Industrial Ecology and Sustainable Engineering

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New

1.3 Using the "master equation," the "Units of Measurement" section in Appendix, and the following data, compute the 2007 GDP/capita and equivalent CO_2 emissions per equivalent U.S. dollar of GDP for each country shown in the following table.

2007 Master Equation Data for Five Countries

Country	Population (millions)	GDP (billion U.S. dollars)	CO_2 emissions (Tg C/yr)
Brazil	188	621	106
China	1,314	2,512	1,665
India	1,095	796	338
Nigeria	132	83	114
United States	298	13,220	1,709

Source: Data for this table were drawn primarily from J.T. Houghton, B.A. Callander, and S.K. Varney, *Climate Change 1992*, Cambridge, UK: Cambridge University Press, 1992.

1.4 Trends in population, GNP, and technology are estimated periodically by many institutions. Using the typical trend predictions below, compute the equivalent CO_2 anticipated for the years 2010 and 2025 for the five countries in the following table. Graph the answers, together with information from 2007 (previous problem), on an ECO_2 vs. year plot. Comment on the results.

Master Equation–Predicted Data for Five Countries

Country	Population (millions)		GNP growth (%/yr)		Decrease in eCO_2/GNP(%/yr)
	2000	2025	1990–2000	2000–2025	
Brazil	175	240	3.6	2.8	0.5
China	1,290	1,600	5.5	4.0	1.0
India	990	1,425	4.7	3.7	0.2
Nigeria	148	250	3.2	2.4	0.1
United States	270	307	2.4	1.7	0.7

Source: Data for this table were drawn primarily from J.T. Houghton, B.A. Callander, and S.K. Varney, *Climate Change 1992*, Cambridge, UK: Cambridge University Press, 1992.

CHAPTER 2

The Concept of Sustainability

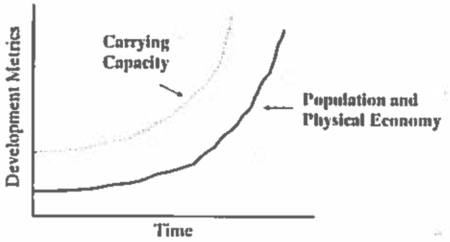
2.1 IS HUMANITY'S PATH UNSUSTAINABLE?

Unpredicted societal collapse is an occasional feature of the history of humanity. The classic case is that of Easter Island in the southeastern Pacific Ocean. It is very remote, and was not settled until about 800 CE. When the Polynesians arrived, they began to cut trees to create farmland and to make canoes. Soon they began to erect the large statues for which the island is famous, and trees were used to transport the statues and erect them. Over time, the island's trees were all cut for these purposes.

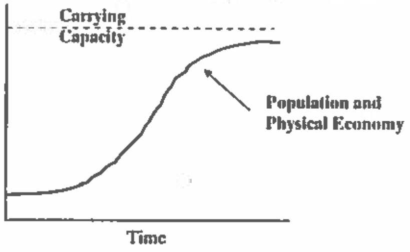
The lack of trees meant that Easter Island had no firewood, mulch, or canoes. Without the ability to catch dolphins from canoes, and with the depletion of nesting birds, the population came under severe pressure, and the island was too remote for help to come. There were no alternatives to a severe and ultimately permanent population collapse.

Easter Island is a special case, certainly, but it is not hard to find other cases in which the misuse of technology has forever changed part of the planet—the acid mine drainage and heavy metal pollution around Butte, Montana, in the western United States is an example.

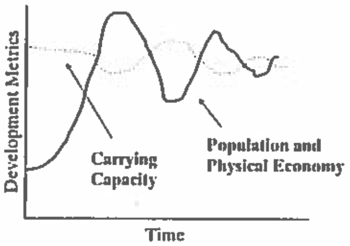
The discussion of collapse can be generalized by examining the alternative behavioral patterns for complex systems shown in Figure 2.1. The exponential path (Figure 2.1a) traces the path of social progress for some 200 years. This pattern occurs when there are no constraints to growth or when innovation causes apparent limits to recede. The s-shaped curve (Figure 2.1b) is characteristic of the system with fixed constraints in which action is controlled by feedback based on a sense of the



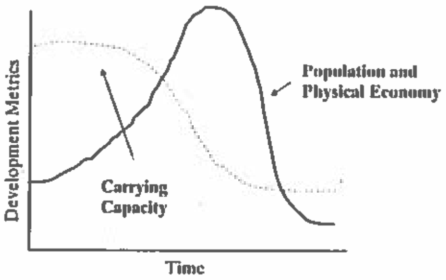
(a) Continuous growth if physical bounds are distant or growing



(b) Sigmoidal path occurs when approaches to bounds are seen



(c) Oscillations occur with delayed signals but robust bounds



(d) Collapse occurs with delays and erodable bounds

Figure 2.1

Four typical behavior patterns for complex systems. (Adapted from D.H. Meadows, D.L. Meadows, and J. Randers, *Beyond the Limits*, White River Junction, VT: Chelsea Green, 1992.)

distance to the limits. To manage the smooth approach, the system must respond without significant lags and with accurate knowledge of the distance yet to go.

