Human Enterprise, Ecosystems, and the Future of Civilization

Introduction

After reading a wide variety of books, newspapers, and magazines over three decades, through my more recent addiction to internet news aggregation sites, and in my professional life as an engineer focused on water resources and urban infrastructure planning, I have noticed that predictions about the future tend to follow one of three major tracks.

The first track assumes that the future will be pretty much like the past. Our civilization will continue to urbanize and industrialize, we will continue to make slow but steady improvements in technology, in health, and in our overall quality of life. This will happen at significant expense to the natural world, which is regrettable, but we will manage to produce adequate food, produce the energy and other resources we need, and find ways to dispose of our wastes without damaging any critical natural processes that our civilization can't do without.

The second track predicts the imminent collapse of civilization. We will run out of fossil fuels and find no viable alternatives to them. Our food production system will collapse. Abrupt and catastrophic changes in the atmosphere and oceans will destroy the ecosystem services our civilization has come to take for granted but will be unable to exist without.

A third track envisions a near-term acceleration of technological knowledge so fantastic that it will change our civilization, our bodies, and our minds forever. With the advent of advanced artificial intelligence, robotics, nanotechnology, and biotechnology, today's concerns over energy, natural resources, and pollution will seem silly within just a few decades. On the other hand, these new technologies could give rise to dangers that make 20th-century nuclear, chemical, and biological weapons seem tame by comparison.

Are these three visions possibly talking about the same planet? People can have radically different visions of the future because no individual person is able to have a complete understanding of what the world is really like. The world is simply too complex for that. What we do all carry around inside ourselves is a mental model of what the world is like. Some of our mental models are simple, while some capture more of the complexity that is actually out there, but not too much because then our heads would explode. Depending on the mental model a person has and which vision he or she believes is most likely, he or she can make drastically different decisions about what sort of career to follow, whether and how to raise a family, and generally how to conduct his or her life and plan for the future.

I once had a high school teacher who said that any idea is only half baked until you write it down. Twenty years later, I see the wisdom in that. Writing forces you to organize your thoughts and then set them down in some coherent, reasonably concise manner. This book is my attempt to write down a wide range of voices and ideas, including a few ideas of my own, and come to some conclusions about what might happen and how I and other reasonable people in our society might want to conduct our lives based on this information.

The Status of Human Civilization

While there are undeniably pockets of suffering and unequal, unfair treatment within our civilization, on balance human beings live longer, healthier, more comfortable lives than ever before in history. The most common health and safety problems in industrialized, urbanized countries today, while they undoubtedly cause great suffering, must be put in perspective by the sufferings of the past. Heart disease, cancer, and diabetes tend to strike older adults following a long life, usually a life without major physical hardship. Our ancestors of just a few generations ago experienced high rates of child mortality, frequent death of women and babies in childbirth, bubonic plague, smallpox, polio, cholera, typhoid fever, and other deadly bacterial infections. Many children died of diarrhea and dehydration, conditions we now know can be easily treated by drinking fluids. (Of course this still happens in the less industrialized, less urbanized countries today, but the situation is improving.) Other deadly conditions have been more difficult to address, but have been so thoroughly addressed that we take them for granted in industrialized countries today. Disinfection of drinking water prevents almost all cases of cholera and typhoid fever in the industrialized world today. We simply did not understand this process until the late 19th century. Other diseases that have caused great death and suffering in the past, such as smallpox and polio, have been eradicated or nearly eliminated by vaccination. Malaria has been eradicated from many countries, although it still causes terrible suffering in some. Most broken bones and bacterial infections, which could have been deadly at any point in the past, are routinely cured by modern medicine.

Danish economist Bjorn Lomborg provides a useful set of statistics illustrating the large gains in health and longevity over the course of the 20th century. Life expectancy increased from a worldwide average of only about 30 years in 1900 to approximately 67 in 1998, with some of the greatest gains in less industrialized countries. Part of the reason for this gain was that infant mortality for the world as a whole fell from over 15% in 1950 to around 5% in 2000, with declines continuing and less industrialized countries catching up to their wealthier counterparts. Another part of the reason is that on balance people suffer far less from infectious diseases today. Using the United States as an example, mortality from infections fell from around 800 per 100,000 people to 50 per 100,000 people over the course of the 20th century. People were much better nourished in 2000 compared to 1900, with calorie intake in developing countries having increased by 38 percent and the proportion of undernourished people having fallen from 35 percent to 18 percent. Life also simply became safer, with the annual death rate from natural disasters falling over 94% during the course of the century[1] and the rate of homicide and violence also undergoing a long-term decline.[2]

One has to think not only about the direct physical effects of suffering and premature death in the past compared to today, but of the psychological effects. The psychological effects of seeing so many children die must have been horrible, as was the grim knowledge every father must have had that complications in childbirth could easily take the life of both his wife and child. City streets were full of human and animal waste, threatening human health and causing serious ecological damage downstream. Cities were a place many people went to die prematurely of disease, malnutrition or violence.[3] Today, people in cities live longer and are healthier and in less danger, on average, than their rural counterparts.[4]

The Status of Earth's Ecosystems

The scale of human civilization is large. There is no dispute that a larger scale of human activity means a smaller physical extent of natural ecosystems. The Millennium Ecosystem Assessment provides a comprehensive review of the scientific literature that illustrates well the scale of land use changes and habitat loss (Box 1).

Box 1: Quotations from the Millennium Ecosystem Assessment[5]

In 2005, the Millennium Ecosystem Assessment collected a comprehensive body of scientific evidence quantifying the magnitude of human impacts on ecosystems. The evidence is clear that the scale of land use change and habitat loss caused by humans is large compared to the original extent of Earth's ecosystems themselves. In other words, humans have altered a large fraction of the surface of the Earth.

- "The structure of the world's ecosystems changed more rapidly in the second half of the twentieth century than at any time in recorded human history, and virtually all of Earth's ecosystems have now been significantly transformed through human actions. The most significant change in the structure of ecosystems has been the transformation of approximately one quarter (24%) of Earth's terrestrial surface to cultivated systems... More land was converted to cropland in the 30 years after 1950 than in the 150 years between 1700 and 1850."
- "Within terrestrial ecosystems, more than two thirds of the area of 2 of the world's 14 major terrestrial biomes (temperate grasslands and Mediterranean forests) and more than half of the area of 4 other biomes (tropical dry forests, temperate broadleaf forests, tropical grassland, and flooded grasslands) had been converted (primarily to agriculture) by 1990... Among the major biomes, only tundra and boreal forests show negligible levels of loss and conversion, although they have begun to be affected by climate change."

[1] Lomborg, 2001
[2] Pinker, 2011
[3] Diamond, 1999
[4] Myers et al., 2013
[5] Millennium Ecosystem Assessment, 2005. It is worthwhile to note that the trend of natural ecosystem loss is continuing, but decelerating in some areas. Temperate forests are experiencing net gains in area, while tropical forests continue to be lost. Conversion of ecosystems to cropland has slowed as production of existing cropland has intensified, and cropland area has been reduced in many developed countries. Urbanized land uses are estimated to cover approximately 2.4% of terrestrial area.

- "In countries for which sufficient multiyear data are available (encompassing more than half of the present-day mangrove area), approximately 35% of mangroves were lost in the last two decades. Roughly 20% of the world's coral reefs were lost and an additional 20% degraded in the last several decades of the twentieth century"
- "Global fishery catches from marine systems peaked in the late 1980s and are now declining despite increasing fishing effort"
- "The global area of forest systems has been reduced by one half over the past three centuries. Forests have effectively disappeared in 25 countries, and another 29 have lost more than 90% of their forest cover"
- "It is speculated that 50% of inland water area (excluding large lakes) has been lost globally. Dams and other infrastructure fragment 60% of the large river systems in the world"
- "Cultivated systems, including croplands, shifting cultivation, confined livestock production, and freshwater aquaculture, cover approximately 24% of total land area. In the last two decades, the major areas of cropland expansion were located in Southeast Asia, parts of South Asia, the Great Lakes region of eastern Africa, the Amazon Basin, and the U.S. Great Plains."

Another profound statistic illustrating the sheer scale of human activity compared to natural systems is the fraction of primary productivity being appropriated directly by human beings as food, energy, and raw materials. A group of researchers led by Steven Running at the University of Montana proposed using the amount of net primary productivity humanity has "appropriated" as a "planetary boundary" or measure of human impact on ecosystems. I will discuss the planetary boundary concept in more detail in the next section.

> ***"Terrestrial plant production is the foundation of the biospheric carbon cycle. Using solar energy, water and atmospheric CO_2 are transformed into plant carbohydrate matter. This plant matter then sustains the global food web and becomes the source of food, fiber, and fuel for humanity. [Net primary productivity] NPP integrates aspects of five of the currently defined planetary boundaries: land-use change, freshwater use, biodiversity loss, and global nitrogen and phosphorus cycles. It is also influenced directly by two others, climate change and chemical pollution."***

Running estimates terrestrial net primary productivity at 53.6 Pg/yr[6]. Of this, humans are estimated to be appropriating, consuming as food or directly co-opting for energy or raw materials, approximately 38%. Running's team has estimated that 53% of NPP is not harvestable because it "includes plant growth in root systems, preserved land (for example, in national parks that are critical for ecosystem services and biodiversity), and wilderness areas where no transportation exists for harvesting." Approximately 10%, or 5 Pg/yr, remains available to be possibly appropriated by humans.[7]

Together, the statistics above suggest that humans have altered on the order of half the land surface of the Earth and appropriated half its ecological productive capacity. These statistics help capture the magnitude of displacement of the natural world by the human world, but it is more difficult to capture

[6] A Petagram (Pg) is one thousand trillion (10^{15}) grams, or one trillion kilograms.
[7] Running, 2012

loss of quality or functions of the ecosystems. We can gain some understanding from scientific estimates of species extinction. While humans have displaced or altered something on the order of half of the area of all ecosystems, and half of the annual terrestrial primary productivity, the statistics on estimated species extinctions are much more profound. Currently, the rate is estimated to be at least 100 extinction events per million species per year, and predicted to increase by another factor of 10 in the coming century. This can be compared to an estimated background rate on the order of 0.1. [8]

Many human beings who have spent time engaging nature throughout their lives cannot help feeling a sense of profound sadness that the natural world is being altered so drastically. These people feel deeply that nature has an intrinsic value and right to exist, independent of any value or usefulness it may have for the human species. I find the statistics on species loss, and the collapse of ancient ecological functions I fear they may represent, deeply shocking. That there is no widespread public outcry suggests either that not everyone shares my own values, or that these scientific results are not being communicated in a way that influences public opinion.

There are some valid scientific criticisms of the work on species loss. Species loss cannot be measured directly; in fact, even the total number of species on Earth is controversial. Species loss can be studied on a smaller scale, for example before and after an area of an ecosystem is cleared for development. Results of these studies are then extrapolated to larger areas. While the Millennium Ecosystem Assessment has documented the scientific consensus view, there is a range of debate in the scholarly literature. Similarly to the case with climate change, those outside the scientific community tend to pick and choose which experts to believe based on their own values. Those who care deeply about nature for its own sake may tend to believe the most pessimistic estimates, while those who care less may tend to believe the more optimistic estimates. If I am right and the scientific results on species loss are being viewed by the public and politicians through the lenses of different preconceived notions, then the way in which the scientific results are being reported may not be affecting overall public opinion.

Although I believe that the more people interact with nature, especially as children, the more they will come to value it for its own sake, I recognize that reasonable, decent human beings hold a range of values and that not everyone shares my values. It reasonable to ask what ecosystems have done for humanity lately, to make sure we understand what would be lost if the functions of those ecosystems were to be lost or degraded beyond repair.

What Earth's Ecosystems do for Humans

When we talk about what ecosystems do for humanity, we can use the economic concept of services – actions performed by one party that have some value to other parties. Ecosystems provide crucial services without which human civilization could not exist. The Millennium Ecosystem Assessment has tried to define and categorize these ecosystem services.

One category of ecosystem services defined by the Millennium Ecosystem Assessment is "cultural" services - aesthetic, spiritual, educational, and recreational services. This category attempts to capture

[8] Rockstrom et al., 2009

health and psychological benefits to people during their interactions with and experiences in nature. These services come closest to capturing the intrinsic value of nature discussed in the previous section, but still represent the point of view of that subset of humans who feel deeply enriched by their interaction with nature or at least their knowledge of nature's existence.

A second category is "supporting" services such as nutrient cycling, soil formation, and primary production. These are critical processes required for the continued existence of ecosystems, including cropland, pasture, and managed forest ecosystems that human society depends on. As long as we depend on these ecosystems, these services are indispensable.

A third category is "provisioning" services: food, water, wood, fiber, and fuel. These are useful objects and substances that humans extract directly from ecosystems. Perhaps we can find higher-tech, alternate sources of some of these substances in the future, and learn how to recycle them better within our own civilization with less help from nature, but we can do this only with major changes to our current knowledge and practices and at a financial cost. An example, which I will return to several times, would be producing food in skyscrapers using artificial light and sea water desalinated by nuclear energy.

A final category is "regulating" services - climate regulation, flood regulation, disease regulation, and water purification. These are more examples of "services" that nature provides to us currently at little to no financial cost. We can and do augment many of these services using manufactured capital and human labor, for example air conditioning to control indoor climate; reservoirs and levees to control the hydrologic cycle; water disinfection, food hygiene, and modern medicine to control disease; and water treatment facilities. However, these practices are all expensive in terms of financial capital and energy. The more we can rely on nature to provide these services for free, the more money and energy we free up for other purposes.

But How Important are Ecosystem Services, Really?

If ecosystem services are virtually indispensable and irreplaceable, surely we can say that they are "valuable", correct? This statement may be correct based on a common sense, dictionary definition of the word "value". However, the economic definition of value differs from the common sense definition because it depends both on the importance of the service and on its scarcity. For example, oxygen is certainly indispensable and irreplaceable to support human life, but because it is abundant and we have no reason to think that will change any time soon, we do not expect to have to take out our wallets and pay money for it. If we imagine ourselves on a space station where we did have to pay for oxygen, we would very quickly decide that it is a service worth paying for.

The paradox is that because nature has so far provided many services in abundance, they are not "scarce" in an economic sense and our human markets place little or no monetary value on them. This would change in the event our human civilization caused the services to be reduced or interrupted in any way. While it may seem strange to value ecosystem services in monetary terms, it can be instructive to ask what we would be willing to pay if we had no choice but to pay for these services. There are many conceptual and practical challenges with this sort of monetary valuation, but there have been some brave attempts to do it, such as those led by Robert Costanza at the Australian National University.[9] By comparing the magnitude of what we would be willing to pay for these services to the magnitude of the human economy, we can get a sense of the importance of ecosystem services in underpinning our human economy. Costanza's estimate of the annual value of global ecosystem services ($33 trillion in 1997 U.S. dollars) is the same order of magnitude as the world output of goods and services in that year (approximately $29 trillion[10])! While the estimated value of ecosystem services is certainly less precisely measured than the monetary value of goods and services produced, the order of magnitude suggests that humanity could not afford to substitute its own technology and efforts in place of the services provided by ecosystems, at least not with the wealth and knowledge available to us now.

How much Natural Capital and Natural Resources are there?

Ecosystem services are generated by natural capital. We can use the analogy of a bank account containing an amount (a "stock") of capital and able to generate a fixed amount of interest each year. If we withdraw only the interest produced each year, the level of capital is maintained. If we withdraw more than the interest produced, the capital is depleted. We can live very well for a period of time by withdrawing capital, but there comes a point where the capital is too depleted to continue supporting our accustomed lifestyle. The financial capital in this bank account is analogous to the natural capital of Earth, including its nonliving and living components. It includes the natural resources and raw materials we can extract and consume directly, the substrates and living tissues of ecosystems themselves, and the ability of ecosystems to act as sinks for humanity's waste products. The natural capital stock is the source of all ecosystem services.

At this point it is important to note that a reasonable definition of natural capital includes only the portion of the Earth's living and nonliving components that are or may eventually be of use to humans, and not all the constituents of the Earth and its ecosystems. Human civilization displaces nature to a certain extent - by consuming any ecosystem services at all, we are reducing the "size" of nature. As long as our value system accepts human civilization as something that has a right to exist, we have to also accept some diminishment of nature. We can however establish a vision of a future civilization that exists in greater harmony with nature than our current one, a topic I will take up toward the end of this book.

The interest paid by the bank is analogous to the ability of natural ecosystems to replenish themselves when some of their resources are consumed (i.e. withdrawn, altered, polluted, damaged) by humans as ecosystem services. Happily, the Earth is not a closed system and receives a considerable influx of solar energy each year, giving it some ability to replenish natural capital that has been depleted by human activity. We can think of primary productivity, the amount of new plant biomass produced each year

[9] Costanza, 1997
[10] International Monetary Fund, 1999

from solar energy, as representing replenishment of natural capital.[11] Each year humans consume a portion of the ecosystem services produced, and the earth replenishes a portion. The difference between what is consumed and what is replenished represents the change in natural capital for that year (Figure 1).[12]

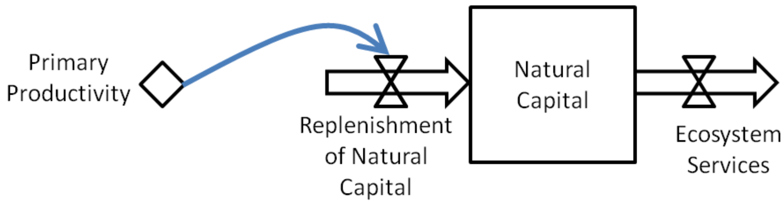

Figure 1: Stock and Flow Diagram for Natural Capital

The natural capital stock can be conceived of as analogous to a bank account, where ecosystem services are interest paid. The account is replenished by deposits made when solar energy is converted to primary production. The difference between what is consumed and what is replenished over time represents a change in natural capital.

The bank account analogy will be most useful if we can find an accurate way to quantify natural capital and ecosystem services. Given an accurate way to do this, we could calculate whether humanity's current consumption of ecosystem services is sustainable, or is destined to deplete natural capital in the long term. There are some serviceable, though inexact and controversial, methods of assigning annual values to ecosystem services. As discussed in the last section, a seminal study on this subject is Robert Costanza's 1997 paper, "The Value of the World's Ecosystem Services and Natural Capital". However, a problem with the bank account analogy is that it is even more problematic to measure the total stock of natural capital than it is to measure the annual flows of ecosystem services. There is no exact, agreed-upon definition of natural capital or of what units it should be measured in. (Costanza's paper, despite its title, contains no estimate of the value of the world's natural capital!) The uncertainties involved in valuing natural capital in terms of current U.S. dollars (or euros or pounds or yen) seem nearly insurmountable.[13]

U.S. dollars and other currencies used by human beings are not the only possible units for an attempt to quantify natural capital. For example, ecologist Howard T. Odum at the University of Florida proposed a unit called "embodied energy". I propose that a reasonable candidate for representing the rough order of magnitude of natural capital is the amount of carbon present in nonliving and living resources that

[11] Tidal and geothermal energy are inputs of energy in addition to solar, but I limit the discussion to solar energy for simplicity.

[12] In this book, I do not make a strong distinction between renewable and non-renewable resources because I suspect that with increasing knowledge, renewable resources or other technologies eventually can be substituted in the future for today's consumption of nonrenewable resources. The reader can judge the validity of this assumption after reading my arguments.

[13] In principle it is possible to take Costanza's estimate of the annual monetary value of ecosystem services, choose an appropriate discount rate, and come up with a dollar figure for current natural capital. However given uncertainties over the rate of replenishment vs. consumption, long-term inflation of any given currency chosen and lack of consensus among economists about appropriate discount rates for very long-term analysis, such a calculation seems meaningless.

are of use to humans. Figure 2 is a visual depiction of the estimated magnitude of fossil fuel reserves and carbon associated with forests worldwide. From this point forward, we will use the sum of these two quantities (about 1.7×10^{15} kg C) as a proxy for the world's natural capital stock.[14] It is interesting to compare this stock of carbon to the flow of annual net primary productivity, recalling our bank account analogy. In our highly simplified but conceptually useful framework, this is theoretically the maximum amount we could "withdraw" each year without depleting our capital.

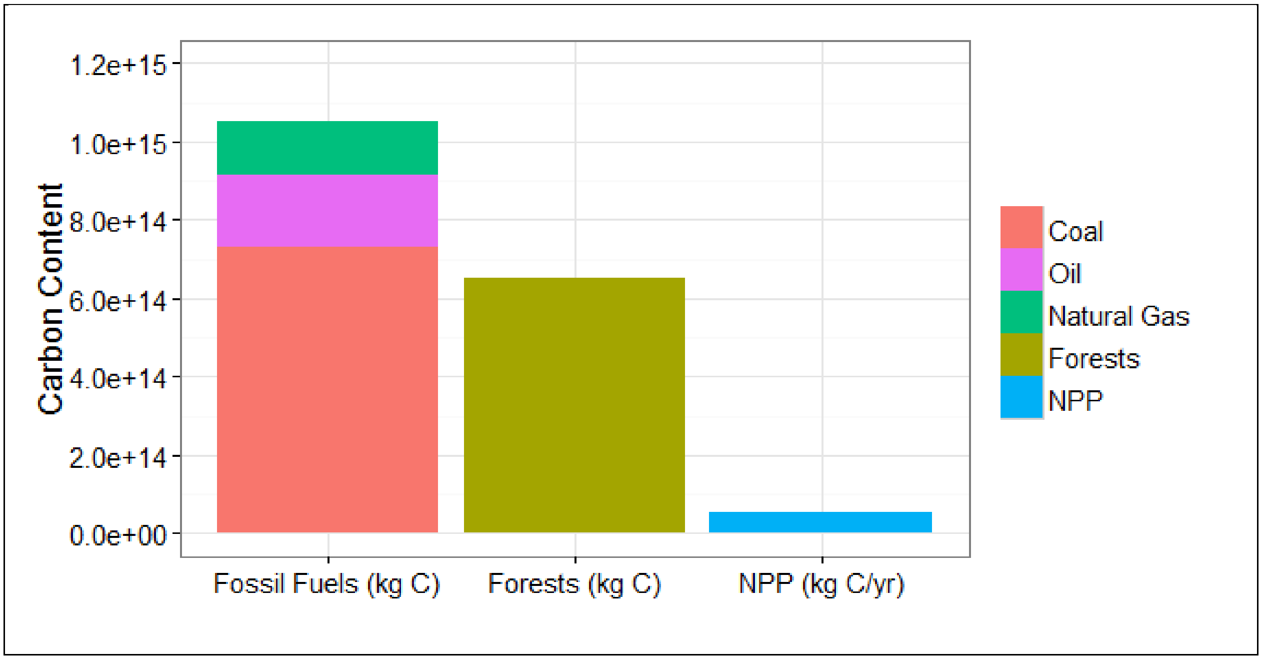

Figure 2: Magnitude of Carbon Stocks and Net Primary Productivity

Estimating the magnitude of the world's carbon stocks is one possible way to quantify natural capital. Fossil fuels and forests are two large stocks of carbon that researchers have attempted to measure. We can also compare the magnitudes of these stocks to the annual flow of net primary productivity on Earth. In this figure, fossil fuels represent only "proved reserves".[15] Carbon in forests is an estimate of living biomass, dead wood, and carbon in soils underlying forests.[16] "NPP" is net primary productivity.[17]

[14] This is an underestimate for at least two reasons. First, fossil fuel estimates represent "proved reserves" only, which is only a fraction of all geological resources existing. Second, there is certainly significant carbon in ecosystems other than forests, such as grasslands and the ocean. Nevertheless, we will treat this value as a reasonable proxy because the exact number is simply unimportant.

