leaders reaffirmed the principles of sustainable development adopted at the Earth Summit 10 years earlier. They also adopted the **Millennium Development Goals** (MDGs), listed in Table 1.1. The eight MDGs represent an ambitious agenda for a better world that can guide engineering innovation and practice. This is a good example of the link between policy and engineering: policy can drive engineering innovation, and new engineering advancements can encourage the development of new policies with advanced standards that redefine "best available technologies."

Class Discussion
In which of the MDGs do engineers have a role to play? Are these traditional or emerging roles for engineers to play in society and practice?

Millennium Development Goals
You can go to www.un.org/millenniumgoals/ Go to this URL to learn more about progress toward meeting the MDGs.

1.2 The Path Forward: Operationalizing Sustainability

Given the many definitions of sustainability (refer back to Application 1.5) and the complexity of a systems perspective to include the linkages and feedback between the environment, economy, and society, there are ongoing efforts to move from discussions to operationally

Table / 1.1

Millennium Development Goals (MDGs) MDGs are an ambitious agenda embraced by the world community for reducing poverty and improving lives of the global community. Learn more at www.un.org/millenniumgoals/.

Millennium Development Goal	Background	Example Target(s) (of 21 total targets)
1. Eradicate extreme poverty and hunger.	More than a billion people still live on less than $1 a day.	(1a) Halve the proportion of people living on less than $1 a day and those who suffer from hunger.
2. Achieve universal primary education.	As many as 113 million children do not attend school.	(2a) Ensure that all boys and girls complete primary school.
3. Promote gender equality and empower women.	Two-thirds of illiterates are women, and the rate of employment among women is two-thirds that of men.	(3a) Eliminate gender disparities in primary and secondary education, preferably by 2005, and at all levels by 2015.
4. Reduce child mortality.	Every year, nearly 11 million young children die before their fifth birthday, mainly from preventable illnesses.	(4a) Reduce by two-thirds the mortality rate among children under 5 years.
5. Improve maternal health.	In the developing world, the risk of dying in childbirth is one in 48.	(5a) Reduce by three-quarters the ratio of women dying in childbirth.
6. Combat HIV/AIDS, malaria, and other diseases.	40 million people are living with HIV, including 5 million newly infected in 2001.	(6a and 6c) Halt and begin to reverse the spread of HIV/AIDS and the incidence of malaria and other major diseases.
7. Ensure environmental sustainability.	768 million people lack access to safe drinking water and 2.5 billion people lack improved sanitation.	(7a) Integrate the principles of sustainable development into country policies and programs and reverse the loss of environmental resources. (7b) Reduce by half the proportion of people without access to safe drinking water. (7c) Achieve significant improvement in the lives of at least 100 million slum dwellers.
8. Develop a global partnership for development.		(8a) Develop further an open, rule-based, predictable, nondiscriminatory trading and financial system. (8b) Address the special needs of the least-developed countries. (8c) Address the special needs of landlocked countries and small island developing states. (8d) Deal comprehensively with the debt problems of developing countries through national and international measures to make debt sustainable in the long term. (8e) In cooperation with pharmaceutical companies, provide access to affordable, essential drugs in developing countries. (8f) In cooperation with the private sector, make available the benefits of new technologies, especially information and communications.

SOURCE: www.un.org/millenniumgoals/.

Figure / 1.4 Daily Activity in Much of the World of Collecting Water.

(Photo courtesy of James R. Mihelcic).

applying a sustainability framework to organizational and engineering activities. There are often considered to be two broad classes of efforts to operationalize sustainability: top-down and bottom-up. That is, one strategy involves high-level decision-makers initiating activities and establishing organizational structures and incentives to push sustainability into the organization from the top. In the other strategy, people throughout the organization are motivated to pursue their functions in a more sustainable manner and drive sustainability into the organization through grassroots initiatives and self-initiated activities.

There are examples of successful changes from governmental and nongovernmental organizations as well as major corporations that have been realized from both of these approaches, but the most successful examples are when all levels of the organization are working toward sustainability outcomes. A successful example of this evolution to operationalize sustainability can be seen in the **Path Forward** at the Office of Research and Development at the EPA (described in Application 1.6).

Once there is an intention to pursue sustainability, there is a clear need to identify an approach to problem solving that is evolved from previous approaches which had not systematically incorporated triple bottom-line considerations. There are two critical frameworks that can be utilized to support the expanded view necessary to move toward sustainability goals: life cycle thinking and systems thinking. While these two frameworks are related, there are clear differences where life cycle thinking is focused on material and energy flows and the subsequent impacts, while systems thinking can also capture the relationship of political, cultural, social, and economic considerations, and potential feedbacks between these considerations and material and energy flows.