The curve showing oscillatory behavior (Figure 2.1c) is typical of systems where feedback mechanisms are inaccurate and responses are slow. At the point that awareness of some limit becomes sufficient to produce action, it is too late to avoid overstepping the limits and the system continues to move beyond what appears to be some long-run sustainable state. If the stress produced by the overshoot does not completely degrade the system, subsequent corrections can enable the system to oscillate about and approach the limit. Curve (d) depicts initial behavior somewhat like the third curve, but with a critical difference. Here the system is insufficiently robust, corrections are insufficient, and collapse occurs. This is the Easter Island trajectory.

It is important to note that the initial stages of these curves are quite similar. We imagine that we are close to the origin and further imagine intuitively that we are on the exponential growth pattern. If we are not, we must look sustainability in the face and think hard about the robustness and stability of our technological society.

It is useful at this point to define what we mean by sustainability. Many have tried to formulate succinct definitions, two of which we feel have particular merit. John Ehrenfeld's is conceptual: "*Sustainability* is the possibility that human and other forms of life will flourish on the planet forever." The International Institute of Environment and Development defines *sustainable development* (often used as a synonym for *sustainability*) as "A development path that can be maintained indefinitely because it is socially desirable, economically viable, and ecologically sustainable." The words have resonance, but offer minimal guidance to engineers, scientists, political leaders, and citizens. What specific actions will move us in the direction of sustainability?

2.2 COMPONENTS OF A SUSTAINABILITY TRANSITION

In the short term, virtually everything can be sustained. On the longest of timescales, nothing can. In between, there are choices to make. Therefore, to begin the process of operationalizing sustainability, we need to determine for ourselves exactly what it is that we wish to sustain, who are we sustaining it for, and for how long. A variety of positions have been taken on these topics; they are grouped in Figure 2.2. The most common position (not necessarily the "correct" one) on what is to be sustained is *life support systems*, especially for humans. The goal tends also to be human-centered, with economic growth and human development as the central themes. The Board on Sustainable Development also identified linkages that connect sustainability and development to varying degrees.

Choosing the timescale is important, because it enables potential actions to be quantified, as will be shown below. "Now and in the future" and "forever" are naïve and unworkable choices. In a practical sense, making policy for more than a human adult lifetime is not realistic, so most operational planning durations for sustainability fall into the 25–50 year range. This creates obvious discontinuities when working with systems such as the carbon and climate cycles, which involve timescales of many hundreds of years.

Given the general agreement that society's current path is not sustainable, getting closer to the sustainability goal will require a significant and multifaceted transition. This could well involve monitoring and influencing a number of long-term trends, some

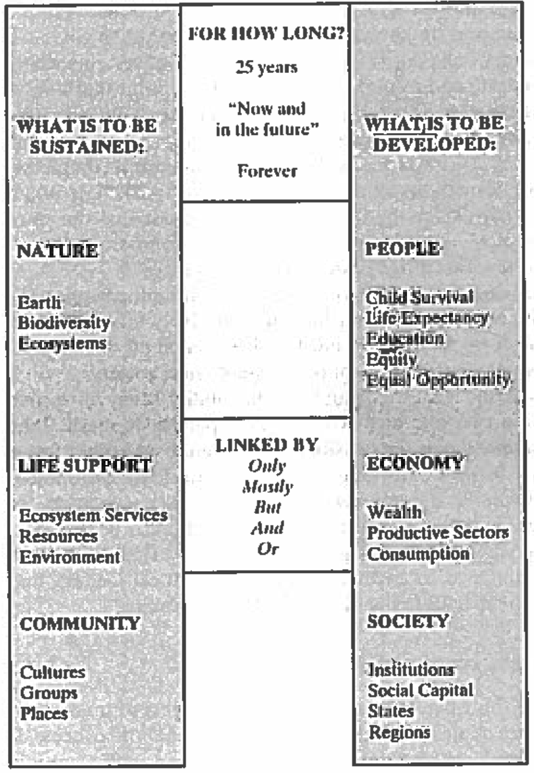


Figure 2.2

Sustainable development: common concerns, differing emphases. (Reproduced with permission from Board on Sustainable Development, *Our Common Journey*, Washington, DC: National Academy Press, 1999.)

of which may not be intuitively associated with sustainability. Industrial ecologists may have minimal influence on some of these, such as health or urbanization, but are clearly central players in changing the rates and modes of use of resources, of energy, and of water, and in minimizing the impacts of technology on the environment.

A feature of the sustainability discussion that is highly relevant to industrial ecology is the distinction between "weak" and "strong" sustainability. The former is the more optimistic position: It holds that sustainability is equivalent to nondecreasing total capital stock, that is, the sum of natural capital and human-made capital. Adherents of strong sustainability take a different position, arguing that natural capital provides certain important functions for which human-made capital cannot substitute. Robert Ayres (2007) lists free oxygen, freshwater, phosphorus, and scarce but very useful heavy elements such as thallium or rhenium in this group and argues that "those who espouse the notion of strong sustainability appear to be closer to the truth than the optimists who believe in more or less unlimited substitution possibilities."