[15] BP, 2013

[16] FAO, 2010

[17] Running, 2012

Can we Really Use Up or Seriously Damage Nature?

Ecological Footprint and Planetary Boundaries

The ecological footprint, first proposed by Mathis Wackernagel[18], attempts to answer the question whether our consumption of ecosystem services is withdrawing capital at a rate greater than natural ecosystems can replenish that capital. Where Costanza and others have attempted to quantify consumption of ecosystem services in terms of currency, and Howard T. Odum in terms of energy, and the discussion above in terms of mass of carbon, the ecological footprint concept attempts to do so using a common denominator of land. The concept is intuitive - if the land required to produce the ecosystem services we are consuming is less than or equal to the amount of land on Earth, natural capital is not being depleted, i.e. we are "living on the interest" of our capital. If the amount of land required is more than the land present on Earth, natural capital is being depleted and eventually there will be consequences. The Global Footprint Network has estimated that humanity as of 2010 is using the equivalent of 1.5 times the annual ecosystem services provided by Earth.[19] At a ratio of 1.0, we would be consuming what the Earth is able to produce in one year, while at 1.5, we exceed what the Earth provides by 50%, and are dipping into our reserve of natural capital to make up the difference.

A more recent academic treatment of ecosystem services and natural capital is the attempt of Rockstrom et al. in 2009 to define a set of "planetary boundaries" or a "safe operating space" for humanity. In addition, S.R. Running proposed the additional planetary boundary of primary productivity appropriation in 2012. We can interpret the concept of planetary boundaries to mean that when we exceed these boundaries, we are depleting natural capital rather than merely subsisting on ecosystem services in a sustainable manner. When we cross the boundaries, we are outside the "safe operating space" and we can eventually expect consequences. Figure 3 is a visual interpretation I have prepared of the published work of Wackernagel, Rockstrom et al., and Running. In addition to the exceedance of ecological footprint by 50%, estimates are that three of the proposed planetary boundaries have been greatly exceeded already, and that humanity is approaching all the others. This evidence leads to a conclusion that the ecosystem services consumed by humanity each year exceed what the Earth can supply sustainably, and represent a drawdown of natural capital. In the words of Rockstrom et al.,

> ***The exponential growth of human activities is raising concern that further pressure on the Earth System could destabilize critical biophysical systems and trigger abrupt or irreversible environmental changes that would be deleterious or even catastrophic for human well-being.***[20]

[18] Wackernagel, 1996
[19] Global Footprint Network, 2012
[20] Rockstrom et al., 2009

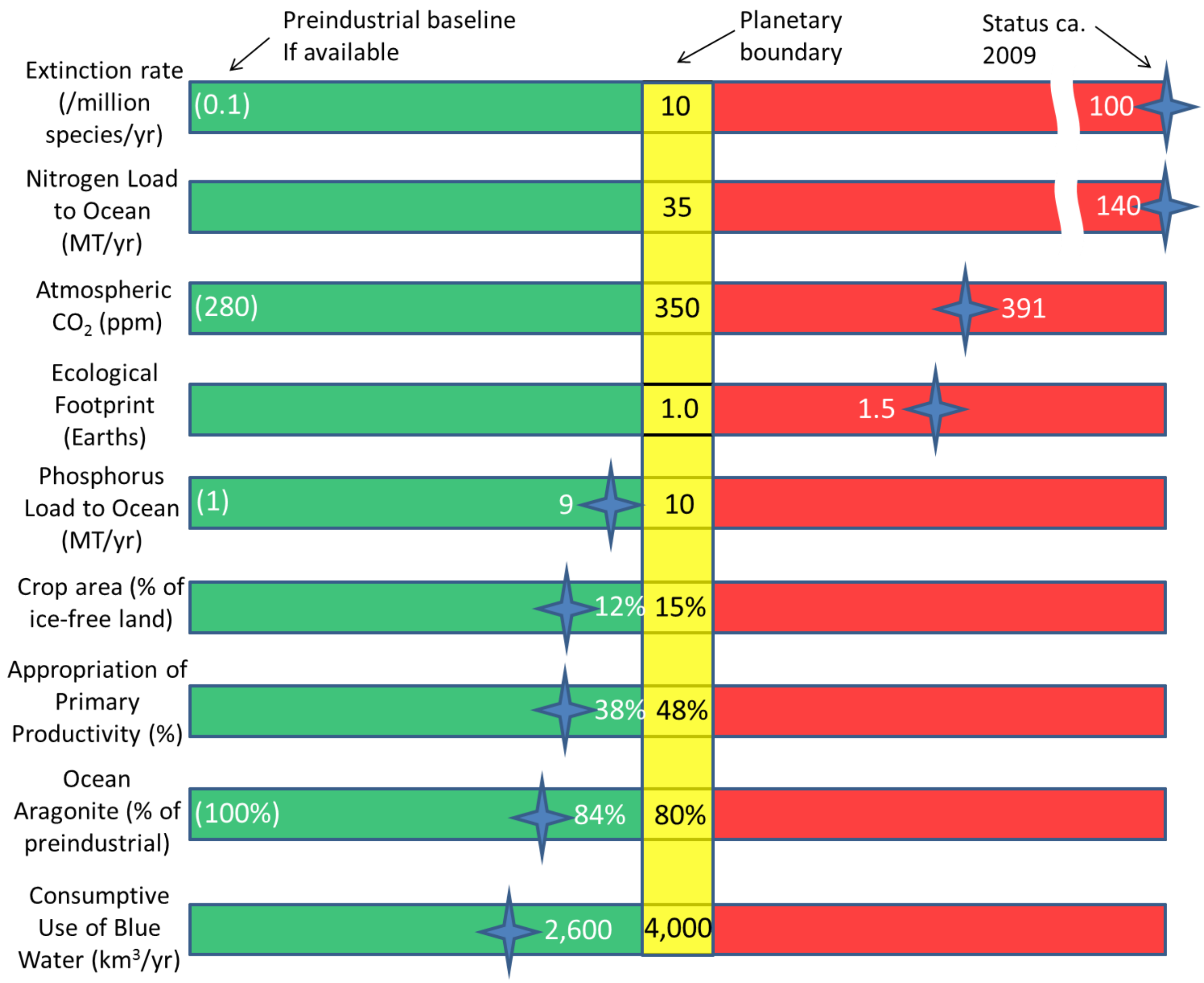

Figure 3: Summary of Ecological Thresholds Proposed by Several Researchers.

Several researchers have attempted to quantify the magnitude of human activity and human impacts on ecosystems, and thresholds at which these impacts may begin to threaten the continued flow of ecosystem services. Please note that this graphic is intended as a visual summary of scientific information but it is not numerically precise, is not to scale, and is highly simplified compared to the information presented by the researchers themselves.

Biodiversity. As I discussed earlier, there is a clear ethical case for biodiversity conservation, for those whose values are consistent with it. For that subset of people, no practical argument may be necessary. Many attempts at practical arguments have been made, but they may fail to sway people who do not already feel a responsibility to conserve nature. A common practical argument is that conserving biodiversity is an indirect method of conserving genetic diversity (which is even harder to measure.) Until the recent dawn of synthetic biology, the incredible variety of genetic patterns that has evolved on Earth since the dawn of life has given rise to all the organisms useful to humans in hunting and gathering, fishing, agriculture, forestry, and medicine. Because only a small portion of the Earth's genetic diversity has been explored by humans, there may be genetic resources of enormous value remaining to be discovered. If, through human activity such as habitat destruction, climate change, or pollution, we cause the extinction of those genetic patterns before they can be discovered, their potential benefits will be lost forever. Richard Posner makes an argument that "[t]he less genetic diversity there is, the greater the potential impact on human welfare of plant disease, climate change, and other environmental stressors... there may be a slight risk of destroying most human agriculture through [a] kind of domino effect...where the disappearance of a species or other group reverberates up and down the food chain, with potentially catastrophic effects if a very large number of species go extinct in a short period of time."[21] The group led by Rockstrom argues that losing biodiversity decreases the resilience of systems, increasing the chance of abrupt change or collapse.: "Previous extinction events, such as the Tertiary extinction of the dinosaurs and the rise of mammals, caused massive permanent changes in the biotic composition and functioning of Earth's ecosystems. This suggests non-linear and largely irreversible consequences of large-scale biodiversity loss." They suggest an upper limit to the "safe operating range" of no more than 10 extinctions per species per year.[22]

Biogeochemical Flows: Interference with phosphorus and nitrogen cycles. Loads of nitrogen and phosphorus are making their way from farm and urban runoff, and from partially treated waste streams, to aquatic ecosystems and particularly marine estuaries, causing severe ecological damage and impacting fisheries. Rockstrom's group suggest limiting flows of nitrogen into the environment to only 25% of the current value, or limiting to 35 MT N/yr. For phosphorus, they suggest no more than 10 times the natural background weathering flux (this background flux estimated at 1 Mt P/yr). The current input to the oceans, over the original background rate, is estimated at 9 Mt/yr, suggesting that the oceans as a whole can withstand the current flux but no more.[23]

Climate Change. Rockstrom's group identify the boundary of the safe operating range as a temperature rise over preindustrial levels of no greater than 2 degrees C and atmospheric greenhouse gas concentrations no greater than 350 ppm CO_2e. Potential consequences of crossing these boundaries include "disruption of regional climates, ...collapse of major climate dynamics patterns such as the thermohaline circulation, and...other impacts difficult for society to cope with, such as rapid sea-level rise."[24] Currently, atmospheric carbon dioxide concentration is approximately 391 ppm CO_2 and continuing to rise.[25]

Land-System Change. Conversion of ecosystems to agricultural and urban uses affects nearly all ecosystem services, from water, carbon, and nutrient cycling, to biodiversity. Rockstrom's group recommend a boundary on "global ice-free land surface converted to cropland" of no more than 15%, compared to a current value of approximately 12%.[26]

Ocean Acidification. Oceans are currently able to absorb approximately 25% of annual CO_2 emissions by dissolving them in seawater and through uptake by marine organisms. However, this process lowers the pH of seawater and will eventually reach levels where marine organisms containing carbonate materials

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[21] Posner, 2004
[22] Rockstrom et al., 2009
[23] Rockstrom et al., 2009
[24] Rockstrom et al., 2009
[25] IPCC, 2013
[26] Rockstrom et al., 2009

will be threatened and no longer able to function as carbon sinks. As a boundary, Rockstrom's group recommend maintaining ocean aragonite (a carbonate-containing material) saturation at 80% or more of its preindustrial level. The current value stands at approximately 84%.[27]

Global Freshwater Use. Rockstrom's group describe the global depletion of freshwater as follows:

> ***Global manipulations of the freshwater cycle affect biodiversity, food, and health security and ecological functioning, such as provision of habitats for fish recruitment, carbon sequestration, and climate regulation, undermining the resilience of terrestrial and aquatic ecosystems. Threats to human livelihoods due to deterioration of global water resources are threefold: (i) the loss of soil moisture resources (green water) due to land degradation and deforestation, threatening terrestrial biomass production and sequestration of carbon, (ii) use and shifts in runoff (blue water) volumes and patterns threatening human water supply and aquatic water needs, and (iii) impacts on climate regulation due to decline in moisture feedback of vapor flows (green water flows) affecting local and regional precipitation patterns.***[28]

Rockstrom's group recommend staying within a boundary of 4,000 km^3/yr of "consumptive use of blue water". The current value is approximately 2,600 km^3/yr.[29]

Air pollution. Rockstrom's group describe the impacts of air pollution both on human health and on the climate system itself, such as suspected effects on the Asian monsoon. However, they conclude that it is not yet possible to define an upper bound to the safe operating range.

Chemical pollution. According to Rockstrom's group, there are 80,000 to 100,000 chemicals on the global market. Toxicity data exist for only a few thousand of them, and there is very little understanding of their combined effects. Chemicals pervade our air, water, food, and consumer products. We know certain chemicals have built up in the fatty tissues of animals, including humans. For some, like mercury and lead, we are well aware of acute toxic affects and have evidence of chronic effects. Even if we address all toxicity concerns, there are still concerns about long-term carcinogenic and endocrine-disrupting effects. While we may not be ready to give up chemicals that are clearly useful and for which there are no immediate substitutes, caution is clearly in order. We simply do not have a complete understanding of even naturally occurring beneficial chemical compounds. For example, when we have tried to replace fresh vegetables with manufactured vitamins or breast milk with manufactured baby formula, we have found that the populations using the original tended to be a little healthier. Impacts of chemicals should be thought of similarly. We simply do not know in many cases what they may be doing to us, particularly in combination. However, perhaps we should admit to ourselves that our concerns about chronic effects of small amounts of chemicals are a luxury we can indulge in only because we have solved more pressing problems that have caused widespread disease, suffering, and death among

[27] Rockstrom et al., 2009
[28] Rockstrom et al., 2009
[29] Rockstrom et al., 2009

the young and healthy in the past. The team led by Rockstrom suggested further research but did not develop a suggested upper limit for chemical pollution.

Food

When humanity transcends these planetary boundaries, how might the results be felt by our civilization? Let us look more closely at food, because food supply is at the intersection of many of the ecosystem services that are potentially subject to planetary boundaries: energy, water, nutrients, climate, and genetic diversity, to name a few.

In economic terms, we can think of the demand for food as the amount people are willing to buy at the current price. If the supply is not able to meet the demand for any significant period of time, an absolute shortage of food will result. A more likely scenario is one in which supply is restricted, causing the market price to rise so that people are not demanding more than the amount that can be supplied. In this situation, either the poorest people will go hungry or governments will be forced to step in with rationing and price controls.

We must begin our discussion of food with the obligatory quote from Thomas Malthus:

> ***Population, when unchecked, increases in a geometrical ratio. Subsistence increases only in an arithmetical ratio. A slight acquaintance with numbers will shew the immensity of the first power in comparison of the second.***[30]

Malthus, writing in 1798, probably could not have imagined the geometric population explosion experienced in the 20th and early 21st centuries. Nor could he have imagined the great increases in agricultural yield made possible by new technologies and far greater inputs of fertilizer, chemicals, and irrigation, which have so far been able to meet the vastly increased demand for food. The fact that the food supply has kept up with demand throughout the 20th century is often cited as evidence that Malthus was wrong and that scarcity, or the threat of scarcity, will drive the necessary innovation to meet demand. However, there is some evidence that Malthus's mathematics may finally be catching up to humanity in the 21st century.

Lester R. Brown provides a well-researched set of reasons why global food security may be a very real concern today. His voice is a pessimistic one, but a pessimistic one backed by an extensive and well-documented body of evidence that can be linked directly to the ecosystem services and planetary boundaries we have been discussing.

[30] Malthus, 1798. I wonder how many people who quote Malthus have read his whole essay from beginning to end. A casual reading of the first few pages leads one to interpret his theory to mean that the tyranny of mathematics will cause population to rise exponentially while resources remain fixed, leading to inevitable catastrophic crashes. With a more careful reading, it is true that he assumed resources to be fixed within a given geographic area. However, he believed various societies develop various social mechanisms ("preventive checks" in his words) intended to limit population growth to what the available resources can support. He referred to famine as "the last and most dreadful mode by which nature represses a redundant population".

Listing factors likely to restrict food supply in the near future, he argues convincingly that soil erosion, dust storms, and expanding deserts have reached critical levels in important food-growing regions. Groundwater aquifers are being overpumped and permanently depleted in several of these important food-growing regions, particularly China, India, and the United States.[31] Glaciers are melting that historically have fed key river and irrigation systems in important food-growing regions.[32] Cropland is being converted to urbanized land uses. Water supplies historically used for irrigation are being diverted to urban areas. Climate change may reduce grain yields by causing more frequent and intense heat waves and droughts in important food-growing regions. At the same time, sea level rise threatens inundation of coastal food-growing areas, particularly in Asia. Many wild fisheries have been depleted and are in danger of collapse.[33] Agricultural technology, such as biotechnology, at the moment is not resulting in large gains in productivity. Brown believes this is because "harvest-expanding scientific advances are ever more difficult to come by as crop yields move closer to the inherent limits of photosynthetic efficiency. This limit in turn establishes the upper bounds of the earth's biological productivity, which ultimately will determine its human carrying capacity." Supplies of conventional fossil fuels may have peaked, and the productivity of modern agriculture depends heavily on fossil fuels not only to drive mechanical processes and to transport agricultural products, but for groundwater pumping and operation of irrigation systems, and for production of fertilizers and pesticides.

At the same time supply is threatened, the demand for food and particularly grain continues to grow. In order for price to rise, supply does not have to drop and can even be growing. Supply only needs to be increasing at a slower rate than demand would increase if price were held constant (exactly the situation Malthus worried about). Brown argues that demand is likely to outpace supply for several reasons. The world's population continues to grow. Even as the population grows, each person is demanding more animal protein, most of which is grain-fed. With wild fisheries severely depleted, farm-raised seafood creates an additional demand for grain and soybean-based feed. Grain also is being demanded for use as fuel for vehicles.

A modernized adaptation of Malthus might state that the *impact of human civilization on ecosystem services that civilization depends on* cannot continue to expand indefinitely. At some point, the impact has to stop expanding either because humanity has found substitutes for ecosystem services, or because the *scale* of human civilization has been reduced either by choice or by catastrophe.

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[31] Brown, 2009: " A World Bank study shows that 175 million people in India are being fed by overpumping aquifers. In China, this problem affects 130 million people."

[32] Brown, 2009: "It is the ice melt from glaciers in the Himalayas and on the Tibetan Plateau that sustain the major rivers of India and China, and the irrigation systems that depend on them, during the dry season. In Asia, both wheat and rice fields depend on this water. China is the world's leading wheat producer. India is number two. (The United States is third.) These two countries also dominate the world rice harvest. Whatever happens to the wheat and rice harvests in these two population giants will affect food prices everywhere. Indeed, the projected melting of the glaciers on which these two countries depend presents the most massive threat to food security humanity has ever faced."

[33] Brown, 2009: "Three fourths of oceanic fisheries are now being fished at or beyond capacity or are recovering from overexploitation. If we continue with business as usual, many of these fisheries will collapse."

Fossil Fuels

We could discuss the production and consumption of any number of natural resources or raw materials. For example, some have suggested that known reserves of phosphorus will all have been extracted and converted to fertilizer within just a few decades. There is no substitute for phosphorus as it is absolutely essential for plant growth. There is no substitute for energy either, and at the moment most of our energy comes from fossil fuels. Much has been written about fossil fuels in general and oil supplies in particular. I will not try to reproduce or summarize that extensive literature, but I will close this section of the book with a brief focus on oil as an illustrative case.

As mentioned earlier, there is a group of people who feel deeply that nature has intrinsic value. To these people, and I consider myself to have at least one foot in this camp, the sheer physical footprint of our current urbanized and industrialized society is unacceptable. Raw material extraction and waste discharges make it even less acceptable, and further exponential growth will only make the situation exponentially worse. However, many people seem to be perfectly happy with the state of urban and industrial society and the comforts it offers in our daily lives. Whether the members of this group should feel concerned about their future comfort depends on which of two camps they fall into: those who think viable alternatives can be found to fossil fuels before they run out, and those who do not.

A particularly shrill voice warning of the dangers of reliance on fossil fuels is that of James Howard Kunstler. In his book *The Long Emergency*, he paints a picture of a society whose population and technological growth over 200 years has been based on depletion of a non-renewable resource, fossil fuels in general and conventional oil in particular. Kunstler believes our civilization is in imminent danger of running out of this resource, or at least the ability to extract what is left in any feasible or economical manner, with no backup plan for any resource or mix of resources to replace it. Rather than the beginning of a long-term trajectory of accelerating growth and progress, he sees the last two centuries of human economic and technological progress as an anomaly that is going to come crashing down, leading to mass starvation and returning our society to a pre-industrial agricultural state.

> ***Everything characteristic about the condition we call modern life has been a direct result of our access to abundant supplies of cheap fossil fuels... Before fossil fuels - namely, coal, oil, and natural gas - came into general use, fewer than one billion human beings inhabited the earth. Today [2005], after roughly two centuries of fossil fuels, and with extraction now at an all-time high, the planet supports six and a half billion people. Subtract the fossil fuels and the human race has an obvious problem. The fossil fuel bonanza was a one-time deal, and the interval we have enjoyed it in has been an anomalous period in human history. It has lasted long enough for the people now living in the advanced industrialized nations to consider it absolutely normative. Fossil fuels provided for each person in an industrialized country the equivalent of having hundreds of slaves constantly at his or her disposal. We are now unable to imagine a life without them - or think within a different socioeconomic model - and therefore we are unprepared for what is coming...***

> ***The U.S. economy of the decades to come will focus on farming, not high-tech, or "information", or "services", or space travel, or tourism, or finance. All other activities will be secondary to food production, which will require much more human labor... To put it simply, Americans have been eating oil and natural gas for the past century, at an ever-accelerating pace. Without the massive "inputs" of cheap gasoline and diesel fuel for machines, irrigation, and trucking, of petroleum-based herbicides and pesticides, or fertilizers made out of natural gas, Americans will be compelled to radically reorganize the way food is produced, or starve.***[34]

This idea, that modern industrialized civilization is not the first leg of a long-term journey of growth and progress, but instead a temporary overshoot made possible by a sudden burst in exploitation of a limited and irreplaceable resource, is echoed by Howard T. Odum:

> ***Few understand that cheap food, clothing, and housing depend on cheap energy and that potatoes are really made from fossil fuel. High agricultural yields are feasible only because fossil fuels are put back into the farms through the use of farm equipment, manufactured chemicals, and plant varieties kept adapted by armies of agricultural specialists supported by the fossil fuel-based economy.***[35]

Let us look at the oil data for the past few decades (a period for which both production and daily price data are readily available.) A reasonable definition of peak oil would be a constant or declining annual production volume due to a physical limitation on what can be pumped out of the ground. Looking at the data on worldwide oil production (Figure 4)[36], we do see a gradual, long-term increase in production, with some years of flat production in the early 1990s and early 2000s, periods of known economic recession. Then, however, we see a suspicious plateau during the economic expansion years of roughly 2004 to 2008. Perhaps we can interpret this as supporting the peak oil theory. However, production has been increasing again for each of the four years from 2009 to 2012, as new technologies for extracting oil from shale formations and tar sands have started to come online. However, we may be able to explain these trends fully in terms of economic expansion and recession affecting demand for oil. To explore the trend more thoroughly, we need to also look at price data. But first let us review the concepts of supply, demand, and use.