Application/1.6 The Path Forward at EPA's Office of Research and Development (Anastas, 2012)

Since 2010, significant changes have been made to EPA's research enterprise. All of EPA's actions and decisions are based on science and research. The EPA has recently embarked on a major effort to realign its research portfolio in order to more effectively address pressing environmental challenges and better serve the Agency's decision-making functions into the future using sustainability as an organizing principle.

In 2010, EPA commissioned a landmark study from the National Academies to provide recommendations on how to systematically operationalize the concept of sustainability into the Agency's entire decision making. The final report entitled "Sustainability and the U.S. EPA" (also known as the "Green Book") outlined several recommendations, including identification of key scientific and analytical tools, indicators, metrics, and benchmarks for sustainability that can be used to track progress toward sustainability goals. EPA scientists have begun to develop the scientific and analytical tools that will be needed in order to respond to and implement sustainability at EPA, including life cycle assessment, ecosystem services valuation, full cost/full benefit accounting, green chemistry, green infrastructure, and more. This effort to develop the tools of sustainability mirrors past EPA efforts to develop the tools for assessing, evaluating, and managing risk.

Access the "Green Book" (Sustainability at the U.S. EPA) at http://www.nap.edu/catalog.php?record_ id=13152#toc

1.2.1 LIFE CYCLE THINKING

Life cycle thinking supports recognizing and understanding how both consuming products and engaging in activities impact the environment from a holistic perspective. That is, **life cycle** considerations take into account the environmental performance of a product, process, or system from acquisition of raw materials to refining those materials, manufacturing, use, and end-of-life management. Figure 1.5a depicts the common **life cycle stages** for a consumer product. In the case of engineering infrastructure, Figure 1.5b depicts the life cycle stages of: (1) site development, (2) materials and product delivery, (3) infrastructure manufacture, (4) infrastructure use, and (5) end-of-life issues associated with infrastructure refurbishment, recycling, and disposal. In some cases, the transportation impacts of moving between these life cycle stages are also considered.

LCA 101
http://www.epa.gov/nrmrl/std/lca/lca.html

There is a need to consider the entire life cycle, because different environmental impacts can occur during different stages. For example, some materials may have an adverse environmental consequence when extracted or processed, but may be relatively benign in use and easy to recycle. Aluminum is such a material. On one hand, smelting of aluminum ore is very energy intensive. This is one reason aluminum is a favored recycled metal. However, an automobile will create the bulk of its environmental impact during the use life stage, not only because of combustion of fossil fuels, but also because of runoff from roads and the use of many fluids during operation. And for buildings, though a vast amount of water, aggregate, chemicals, and energy goes into the production of construction materials, transport of these items to the job site, and construction of a building, the vast amount of water and energy occurs after occupancy, during the operation life stage of the building.

2.1 Mass Concentration Units

Chemical concentration is one of the most important determinants in almost all aspects of chemical fate, transport, and treatment in both natural and engineered systems. This is because concentration is the driving force that controls the movement of chemicals within and between environmental media, as well as the rate of many chemical reactions. In addition, concentration often determines the severity of adverse effects, such as toxicity, bioconcentration, and climate change.

Concentrations of chemicals are routinely expressed in a variety of units. The choice of units to use in a given situation depends on the chemical, where it is located (air, water, or soil/sediments) and how the measurement will be used. It is therefore necessary to become familiar with the units used and methods for converting between different sets of units. Representation of concentration usually falls into one of the categories listed in Table 2.1.

Important prefixes to know include pico (10^{-12}, abbreviated as p), nano (10^{-9}, abbreviated as n), micro (10^{-6}, abbreviated as µ), milli (10^{-3}, abbreviated as m), and kilo (10^{+3}, abbreviated as k). Other important units are the tonne (which is also called the metric ton by some in the United States), which equals 1,000 kg (or 2,204 lb), and the common ton, which equals 2,000 lb. In addition, 1 teragram (Tg) = 10^{12} g = 1 million metric tons.

Concentration units based on chemical mass include mass chemical per total mass and mass chemical per total volume. In these descriptions, m_i is used to represent the mass of the chemical referred to as chemical *i*.