2.3 QUANTIFYING SUSTAINABILITY

How is one to approach the challenge of providing sustainability guidance in such a way that it can be implemented? We explore in this section of the chapter a few examples, all potentially contentious, of how such guidance might be established and provided in such a way that the "journey toward sustainability" might begin.

Realistic and defensible goals for sustainability and their implementation will not be easy to establish in practice, but the principles by which one could proceed are reasonably straightforward. They are:

- Establish the limiting rate of use of the environmental, economic, or equity component.
- Allocate the allowable limit by some appropriate method to those who are influenced by that limit.
- Compare the current situation with the permitted allocation.
- Consider potential corrective actions.

In a number of cases, it will be necessary to select a time-horizon over which sustainability is to be evaluated. In accordance with the Board on Sustainable Development (1999), we regard 50 years (i.e., roughly two human generations) as a reasonable period for assessment. By most accounts, the next 50 years will be crucial in determining the long-term sustainability of ecological and human systems. Population is likely to increase dramatically over the next 50 years from 6 billion to 9 billion. A discernable human-induced climate change on the order of 2–5°C could well occur, and commonly used industrial minerals and both oil and natural gas could become increasingly scarce over the next 50 years. We further assume that resource consumption should be planned so that existing resources will last for 50 years at current rates. This allows time for substitution of other resources or the development of alternative ways of meeting the needs that are served by resource consumption.

Once a resource of interest is chosen, then we see four basic steps for beginning a preliminary measure of sustainability.

1. **Establish the virgin material supply limit** by calculating the amount of a resource that can be used per year if that resource is to last for 50 years. To do so, you must first establish the known quantity of the resource available within the region of interest (the globe, a country, a state, etc.). For a nonrenewable resource, the amount often used is the "reserve base," defined as those resources that can be extracted at a profit plus some resources that are known but are not presently economically viable.
2. **Allocate the virgin material supply** according to a reasonable formula (such as dividing it equally among the global population, perhaps). Throughout the following examples, we assume that the *average* global population over the next 50 years will be 7.5 billion people.

3. **Establish the regional "re-captureable" resource base,** which is the known quantity in stockpiles, landfills, and so on, where it might reasonably be accessed. Assume that this resource can be replenished from existing stock in use at the current regional rate of recycling of the chosen material.
4. **Compare the current consumption rate to the sustainable limiting rate** for that resource within the region being assessed.

Once this basic measurement is done, one can begin to speak intelligently and realistically about any necessary policy actions to respond to excess consumption. As the following examples will show, this basic calculation clearly shows the unsustainable nature of current "Western" consumption patterns, especially when available technological resources are equitably distributed across the globe. Whether or not this is a reasonable allocation of resources is a question that will be briefly addressed herein. As is patently obvious, equity in allocation of the global common resources will be a topic for serious and intense political debate for many years to come. However, even the simple sustainability calculations for zinc, germanium, and greenhouse gasses below can serve as starting points for these policy debates.

2.3.1 Example 1: Sustainable Supplies of Zinc

To illustrate the approach, let us proceed to derive a sustainability limit for the use of zinc. Zinc, a fairly representative industrial mineral, is widely used by our modern technological society, yet it is in a relatively short supply from known reserves. About half of zinc production goes to make galvanized steel, in which a thin coating of zinc protects the underlying steel from rusting. Our industrial society also uses zinc in brass, bronze, and other alloys, die casting, and tire manufacture. Applying the four basic steps above, we determine a sustainable limiting rate of zinc consumption in Table 2.1.

Is 1.5 kg of zinc per person per year sufficient for an average person's technological and social requirements? Consider the following exploration of a common technological appliance, the automobile. Automobiles are one of the major technological goods that contain zinc, in the form of galvanized steel chassis and body parts. The zinc content of an average car is about 3–4 percent of the total weight of the automobile. Assuming that an average automobile weighs about 2000 pounds (or about 900 kg), then the average automobile contains about 900 kg × 0.035 = 32 kg of zinc. From a "zinc-perspective," the sustainable rate of automobile purchase is thus 32/1.5 = 21 years. Thus, your annual sustainable zinc allotment lets you buy a new car every 21 years. Furthermore, if during those 21 years you want anything else containing zinc, like a brass doorknob or some galvanized fencing, your new-car-purchase cycle will be lengthened.

TABLE 2.1 Calculation of a Global Sustainable Limiting Rate of Zinc Consumption

1. **Virgin material supply limit:** For zinc, the reserve base as of 1999 was 430 Tg, so the virgin material supply limit over the next 50 years is 430 Tg/50 years = 8.6 Tg/yr.
2. **Allocation of virgin material:** Allocating the available zinc equally among all the world's population gives approximately (8.6 Tg/yr)/(7.5 billion people) = 1.15 kg/(person-yr).
3. **Regional "re-captureable" resource base:** For illustrative purposes, assume a 30% zinc recycling rate (the current best-available zinc recycling rate). If 30 % of the 1.15 kg/(person-yr) is recycled, then each person in the region actually has 1.15 + (0.3)(1.15) kg/(person-yr) of zinc available, or 1.5 kg/(person-yr).
4. **Current consumption rate vs. sustainable limiting rate:** This step raises the fundamental question: How we are doing currently? For instance, the United States' zinc consumption in 1999 was 1.6 Tg for a population of 260 million people. This translates to a U.S. per capita zinc use of 6.2 kg per year. The Netherlands zinc use in 1990 was 28.5 Gg for a population of 15 million people. This translates to a Netherlands' per capita zinc use of 1.9 kg per year. The United States clearly exceeds its global sustainable allocation of zinc per person, while the Netherlands is much closer to its global sustainable allocation.