Oil supply is simply the amount of oil pumped out of the ground each year. Demand is the amount consumers are willing and able to purchase. Clearly, this amount is a function of price. If price goes up, people will be willing and able (demand) to purchase less, and if price falls, people will be willing and able (demand) to purchase more. If the amount demanded is momentarily more than the market is able to supply, the price will rise nearly instantly until demand is lowered to the available supply. In a well-functioning market, supply will always equal demand. The amount actually used will also equal the

[34] Kunstler, 2005
[35] Odum, H.T., 2007
[36] BP, 2013

demand, unless there is some catastrophic physical breakdown in the system.[37] Because of the way markets equilibrate supply, demand, and use, it is not so much the supply data itself that is informative, but the history of price.

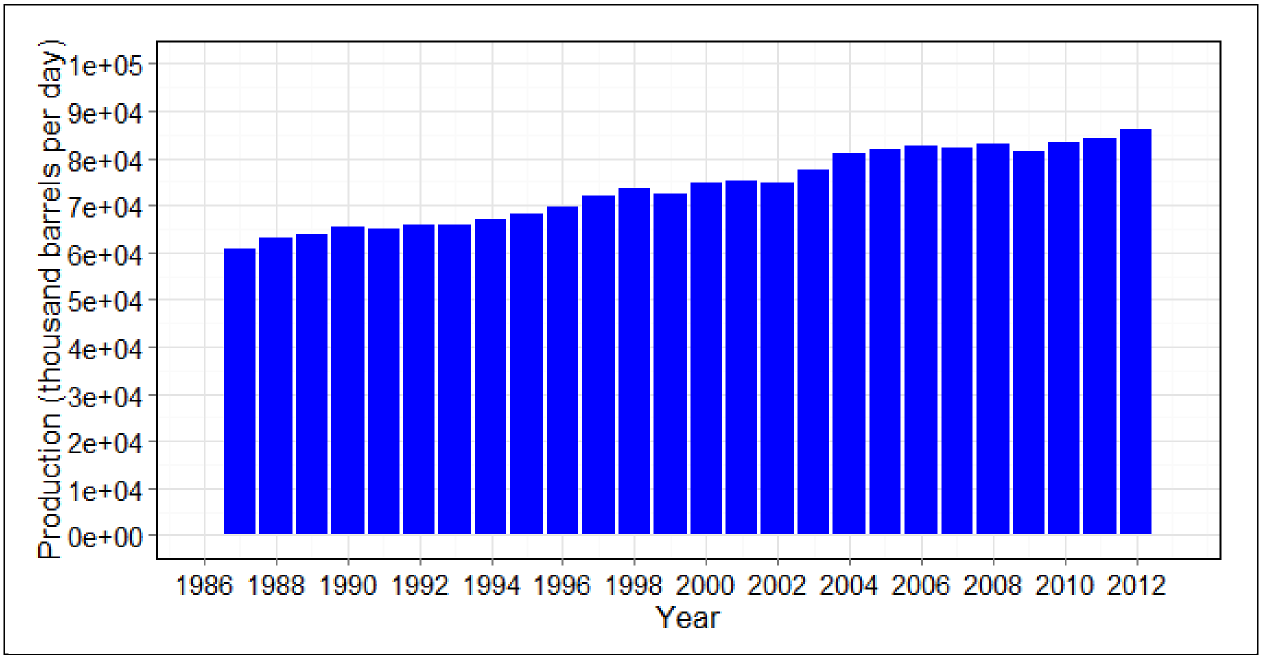

Figure 4: Long-Term Trend in World Oil Production

The historical trend is a gradual, long-term increase in production, with some years of flat production in the early 1990s and early 2000s, periods of known economic recession. However, we see a plateau during the economic expansion years of roughly 2004 to 2008, when we might expect to see an increase. However, production has been increasing again for each of the four years from 2009 to 2012, as new technologies for extracting oil from shale formations and tar sands have started to come online.

Looking at price data (Figure 5)[38] along with supply data tells a much more informative story. Median[39] oil prices stayed within the range of $20-40 per barrel (in 2012 U.S. dollars, adjusted for inflation) for the entire period 1987 to 2003. During the expansion years of 2004 to 2008, the years of flat production, median prices skyrocketed to over $100 per barrel. Over a short period such as a year, there is a fixed upper limit on what can be physically supplied, so prices rise to force demand down to what can be

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[37] Even then, without government intervention a breakdown would mean a sharp decrease in supply, and prices would quickly skyrocket. Of course, as elegant as this system might seem in economics textbooks, in the real world high prices mean cold and hungry people, particularly poor people. In a shortage situation, the alternative to high prices is government price controls, rationing, and likely long lines like the gas lines of the 1970s (perhaps a more democratic outcome as rich people and poor people alike have to wait in the same line).

[38] U.S. Energy Information Administration, 2013

[39] Prices of oil and other commodities change daily. Median means that the price was greater for half the days of the year, and less for half the days of the year. I have included data on the range of prices to give some idea of how much they fluctuate in a given year.

supplied. Another way to state this is that people would almost certainly be willing to buy and use more oil at $30 per barrel than at $110 per barrel. These data suggest a system struggling to meet demand.

Supply ticked up again in 2011 and 2012. At the current high oil prices, it has become economical to extract "unconventional" oil using new technologies such as hydraulic fracturing and horizontal drilling. To be fair, improvements in these technologies, pursued by entrepreneurs over many decades, have also played a role in bringing down the cost of these technologies. It is both the decreased cost of the technologies, and the higher price to be had when selling the oil, that makes them viable. This uptick in supply has reduced median prices slightly, but they remain at well over $100 per barrel. From this we can conclude that the new technologies are struggling to meet demand as rapid economic growth continues in many parts of the world, particularly Asia. It seems unlikely that prices will fall back to the $20-40 range without a major slowdown in worldwide economic activity, major new discoveries of conventional oil, major breakthroughs in technology for extraction of unconventional oil, discovery of a serious substitute for oil, or some combination. Of course, while they might temporarily lower price, major new discoveries or breakthroughs in extractive technology would serve to hurtle us ever closer to our planetary boundaries.

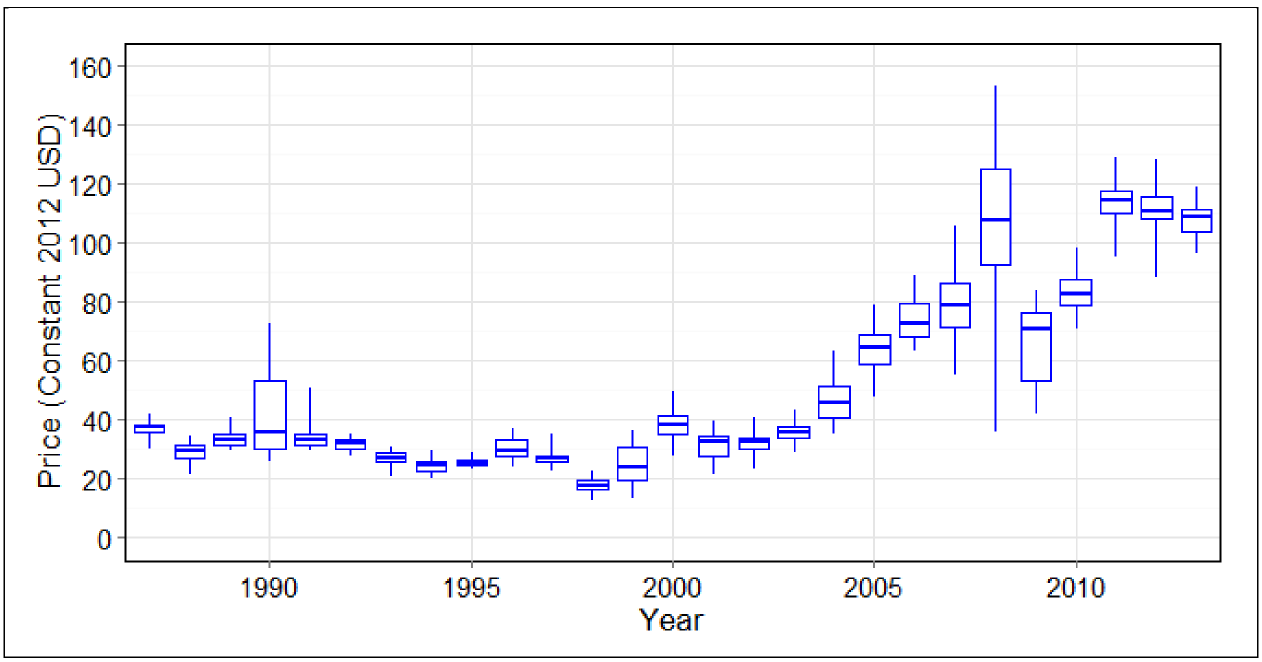

Figure 5: Long-Term Trend in Oil Price

Median oil prices stayed within the range of $20-40 per barrel (in 2012 U.S. dollars, adjusted for inflation) from 1987 to 2003. During the expansion years of 2004 to 2007, the years of flat production, median prices rose to over $100 per barrel. Prices are for Brent North Sea crude. Boxplots show the minimum, 25th percentile, median, 75th percentile, and maximum price for each year. 2013 prices have not been adjusted to reflect inflation between 2012 and 2013.

The Economist's View

An economist's idealized conception of the economy is something like Figure 6[40]. Economists have proposed a variety of recipes for the "soup" that leads to increasing human wellbeing, which they generally hope can be approximated by the amount of money changing hands in exchange for goods and services each year. While the recipes proposed by individual researchers differ in detail, the ingredients are generally the same. Manufactured capital (machines, factories, highways, office buildings, etc.) is necessary to produce economic activity, and more capital leads to more activity up to some limit. Technology, and more generally knowledge, provides the "recipe" for how to use capital and natural resources. These recipes can be improved continually into the future with no theoretical limit. Some researchers emphasize "human capital" as a particular type of knowledge produced by education, training, skills, and on-the-job learning. While a portion of knowledge can be written down, shared, and passed directly to the next generation of workers, human capital exists inside individual human minds and requires substantial effort to transfer.[41] New knowledge may be produced in some cases by individuals acting purely out of curiosity or by governments choosing to create new knowledge in the public domain, but private actors investing in research and development in hopes of making a future profit are also important. [42]

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[40] This diagram reflects the somewhat orthodox concept that all services improving the wellbeing of humanity are flows originating from some stock. There are many practical problems in measuring these stocks and flows. The gross domestic product concept has been developed because it is measurable, but at the same time has been criticized because it is not strictly a measure of the value of services – it is a mixture of items added to maintain and increase levels of the stocks, and of more easily measurable aspects of services provided. While the shortcomings of GDP are recognized, mainstream economists tend to think it is the best we can do and hope that at least the changes from year to year provide meaningful information about changes in human wellbeing.

[41] If "human capital" by definition is knowledge that exists only in peoples' heads, and we assume this "capital" stock must be maintained like any other, then an interesting implication is that much of education is simply "maintaining" the stock of human capital by educating new workers as older ones leave the work force. This suggests there may be a good reason why education systems emphasize the cramming of existing knowledge into students' heads, leaving limited time to challenge them to come up with their own new, creative, innovative ideas. This time spent teaching the same existing ideas over and over again may be necessary up to a point, but it may also tend to reinforce suboptimal practices and our many social institutions which are so stubbornly resistant to change.

[42] e.g. Romer, 1990; Solow, 1956 and 1957. Solow estimated that technological change (using a broad definition of technology to include human capital and institutional change) is by far the dominant driver of economic growth.

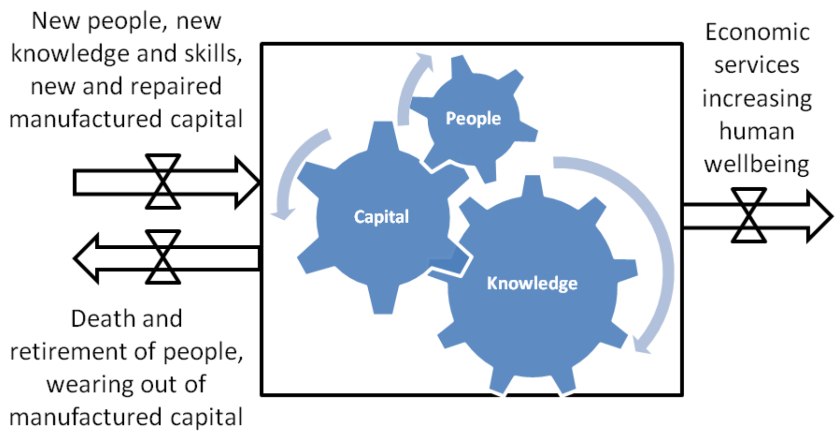

Figure 6: The Economic System as Envisioned by Economists

Economic services are produced by stocks of people, knowledge, and manufactured capital such as machines, factories, buildings, and infrastructure. People are born, educated and trained in current knowledge, and added to the system. Once added to the system, they can produce new knowledge. People who retire or die are subtracted from the system, and capital physically wears out over time. The quantity and quality of the stocks determine economic services that can be produced, and generally allow the amount of services to increase over time.

When we've established that we can't afford to do without ecosystem services in the foreseeable future, it is at first surprising that ecosystem services (including food, energy and raw materials) and even land itself are left out of this framework. Indeed, the origins of modern "political economy" were in the study of land and labor as the two important factors of production.[43] In the original framework, energy and raw materials were assumed to be derived from land. However, we have established the paradox that the market tends to put no monetary value on many ecosystem services for the reason that they have always been so plentiful as to never be in doubt. An example is the ability of the oceans to absorb nutrients in runoff from farms and cities. If price is determined by supply and demand, we can think of the (perceived, so far) supply in this case as being infinite, and the price therefore zero.

Prices of food and energy certainly are not zero, but they are lower as a fraction of all our expenses than they have ever been before in history. Like other ecosystem services such as nutrient cycling, they are perceived to be so abundant that we can take them largely for granted. For example, the entire industries of agriculture, forestry, fishing, hunting, mining, and utilities accounted for just 4.8% of all the money that changed hands in the United States economy in 2012.[44] Even though the demand for food is high, we are so good at producing it, and the inputs required (energy, fertilizers, etc.) have been affordable enough, that the price of food has stayed relatively low so far and we can afford to spend our limited monetary resources on other things that are more difficult to obtain. Likewise, while energy and raw materials needed by business are not free, their cost is relatively small compared to the cost of workers and machines. So although economists can certainly account for land, energy, and raw materials as factors of input to production if they become expensive enough to affect the math, the

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[43] Czech, 2013
[44] U.S. Bureau of Economic Analysis, 2013

most popular approaches in economics today often neglect them, simplifying to just labor and capital[45], with increases in knowledge sometimes considered.

Economists, by and large, define scarcity in relative terms as whether a particular commodity is accessible to people when they want or need it, at a price they can afford. Using monetary prices in this way as a measure of scarcity, even adjusted for inflation and for peoples' incomes, economists can show empirically that food and many other natural resources have become less scarce up to the present as a long term trend. Julian Simon expresses this view in perhaps its most extreme form:

> ***[N]atural resources are not finite in any meaningful economic sense, mind-boggling though this assertion may be. The stocks of them are not fixed but rather are expanding through human ingenuity. There is no solid reason to believe that there will ever be a greater scarcity of these extractive resources in the long-run future than now.***[46]

After making this perhaps deliberately provocative statement, Simon goes on to make some distinctions. First, a naturally occurring material, such as copper, does not become a "resource" to humans until we have a need for it and develop the technology to extract and use it. In this sense, our need can drive the "creation" of a resource like copper, even though the physical element copper, as represented in the periodic table of the elements, makes up a finite mass within the Earth's crust (although Simon famously refused to admit even this). As the need increases and technology for exploiting the resource increases, the quantity of the accessible, usable resource increases along with the need.[47] Technology may also allow us to use a resource more efficiently, or to find substitutes for a resource, so that even though the physical quantity may be limited, the length of time we can use the resource or the total amount of usefulness we can derive from the resource may not have any limit which can be known in advance. For example, humanity wishes to cook food and copper pots are a convenient way to do that, but if they are too expensive or not available, other ways can be found to achieve the same result. When forced to find those other ways, we may in fact find much better ways to cook food than copper pots ever were, and have no desire to go back to copper pots even if they are abundant in the future.

Food and energy[48] are cheap by historical standards because we have become good at producing them. When an industry gets really good at doing something, the profit margin tends to gradually decrease. Eventually we turn the activity over to just a few specialists in the field who are big enough and efficient enough to squeeze out whatever profits are remaining to be had. To continue making a living, the rest of

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[45] Land and natural resources are sometimes lumped in with "capital", but this creates ambiguity given the definition of capital as something manmade.
[46] Simon, 1996
[47] This is exactly the pattern we see with "proved reserves" of oil and natural gas.
[48] Perhaps this statement that energy is "cheap" seems to contradict the conclusion of my oil price analysis in the previous section. However, even though oil prices have trended higher in the past decade, expenditure on energy is still historically low as a percentage of the total economy. The conclusion of the previous section was not that energy is scarce or expensive now relative to the total economy, but that the trend points toward greater scarcity and higher prices in the future.

us have to move on to something else. Businesses have to continually innovate, desperately trying to stay one step ahead of the competition as the profit margin of any given technology or practice gradually diminishes. Businesses[49] are locked in a death struggle where they must innovate or die. This is Schumpeter's "perennial gale of creative destruction", where firms have to innovate continually merely to "keep on their feet, on ground that is slipping away from under them."[50] The process is ruthless but acts as a highly effective spur for innovation.

In the orthodox economists' view, the existence of scarcity, or the expectation of future scarcity, will always lead human beings to find ways of using a resource more efficiently, finding new sources of the resource, or finding a substitute for the resource. They generally believe that when it becomes necessary, a substitute can always be found, and they typically assume that manmade capital can be substituted for natural capital when the need arises[51] (the so-called "weak sustainability" hypothesis.) Given this assumption, a current generation can ethically deplete natural resources as long as it leaves future generations with the ability (resources, machines, knowledge, etc.) to produce the same or greater level of output as the current generation. In the words of Robert Solow,

> ***The current generation does not especially owe to its successors a share of this or that particular resource. If it owes anything, it owes generalized productive capacity or, even more generally, access to a certain standard of living or level of consumption. Whether productive capacity should be transmitted across generations in the form of mineral deposits or capital equipment or technological knowledge is more a matter of efficiency than equity.***[52]

Simon gives an example of substituting manmade capital for natural capital; in his view, constraints on farmland are not a problem because we can build high-rise farms as tall as necessary, create artificial light to light them, and desalinate as much ocean water as necessary to water them. We will develop the necessary energy sources, such as nuclear fission, fusion, or space-based solar arrays, when they become necessary.

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[49] In addition to for-profit firms in competitive markets, I would add business-like nonprofit and quasi-governmental entities. Utilities and authorities, for example a transportation authority collecting tolls on a bridge, are examples. Even if they are protected from direct competition, they are vulnerable to new challenges from outside the industry. In our bridge example, that challenge could come from telecommuting, car-pooling, or long-term changes in where people choose to live relative to where they work.

[50] Schumpeter, 2012. To repeat the point from the previous note, Schumpeter did not believe that "perfect competition" within an industry is necessary for innovation to occur. Even if a business has a monopoly in providing a particular good or service, either through government protection or because it is so efficient that its price and quality simply can't be beat, it is at risk from an outside innovator coming up with substitute goods and services that consumers prefer. This competition to innovate over time is more important than short-term competition over price.

[51] e.g. Solow, 1986: "a society that invests in reproducible capital the competitive rents on its current extraction of exhaustible resources, will enjoy a consumption stream constant in time... an appropriately defined stock of capital - including the initial endowment of resources - is being maintained intact, and that consumption can be interpreted as the interest on that patrimony."

[52] Solow, 1986

I think we can accept the arguments and evidence offered by Schumpeter, Romer, Simon, and other economists that competitive enterprise is an effective spur to innovation. The role of innovation in improving human quality of life over the past two centuries is indisputable. However, it is equally obvious that this increase in quality of life has come with an increase in ecological footprint and associated drawdown in natural capital. While agriculture, forestry, mining, and energy production represent a relatively small share of GDP, there is no reason to expect the "value added" to GDP by various industries to be proportional to ecological footprint. In fact, quite the opposite is true because the food production and resource extraction industries have the largest ecological footprints.

I have argued that these industries represent a small share of GDP because their products are perceived to be so abundant as to be largely taken for granted. The question is whether the drawdown of natural capital will reach a point at which ecosystem services (including raw materials, fuels, food, and waste absorption capacity) become truly scarce and begin to exert a drag force on further progress. If we believe ecosystem services may be less abundant in the future, that means the markets are not putting an appropriate price on them now based on their long-term prospects. Markets will spur sustainable innovation only if people by and large interpret available information to make accurate predictions about the future. That is, markets are very efficient at reflecting peoples' aggregate interpretation of the information available, including the probability of future scarcity. Markets will react readily to an obvious drop in ecosystem services. However, they will react to a drawdown of the natural capital stock before it causes this drop in services only if enough people understand the system and draw the correct conclusions about the future from the current condition of this stock. Although obvious scarcity will drive innovation as the economists predict, this result will not necessarily happen fast enough to prevent a lot of human misery before society reacts by producing the necessary innovations to correct the situation.

What is the Relationship between Natural Capital, Ecosystem Services, and the Human Economic System?

A few economists have attempted to link the economy to natural capital and ecosystem services more explicitly. Herman Daly envisions the economy as stocks of people and capital sustained by "flows of matter and energy from the first stage of production (depletion of low-entropy materials from the environment) to the last stage of consumption (pollution of the environment with high-entropy wastes and exotic materials)."[53] Figure 7 is a visual depiction of this idea.