Clear Water Act Analytical Methods

http://www.epa.gov/waterscience/methods

Air Pollution Monitoring Techniques

http://www.epa.gov/ttn/amtic/

2.1.1 MASS/MASS UNITS

Mass/mass concentrations are commonly expressed as parts per million, parts per billion, parts per trillion, and so on. For example, 1 mg of a solute placed in 1 kg of solvent equals 1 ppm_m. **Parts per million by mass** (referred to as **ppm** or **ppm_m**) is defined as the number of units of mass of chemical per million units of total mass. Thus, we can express the previous example mathematically:

$$\boxed{\text{ppm}_\text{m} = \text{g of } i \text{ in } 10^6 \text{ g total}} \tag{2.1}$$

Table / 2.1

Common Units of Concentration Used in Environmental Measurements

Representation	Example	Typical Units
Mass chemical/total mass	mg/kg in soil	mg/kg, ppm_m
Mass chemical/total volume	mg/L in water or air	mg/L, µg/m^3
Volume chemical/total volume	volume fraction in air	ppm_v
Moles chemical/total volume	moles/L in water	M

SOURCE: Mihelcic (1999); reprinted with permission of John Wiley & Sons, Inc.

This definition is equivalent to the following general formula, which is used to calculate ppm_m concentration from measurements of chemical mass in a sample of total mass m_total:

$$\boxed{\text{ppm}_\text{m} = \frac{m_i}{m_\text{total}} \times 10^6} \tag{2.2}$$

Note that the factor 10^6 in Equation 2.2 is really a conversion factor. It has the implicit units of ppm_m/mass fraction (mass fraction = m_i/m_total), as given in Equation 2.3:

$$\text{ppm}_\text{m} = \frac{m_i}{m_\text{total}} \times 10^6 \frac{\text{ppm}_\text{m}}{\text{mass fraction}} \tag{2.3}$$

In Equation 2.3, m_i/m_total is defined as the mass fraction, and the conversion factor of 10^6 is similar to the conversion factor of 10^2 used to convert fractions to percentages. For example, the expression 0.25 = 25% can be thought of as:

$$0.25 = 0.25 \times 100\% = 25\% \tag{2.4}$$

Similar definitions are used for the units ppb_m, ppt_m, and percent by mass. That is, 1 **ppb_m** equals 1 **part per billion** or 1 g of a chemical per billion (10^9) g total, so that the number of ppb_m in a sample is equal to $m_i/m_\text{total} \times 10^9$. And 1 **$\text{ppt}_\text{m}$** usually means 1 **part per trillion** (10^{12}). However, be cautious about interpreting ppt values, because they may refer to either parts per thousand or parts per trillion.

Mass/mass concentrations can also be reported with the units explicitly shown (e.g., mg/kg or µg/kg). In soils and sediments, 1 ppm_m equals 1 mg of pollutant per kg of solid (mg/kg), and 1 ppb_m equals 1 µg/kg. **Percent by mass** is analogously equal to the number of grams of pollutant per 100 g total.

© Anthony Rosenberg/iStockphoto.

example/ 2.1 Concentration in Soil

A 1 kg sample of soil is analyzed for the chemical solvent trichloroethylene (TCE). The analysis indicates that the sample contains 5.0 mg of TCE. What is the TCE concentration in ppm_m and ppb_m?

solution

$$[\text{TCE}] = \frac{5.0 \text{ mg TCE}}{1.0 \text{ kg soil}} = \frac{0.005 \text{ g TCE}}{10^3 \text{ g soil}}$$
$$= \frac{5 \times 10^{-6} \text{ g TCE}}{\text{g soil}} \times 10^6 = 5 \text{ ppm}_\text{m} = 5{,}000 \text{ ppb}_\text{m}$$

Note that in soil and sediments, mg/kg equals ppm_m, and µg/kg equals ppb_m.

2.1.2 MASS/VOLUME UNITS: mg/L AND μg/m^3

In the atmosphere, it is common to use concentration units of mass per volume of air, such as mg/m^3 and μg/m^3. In water, mass/volume concentration units of mg/L and μg/L are common. In most aqueous systems, ppm$_m$ is equivalent to mg/L. This is because the density of pure water is approximately 1,000 g/L (demonstrated in Example 2.2).