An argument against this simple calculation would be that substitutes are widely available for galvanized steel (such as aluminum or composite materials for automobile manufacture) that would reduce the need for mined or recycled zinc. Substitution raises a few important questions, such as the following: Is a substitute technologically feasible? Is the substitute economically feasible? Is the substitute sustainable? Is the substitute of equal quality? Is the substitute socially (morally, ethically, etc.) acceptable? Will the substitute be accepted by consumers (due to aesthetics, "feel," or style)? These questions range from the scientific to the political and social. For the case of aluminum or composite materials substituting for zinc-galvanized steel in automobile manufacture, all of these questions could be satisfactorily answered (and probably will have to be in the near future). Answering these and other questions (such as, how do you increase zinc reuse and recycling?) will help policy makers devise the necessary corrective actions and incentives to achieve sustainable zinc use. As the following example for germanium will elucidate, what happens when the material in question has no readily apparent substitute?

2.3.2 Example 2: Sustainable Supplies of Germanium

One potential example of an "unsubstitutable" industrial mineral is germanium, 75 percent of which is used in optical fiber systems, infrared optics, solar electrical applications, and other specialty glass uses. Germanium plays a key role in giving these glasses their desired optical properties. Its most common use is as a dopant in the cylindrical core of glass fibers slightly increasing the refractive index of the core glass compared to the cladding. Lightwaves impinging on the core–cladding interface are trapped inside the core and can transmit the light signal for distances up to 30–60 km. Germanium is more reliable and outperforms all currently known substitutes in these applications. Furthermore, germanium use will likely increase in the future as fiber optic cables replace traditional copper wires and as solar-electric power becomes more widely available. We compute a U. S. sustainable limiting rate of germanium consumption in Table 2.2.

Is the sustainable allocation of 2 mg of germanium per person per year sufficient for an average person's technological and social requirements? Consider the following exploration of fiber optic cable replacing U.S. telephone wire needs. The germanium content of an average telecommunications fiber core is typically 5 mole percent GeO_2. This translates to roughly 14 mg of germanium per kilometer. Assuming that an average road has at least one telephone cable along its length, then replacing the copper telephone cable with fiber optic cable along the 3,830,000 km of paved roads in the United States would require approximately 2 Mg of germanium. Dividing by the 260 million people in the United States, each person would have to contribute

TABLE 2.2 Calculation of a U.S. Sustainable Limiting Rate of Germanium Use

1. **Virgin material supply limit:** Similar to the above analysis for zinc, the first step is to establish the amount available. For germanium, the reserve base in the United States as of 1999 was 500 Mg (world reserves are unknown at this time), so the virgin material supply limit over the next 50 years is 500 Mg/50 years = 10 Mg/yr.
2. **Allocation of virgin material:** Allocating the available germanium equally among all the world's population gives approximately 10 Mg/yr/7.5 billion people = 1.3 mg/(person-yr).
3. **Regional "re-captureable" resource base:** Worldwide, approximately 25% of the total germanium consumed is produced from recycled materials. If 25% of the 1.3 mg/(person-yr) is recycled, then each person actually has 1.3 + (0.25)(1.3) mg/(person-yr) of germanium available, or 1.6 mg/(person-yr).
4. **Current consumption rate vs. sustainable limiting rate:** The United States' germanium consumption in 1999 was 20 Mg for a population of 260 million people. This translates to a current U.S. per capita germanium use of 77 mg per person per year, compared to the sustainable limiting rate of 1.6 mg per person per year. The United States clearly exceeds its global sustainable allocation of germanium per person.

a one-time donation of about 8 mg of germanium to rewire the country. From a "germanium-perspective," replacing copper wire with fiber optic cable for telephone service in the streets of the United States would most likely be sustainable.

Obviously, most countries of the world do not currently have the demand for fiber optic cable suggested above. In a developing country, such an analysis could begin a discussion on whether wiring the streets with fiber optic cable from the beginning, instead of copper wire, would be a more sustainable choice. A third alternative, now apparently going forward but not from a sustainability perspective, is to communicate entirely by cellular telephone and thus avoid much of the necessary cabling completely. Such a choice should, of course, initiate a discussion around the sustainability of all the constituent materials in cellular telephones and base stations.