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[53] Daly, 1977

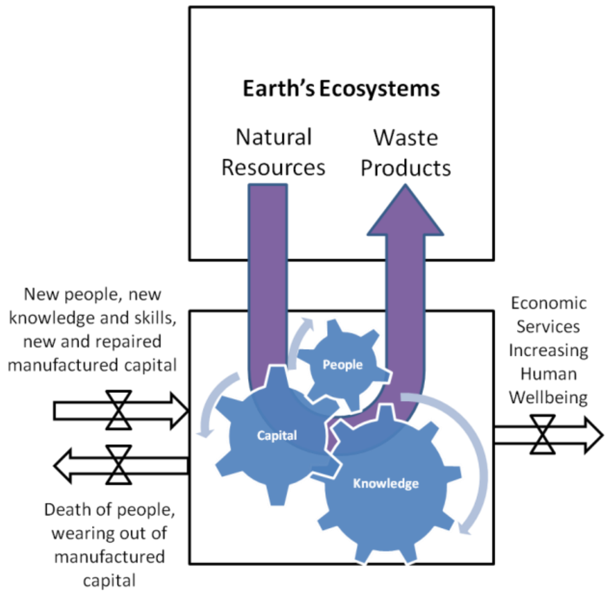

Figure 7: Daly's Concept of Economy-Ecosystem Linkages

The human economy, as envisioned by economists, depends on natural ecosystems as a source of natural resources, and as a sink for waste products. A constant flow of these materials is required for the economy to function. Natural resources are continually converted to wastes, and as we approach some limit to either natural resources that can be extracted, or wastes that can be absorbed, the economy will be affected. Note that this graphic was not taken directly from Daly, but is a visual interpretation of theories described in his work.

Daly called these flows of matter and energy "throughput", defined as the conversion of raw materials (i.e., matter and energy in forms humans can easily use with current technology) to waste and pollution. This throughput is what drives the industrial economy, and the amount of throughput necessary to drive the industrial economy is what determines the environmental impact. Throughput can be compared directly to the carrying capacity of the earth, and if it exceeds the carrying capacity then the logical thing to do is limit it. Rather than taxing or regulating waste or pollution, Daly advocates a quota system to limit the amount of raw materials that can be produced each year. Credits, or the right to produce, would be auctioned off by the government each year.

What kind of simple modeling framework could we use to represent this linked system of the natural capital of the Earth and the activity of human civilization? One candidate is the type of algebraic model of steady state conditions favored by economists. Statistical analysis of historical data, such as the data on oil production and price shown earlier, are also tools we might consider. Julian Simon makes an argument that simply extending past trends is the most logical thing to do in the absence of other information:

> ***A prediction based on past data is sound if it is sensible to assume that the past and the future belong to the same statistical universe, that is, if you can expect conditions that held in the past to remain the same in the future... The fall in the***

> ***costs of natural resources, decade after decade and century after century, should shake us free from the idea that scarcity must increase sometime.***[54]

When trends are exponential, extrapolating them into the future can lead to some surprising predictions, as discussed by Ray Kurzweil:

> ***[E]xponential growth is seductive, starting out slowly and virtually unnoticeably, but beyond the knee of the curve it turns explosive and profoundly transformative. The future is widely misunderstood. Our forebears expected it to be pretty much like their present, which had been pretty much like their past. Exponential trends did exist one thousand years ago, but they were at that very early stage in which they were so flat and slow that they looked like no trend at all. As a result, observers' expectation of an unchanged future was fulfilled. Today, we anticipate continuous technological progress and the social repercussions that follow. But the future will be far more surprising than most people realize, because few observers have truly internalized the implications of the fact that the rate of change itself is accelerating.***[55]

However, the main criticism of extending trends "in the absence of other information" is that we do have other information, such as the effects of planetary boundaries which will make themselves felt if crossed. This is a classic "feedback effect", in which the state of one variable (in this case the stock of natural capital) influences others (in this case the rate of increase in human activity.) The simple, statistical approach does not sufficiently capture some key processes that govern the behavior of systems over time. The authors behind the *Limits to Growth* study explain this well using their "World3" simulation model as an example.

> ***[World3] focuses especially on the time it takes for things to happen, the delays in flows, and the slow unfolding of physical processes. It comprises many, many dozens of feedback loops... Another feature are its many nonlinear relationships. Such relationships cannot be drawn with straight lines; they do not produce proportional changes over all ranges of related variables... linearity is seldom found in the real world.***[56]

We do not have to agree with all the assumptions and methodologies behind *Limits to Growth* to acknowledge that the type of model it employed was able to represent nonlinear processes we are interested in, such as the way in which ecosystem services are necessary for growth in human activity, and have the potential to limit or even reverse that growth. For the simulations discussed in this book, I have employed a dynamic system simulation model reminiscent of *World3*. My model is much, much

[54] Simon, 1996
[55] Kurzweil, 2005
[56] Meadows, 2004

simpler that *World3*, but is adequate to answer my questions about the broad behavior of the linked economic-ecological system over long periods of time.

To begin, I take the diagram of natural capital and ecosystem services from Figure 1 and link it to the diagram of the human economy from Figure 6, so that ecosystem services are now feeding the human economy (Figure 8). The human economy determines the demand for ecosystem services, and that demand will be met as long as the natural capital stock is able to supply the services demanded.

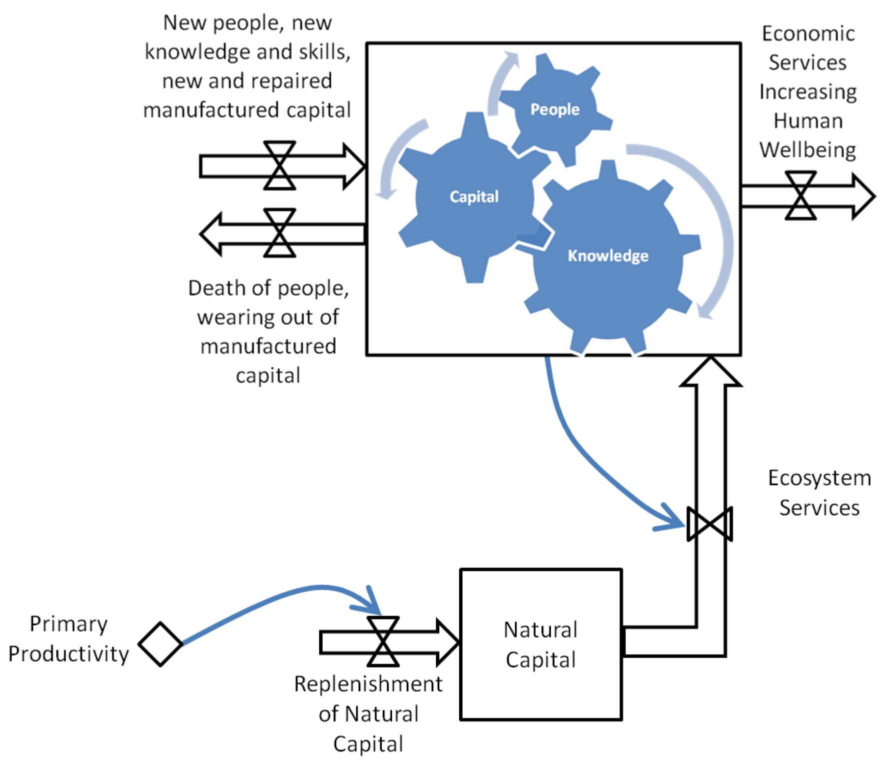

Figure 8: Linking Natural Capital and Ecosystems Services to the Human Economy

The human economy determines the demand for ecosystem services. Primary productivity replenishes the natural capital stock, but the natural capital stock will be drawn down if ecosystem services extracted exceed the rate of replenishment. If the natural capital stock is drawn down to the point where it can no longer supply the ecosystem services demanded by the human economy, the human economy will be affected.

The figure above, while correctly illustrating the key stocks and flows involved, is difficult to operationalize in a working model. The human economy is very complex and trying to simulate it in detail would be a very complex undertaking. For my purposes, such a complex model is not necessary, and would represent a great deal of precision without adding any accuracy relevant to my goal, understanding the broad behavior of the linked system over long periods of time. As a shortcut, I have reduced the entire human economy to a simple stock called "human activity" (Figure 9). This stock represents the amount of human activity generated in the course of a year by the underlying stocks of people, capital, and knowledge. I could have called this stock "growth" or "progress" or the "state of civilization". I chose the neutral "human activity" because I make no value judgments at this point about whether more activity is good or bad for the daily experience of being a human being. Growth in the amount of human activity is simply the trajectory we are on. The stock is meant to represent the scale of human civilization at a given point in time.

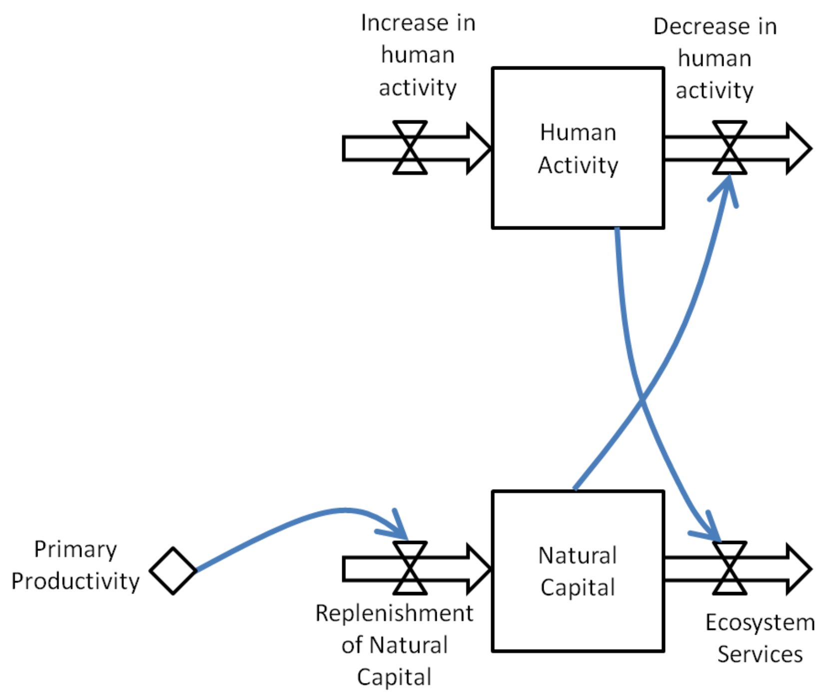

Figure 9: A Simplified, Operational Concept of the Linked Economic and Natural Capital System

The amount of human activity determines the flow of ecosystem services, which draws down natural capital. If the natural capital stock is draw down to a certain level, it will exert a force tending to decrease the rate of human activity.

I could have chosen to represent human activity in terms of U.S. dollars or even in terms of information processed by civilization each year. However, I have chosen total energy consumption to benchmark the level of human activity. There is some precedent for this choice. The anthropologist Leslie White proposed energy use as a way of benchmarking cultural development, from pre-agricultural cultures to the present modern culture.

> ***Cultural systems, like biological organisms, expend the energy that is captured and harnessed in self-extension as well as self-maintenance. Like biological organisms, cultural systems extend themselves both quantitatively and qualitatively. Cultural systems extend quantitatively by multiplication or reduplication; i.e., peoples multiply, tribes divide, forming new tribes and therefore new sociocultural systems. Cultural systems expand qualitatively by developing higher forms of organization and greater concentrations of energy.***

Degree of organization in any material system is proportional to the amount of energy incorporated in it. As the amount of energy harnessed by sociocultural systems increases per capita per year, the systems not only increase in size, but become more highly evolved; i.e. they become more differentiated structurally and more specialized functionally.[57]

My human activity stock is the total energy used by civilization in one year, the product of the human population and the per capita energy use of that population. This product captures population growth, economic growth, growth in consumption patterns, and changes in technology in a general sense without respect to their environmental or social impacts. I do not attempt to simulate these factors independently, but instead assume that in the absence of limiting environmental factors, this product would tend to grow exponentially over time. Over the past 200 years, this assumption has held approximately true. Figure 10 plots energy supply (which closely tracks demand) over the 200 year period.[58] Over this period, fitting an exponential trend shows that world energy supply has grown approximately 2.5% per year.

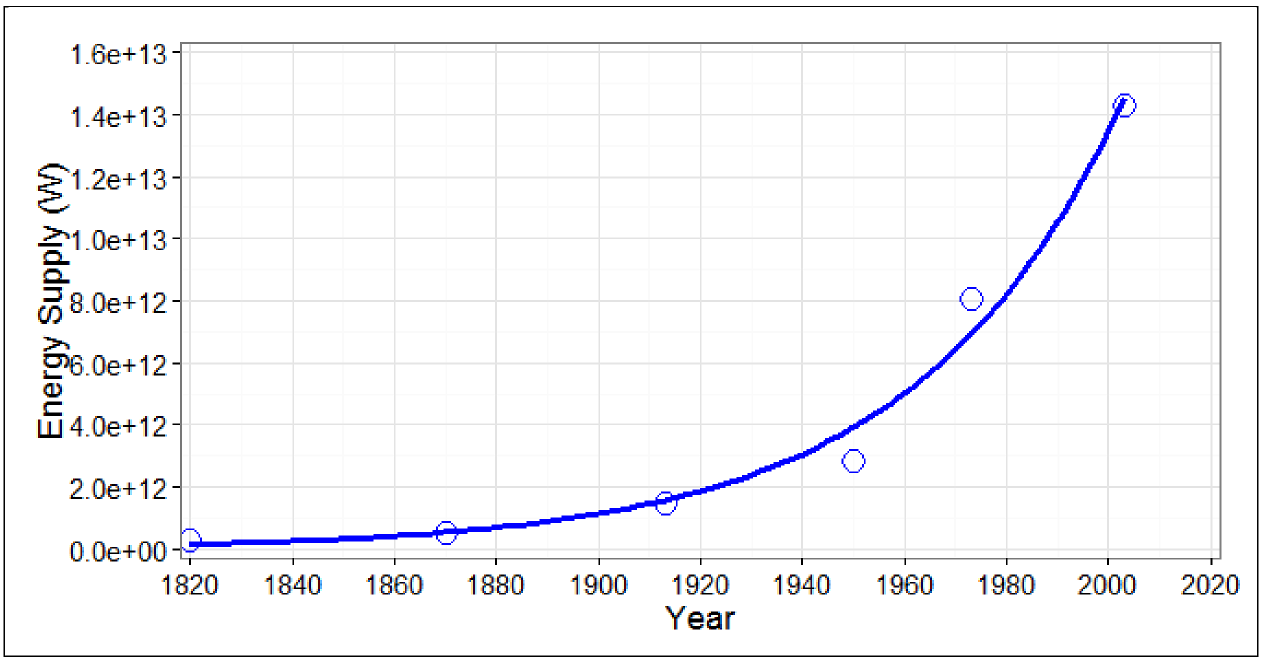

Figure 10: World Energy Supply 1820-2003

Energy supply, which closely tracks energy use, has grown exponentially over the last two centuries. The open circles represent data, while the line represents a fitted trend.

As discussed earlier, the natural capital stock represents the source of all ecosystem services, including the sources of natural resources; the substrates, genes, and living tissues of ecosystems themselves; and the ability of ecosystems to act as sinks for humanity's waste products. As we begin to transcend the

[57] White, 2009
[58] Keay, 2007

planetary boundaries, we will have depleted this stock to the point where it begins to exert a drag on further growth.

Figure 10 illustrates the two major feedback pathways. As human activity increases, it "consumes" ecosystem services, or depletes the stock of natural capital representing Earth's ability to support that human activity. Ecosystems do have some capacity to renew themselves, and thus if the rate of depletion and renewal of the stock are in balance, the environment does not exert any negative force that, all other things being equal, would cause human activity to decrease. However, when there is net depletion of the natural capital stock, there is a tendency for human activity to decrease. At the same time, there is also a tendency for the human activity stock to increase driven by population growth, increasing capital investment, and innovation. Whether there is actually a net increase or decrease in human activity depends on the level of the natural capital stock, and hence whether the flow out of the natural capital stock over time is greater than the flow into it.

Figure 10 was deliberately simplified to introduce the most central stocks and flows. Figure 11 adds all the important relationships. Replenishment of the natural capital stock depends on net annual primary productivity.[59] Depletion of the natural capital stock is the product of the magnitude of human activity and the environmental impact of each unit of human activity. The rate of increase in human activity is assumed to be an exogenous variable (not depending on other variables inside the system), while the rate of decrease in human activity is the product of the natural capital stock (specifically, the gap between today's natural capital and the future stock at any time) and the effect on human activity growth of each unit of gap.

[59] This is itself a great simplification as the natural capital stock represents many, many processes. However, it is reasonable to assume that net primary productivity, depending on the constant input of the sun, is the greatest driving force behind long-term resilience of natural ecosystems and ultimately the ecosystem services on which humanity depends.

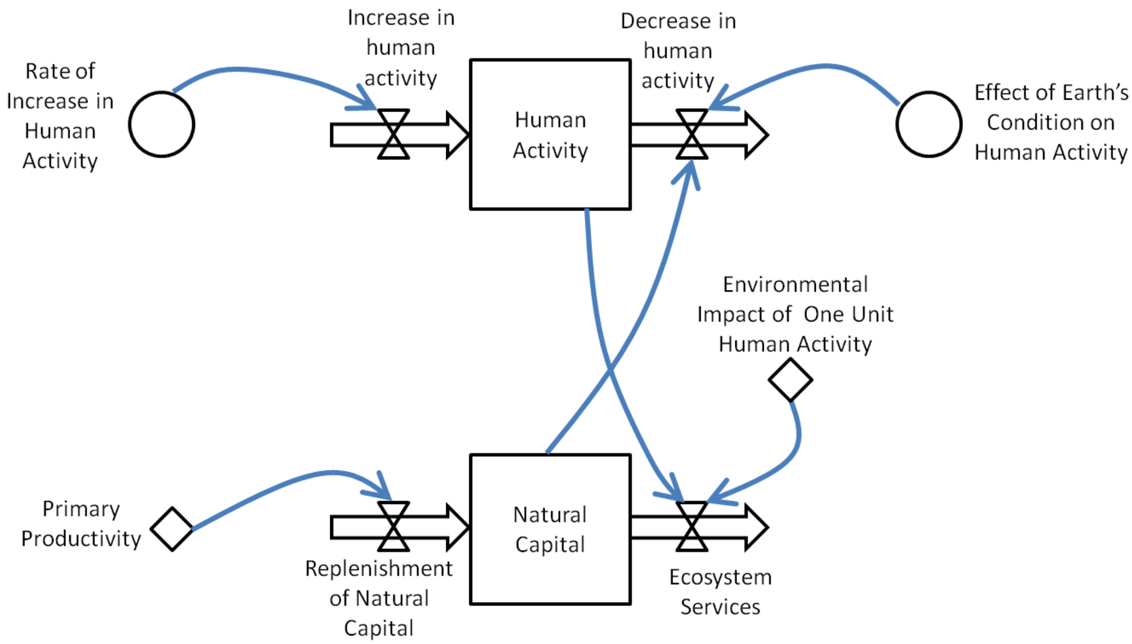

Figure 11: Adding Key Constants and Relationships to the System Representation

Adding to Figure 9, this figure shows that the rate of increase in human activity is assumed to be an exogenous variable that does not depend on other variables in the system. At the same time, the rate of decrease in human activity depends on the natural capital stock and a constant describing how strongly the natural capital stock affects human activity. Replenishment of natural capital depends on primary productivity. Withdrawal of natural capital depends on the level of human activity and a constant describing how strongly the level of human activity affects natural capital.

This simple formulation cannot tell us whether the feedback caused by depletion of natural capital is due to fossil fuel depletion ("peak oil" or peak natural gas), insufficient food production caused by heat or inbred crops succumbing to disease, damage caused by sea level rise, accumulation of a pollutant causing a widespread toxic effect or a drop in fertility, impaired immunity, or some other cause. It could be any of these factors, or a combination. A much more complex model could attempt to distinguish between them, of course, but I am trying only to discern the broad behavior of the system over long periods of time. Other, much more complex models such as the one used in the *Limits to Growth* study have attempted to distinguish between many different limits, and concluded that "in a complex, finite world, if you remove or raise one limit and go on growing, you encounter another limit. Especially if the growth is exponential, the next limit will show up surprisingly soon. There are *layers of limits*."[60] An example would be if we escape peak oil through discovery of new oil and gas fields or breakthroughs in extraction of methane hydrates from the ocean floor, only to come up against a limit on tropical agricultural production imposed by climate reaction to greenhouse gas emissions. My simple simulation only determines that feedback of some form occurs.

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[60] Meadows, 2004

Results of Simulation without Technological Progress[61]

The results of a 1000-year simulation of this system are shown in Figures 12 and 13, and the Malthusian trap is evident. The Earth is able to support continued growth in human activity for several decades, and life seems good to those on the initial rising limb of the curve. However, when human activity reaches a certain threshold, there is a collapse in natural capital, leading to a crash in human activity. After the crash decreases human activity, natural capital is able to recover and the cycle starts over again. This boom-and-bust cycle repeats itself on the order of every 50-100 years, over and over, forever, in the classic Malthusian trap.