The density of pure water is actually 1,000 g/L at 5°C. At 20°C, the density has decreased slightly to 998.2 g/L. This equality is strictly true only for *dilute* solutions, in which any dissolved material does not contribute significantly to the mass of the water, and the total density remains approximately 1,000 g/L. Most wastewaters, reclaimed waters, and natural waters can be considered dilute, except perhaps seawaters, brines, and some recycled streams.

example/ 2.2 Concentration in Water

One liter of water is analyzed and found to contain 5.0 mg of TCE. What is the TCE concentration in mg/L and ppm$_m$?

solution

$$[\mathrm{TCE}] = \frac{5.0\,\mathrm{mg\ TCE}}{1.0\,\mathrm{L\,H_2O}} = \frac{5.0\,\mathrm{mg}}{\mathrm{L}}$$

To convert to ppm$_m$, a mass/mass unit, it is necessary to convert the volume of water to mass of water. To do this, divide by the density of water, which is approximately 1,000 g/L:

$$\begin{aligned}\mathrm{TCE} &= \frac{5.0\,\mathrm{mg\ TCE}}{1.0\,\mathrm{L\,H_2O}} \times \frac{1.0\,\mathrm{L\,H_2O}}{1{,}000\,\mathrm{g\,H_2O}}\\ &= \frac{5.0\,\mathrm{mg\ TCE}}{1{,}000\,\mathrm{g\ total}} = \frac{5.0 \times 10^{-6}\,\mathrm{g\ TCE}}{\mathrm{g\ total}} \times \frac{10^6\,\mathrm{ppm_m}}{\mathrm{mass\ fraction}}\\ &= 5.0\,\mathrm{ppm_m}\end{aligned}$$

In most dilute aqueous systems, mg/L is equivalent to ppm$_m$.

In this example, the TCE concentration is well above the allowable U.S. drinking water standard for TCE, 5 μg/L (or 5 ppb), which was set to protect human health. Five ppb is a small value. Think of it this way: Earth's population exceeds 6 billion people, meaning that 30 individuals in one of your classes constitute a human concentration of approximately 5 ppb!

2.2 Volume/Volume and Mole/Mole Units

Units of volume fraction or mole fraction are frequently used for gas concentrations. The most common volume fraction units are **parts per million by volume** (referred to as **ppm** or **ppm$_v$**), defined as:

$$\boxed{\mathrm{ppm_v} = \frac{V_i}{V_\mathrm{total}} \times 10^6} \qquad (2.5)$$

example/ 2.3 Concentration in Air

What is the carbon monoxide (CO) concentration expressed in μg/m^3 of a 10 L gas mixture that contains 10^{-6} mole of CO?

solution

In this case, the measured quantities are presented in units of moles of the chemical per total volume. To convert to mass of the chemical per total volume, convert the moles of chemical to mass of chemical by multiplying moles by CO's molecular weight. The molecular weight of CO (28 g/mole) is equal to 12 (atomic weight of C) plus 16 (atomic weight of O).

$$\begin{aligned}[\mathrm{CO}] &= \frac{1.0 \times 10^{-6}\,\mathrm{mole\ CO}}{10\,\mathrm{L\ total}} \times \frac{28\,\mathrm{g\ CO}}{\mathrm{mole\ CO}}\\ &= \frac{28 \times 10^{-6}\,\mathrm{g\ CO}}{10\,\mathrm{L\ total}} \times \frac{10^6\,\mu\mathrm{g}}{\mathrm{g}} \times \frac{10^3\,\mathrm{L}}{\mathrm{m^3}} = \frac{2{,}800\,\mu\mathrm{g}}{\mathrm{m^3}}\end{aligned}$$

where V_i/V_total is the volume fraction and 10^6 is a conversion factor, with units of 10^6 ppm$_v$ per volume fraction.

Other common units for gaseous pollutants are **parts per billion (10^9)** by volume (**ppb$_v$**). Table 2.2 provides examples of the change in the atmospheric concentration of three major **greenhouse gases (GHGs)** since preindustrial times, around the year 1750.

The advantage of volume/volume units is that gaseous concentrations reported in these units do not change as a gas is compressed or expanded. Atmospheric concentrations expressed as mass per volume (e.g., μg/m^3) decrease as the gas expands, since the pollutant mass remains constant but the volume increases. Both mass/volume units, such as μg/m^3, and ppm$_v$ units are frequently used to express gaseous concentrations. (See Equation 2.9 for conversion between μg/m^3 and ppm$_v$.)

Table / 2.2

Change in Atmospheric Concentration of Major GHGs Since Preindustrial Times

	2011 Atmospheric Concentration	Preindustrial Atmospheric Concentration	Percent Change Since Preindustrial Times
Carbon dioxide (CO_2)	391 ppm	280 ppm	+140%
Methane (CH_4)	1,813 ppb	700 ppb	+259%
Nitrous oxide (N_2O)	324 ppb	270 ppb	+120%

SOURCE: Data from World Meteorological Organization (2012).