2.3.3 Example 3: Sustainable Production of Greenhouse Gases

As stated above, two of the major Earth system conditions we wish to maintain are a Holocene-style climate and functioning planetary engineering systems (forests, wetlands, etc.). The sustainability of each is closely linked to global climate change. Perhaps one sustainability threshold for climate change would be to limit human disruption of climate below that which significantly alters ocean circulation patterns, such as the North Atlantic thermohaline circulation. According to some climate change models, a doubling of atmospheric CO_2 (i.e., to approximately 550 ppmv) would most likely not permanently alter Atlantic Ocean circulation (although the circulation would weaken significantly and would take hundreds of years to recover in that case). It would be easy to debate that a doubling of CO_2 would still have some nonzero effects on maintaining climate conditions and ensuring the viability of ecosystem function. Yet, doubling of atmospheric CO_2 has emerged as a political target and a focal point for scientific analysis in most climate change models. Therefore, using the basic steps described above, we calculate in Table 2.3 a sustainable level of CO_2 addition to the atmosphere, if we make the controversial assumption that CO_2 doubling will be reasonably sustainable.

Is a sustainable allocation of 1 metric ton of carbon per person per year reasonable? Consider the following data on automobile usage and carbon production.

TABLE 2.3 Calculation of a Global Sustainable Limiting Rate of Carbon Dioxide Production

1. **Virgin material supply limit:** The IPCC indicates that in order to level off atmospheric CO_2 concentration (the major greenhouse gas of concern for our technological society) below a doubling from the preindustrial level (i.e., below approximately 550 ppmv by the year 2100), global anthropogenic emissions must be limited to ~7–8 Pg of carbon per year.
2. **Allocation of virgin material:** Again, following the simple examples above, each of the average 7.5 billion people on the planet over the next 50 years is allocated an equal share of CO_2 emissions. This translates to roughly 1 metric ton of carbon per person per year.
3. **Regional "recaptureable" resource base:** "Recycling" of carbon in the form of permanent or semipermanent sequestration may eventually be possible through controversial techniques such as deep well injection of carbon dioxide. However, this is still largely theoretical or in the very early stages of experimentation. Future sustainability measures could incorporate carbon recycling if it is eventually accepted as part of the carbon "management" alternatives.
4. **Current consumption rate vs. sustainable limiting rate:** The United States on average produces 6.6 metric tons of carbon equivalents per person, which is clearly well beyond the global sustainable rate of 1 metric ton of carbon per person per year. Inhabitants of Switzerland produce approximately 2.0 metric tons of carbon equivalents per person, which is still approximately twice our calculated sustainable limit.

Driving an automobile produces approximately 100 g of carbon per vehicle mile traveled. Drivers in the United States average 12,500 miles per person per year, which translates to 1.25 metric tons of carbon produced per year by driving. A driver would have to reduce his or her yearly driving miles by 2,500 miles in order to achieve the 1 metric ton of carbon per person sustainability goal. Regardless, a person could use all of his or her sustainable carbon credit on driving, but this would leave nothing for home heating, electricity for a computer, or a personal share in the larger industrial-technological systems that support the economy. Alternative energy sources, carbon sequestration possibilities, less-carbon-intensive production systems, personal driving habits, vehicle technology, public transportation systems, or some combination thereof must all be incorporated into the public discourse. However, as is the theme of this exercise, this public discourse would be well served by having a sustainable target toward which to aim.

These examples and the assumptions made herein raise contentious issues, two of which we address below.

2.3.4 Issues in Quantifying Sustainability

The Simplicity vs. Complexity Issue. Our analysis here is necessarily simplified, and the simple metrics do not yet handle the inherent complexity of our global environmental system. It is easy to punch holes in the measurements and data, and cumulative and unintended effects are particularly troublesome. We say little about the methods of production for resources, which can involve enormous energy use, serious habitat disruption, environmental degradation, and so forth. For instance, even something seemingly positive such as increased zinc recycling to address sustainability issues may have negative effects on energy consumption and greenhouse gas production through transportation of recyclable material. Whether the sustainability-enhancing aspects of the one outweighs the unsustainability of the other two is cause for serious debate and more in-depth analysis that is beyond the scope of the simple metrics outlined herein.

There is a point where complexity for complexity's sake offers only marginal benefits. Each of our calculations raises the possibility that our current technological systems operate at at least twice the sustainable rate. On the order of magnitude scale, even the simple sustainability measurements herein offer a perspective on the challenges ahead.

The Property Rights Issue. In calculating preliminary values for sustainable rates of use of various resources on an individual basis, we have allocated resources in the simplest possible way—an equivalent amount to each human being. This choice is comfortable from a global equity standpoint (although in reality far from current social norms), but immediately raises potential legal issues surrounding property rights. Resources are not equally distributed on a geographical basis and they are owned by a variety of entities, including nations, corporations, and individuals. To allocate resources on a global basis is to dictate at least to whom those resources must be sold, and doubtless to have at least some influence on price. Some alternative approaches, all problematic to varying degrees, are as follows:

- The global total extraction rate could be dictated, but allocation left to market forces.
- Regional total extraction rates could be dictated, and residents of resource-rich regions allocated more of the local resource than nonresidents.
- Regional allocations could be based on both local virgin and secondary resources.

Regardless of what choice is adopted, sustainability from a resource standpoint may require the establishment of an upper extraction limit followed by some method for allocating each year's virgin material supply. This would redefine current notions of private property, by imposing limits on extraction, and would transfer these property rights to disenfranchised masses. These are questions of policy, politics, diplomacy, and law. Nevertheless, the few simple calculations presented above can greatly inform the debate that rages among the developed and developing world, the rich and the poor, the large nations and small islands, the North and the South, and Republicans and Democrats.