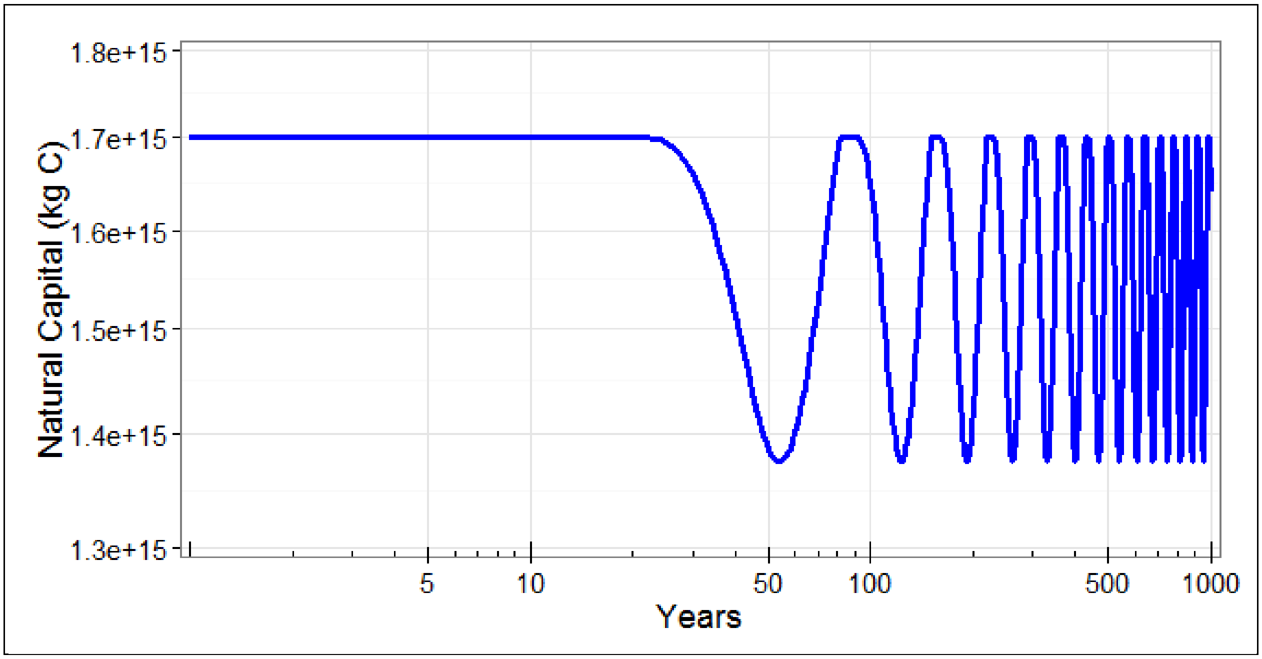


Figure 12: Simulation Results - Natural Capital Stock over 1,000 Years without Technological Progress

The natural capital stock is depleted to a certain level, then is able to grow again to a certain level, then is depleted again in an endless cycle. This is the classic Malthusian trap.

[61] The increasing trend in human activity may itself be driven by technological progress, for example new technology for mining and burning coal to produce more electricity. When I refer to technological progress in this section, I mean technological progress that would tend to decrease the environmental impact of each unit of human activity. This concept will be discussed in much greater detail in coming sections, when I will refer to it as progress in "green technology".

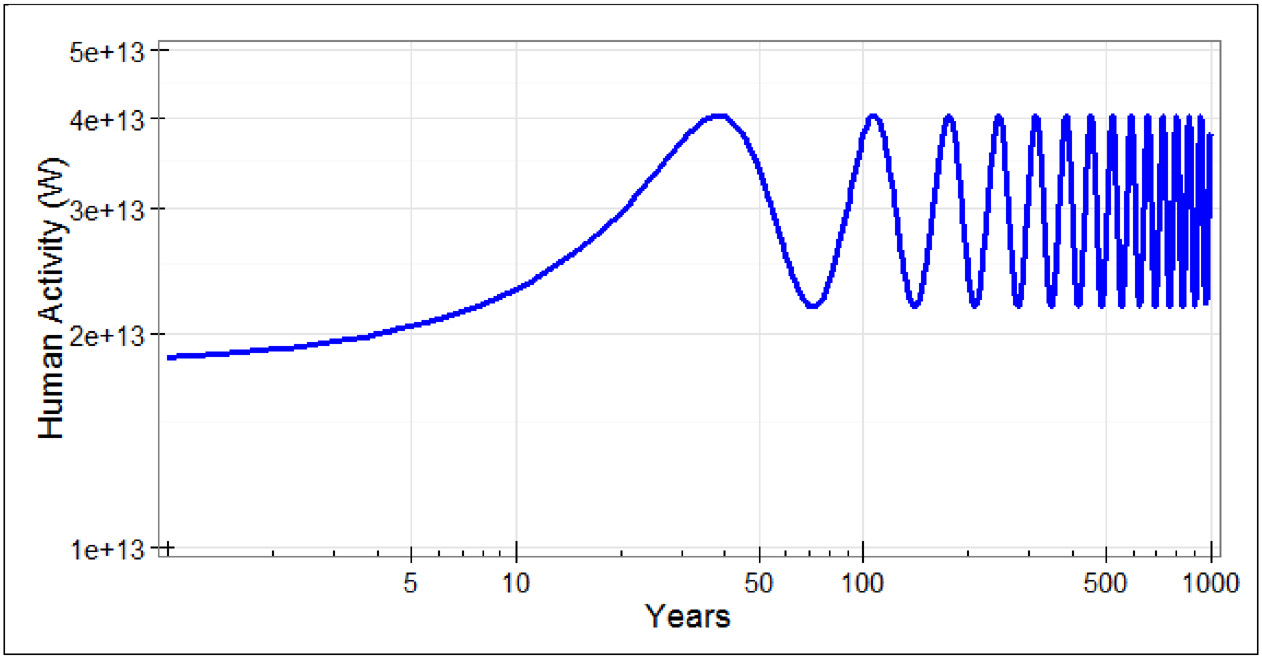


Figure 13: Simulation Results – Human Activity over 1,000 Years without Technological Progress

The level of human activity increases to a certain maximum level that the environment can support, then crashes, then grows again in an endless cycle. In Malthus's original conception, it was the human population itself that would keep growing to the limit of the food supply that could be produced by the available land, then overshoot that food supply, then crash, then repeat over and over again.

Accounting for Increasing Knowledge and Technology

There is, of course, a key variable missing from this system. The environmental impact of each unit of human activity is not constant over time, but can be shown to decrease over time along with technological progress. A portion of technological progress can be considered "green" because it tends to reduce the impact on natural capital of each unit of activity. The long-term behavior of the system then depends on the rate of growth in human activity, and the rate of this decrease in impact per unit of activity. Figure 14 adds this rate of decrease in unit impact to our system. The diagram is now complete.

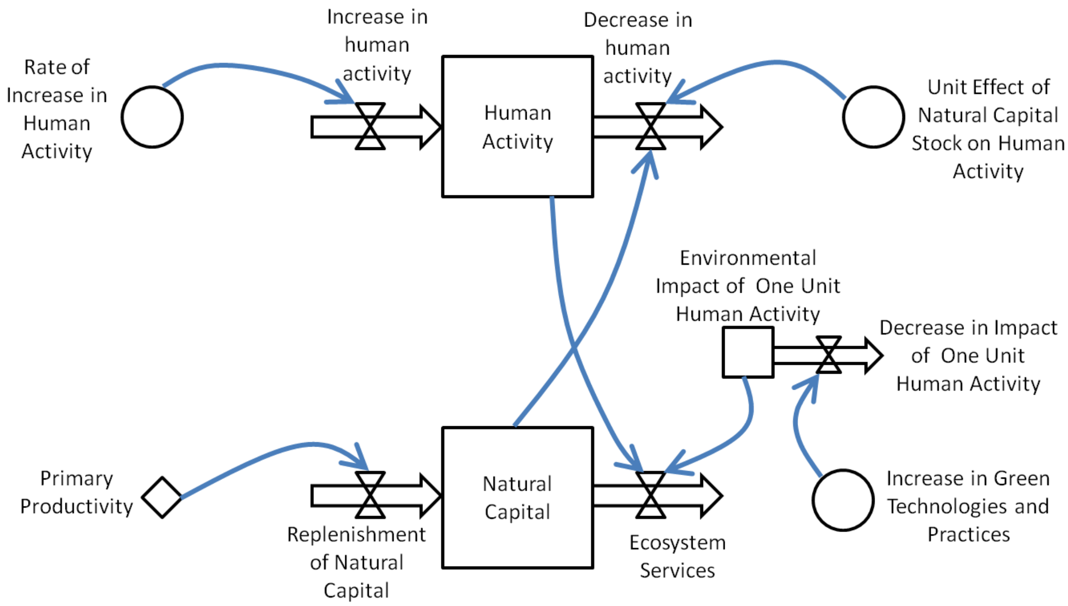


Figure 14: Adding Technological Progress to the System

Adding to Figure 11, the amount of natural capital (demand for ecosystem services) depleted by each unit of human activity is now allowed to decrease over time.

Past studies of economic-ecosystem linkages have struggled with the best way to account for technological progress. The authors of *Limits to Growth* have defended themselves against the charge that they did not account for market-driven technological progress in their "World3" framework:

> ***The most common criticisms of the original World3 model were that it underestimated the power of technology and that it did not represent adequately the adaptive resilience of the free market. It is true that we did not include in the original World3 model technological progress at rates that would automatically solve all problems associated with exponential growth in the human ecological footprint. That was because we did not - and still do not - believe such tremendous technological advance will occur by itself, nor through the unaided operation of "the market". Impressive - and even sufficient - technological advance is conceivable, but only as a consequence of determined societal decisions and willingness to follow up such decisions with action and money. Even with all that, the desired technology will only appear after significant time delays.***[62]

To represent technological progress, the authors of *Limits to Growth* simulated scenarios in which technological progress was more rapid than in their baseline assumption, such as 100% waste recycling, quadrupling of agricultural yields, and a 4% annual reduction in greenhouse gas emissions for 100 years. When they did this, they found the model behavior of overshoot and collapse unchanged. They cite the

[62] Meadows, 2004

ongoing collapse of the world's wild fish catch as evidence that this pattern is pervasive in the real world. Of interest, we may be able to adopt their assumption of a 4% annual technological improvement under laboratory conditions as an upper bound on what is feasible.

It is important to note that only the environmental impact of *each unit* of human activity is decreasing over time. I will refer to this decrease in unit impact as “progress in green technology and practices" or as “green growth”. At the same time green technology is developing, the overall scale of human activity is also growing. All technological progress will not automatically be green progress. New technology may increase impact, or even increase catastrophic risks as I will discuss later. Unless the rate of growth in green technology and practices is equal to the overall rate of growth, or in other words if all the growth that occurs is green in nature, meaning it has *zero net impact*, the total impact of human activity on the environment will continue to increase. *Total impact will increase unless all growth is green growth.*

At what rate is our unit environmental impact decreasing, and how realistic is it to hope that innovation in green technologies and practices will deliver us from the boom and bust cycle? Continuing to use energy as a proxy for overall human activity and carbon emissions as a proxy for impact on ecosystems, we can get a sense of the unit impact of human activity by examining the carbon content of civilization's overall fuel mix over time. A research team led by __ Grubler in 1999 showed that the carbon content of each unit of energy used by civilization has been declining slowly but steadily over the past 200 years. In this period, the fuel mix has changed repeatedly, initially dominated by wood, then coal, then oil and natural gas. The relatively small contributions of nuclear and hydroelectric power have also reduced unit carbon content over the past half-century or so. Based on this data, Grubler et al. estimated the steady rate of decarbonization at 0.25% per year for the United States and 0.3% for the world (Figure 15).

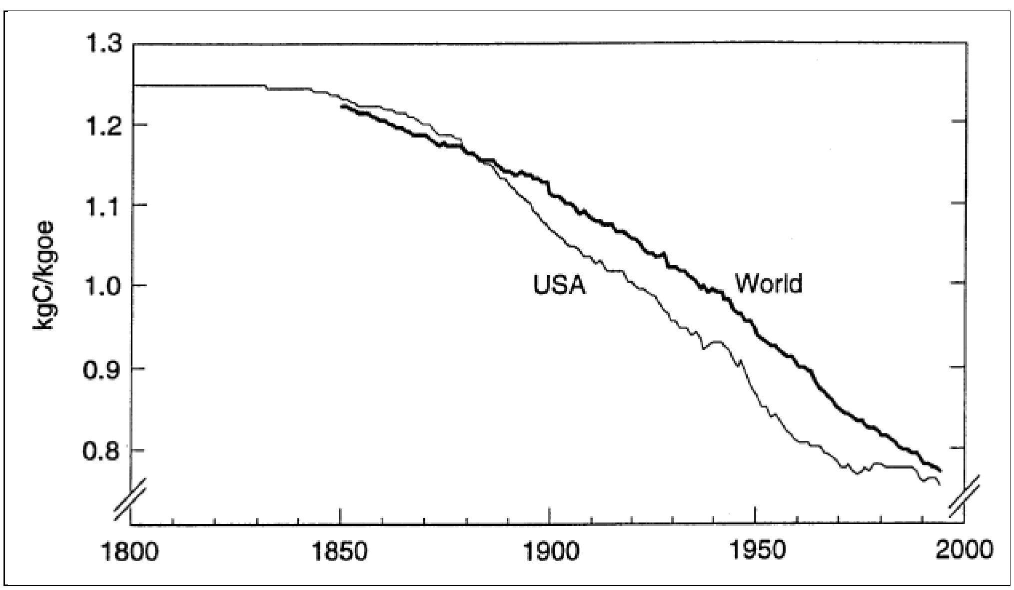


Figure 15. Gradual Decarbonization of the World's Energy Supply over Time[63]

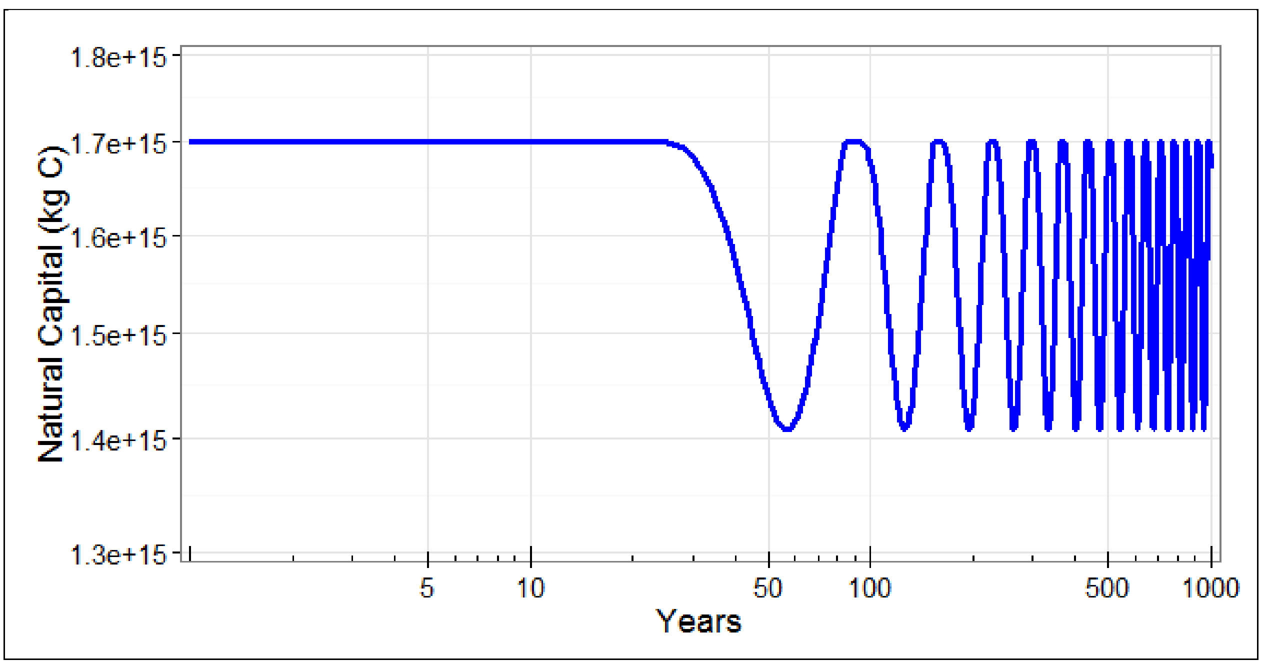
[63] Grubler, 1999. Reprinted with permission.

> The amount of carbon in each unit of energy supply has decreased by about 0.25% per year in the United States and 0.3% for the world as a whole over the last 200 years. The unit "kgoe" refers to kg of oil equivalent.

Thus, although the *unit* environmental impact of energy use is decreasing, the *total* rate of decrease is approximately an order of magnitude smaller than the annual increase in energy use (0.3% versus 2.5%). We must conclude from these numbers that if the historical trend continues, total impact will continue to grow despite the current progress in green technology. In other words, the increase in activity will continue to overwhelm the small decrease in impact per unit activity.

Brian Czech has estimated that the percentage of research and development (R&D) funding at universities, most of which is government- or corporate-funded, that can be considered "green" is on the order of 1% of all U.S. R&D. The percentage of green R&D inside corporate laboratories is unknown but probably lower.[64] We can assume that most of the remainder is focused on opportunities for profit, economic growth, and national defense, mostly regardless of environmental impact. This suggests that even my estimate that the rate of progress in green technology and practices is one order of magnitude (10 times) too low may be overly optimistic. It may be two orders of magnitude (100 times) too low!

Figures 16 and 17 illustrate the behavior of the system with 2.5% annual growth in activity and 0.3% annual decrease in unit impact. Because activity increases at a faster rate than unit environmental impact decreases, the cycle of natural capital depletion and replenishment looks much the same as it did before we added technological progress to the model. Human activity still grows and crashes on the order of once every century. However, the peak of the cycle reaches a higher level each cycle, and over a long period of time humanity does in fact escape the Malthusian trap.



[64] Czech, 2013

Figure 16: Simulation Results – Natural Capital Stock over 1,000 Years with Progress in Green Technology

Because human activity grows much faster than progress in green technology, there is always a net withdrawal of natural capital and an eventual impact of natural capital depletion on human activity. The natural capital stock continues to follow a boom and bust cycle that looks like the classic Malthusian trap.

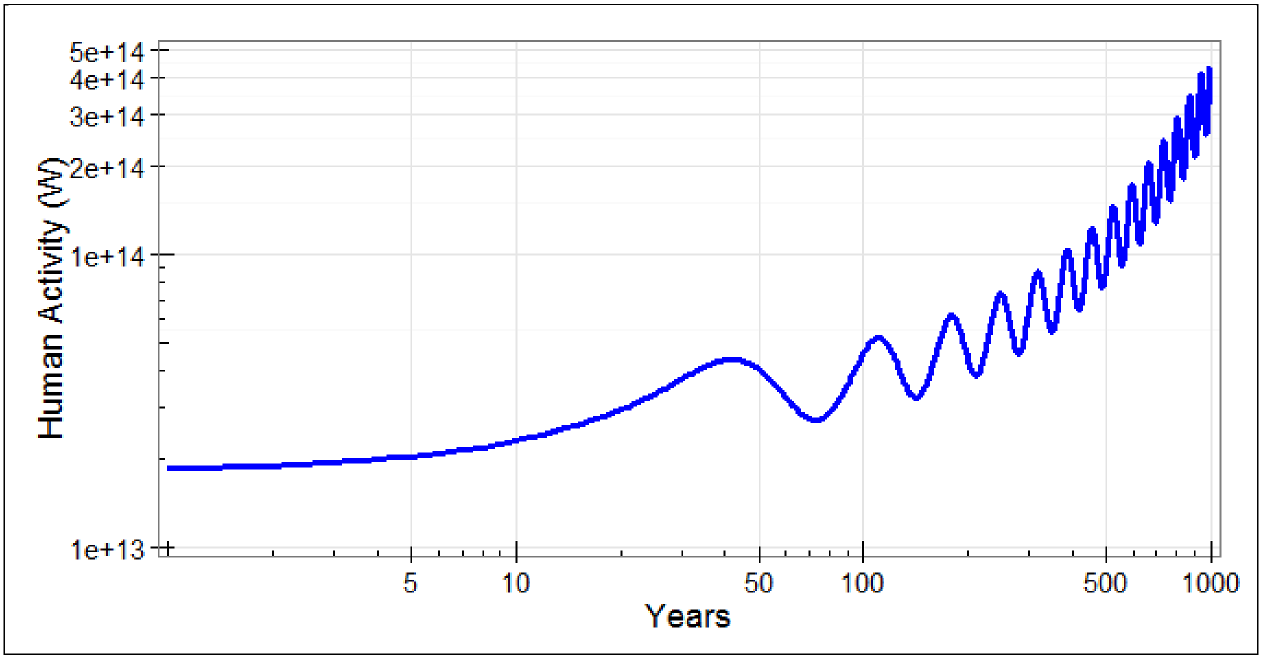


Figure 17: Simulation Results – Human Activity over 1,000 Years with Progress in Green Technology

Human activity follows a boom and bust cycle, but because green technology is reducing the unit impact on natural capital over time, the boom and bust cycle is centered on an underlying trend of steadily increasing human activity over time. Generations of humans go through hard times, ecosystems are repeatedly devastated, but humanity does eventually escape the Malthusian trap.

Humanity escapes the Mathusian trap, but experiences many cycles of boom and bust along the way, leading to unimaginable suffering that is likely to encompass entire generations. Unfortunately, given current trends it seems reasonable to be pessimistic that green technology and practices will increase fast enough to offset growth in overall human activity.

The behavior of the same system changes dramatically with a different balance between growth in activity and progress in environmentally friendly technologies and practices. To illustrate the effect of a change in this balance, we can hold growth constant at 2.5% but dramatically increase the rate of innovation in green technologies and practices, to 3% per year. Figure 18 illustrates what happens - the effect is a smooth, interrupted exponential growth trend. Human beings experience no hardship, natural capital is never depleted, and humanity approaches an almost unimaginable state of technology and energy use. I say almost unimaginable, because in the next section we will try to imagine what this means.

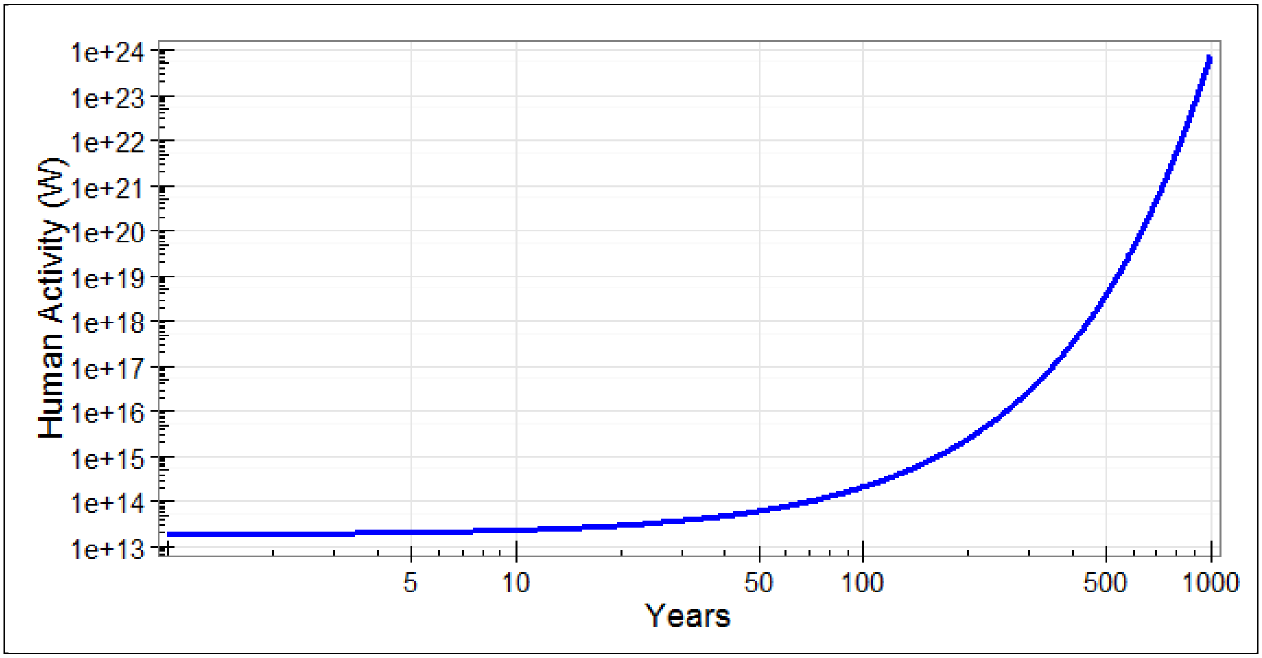


Figure 18: Simulation Results – Human Activity over 1,000 Years with Very Fast Progress in Green Technology

In this simulation, green technology increases faster than overall human activity. Natural capital is never depleted, no cycles of boom and bust occur, and humanity reaches far, far higher level of ultimate activity than it did in boom-and-bust scenarios.

The far future

Some authors have expressed the opinion that humanity's great discoveries in science and technology are behind it, that breakthroughs on the order of the agricultural revolution and the industrial revolution will never happen again. There has been some scholarly economic work presenting evidence that information technology has not yet yielded productivity gains anywhere near those achieved during past technological revolutions, particularly the second industrial revolution which saw the advent of "electricity, [the] internal combustion engine, running water, indoor toilets, communications, entertainment, chemicals, [and] petroleum...from 1870 to 1900".[65] For most who express this view, however, I believe it simply represents a pessimistic belief in the continued human ability to innovate. For example, the late Howard T. Odum believed that the current information revolution is not a true technological advance, but rather the last stages of a frenzy of activity made possible by the energy excess unleashed by the 19th century Industrial Revolution.[66] Herman Daly dismisses any discussion of

[65] Gordon, 2012
[66] Odum, 2007

breakthrough technologies as science fiction dreaming about "magical energy sources" and a belief that "the whole universe could be 'ours' at last."[67]

I cannot tell you what breakthrough innovations will occur in the years and decades to come, because by definition nobody knows what they are yet. However, when we know so much more than our predecessors, it requires a lack of imagination to think that we will not be able to build on their foundation and make even greater discoveries. The trend so far has been not only continual progress, but a trend of ever-accelerating progress over time. I have no reply to those with such a lack of imagination, except to suggest they try to imagine living a century or several centuries in the past, then traveling to the present and seeing our lifestyle, science and technological advances with fresh eyes. When the pace of change in the next century can be expected to be faster than that of the last century, how can we not expect to see even more profound, even unimaginable changes?

Perhaps, to be fair, I should allow that the reason for some peoples' skepticism about the future may not be a complete lack of imagination. Some people may enjoy reading science fiction, for example, but think it has no relevance to any time frame that could conceivably impact them, their children, or even their grandchildren. But as we will see in a minute, some prominent technologists and futurists think the fabulous science fiction future, or the horrible science fiction dystopia, could arrive as soon as the next decade or two!

What are some imaginative visions of future progress in green technology and practices that could come online in the next few decades? To take one example, a clean, cheap energy source is one holy grail of green progress. Given a hypothetical no-impact energy source, Julian Simon's high-rise farms, under artificial lighting and fed by desalinated sea water, become practical. What could the hypothetical low- or no-impact energy source be? Perhaps physics will produce the answer. As we study subatomic particles in more and more detail, perhaps we will solve the mystery of controlling atomic fusion to produce abundant, clean, cheap energy. Even if that does not happen, perhaps a new breed of smaller, safer fission reactors will come to our aid. Perhaps they will use a more abundant and safer fuel than uranium, such as thorium, and perhaps we will find novel and safe uses for what today are consider low-level nuclear wastes.

Another candidate, even mentioned by Julian Simon, is space-based solar arrays that beam electricity back to Earth on microwaves. Because much of the energy radiated by the sun is reflected or dispersed by the Earth's atmosphere, a space-based array could intercept much more energy than a ground-based one. Unless we turn to nuclear power on a large scale, the most energy we can collect from our position here on Earth is the solar energy striking the Earth[68], which of course is only a tiny fraction of the energy emitted by the sun. And any solar energy we intercept, use, and dissipate is no longer available to plants in the planet's ecosystems. Likewise, any solar radiation we intercept in space, that would have otherwise made it to the Earth's surface, is no longer available to plants in natural ecosystems, or to humanity's farms, pastures or tree plantations. We might have to build such a device a bit away from the Earth, so that it intercepts energy that otherwise would have bypassed the Earth altogether.

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[67] Daly, 1991

[68] I have neglected geothermal and tidal energy here.

Whenever we need more energy, we can expand it.[69] Only a minuscule amount (much less than 1%, approximately 10^{-8} percent) of the sun's energy intersects the Earth. The rest is "wasted" from the point of view of supporting life here in our solar system. Intercepting more of this energy is the concept of the Dyson sphere, discussed later in this chapter. It takes an active imagination to envision humanity building such a structure. Certainly we do not have the knowledge and resources to do it now. However, no one can claim that the laws of physics as we know them would preclude such a structure. Bridging the gap between what we can do with current resources and knowledge, and what we cannot do but know is within the realm of physical possibility, is long-term technological progress.

Let us try a thought experiment (and yes, this requires imagination, so please skip ahead if you prefer not to exercise yours) where humanity has the materials, knowledge, and financial resources to construct our cities, industries, and infrastructure on stilts 1,000 feet above the ground, perhaps on thin but ultra-strong carbon fiber poles constructed using nanotechnology. Cities are lit by artificial lighting produced from solar energy beamed down from space-based solar panels, which do not block any sunlight that would otherwise be incident on the Earth. Actual sunlight is bent around the cities to the ground using mirrors or fiber-optic cables, and rainfall is allowed to pass through and reach the ground. In the cities, food is grown under artificial lights in high-rise towers. Virtually all water, nutrients, and materials are recycled in a closed loop. The surface of the Earth is left in a wild state (with perhaps some cultivated park-like areas), and people can take an elevator down to the surface to enjoy it whenever they want. In this imaginary situation, human civilization exists with virtually no impact on the Earth's ecosystems.[70] The purpose of this extreme thought experiment is to illustrate a condition that might seem unattainable today, but certainly does not violate any known laws of physics, or even involve technology that would be impossible to build today (although we could not afford to build it on any significant scale.) Compact cities with urban growth boundaries, urban agriculture, used water recycling and resource recovery plants are a small step in this direction today.

People who are immersed in information technology tend to be optimistic about its long-term potential, and the long-term potential of technology in general. Ray Kurzweil is one such person who has collected an extensive body of evidence that the trend in technological advance is exponential over long periods of time, and in fact can even exceed exponential growth. His examples include rate of adoption of the telephone and other communication technologies; capacity and price of computer memory, transistors, microprocessors, and overall computing power; cost and speed of DNA sequencing; growth of the internet; decrease in size of mechanical devices and emergence of nanotechnology; and the decreasing time between major "milestones" in historical evolution both biological and technological.[71] Projecting

[69] In this way, we can capture and use more solar energy than what is naturally incident on the Earth without violating any laws of thermodynamics. The amount of energy we could capture would be limited only when we build an enclosure around the entire Sun, operating at the maximum efficiency the laws of thermodynamics will allow. Then we would presumably have to move on to other stars (transitioning from a Kardashev Type II to Type III civilization).

[70] Okay, I admit that the footprint of the stilts has some small impact. I picked stilts rather than some antigravity hover technology because I didn't think you would believe in that.

[71] Kurzweil, 2005

this exponential growth trend uninterrupted into the future, even the relatively near future such as the first half of the twenty-first century, leads to fairly startling projections.

> ***The acceleration of paradigm shift (the rate at which we change fundamental technical approaches) as well as the exponential growth of the capacity of information technology are both beginning to reach the "knee of the curve", which is the stage at which an exponential trend becomes noticeable. Shortly after this stage, the trend quickly becomes explosive. Before the middle of this century, the growth rates of our technology - which will be indistinguishable from ourselves - will be so steep as to appear essentially vertical. From a strictly mathematical perspective, the growth rates will still be finite but so extreme that the changes they bring about will appear to rupture the fabric of human history.***[72]

Joseph Schumpeter, writing in 1942, also understood how revolutionary innovation can be over time.

> ***[T]he history of the productive apparatus of a typical farm, from the beginnings of the rationalizations of crop rotation, plowing and fattening to the mechanized thing of today - linking up with elevators and railroads - is a history of revolutions. So is the history of the productive apparatus of the iron and steel industry from the charcoal furnace to our own type of furnace, or the history of the apparatus of power production from the overshot water wheel to the modern power plant, or the history of transportation from the mail-coach to the airplane... [I]ndustrial mutation...incessantly revolutionizes the economic structure from within, incessantly destroying the old one, incessantly creating a new one.***[73]

Robotics and a limited form of artificial intelligence are here now and gaining momentum. Some cynics will counter with statements like "you can't eat information". However, Kurzweil's vision is that very fast computers will eventually be able to easily solve problems that baffle us today, greatly accelerating the rate of progress. Perhaps they will solve the problem of fusion power, or safe fission power, or affordable space-based solar arrays. Then they will be able to design faster, better computers to solve even harder problems even faster. At some point, humans will choose to have computational hardware embedded in our brains, or our consciousness embedded in computational hardware, leading to a future in which the distinction between the biological and technological aspects of humanity are blurred.

Biotechnology is here now. Scientists now have the ability to create completely synthetic DNA in a design of their choosing. While humans cannot actually create life, we can now create entirely new organisms by inserting these manmade DNA strands into an existing bacterial cell. This new technology opens up huge possibilities in agriculture and medicine, while of course creating new risks.

[72] Kurzweil, 2005
[73] Schumpeter, 2012

Advances in materials science are also occurring, particularly using nano-scale materials, and are likely to accelerate. For example, advances in carbon fiber are creating very strong, light-weight materials. Airplane bodies have long been made of carbon fiber, but this material has been much too expensive for many consumer products. Carbon-fiber cars and trucks would radically change a world in which we are accustomed to thinking of stronger materials as necessarily being heavier and more energy-intensive to move around.

Three-dimensional printing holds some promise to revolutionize manufacturing as we have known it for the past two hundred years. Economies of scale and globalization may give way to a more customized, localized form of manufacturing.

Molecular manufacturing, the possibility of creating almost anything very inexpensively by manipulating individual atoms at the nanoscale, may seem more like science fiction, and does have its skeptics. However, we cannot simply assume that this dream is beyond reach because nature does it routinely. Every cell division is an example of molecular manufacturing. What nature does now, we certainly can't claim to be a violation of the laws of physics, and we can eventually learn to do.

Kurzweil's prediction of an abrupt, seemingly instantaneous from the human perspective, rate of change has been referred to as the "Singularity". According to Kurzweil, the Singularity can be thought of as a sudden increase in the information content or complexity or order[74] of civilization. In Kurzweil's framework, civilization would have so much knowledge that many of our current concerns about natural resource availability and waste products would no longer be concerns: "For example, nanotechnology-based manufacturing devices in the 2020s will be capable of creating almost any physical product from inexpensive raw materials and information."[75]

To help us understand the far future potential proposed by the techno-futurists such as Kurzweil, we can turn to a measure of human activity called the Kardashev scale. N.S. Kardashev was a Soviet astronomer concerned with the technical aspects of humanity's ability to send and receive signals from alien civilizations. He postulated that our current society does not have enough power available to communicate successfully with a far-away civilization, nor does an alien society at a similar level of development have the capability to communicate with us. However, if there were a civilization with vastly more power available, there is a high likelihood we would be able to detect their signals and they ours. Thus, regardless of the existence of any aliens, the Kardashev scale can spark our imagination about a future human civilization of presently unimaginable energy abundance. Like economists and techno-futurists, some astronomers and cosmologists have little trouble imagining a future of uninterrupted exponential growth.

> ***Calculations show that the total quantity of energy expended by all of mankind per second at the present time [writing in 1964] is about 4×10^{19} erg, and the***

[74] Kurzweil, 2005. Kurzweil explains his concept of order as "information that fits a purpose. The measure of order is the measure of how well the information fits the purpose." He further suggests that this concept of increasing order can be thought of as the further evolution of humankind through technological means as a successor to biological means.
[75] Kurzweil, 2005

annual increase in this energy expenditure is placed at 3-4% over the next 60 years... [Assuming an annual increase of] 1%, the energy consumption per second will be equal to the output of the sun per second, 3200 years from now, i.e., 4×10^{33} erg/sec, and that in 5800 years the energy consumed will equal the output of 10^{11} stars like the sun. The figures arrived at seem to be inordinately high when compared to the present level of development, but we see no reasons why the tempo of increase in energy consumption should fall substantially than predicted.

In line with the estimates arrived at, it will prove convenient to classify technologically developed civilizations in three types:

I - technological level close to the level presently [1964] attained on earth with energy consumption at ~4×10^{19} erg/sec [4×10^{12} W].

II - a civilization capable of harnessing the energy radiated by its own star (for example, the stage of successful construction of a "Dyson sphere"); energy consumption at ~4×10^{33} erg/sec [4×10^{26} W].

III - a civilization in possession of energy on the scale of its own galaxy, with energy consumption at ~4×10^{44} erg/sec [4×10^{37} W].[76]

Let us return to our space-based solar array that we keep expanding whenever we need a bit more energy. Utilizing our imaginations to envision a future society that is very wealthy and with advanced materials and construction techniques, we can imagine a case where we build a structure that finally surrounds the entire sun, intercepting all its energy. This case was imagined by the physicist Freeman Dyson and has been named the "Dyson Sphere" in his honor. Achieving such a structure would represent reaching the Kardashev Level II civilization.

Kardashev projected this achievement happening 3,200 years in the future. In Figure 19, we extend our earlier "most likely" simulation (2.5% growth in activity per year, 0.3% growth in green technologies and practices per year), and allowing for boom and bust cycles, for 10,000 years. We do not approach Kardashev's Level II threshold in 3,200 years as he predicted using an uninterrupted exponential trend. We take 10,000 years to approach this level because of our repeated depletion of natural capital along the way.

This projection of a fabulous science fiction future in "just" a few thousand years may be scant comfort to humans alive in 2013 with a life span of a century or less. To those of us alive today with children and grandchildren, it is much less than comforting to consider that their entire lives may be characterized by the first crash. Whether a given human being has a great life or a horrible life depends entirely on the luck of which future generation they are born into. I believe this simulation is the most likely one, or the "business as usual" simulation, given the trajectory our civilization is currently on.

[76] Kardashev, 1964

The final simulation I have run makes the optimistic assumption that all progress is green progress. In Figure 20, I have stopped plotting the results when we approach the Kardashev Level III civilization, in which we are able to harness all the energy of the Milky Way galaxy, roughly 100 billion suns. This level, finally, reaches the limit of my imagination, and I hope you have made the journey with me. With all progress being green progress, we reach this level in about 3,000 years. The difference between business as usual innovation and green innovation is the difference between Level II and Level III, or a moderately impressive spacefaring civilization and near-godhood, at the 3,000 year mark. Another way of looking at this is that the choices made by our current generation and the next few generations may matter greatly to the future of humanity.

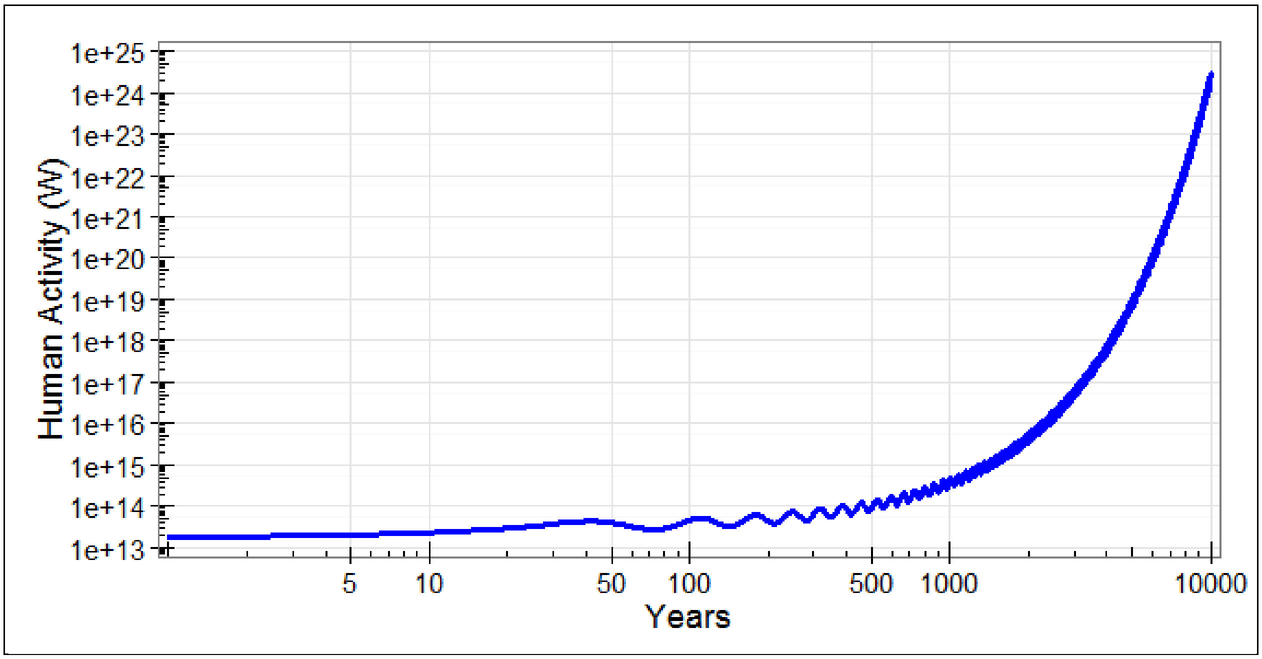

Figure 19: Simulation Results – Human Activity over 10,000 Years with Progress in Green Technology

After 10,000 years, following repeated boom and bust cycles, we approach Kardashev's Level II civilization (harnessing all the energy of the Sun).

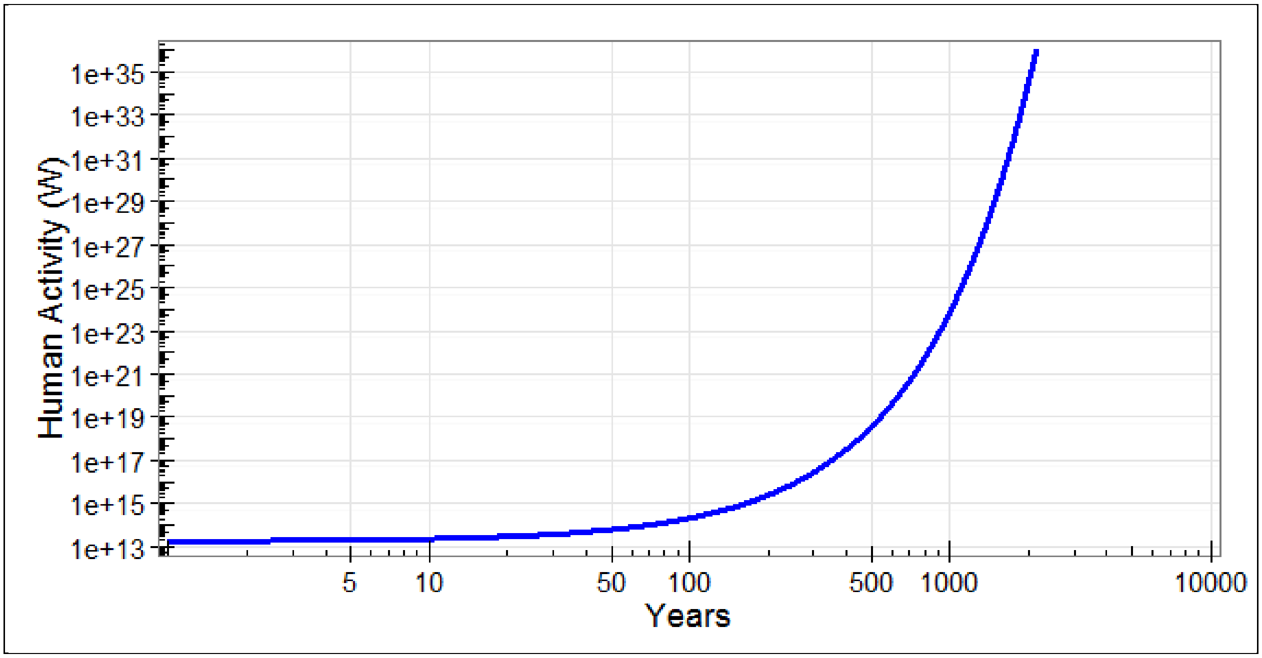

Figure 20: Simulation Results – Human Activity over 10,000 Years with Very Fast Progress in Green Technology

With fast progress in green technology, leading to uninterrupted exponential growth, we pass Kardashev's Level II civilization in less than 2,000 years and approach Kardashev's Level III civilization (harnessing all the energy in the galaxy) in only about 3,000 years.

The Big Risks

The simulations suggest that a radical acceleration of technological progress is indeed the logical future of the human race. The important questions are (1) whether it will be relatively benign or extremely dangerous to the human civilization and species, and (2) whether it will happen in the next few decades as optimists like Kurzweil predict or whether human actions, mistakes, or bad luck in the next few decades could cause it to be indefinitely delayed or permanently averted.

While Kurzweil states that his vision is "neither utopian nor dystopian"[77], his writing seems to assume the long-term survival[78] and (by his measures) improvement of the human species. On the question of whether future technology will be benign for the human species and human civilization, some thinkers are less optimistic. Martin Rees, a physicist, has predicted only a 50% chance of civilization in its current form surviving the coming 100 years, while the philosopher John Leslie[79] has given a 70% chance of avoiding human extinction. Eric Drexler, who is generally positive on the implications of advanced technology, is best known for a few memorable speculative sentences imagining ecological disasters such as "'[p]lants with 'leaves' no more efficient than today's solar cells [that] could out-compete real

[77] Kurzweil, 2005

[78] Bill Joy quotes him as giving "'a better than even chance of making it through,' with the caveat that he has 'always been accused of being an optimist.'"