2.4 LINKING INDUSTRIAL ECOLOGY ACTIVITIES TO SUSTAINABILITY

2.4.1 The Grand Environmental Objectives

Many of the sustainability dialogs involve environmental perturbations, in part because much of sustainability arose from previous environmental movements. Accordingly, it is useful to consider how such issues might be prioritized, without forgetting that sustainability itself requires consideration of a number of dimensions in addition to the environmental. Here, there has been significant progress: Although a number of environmental issues are worth attention, there is indisputable evidence that some environmental concerns are regarded generally or even universally as more important than others. For example, a major global decrease in biodiversity is clearly of more concern than the emission of hydrocarbon molecules from residential heating, and the Montreal Protocol and the Rio Treaty demonstrate that at least most of the countries of the world feel that understanding and minimizing the prospects for ozone depletion and global climate change are issues of universal importance. If one accepts that there are indeed such issues that have general acceptance by human society, one may then postulate the existence of a small number of "Grand Objectives" having to do with life on Earth, its maintenance, and its enjoyment. Determining these objectives requires societal consensus, which may or may not be achievable. For purposes of discussing the concept, a reasonable exposition of the Grand Objectives is the following:

The Ω_1 Objective: Maintaining the existence of the human species

The Ω_2 Objective: Maintaining the capacity for sustainable development and the stability of human systems

The Ω_3 Objective: Maintaining the diversity of life

The Ω_4 Objective: Maintaining the aesthetic richness of the planet

If it is granted that these objectives are universal, there are certain basic societal requirements that must be satisfied if the objectives are to be met. In the case of Ω_1, these are the minimization of environmental toxicity and the provision of basic needs: food, water, shelter, as well as the development of social and environmental resiliency adequate to maintain the species in light of low probability or unanticipated challenges (e.g., nuclear winter). For Ω_2, the requirements are a dependable energy supply, the availability of suitable material resources, the existence of workable political structures, and minimizing cultural conflict. For Ω_3, it is necessary to maintain a suitable amount of natural areas and to maximize biological diversity on disturbed areas, through, for example, the avoidance of monocultural vegetation. Perturbations due to rapid shifts in fundamental natural systems such as climate or oceanic circulation must also be addressed under this objective. Ω_4 requires control of wastes of various kinds: minimizing emissions that result in smog, discouraging dumping and other activities leading to degradation of the visible world, encouraging farming and agricultural practices that avoid land overuse and erosion, and the preservation of commonly held undeveloped land.

The Ω framework is an important prerequisite to determining what societal activities would be desirable, but the framework does not ensure progress toward achieving the objectives, especially when social consensus is involved. That progress results when desirable actions encouraged by the framework occur over and over again. In an industrialized society, a number of those actions are decisions made by product designers and manufacturing engineers. Thus, technological recommendations informed by the Grand Objectives are one means by which favorable decisions can be made.

2.4.2 Linking the Grand Objectives to Environmental Science

The Grand Objectives are, of course, too general to provide direct guidance to the product designer, who deals with specific actions relating to environmental concerns. The objectives and concerns can readily be related (see Table 2.4), but industrial decisions often require, in addition, a ranking of the relative importance of those concerns. This requirement is, in fact, a throwback to the philosophy that societal actions should be taken so as to produce the maximization of the good, and it produces in turn the question, "How does society determine the best actions?"

TABLE 2.4 Relating Environmental Concerns to the Grand Objectives

Grand objective	Environmental concern
Ω_1: Human species existence	
	1. Global climate change
	2. Human organism damage
	3. Water availability and quality
	4. Resource depletion: fossil fuels
	5. Radionuclides
Ω_2: Sustainable development	
	3. Water availability and quality
	4. Resource depletion: fossil fuels
	6. Resource depletion: non-fossil fuels
	7. Landfill exhaustion
Ω_3: Biodiversity	
	3. Water availability and quality
	8. Loss of biodiversity
	9. Stratospheric ozone depletion
	10. Acid deposition
	11. Thermal pollution
	12. Land use patterns
Ω_4: Aesthetic richness	
	13. Smog
	14. Aesthetic degradation
	15. Oil spills
	16. Odor

Note: The numbers in the right column are for later reference purposes.

The particular difficulty of identifying the best actions of society in this instance is that societal activities related to the environment inevitably involve trade-offs: wetland preservation versus job creation, the lack of greenhouse gas emissions of nuclear power reactors versus the chance of nuclear accident, or the preservation and reuse of clothing versus the energy costs required for cleaning, to name but a few. To enable choices to be made, many have proposed that environmental resources (raw materials, plant species, the oceans, etc.) be assigned economic value so that decisions could be market driven. The concept, though potentially quite useful, has proven difficult to put into practice, and this has been further confounded by the fact that the scientific understanding of many of the issues to be valued is itself evolving and thus would require that valuation be continuously performed.