[79] Joy, 2000

plants, crowding the biosphere with an inedible foliage", or even more dire scenarios involving bacteria or even self-replicating nano-scale robots that destroy all matter (the "gray goo" scenario).[80] Bill Joy, while sharing themes with Kurzweil and Drexler, has taken a much darker view of the long-term implications in his essay on advanced technology, *Why the Future Doesn't Need Us*:

> ***The 21st-century technologies - genetics, nanotechnology, and robotics (GNR) - are so powerful that they can spawn whole new classes of accidents and abuses. Most dangerously, for the first time these accidents and abuses are widely within the reach of individuals or small groups. They will not require large facilities or rare raw materials. Knowledge alone will enable the use of them...***
>
> ***The nuclear, biological, and chemical (NBC) technologies used in 20th-century weapons of mass destruction were and are largely military, developed in government laboratories. In sharp contrast, the 21st-century GNR technologies have clear commercial uses and are being developed almost exclusively by corporate enterprises. In this age of triumphant commercialism, technology - with science as its handmaiden - is delivering a series of almost magical inventions that are the most phenomenally lucrative ever seen. We are aggressively pursuing the promises of these new technologies within the now-unchallenged system of global capitalism and its manifold financial incentives and competitive pressures.***[81]

So the coming century or so could be very dangerous. These techno-futurist authors seem to agree that if we survive the near term, the future of humanity is exceedingly bright - our ultimate destiny in the far, far future is an expansion of human intelligence and awareness to encompass the entire universe. Their writings, while they may seem fantastically long-term and of limited relevance to those of us alive today, are worth reading to spur our imaginations about what the long-term future might be like. If these authors are right, our generation and the next few generations have an awesome responsibility to make sure the possibility of this bright future is not closed off.

What are the really bad things that could happen? I see four major categories, all of which have happened in the past: famine, war, plague, and disaster. I will assume famine is covered by the natural capital - human activity feedback loop discussed earlier. In fact, any "disaster" caused by natural capital depletion is covered by the feedback loop - this includes obvious candidates like famine and natural resource depletion, and perhaps less obvious ones like a new plague that jumps from monkeys to humans when a deep rainforest is disturbed for the first time, or the unknowing destruction of a wild plant species that could have been crossed with a grain crop, avoiding a catastrophic crop loss. Outside

[80] Drexler, 2006. Drexler's vision for nanotechnology is truly mind-blowing and highly recommended reading. In fact, I don't have time to go into great detail on visions of the future in this book, but Kurzweil, Drexler, and Joy are all well worth reading.

[81] Joy, 2000. This essay is a great read and also introduces many classic works of science fiction, illustrating how they can open our minds and imaginations to how strange, frightening, and wonderful the future may be.

this natural capital – human activity feedback loop we are left with events that truly come out of "left field" - war, plague, and natural or manmade disaster. These events have causes of course, but it is difficult to know in advance what the causes might be. For our purposes, we will assume these events to be random.

War

I will consider two categories of wars - first, a large-scale war with "conventional" weapons and at least some nominal concern for civilians. I will consider World War II a rough model for this type of war. World War II killed an estimated 40-50 million people, or roughly 2% of a world population of 2.3 billion.[82] Certainly, the suffering and loss of life in World War II was horrible, but ultimately it did not threaten the future of the planet, the species, or even the continuation of a recognizable form of modern civilization. Since it has been a little over half a century since World War II, I make a wild assumption that a war of this magnitude might occur on average once a century in the future. We do not know what types of weapons future "conventional" wars might be fought with. It seems somewhat unlikely that large-scale land battles will be fought in the future the way they have been in the past. Naval, air, and even space battles may be fought that endanger mainly combatants and military targets without widespread targeting of civilians. Battles may be violent but fought primarily by automated or remotely-controlled means. Unconventional weapons (chemical, biological, nanotechnological) may be developed that act selectively on individuals or small groups without indiscriminate killing. Cyberwarfare may cause widespread damage to economies and infrastructure without directly killing humans. Such warfare could be horrible but still survivable for the bulk of the human population. Even a limited nuclear exchange involving a few dated weapons, such as between India and Pakistan, could fall in this category. While it would be regionally devastating, and could produce dust which might affect agriculture worldwide, we would expect global civilization to recover and persist on more or less its accustomed path.

A much more devastating war, threatening the survival of many ecosystems and civilization itself, would be a global conflict involving weapons of mass destruction and widespread targeting of cities, civilians, agriculture and infrastructure. One model for this is a hypothetical global thermonuclear conflict between the United States and the Soviet Union, involving thousands of advanced warheads, perhaps in the 1970s or 1980s. John F. Kennedy famously put the probability of nuclear war during the 1962 Cuban Missile Crisis alone at 25-50%, while Robert McNamara put the odds during the entire Cold War at "substantially higher than one in six".[83] While there is a lively controversy about the likely death toll in a full-scale nuclear war and aftermath, such a conflict certainly would have killed at least several hundreds of millions[84] of human beings and devastated civilization, and at least some scientists have suggested far higher death tolls up to and including human extinction.[85]

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[82] Posner, 2004
[83] Rees, 2003
[84] Martin, 1982
[85] Wikipedia - Nuclear warfare

Plague

Plagues have repeatedly devastated civilization. We will consider the 1918-1919 Spanish influenza pandemic as an example of a "small" plague, killing an estimated 20-40 million people, or roughly 2% of the population at that time.[86] The bubonic plague outbreak in Europe in the 15th century killed an estimated 30-60% of the population.[87] Perhaps the most devastating plague in history was the wave of smallpox and other diseases that devastated the "immunologically unprepared" native populations of North and South America following the first European visits to the hemisphere. While there is scholarly disagreement both about the extent of the native population at the time of the first European arrivals, and about the extent of the death toll, the most extreme estimates give us some sense of what a truly devastating plague could do to the human species. At the high end of the scale, Henry F. Dobyns has estimated that there were on the order of 100 million Native Americans in 1491, and that 95% of them were wiped out by disease.

> ***Smallpox was only the first epidemic. Typhus (probably) in 1546, influenza and smallpox together in 1558, smallpox again in 1589, diphtheria in 1614, measles in 1618—all ravaged the remains of Incan culture... If all those people died, how many had been living there to begin with? Before Columbus, Dobyns calculated, the Western Hemisphere held ninety to 112 million people. Another way of saying this is that in 1491 more people lived in the Americas than in Europe.***
>
> ***His argument was simple but horrific. It is well known that Native Americans had no experience with many European diseases and were therefore immunologically unprepared—"virgin soil," in the metaphor of epidemiologists. What Dobyns realized was that such diseases could have swept from the coastlines initially visited by Europeans to inland areas controlled by Indians who had never seen a white person. The first whites to explore many parts of the Americas may therefore have encountered places that were already depopulated. Indeed, Dobyns argued, they must have done so... From the few cases in which before-and-after totals are known with relative certainty, Dobyns estimated that in the first 130 years of contact about 95 percent of the people in the Americas died—the worst demographic calamity in recorded history.***[88]

This was an example of a large population spread over a large geographic area, technologically and socially advanced for its time particularly in the southern hemisphere, that was nearly wiped out by aggressive diseases to which it had no natural resistance. This may serve as a cautionary model for the impact of a catastrophic global bioterrorism attack.

[86] Posner, 2004
[87] Wikipedia - Black Death
[88] Mann, 2002

Disaster

This is a catch-all category that has to cover everything else. First, let me mention what I have left out: earthquakes, hurricanes, tsunamis, volcanoes, and small asteroid strikes. These events all can devastate a city, nation, or region, but are not global disasters. At the other end of the scale is a strike by a "planet-killing" asteroid such as the one that may have wiped out the dinosaurs and caused other mass extinctions in history. An asteroid with a diameter of 10 km or more is estimated by scientists to hit the Earth once in 50-100 million years, on average.[89] From the point of view of anyone alive today, this probability is so low as to be negligible. Besides, we will see below that there are more likely events which could be even more damaging, up to and including destruction of the universe.

Perhaps a surprising category to consider under "disasters" is large economic or other system failures such as the worldwide economic depression in the 1930s. Nonetheless, these events have repeatedly happened in history and can have long-lasting consequences. The Great Depression decreased world economic activity by an estimated 30%.[90] The real damage from this sort of event is the fear and loss of confidence it causes that the machinery of civilization will continue to function. Besides a typical financial recession, one can imagine a collapse of international information technology and communication systems, whether caused by cyberattack or by cascading complex system failure, causing a similar loss of confidence. The "flash crash", in which high-frequency computer trading algorithms are believed to have caused the New York Stock Exchange to briefly lose 9% of its value in about 5 minutes in May 2010[91], is an example of a completely unexpected event that could have been devastating if it had gotten further out of hand. A series of terrorist attacks using conventional weapons, or industrial accidents such as the nuclear meltdowns at Chernobyl and Fukushima, are more examples of events that do not threaten existential doom but could cause widespread fear and loss of confidence in the complex systems underpinning civilization.

Finally, there is a category of disasters, even neglecting asteroid strikes, that could hypothetically lead to human extinction or even planetary destruction. Physicists believe that there is a tiny, but real, risk that a particle accelerator accident could destroy the Earth or even the universe itself. This risk has been estimated at 1 in 50 million during an experiment run for a 10 year period, and the experiments have continued with knowledge of the risk. While that may not sound so risky, technologies that may be possible within a few decades, such as self-replicating nano-scale robots, could theoretically also destroy the Earth. This is the "gray goo" scenario mentioned by Drexler and Joy. Also in this category would be a plague capable of causing total extinction. Extinction could be caused by an engineered virus that spreads easily (like the common cold), has a long incubation period (like the AIDS virus), then kills suddenly (like the Ebola virus).

Although the risk of a planet-killing asteroid or catastrophic physics experiment is almost laughable, there are reasons to take gray goo seriously. The risk of nanotechnology or bioterror catastrophe is unknown, and as Bill Joy points out these technologies may be widespread in many different corporate

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[89] Rees, 2003
[90] Posner, 2004
[91] Wikipedia - 2010 Flash Crash

and individual hands, some of which will be amoral at best and psychopathic at worst. As Joy describes, nuclear physicists working on the Manhattan Project were initially concerned that the first nuclear test might ignite the Earth's atmosphere, ending life on the planet. They initially estimated these odds at 3 in a million. Although they later decided that this calculation was in error, while under the stress of World War II they were prepared to proceed with those odds. This suggests that we can assume that even members of the human species with some moral scruples are prepared to take risks of this magnitude under stressful conditions. Stressful conditions are guaranteed to happen in the future, the technology will be accessible, and not everyone with access will be morally scrupulous. With this argument, I have made a wild guess that the annual probability of a "gray goo" mistake is on the order of one in one million. In Table 1, I summarize all the wild guesses I have made about the big risks. It is okay to make wild guesses because I am not trying to make an accurate prediction here. I merely want to capture the broad idea that very bad things can occur, and that the worse they are, the less likely they are to occur.

Table 1: Summary of the Big Risks

We do not know the precise risk of catastrophic events such as wars, pandemics, and disasters. However, based on their past occurrence, we can make some unscientific guesses about rough orders of magnitude over long periods of time, as we have throughout this book.

Event	Examples	Rough Drop in Human Activity	Wild Guess as to How Often this Might Happen
Global War with Conventional Weapons - OR - Major but Contained Pandemic	World War II 1918-1919 Influenza Epidemic	5%	Once in 100 Years
Major System Collapse	Great Depression; Major Cyberattack	30%	Once in 200 Years
Global War with Weapons of Mass Destruction - OR - Severe Pandemic	U.S./Soviet Union Global Thermonuclear War Black Death	50%	Once in 500 Years
Catastrophic Pandemic	16th-17th Century American Pandemics	95%	Once in 1000 Years
Gray Goo	Writings of Eric Drexler and Bill Joy	100%	Once in 1 Million Years

I have rerun one of our earlier simulations (2.5% annual growth in human activity, 0.3% annual growth in green technologies and practices) with these big risks factored in. Each year of the simulation, they are given a chance to occur based on the probabilities in the table above. Because the occurrence of an event is based on a random number generator, I can run the same simulation twice and get completely different results. In fact, an academic or professional analyst doing this type of simulation might run it 10,000 times and analyze the results statistically to gain a thorough understanding of the system's behavior. I have run it just 10 times (Figure 21), and the results illustrate the behavior clearly.

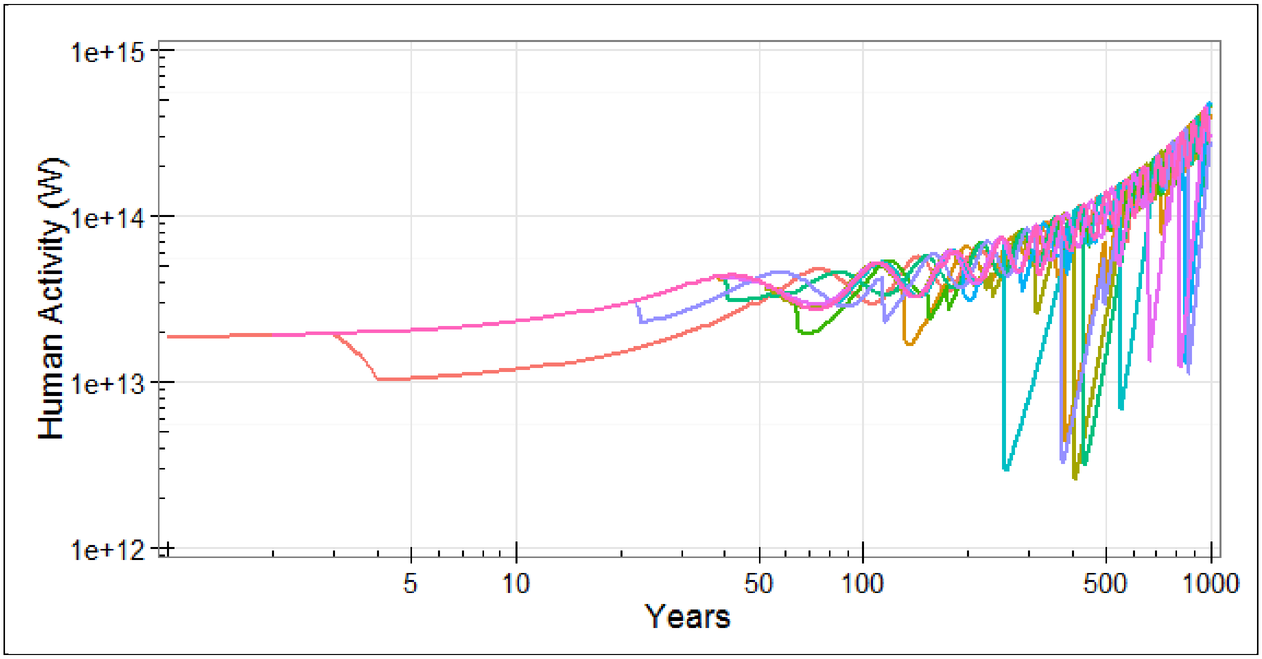

Figure 21: Human Activity over 1000 Years with Random Events

These 10 simulations include our business-as-usual assumptions but allow random wars, plagues, and disasters to occur at the frequencies and magnitudes listed in Table 1. Some "lucky" simulations follow the business-as-usual track very closely, while less lucky ones show drops in human activity due to random events. Following the events, natural capital depletion no longer limits growth and the system recovers quickly.

In a few relatively lucky simulations, few disasters happen and the simulation behaves much like the earlier simulations. Human activity oscillates up and down as natural capital is alternately depleted and replenished, but the oscillation is centered on a trend of increasing activity over time. When a war, plague, or disaster occurs, human activity is reduced. No matter how big the disaster is, the system recovers "quickly" back to the same trend it would be on if no disasters had occurred. This can take a hundred or more years, and therefore be devastating to generations of human beings, but it is clear that human civilization and the species itself are resilient in the face of disaster. The reason for this is that after activity is reduced, all limits caused by natural capital are lifted, allowing activity to grow at an uninterrupted exponential rate until it again reaches the envelope where natural capital is limiting. There are some particularly unlucky runs where successive disasters occur before full recovery is achieved, but even in these cases the system ultimately recovers. The one in a million chance of "gray goo" is extremely unlikely to show up in a 1000 year simulation, and indeed it does not in any of these ten runs. If it did, the result would simply be a flat line at zero following the disaster, the end of everything.

We do need to codify our knowledge as much as possible. The rapid recovery of the system to trend following disasters assumes loss of people and capital, but no loss of knowledge. This is clearly an overoptimistic assumption, given our earlier discussion of the difference between codified "technology" and uncodified "human capital". A disaster would clearly wipe out a lot of human capital. This contingency is something we can plan for in advance if we choose to make it a priority.

Conclusions of the Modeling Exercises

Ecosystem services are being consumed faster than they can be replenished, and natural capital is therefore being depleted. At present, remaining natural capital is still generating sufficient ecosystem services to sustain civilization. However, the important conclusion of the modeling exercises is that under "business as usual" conditions, which include the current rate of innovation and progress in green technologies and practices, civilization crashes repeatedly producing untold human misery and destruction of natural ecosystems. In the very long term, innovation does allow humanity to escape the Malthusian trap, but not before many generations of human beings (likely beginning with the children and grandchildren of people alive today) experience unspeakable misery. To escape the misery and avoid the wanton destruction of natural ecosystems requires an order-of-magnitude increase in the rate of innovation.

Two Critical Steps to Stop the Madness

Every book must end with a chapter of prescriptions on what should to be done. In many books I find that this final chapter is a let-down because it is easier to criticize others and describe a problem than to offer solutions. I don't want to let my reader down. Nonetheless, one of the main objectives of this book was to help me figure out what to do next. So, I have decided to include *two* chapters on potential solutions. In this next to last chapter, I offer just two steps that I am very confident are absolutely necessary for our civilization to adopt. In this chapter, I will refrain from speculating on specific technologies or policy measures that I think might help accelerate green innovation. In the final chapter, I will let my hair down a bit and do just that.

Critical Step #1: Make Ethics[92] a Central Focus of our Decision-Making Process

We have established that the rate of green innovation is much too slow. But perhaps in spite of that the best thing to do is still nothing, or to continue with business as usual. Joseph Schumpeter, Paul Romer, Julian Simon, and others quoted in this book have made a case that relatively unregulated markets operating in a stable political system can gather the relevant information and broadcast the right signals

[92] I have tried to figure out if there is a clear, well accepted distinction between the terms "ethics" and "morality". I have been able to find no such distinction, and have concluded that the terms are sometimes used interchangeably, and definitions of the terms are overlapping and ambiguous. I have chosen "ethics" because I feel that, in the popular usage at least, the term has less religious connotations and at least the possibility that the ethical framework put forth by one's society (parents, religion, country, profession, etc.) can be adapted to one's personal world view. From the Stanford Encyclopedia of Philosophy, "Following Aristotle, 'ethics' is sometimes taken as referring to a more general guide to behavior that an individual adopts as his own guide to life, as long as it is a guide that one views as a proper guide for others."

to spur innovation and problem solving when they are needed. But despite these powerful abilities of markets, we have seen that the market response is too little, too late to prevent collapse and crisis. Even if markets can be relied on to spur recovery from collapse and crisis, any collapse or crisis could ruin the lives (or destroy the lives) of generations of human beings. *Homo economicus*, the rational profit-seeking robot, would do nothing. *Homo sapiens* cannot ethically do nothing. If we conclude, as I have, that there is a significant chance the trajectory human civilization is now on may lead to very serious harm and suffering for future human beings, likely including our own children and grandchildren, we have no ethical choice but to act to reduce that risk.

The ethics I am talking about is deciding what we think is right and wrong, and choosing right. It is not "business ethics". If you work for a corporation, your employer may require you to take a course on "ethics" which basically tells you to follow the rules and avoid doing anything that might get the company sued. In both cases this is good advice for your continued employment. However, by itself it is certainly not a sufficient guide to right and wrong.

Nor is my definition of ethics about codes of "professional ethics" imposed or self-imposed on credentialed professionals, such as doctors, lawyers, engineers, and accountants. These codes include some elements that address right and wrong, such as the doctor's oath to "first do no harm" and the engineer's responsibility to the safety of the public. But they also include elements such as professionals' agreeing not to criticize each other's work in public. This may be a good policy to protect the reputations and fees of the professionals involved, but it is hardly a sufficient guide to right and wrong.

Ethical frameworks differ but all have the common element of condoning choices and behavior that reduce harm and suffering in others.[93] We are all given an ethical starting point as young children first by parents, then later by teachers, religious and other role models, and finally by the larger culture. But after early childhood, we are no longer challenged to think about ethics every day. It wouldn't hurt for students to engage in formal study of ethics at some point in their careers, for example, what the great philosophers and major religions have to say on the subject. But for people to really think and act ethically, teachers and parents need to challenge young people to identify and challenge their ethical beliefs constantly and to think about right and wrong choices constantly, not just as small children but through their most formative development years and on into adulthood. As adults, we each need to ask ourselves whether we think our daily actions are ethical, rather than uncritically accepting any job that provides a paycheck or makes a profit for our business. Avoiding harm and suffering to other persons also should include some consideration of persons who will exist in the future.[94]

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[93] Stanford Encyclopedia of Philosophy

[94] The American Society of Civil Engineers, to its credit, has added consideration of "sustainable development" to its code of practice. However, this has not migrated to the codes of ethics of the National Society of Professional Engineers or my state licensing board (Pennsylvania), and from my personal observations I do not believe it is being implemented or even discussed (or even carefully defined) in the daily practice of the civil engineering profession. In my view, any definition of sustainable development includes consideration of social and environment impacts of engineering decisions affecting current and all future generations. Of course, some people including myself would go further and include avoidable harm to natural ecosystems as wrong under our personal ethical codes.

A few of us will be in a position to take measures to prevent the really bad things, like nuclear war, catastrophic plague whether naturally arising or man-made, the planet killing asteroid strike, the "gray goo" scenario or the physics experiment run amok. These are the mistakes that, even if improbable, we cannot make, because making them just once means the end of everything.

The rest of us are in a position to take smaller daily actions and decisions that either improve the outlook for our species, civilization, and ecosystems, or do not. Many small decisions and actions by many people can add up to revolutionary change, but this happens only if we are constantly challenging ourselves to make ethical decisions.

Critical Step #2: Adopt a Systems Approach to Problem Solving

Once we discipline ourselves to think about right and wrong every day, and are prepared to reorient our decisions and actions in the service of what we think is right, we are in a position to define what our goals and values are, understand the systems we are dealing with, and influence those systems to help us meet our goals.[95] I came to this approach through my engineering training, and through my experience planning urban water resources and infrastructure systems, but I believe the concepts apply equally well to many fields. I will refer to the process as "a systems approach to problem solving" or simply as "system thinking".