Given this uncertain and shifting foundation for relative ranking, how might specific environmental concerns, several of which are responsive to one or more of the Grand Objectives, be grouped and prioritized in an organized manner? We begin by realizing that sustainability ultimately requires

- Not using renewable resources faster than they are replenished
- Not using nonrenewable, nonabundant resources faster than renewable substitutes can be found for them

- Not significantly depleting the diversity of life on the planet
- Not releasing pollutants faster than the planet can assimilate them

The relative significance of specific impacts can then be established by consideration of those goals in accordance with the following guidelines for prioritization:

- The spatial scale of the impact (large scales being worse than small)
- The severity and/or persistence of the hazard (highly toxic and/or persistent substances being of more concern than less highly toxic and/or persistent substances)
- The degree of exposure (well-sequestered substances being of less concern than readily mobilized substances)
- The degree of irreversability (easily reversed perturbations being of less concern than permanent impacts)
- The penalty for being wrong (longer remediation times being of more concern than shorter times)

These general criteria are perhaps too anthropocentric as stated, and are, of course, subject to change as scientific knowledge evolves, but are nonetheless a reasonable starting point for distinguishing highly important concerns from those less important. Using the criteria and the Grand Objectives, local, regional, and global environmental concerns can be grouped as shown in Table 2.5. The exact wording and relative positioning of these concerns are not critical for the present purpose; what is important is that most actions of industrial society that have potentially significant environmental implications relate in some way to the list.

Of the seven "crucial environmental concerns," three are global in scope and have very long timescales for amelioration: global climate change, loss of biodiversity, and ozone depletion. The fourth critical concern relates to damage to the human organism by toxic, carcinogenic, or mutagenic agents. The fifth critical concern is the availability and quality of water, a concern that embraces the magnitude of water use as well as discharges of harmful residues to surface or ocean waters. The sixth is the rate of loss of fossil fuel resources, vital to many human activities over the next century, at least. The seventh addresses humanity's use of land, a factor of broad influence on many of the other concerns.

Four additional concerns are regarded as highly important, but not as crucial as the first six. The first two of these, acid deposition and smog, are regional-scale impacts occurring in many parts of the world and closely related to fossil fuel combustion and other industrial activities. Aesthetic degradation, the third highly important concern, incorporates "quality of life" issues such as visibility, the action of airborne gases on statuary and buildings, and the dispersal of solid and liquid residues. The final concern, depletion of non-fossil fuel resources, is one of the motivations for current efforts to recycle materials and minimize their use.

Finally, five concerns are rated as less important than those in the first two groupings, but still worthy of being called out for attention: oil spills, radionuclides, odor, thermal pollution, and depletion of landfill space. The justification for this grouping is that the

TABLE 2.5 Significant Environmental Concerns

Crucial environmental concerns

1. Global climate change
2. Human organism damage
3. Water availability and quality
4. Depletion of fossil fuel resources
8. Loss of biodiversity
9. Stratospheric ozone depletion
12. Land use patterns

Highly important environmental concerns

6. Depletion of non-fossil fuel resources
10. Acid deposition
12. Smog
13. Aesthetic degradation

Less important environmental concerns

5. Radionuclides
7. Landfill exhaustion
11. Thermal pollution
15. Oil spills
16. Odor

Note: The numbers are those of Table 2.4. Within the groupings, the numbers are for reference purposes and do not indicate order of importance.

effects, while sometimes quite serious, tend to be local or of short time duration or both, when compared with the concerns in the first two groups.

2.4.3 Targeted Activities of Technological Societies

The mitigation of the environmental impacts of human activities follows, at least in principle, a logical sequence. First is the recognition of an environmental concern related to one or more of the Grand Objectives. Global climate change, for example, is related to two: Ω_1 and Ω_3. Next, once that concern is identified, industrial ecologists study the activities of humanity that are related to it. For global climate change, the activities include (though are not be limited to) those that result in emissions of greenhouse gases, especially CO_2, CH_4, N_2O, and CFCs; Table 2.6 lists a number of examples. The concept is that societal activities from agriculture to manufacturing to transportation to services can be evaluated with respect to their impacts on the Grand Objectives and that the link between activities and objectives is the purpose for the environmental evaluation of products, processes, and facilities.

A characteristic of many of the activities of a technological society is that they produce stresses on more than one of the environmental concerns. Similarly, most environmental concerns are related to a spectrum of societal activities. This analytical complexity does not, however, invalidate the framework being developed here.

TABLE 2.6 Targeted Activities in Connection with Crucial Environmental Concerns

Environmental concern	Targeted activity for examination
1. Global climate change	1.1 Fossil fuel combustion
	1.2 Cement manufacture
	1.3 Rice cultivation
	1.4 Coal mining
	1.5 Ruminant populations
	1.6 Waste treatment
	1.7 Biomass burning
	1.8 Emission of CFCs, HFCs, N_2O
2. Loss of biodiversity	2.1 Loss of habitat
	2.2 Fragmentation of habitat
	2.3 Herbicide, pesticide use
	2.4 Discharge of toxins to surface waters
	2.5 Reduction of dissolved oxygen in surface waters
	2.6 Oil spills
	2.7 Depletion of water resources
	2.8 Industrial development in fragile ecosystems
3. Stratospheric ozone depletion	3.1 Emission of CFCs
	3.2 Emission of HCFCs
	3.3 Emission of halons
	3.4 Emission of nitrous oxide
4. Human organism damage	4.1 Emission of toxins to air
	4.2 Emission of toxins to water
	4.3 Emission of carcinogens to air
	4.4 Emission of carcinogens to water
	4.5 Emission of mutagens to air
	4.6 Emission of mutagens to water
	4.7 Emission of radioactive materials to air
	4.8 Emission of radioactive materials to water
	4.9 Disposition of toxins in landfills
	4.10 Disposition of carcinogens in landfills
	4.11 Disposition of mutagens in landfills
	4.12 Disposition of radioactive materials in landfills
	4.13 Depletion of water resources
5. Water availability and quality	5.1 Use of herbicides and pesticides
	5.2 Use of agricultural fertilizers
	5.3 Discharge of toxins to surface waters
	5.4 Discharge of carcinogens to surface waters
	5.5 Discharge of mutagens to surface waters
	5.6 Discharge of radioactive materials to surface waters
	5.7 Discharge of toxins to groundwaters
	5.8 Discharge of carcinogens to groundwaters
	5.9 Discharge of mutagens to groundwaters
	5.10 Discharge of radioactive materials to groundwaters
	5.11 Depletion of water resources
6. Resource depletion: fossil fuels	6.1 Use of fossil fuels for energy
	6.2 Use of fossil fuels as feedstocks
7. Land use patterns	7.1 Urban sprawl
	7.2 Agricultural disruption of sensitive ecosystems

2.4.4 Actions for an Industrialized Society

The final step in the structured assessment process we are describing is that, given activities for examination, analysts can generate specific design recommendations to improve the environmental and social responsibility of their products.

Thus, the overall process described here occurs in four stages: (1) the definition by society of its Grand Objectives for life on Earth, (2) the identification by environmental scientists of environmental, societal, and sustainability concerns related to one or more of those objectives, (3) the identification by technologists and social scientists of activities of society related to those concerns, and (4) the appropriate modification of those activities. Note that implementing the fourth step in this sequence depends on accepting the definition of step one, believing the validity of step two, and acknowledging the correct attribution in step three, but not necessarily in knowing the magnitude of the impact of step four on improving the environment, that is, the information that is needed tends to be qualitative, not quantitative. From the standpoint of the industrial manager or the product design engineer, what is important is knowing that if step four is taken the corporation's environment and sustainability performance will be improved to at least some degree, and, perhaps at least as important, knowing that customers and policy makers will regard the action as a positive and thoughtful one.

In overview, the four steps of the process are schematically displayed in Figure 2.3, in which it is clear that their influence on the Grand Objectives determines the importance of each of the environmental concerns and that each of the environmental concerns leads to a group of activities for examination, each of which in turn leads to a set of product design recommendations. Note that each of the Grand Objectives and most environmental concerns relate to a number of recommendations, rather than to only one or two, and, conversely, many recommendations respond to more than one environmental concern and perhaps more than one Grand Objective. As shown at the bottom of the diagram, the relationships among the Grand Objectives and recommendations provide logical interconnections among societal consensus, environmental science, and industrial ecology.

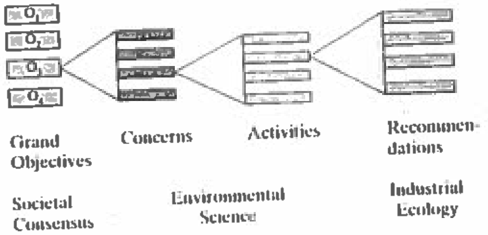


Figure 2.3

A schematic representation of the conceptual sequence in life cycle assessment. Each of the four grand challenges is related to a number of concerns, such as climate change (each concern suggested be a horizontal bar); similarly, each of the concerns is related to a number of activities, such as fossil fuel combustion (again, horizontal bars indicate different activities); and each activity is related to a number of recommendations, such as higher-efficiency combustion. As noted at the bottom, different specialist fields treat different stages in the sequence.

FURTHER READING

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EXERCISES

2.1 Section 2.2 proposes that 25–50 years is the best choice for a sustainability planning timescale. Do you agree? Explain.

2.2 Use the information in Table 2.1 to estimate how much zinc could be used in a "sustainable" automobile. Clearly show your reasoning.

2.3 Consider the quantitative sustainability example of greenhouse gases in Section 2.3.3. Discuss the options for allocating the allowable CO_2 emissions, together with the benefits and problems of the options.

2.4 Section 2.4.1 defines four "example" Grand Objectives for sustainability. Do you agree that this is the ideal set? If so, why? If not, present and discuss alternatives.

Industrial Ecology and Sustainable Engineering

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The first book of its kind devoted completely to the emerging field of industrial ecology/green engineering, this introduction uses industrial ecology principles and cases to ground the discussion of sustainable engineering—and offers practical and reasonable approaches to design decisions.

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- **Methods to better incorporate concerns about environmental and social issues into design decisions**—from the level of products and manufacturing processes to factories and material flow systems—are discussed.
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