The first step in a systems approach to problem solving is to define the system itself, the goals to be pursued, and the time frame to be considered as broadly as possible. In today's world of intense specialization, highly intelligent people tend to focus their efforts in pursuit of very narrow goals. I will give an example from my own experience in the field of urban infrastructure. Transportation engineers are often tasked with determining the best way to get people from their homes to places where they work and shop. They will then study how many people live where, where they work and shop, and possible routes for roads to connect these various destinations. The goal is to determine the alignment and configuration of a set of roads that will maximize traffic flow, minimize congestion, and minimize the time and expense of commuting. This all sounds fine, but it misses out on an opportunity to define the goals more broadly. Rather than maximizing traffic flow, the goal should be to get people where they need to go by the fastest, healthiest, and safest way possible. In fact, by broadening the system under consideration even further to encompass the location of homes, work places, and shops themselves, an interdisciplinary team of engineers and planners can work through the political process to solve many problems at once. We may also want to consider the implications of land required for car parking under various scenarios. Land reserved for car parking is not available for any other use, such as recreation, habitat, or commerce. Clearly, when changing the configuration of an urban area is on the table, a much longer time frame must be considered. Where a new road can be constructed in a few years, improving the layout of a city might take decades. So the first step in system-based problem

[95] There is an academic literature on "decision science" and decision making under uncertainty, but I recommend the 1996 book *Value Focused Thinking: A Path to Creative Decisionmaking* by Ralph Keeney for an excellent and accessible discussion of how to set broad goals based on values and identify a wide range of potential options to meet those goals.

solving is to be open to greatly broadening both the goals to be achieved and the time frame to be considered.

The next step in a systems approach to problem solving is to consider as broad a range of possible solutions as possible. If the goals have been defined broadly enough, it will be easier to think of those "outside the box" solutions that might have been overlooked given a more narrow problem definition. Continuing the example above, the options to be studied will include much more than a limited access highway versus a local highway with various types of control signals (although the traditional solutions should never be rejected out of hand - they may have withstood the test of time for a reason). Options to be studied now may include better pedestrian and cycling infrastructure along urban boulevards, bus rapid transit, light rail, cable cars, car share and bike share systems, and even facilitation of telecommuting. Various zoning, development rights, and land use control or incentive strategies might be considered to bring residences and businesses closer together, reducing the length of trips taken and influencing the choice of modes to take those trips.

Now that we have defined the system to be studied, the time frame to be considered, and the problem to be solved (i.e. the goals to be achieved), we come to the relatively mundane task of technical analyses to identify one or more combinations of measures that can solve the problem. I say relatively mundane, but this is the fun part for many technocratically minded professionals like engineers and economists. In fact, we find it so much fun that we often skip right to it. (In our example, we might assume we know the system to be studied is a road, the solution is a road, and the problem is how big the road needs to be. Why waste time defining the system, talking to stakeholders and decision makers, setting goals, and identifying other solutions?) Society tends to pay more respect and money to the professionals who perform these analyses, compared to, say, planners, sociologists or ecologists, who may be in a position to oversee a broader, more creative planning process (while still employing engineers and economists for the important number crunching).

There is a further process that tends to discourage really good system-based problem solving. This is that decision makers themselves expect too much from the technical analyses and discount the value of the larger process. Often, people in positions of power are just as happy not to consult other stakeholders for input on their decisions. Even when sophisticated technical analyses are done using sophisticated tools, they will not often arrive at a single "optimum" solution that precludes the need for human decision making. If they do, it is a sign that the problem has been oversimplified, most likely considering only a very small subsystem, a short time frame, and very narrow objectives or even the single objective of financial cost. Systems and problems in the real world are too complex for this simple approach. The job of the analyst is to identify a set of solutions that can solve the problem efficiently in a technological and cost-effectiveness sense, and to give decision makers the information they need to make a good decision. When decisions must be made on a short time frame, as they almost always must be, it is better for the analyst to provide information at the right time, even if derived from a simple set of tools, than to provide no information because the tools used were too complicated to provide an answer in time.

As I mentioned, tools for technical analyses are the relatively mundane part of a system-oriented problem solving approach. Given a good system definition, set of goals, and set of possible solutions, the competent analyst is likely to come up with some good answers using any reasonable tools. Without a good system definition, goals, and set of possible solutions, no amount of sophisticated tools will produce a good solution. But of course technical analyses are hard work and a good set of tools helps. So let me briefly discuss tools.

Economists have their theory of utility and framework of cost-benefit analysis. This is a reasonable framework, provided there is some reasonable way of estimating relevant costs and benefits. Originally, "utility" was not exclusively about money. It was about whatever people thought were the main keys to living a good life. "Goodness" might be a better term, capturing the double meaning both of living a prosperous and comfortable life and living up to some ethical responsibility of being good to others. The current emerging fields of "behavioral economics" and "science of happiness" are a step back in the right direction. People can make choices that are rational in terms of maximizing whatever it is they think is important in their lives, whether or not that results in maximum money in their pockets. The basic idea of trying to identify and quantify all the costs and benefits of a given course of action is a sound one. If we can reasonably define goals, costs, and benefits either in money or in other appropriate terms, we can use this theory to examine choices in many fields, from economics to politics to science and technology to sociology and crime.

For better or worse, economics is the single field we look to most to guide the course of our civilization. It is the accepted system science of our time. However, before it can guide society much better than it does now, it will need to drop its obsession with algebraic solutions to steady state mathematical problems. Economists tend to define problems in a way they know they can solve analytically (symbolically) using algebra and calculus. However, the real world is much too complex for this and it does not make sense to pick the problems to be solved on the basis of which ones can be simplified to the point that they have simple solutions. Engineers know better than this. Most engineers long ago abandoned analytical solutions to simple equations in favor of numerical approximations to more complex equations that can account for processes that vary over distance and time. Only computers can do these computations. Engineering is, in fact, the original system science. Well-trained engineers try to understand a system and figure out what variables within the design of that system they can manipulate to make it function the way they want it to function, in service of some goal or set of goals. This framework of engineering problem solving could be the savior of civilization, except that engineering as typically practiced tends to define the system of interest, the time frame of interest, and the goals to be accomplished much too narrowly.

Another discipline that appropriates some of the best features of engineering system analysis is the self-described system thinking discipline and the dynamic system modeling approach it recommends.[96] This discipline has shown how to apply dynamic system modeling to diverse fields ranging from engineering

[96] Perhaps the most prominent system thinking group is the one established by the late Jay Forrester at the Massachusetts Institute of Technology.

to economics to public policy. There is also a school of ecologists who advocate and practice system thinking.[97]

So, in summary, at least three fields provide useful tools and approaches that in combination provide a solid framework for whatever technical analyses need to be performed. The economists' framework of utility maximization and cost-benefit of analysis can be adapted to making reasonable choices in our complex world. The tools of engineering systems analysis and dynamic system modeling should be adopted by economists and others. The system thinkers' advocacy of much broader and longer-term system definition and understanding should be adopted by everyone.[98]

A caution in the application of a system approach is to give at least equal consideration to policies, practices, formal and informal institutions as to the more technological solutions. Continuing our example, although designing better streets is not a trivial technological problem for engineers and urban designers, the human element involved (for example, driver anger at cyclists, a feeling of entitlement to high speeds and free parking, fear of crime on public transportation, etc.) is much more likely to present an obstacle to progress. The education system needs to give the study of social institutions consideration and respect equal to that enjoyed by the natural sciences, engineering, and economics today. Social scientists can clearly play a key role in this revolution, but to do so they need to evolve from their current almost purely observational approach to become more practical, applied sciences. If they do not do this, economics will continue to wear the mantel of the only practical social science, particularly as it gradually evolves to incorporate aspects of human behavior, psychology, and even neuroscience.

To summarize this long section on the importance of a system-oriented approach to problem solving, let me restate the main points in the form of advice:

1. Define the system more broadly than your first impulse. Go up at least one level in defining the system. Whatever your first impulse is, ask what the larger system is that contains the subsystem you were thinking of. Don't forget to include social institutions in addition to the physical world.
2. Consider a longer time frame than you were going to. At least double it, and even think about going out to the proverbial "seven generations".
3. Think hard, consult decision makers and stakeholders, and come up with a set of goals that encompasses the broad system you are studying. Think hard about what you believe is right and wrong, as we have discussed earlier, and make your goals consistent with right. Consider what you think your responsibility is to the natural world, to our human civilization, and to individuals within our civilization.
4. Think hard, consult a wide range of knowledgeable people and stakeholders, and come up with a very long list of potential ways to meet your goals. Consider institutional changes and new practices and policies in addition to traditional physical approaches.

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[97] Perhaps the most prominent systems ecology group is the one established by the late Howard T. Odum at the University of Florida.

[98] I can recommend some further reading: *Thinking in Systems: A Primer* by Donella Meadows and *Business Dynamics: System Thinking and Modeling for a Complex World* by John Sterman.

5. Do the math. This is hard work but straightforward. Get some engineers, economists, scientists, and planners together and come up with a reasonable approach using reasonable tools.
6. Figure out a way to frame your conclusions so they can be put into practice.

Even if governments and businesses operate efficiently and rationally, and people make efficient, rational choices, this still is not guaranteed to lead to innovation. Innovation can come only from the creative thinking of human minds.[99] Innovation must start with vision. If that vision is green and not simply the modification of consumer products in the amoral pursuit of profit, green innovation can result.

Not everyone will act in an ethical manner or adopt a systems approach to problem solving. But we can think of more widespread adoption as akin to vaccination. If we vaccinate most of a population against a disease, the population is protected against a few remaining unvaccinated individuals because diseases are now unlikely to spread. The disease we are trying to prevent is madness, the madness that has us rushing headlong for the cliff of that first crash. Our species and civilization may be fine a thousand years from now, but this does not guarantee that you, I, our children and grandchildren will not suffer horribly and die untimely deaths. If we can vaccinate enough of our population against the madness, perhaps we can avoid rushing over that first cliff.

Some Additional Ideas to Ponder

In the last chapter, I discussed two ideas - infusing ethics into our everyday decisions and actions, and employing a systems approach to problem solving – both of which I am absolutely sure our civilization needs if we are going to have a shot at avoiding that first crash. Beyond that, I am not going to prescribe exactly which ideas, technologies, and approaches we need most. Because I don't know. We all need to think ethically and think in systems and search for those solutions together. I can gather some ideas based on my own concept of right and wrong and involving some of the systems I know best from my academic and professional experience. And based on reading, thinking, and discussions with others from a variety of backgrounds, I can speculate in a few more areas. Below I will do just that, going into some detail on my favorite ideas in the systems I know best, primarily urban water resource and urban infrastructure systems. Then I will speculate in many more areas. I don't know if these are the right ideas or not. If you would like to work with me on exploring and implementing some of these ideas, I would love to hear from you! If you don't like my ideas, I encourage you to come up with your own and I would love to hear them too!

The point is not for any one person or group to prescribe a solution, or governments or non-governmental organizations to shoulder the whole burden with massive R&D programs, but for those of us on the ground (which is all of us) to actively search for workable sustainability decisions in our everyday work and lives.

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[99] At least, this is true until the day when artificial intelligence is able to augment and eventually surpass the human mind.

All of us can play a role in accelerating the rate of progress in environmentally benign technologies and institutional practices. A few of us will be involved in research and development leading to the really big breakthroughs. A few of us will be movers and shakers in the business and political worlds who have the raw power to get things done. One or two of us may be an Einstein or a Ghandi, if the world is lucky. But most of us will live somewhat mundane lives and do somewhat mundane jobs. However, all of us, no matter what our fields of endeavor, can do something small to accelerate progress, if we think about it and act on it often enough. One reason for my own optimism about the possibility of an order-of-magnitude acceleration in green innovation is that there is a lot of low-hanging institutional fruit out there. By "institutions", I mean our patterns of behavior, or simply the way we do things. The way governments, businesses, non-profit organizations, formal and informal groups, families, and individuals do things is at least as important as technology, and gets much less attention and respect. Education about institutions is almost entirely lacking in our education system, and that needs to change. Students at all levels need to learn that human behavior, learning patterns, self-interested behavior, skepticism, and resistance to change are critical determinants of why our society succeeds or fails.

Harmony with Nature

Perhaps the idea of achieving harmony with nature sounds idealistic, or even corny, to some. But the concept captures both a sense of human responsibility to the natural world, and a sense of what the natural world does for us. To work towards harmony with nature, we have to have vision and imagination. A first step is to fully appreciate the diversity and productivity of our lost ecosystems. For example, developed countries have greatly reduced pollution in urban waterways in recent decades, and this is commendable. However, before urbanization these waterways had much more than "clean water" - they supported diverse and productive ecosystems, including wetland and estuarine systems. Forests and grasslands were also diverse and productive. We are victims of "shifting baseline syndrome", in which the current generation has never experienced those productive ecosystems and assumes that the way they are now is the way they have always been, and the best they can be. We are in an ecological dark age, a period when our civilization has lost its cultural memory of what once existed. We assume this level of diversity and productivity cannot be restored.

Urban Ecology

We will begin our discussion of harmony with nature in the city and work our way out to the countryside. Many people assume that urban areas are essentially ecological dead zones, but to work toward harmony with nature, we need a vision that in fact this does not have to be true. We can draw some inspiration from one of our fellow organisms - the lowly ant. Surprisingly, the body mass of all ants on planet Earth is similar to the body mass of all humans![100] Ants are found in virtually all ecosystems. They build structures analogous to housing, mines, tunnels, highways, and farms. They hunt, gather, conduct warfare, and engage in forms of cultivation. The scale of ant enterprise is huge! They certainly have an ecological footprint, yet we do not think of it as a negative one. They are intimately intertwined with the planet's ecosystems and provide critical functions within them as well as subsisting on them.

[100] Braungart and McDonough, 2002

An urban area is certainly not an undisturbed natural ecosystem, but it is an ecosystem nonetheless. Like ants, we can aim to reshape the ecosystems in our midst while still providing a wide range of benefits both to ourselves and to other species. The idea of harmony with nature must begin in our cities, towns, and other human settlements, because this is where the people are. Robert and Edward Skidelski have described the human need for interaction with nature in cities:

> ***Harmony with nature has often been understood to favor rural over urban life. Ever since the days of Babylon and Rome, cities have appeared as sinks of squalor and vice. But the opposite point of view has also had its defenders. Socrates found all the wisdom he needed within the walls of Athens. Marx spoke of the idiocy of rural life. There is no need for us to enter into this old debate; both sides have some truth to them. What is new, however, is the sheer scale of the modern city. An inhabitant of eighteenth-century Paris, then the largest city in the world, had only to walk thirty minutes to find himself in farmland. His modern equivalent would have to walk six hours through crowded traffic. Here is the source of that typically modern feeling of urban malaise and that yearning, often comic in its effects, to "get back to nature."*** [101]

Since cities are by definition where the people are, and we can't all "get back to nature" in the sense of living in a rural environment, we have to bring nature to the people. Going back to our ecosystem services as defined at the global scale by the Milennium Ecosystem Assessment, we can see that many of them have echoes at the local scale. In fact, the "cultural" services of aesthetic, spiritual, educational, and recreational experiences will reach the most people, and thus have the most cumulative impact, if they happen at a small scale every day in our urban parks, on our streets and plazas, and in our yards.

The "supporting" services: nutrient cycling, soil formation, and primary production, may be most important on our agricultural lands, but they can also happen at the city and neighborhood scale. Partial nutrient cycling that happens now in wastewater treatment plants and landfills, and in natural water bodies that receive our treated and untreated wastes, can be augmented or even replaced by green infrastructure systems that use soil and plants to cycle nutrients. These systems can be integrated with wildlife habitat, with educational and recreational opportunities, and with urban food production.

The "regulating" services of water provision, water purification, and flood regulation apply directly to cities and towns and except for the poorest of countries, the public demands and expects these services. Typically they have been provided by heavy infrastructure systems - pipes, pumps, and concrete. These are additional areas where green infrastructure can work its magic, potentially providing these services with less cost and disruption while at the same time providing the cultural services. Creatively conceived green infrastructure can provide the cultural, provisioning, and regulating services at the same time and place in one integrated system, rather than in separate systems (for example, sewer systems, treatment plants, levees, and parks) being required to provide them.

[101] Skidelski and Skidelski, 2012

A good start on a green infrastructure system is to plant trees - a lot of trees - and to choose them carefully. Trees and other landscaping on streets and public lands can be chosen with biodiversity and ecological function in mind. Beyond trees, we can consider what could be done to enhance ecological function of every scrap of public land that is currently covered with simple turf grass or with underutilized pavement. On private lands, some combination of education, incentives, and regulations can be considered to encourage landowners to contribute to the overall system. For example, taxes or fees could be tied to the amount of pavement and turf grass on a property, and positive incentives to the presence of trees and native species.

We can create more community gardens and shared garden spaces. I believe there are a lot of frustrated gardeners in cities. Some people own land but have no interest in doing anything with it, while others own no land but would love to try gardening for food, habitat, recreation, or all three. By connecting these groups, many more spaces can be made accessible to people who have the motivation and knowledge to make them ecologically functional.

Many cities are constructed on filled-in land near bodies of water, where productive wetland and estuarine systems used to exist. Part of the new green infrastructure system can be to establish parks along stream and river corridors whenever possible, for both recreational and ecological reasons. We should incorporate wetland and floodplain areas into these parks. To restore even more of the lost functions of wetlands, we can experiment with floating wetlands along the edges of urban rivers to provide refuges for fish and invertebrate spawning. We can imagine the incredible abundance of fish in the rivers and estuaries before urbanization and industrialization, and strive to engineer such a diverse, productive system again.

Urban Hydrology

The hydrologic system is overlaid on and intertwined with the ecological system. When a natural area is urbanized in the usual way, large quantities of rainfall that used to soak into the ground, recharging groundwater and nourishing plants, now run off immediately into streams, rivers, and other water bodies. This causes pollution and erosion, in addition to the fact that the water drained away so quickly is no longer available to either people or vegetation in the city. To remedy this, we can overlay a vision of a hydrologically functional urban landscape on top of our ecological one. We begin with our ecologically functional green infrastructure system, then fine tune our overall urban design to bring water, soil, and plants together. Green infrastructure elements such as rain gardens, bioswales, vegetated roofs, porous materials, and extensive tree canopy can be engineered to achieve an urban hydrologic cycle similar to what would have existed before development, such as a forest or grassland. This is a complex but completely solvable engineering and landscape design problem. The reason it is not often done today is partly a lack of imagination, but also a variety of difficult institutional challenges.

One institutional barrier to achieving multiple ecosystem services in one integrated system is that different organizations are often responsible for each type of traditional infrastructure system (for example, treatment plants, sewers, flood protection, transportation corridors, parks) and have little incentive or tradition of working together. Big business, big government, and big nonprofit entities such as utilities and authorities have made large investments in these long-lived, centralized heavy infrastructure systems, and this works against smaller-scale, more decentralized technologies such as green infrastructure. As Schumpeter convincingly argued, big business will innovate when it feels threatened by disruptive innovations that might arise from outside players. However, big investments in long-lived capital present a problem. An organization that has made a given investment will have little incentive to develop technologies that bypass the infrastructure it has built. For example, why would a wastewater utility encourage waterless toilets once it has built a sewer system, or an electric utility encourage solar panels once it has built a power plant? These entities may even fight tooth and nail against smaller entities that come up with technologies potentially able to bypass their infrastructure, making it obsolete and threatening the revenue stream it generates.

There are cases where decentralized, small-scale infrastructure can be integrated with existing large-scale infrastructure systems in a win-win way, for example rain gardens or waterless toilets reducing the rate of flow into already overloaded sewer systems. In this case, the owner of the centralized, long-lived infrastructure system may have an incentive to avoid or defer further capital investments. It may also be rational to bring newer, decentralized systems online as the older systems become obsolete, although this can take very long periods of time. Far-sighted leaders may realize that even when a capital-intensive system makes sense now, if it takes too long to build it may be obsolete the day it starts operating, let alone throughout its operating life. The 1950s-era nuclear reactor designs that brought us the Three Mile Island, Chernobyl, and Fukushima accidents decades later are examples. Even in cases where innovations such as these make rational sense for the owner of a traditional capital-intensive system, the leadership needs to have a good enough understanding of the system, a long-enough time perspective, and open enough minds to try something new.

Recreation and Livability

In addition to ecological and hydrologic function, it is important to design landscapes for recreation and simply for quiet enjoyment by people. A variety of studies have suggested that exercising in nature is particularly good for both physical and mental health.[102] Bringing people, particularly children, into contact with nature is important for another reason - it creates a society of people who feel an affinity with nature, who will know what they are missing if they do not have contact with nature, and who therefore will be advocates for creating harmony between our civilization and nature. Over time, we can shift the baseline expectation back in the positive direction, creating a virtuous cycle where each new generation experiences and feels more affinity with nature, rather than less.

Cities in the Larger Ecosystem

In the countryside, for those countries that still have a countryside, it is important to protect and extend the remaining natural (relatively undisturbed) ecosystems. Humanity has taken up a lot of space already, and we can continue to advance civilization in the space we have already altered. So we need to try to prevent any further loss of natural ecosystems, and try to roll back past losses where we can. Some species thrive only deep inside the largest protected areas, and need enormous territories to maintain viable populations. Others will be fine with a network of smaller patches if they are connected by protected corridors. We need to visualize the entire landscape, from the smallest patch of habitat

[102] Louv, 2012

between street and sidewalk, to the urban backyard, to the small neighborhood park, to the large regional park, to the rural nature reserve, as a single interconnected system. We can create connections and protected corridors that allow people and wildlife to move between patches of urban habitat and from urban to undisturbed rural habitats. For particular species, biologists can work out a network of smaller patches, reserves, and corridors that mathematically should function similarly to a larger reserve. This technical work of designing a functioning system is not the hard part; rather, implementing the system through long-term land use and development decisions is the hard part. To do this, engineers, developers, politicians, planners, biologists, and members of the public need to buy into the vision and realize that we can all work together to achieve it. With vision, ethics, and a whole-system perspective, we can maximize biodiversity, productivity, and ecosystem services of use to humans.

Food

As discussed in the main body of this book, food is perhaps the most important link between human civilization and ecosystem services, and perhaps the most vulnerable. Food production on the massive scale of our industrial, urbanized, populous civilization probably cannot be done entirely at the local scale by the people eating the food. As discussed earlier, agriculture has become so efficient and productive that it is largely taken for granted by our society and assigned a relatively low economic value. However, some involvement in food production at the local scale is highly desirable for two reasons. First, producing even a small fraction of our food at the local scale will provide some resilience if there were to be some breakdown in the larger industrial food production and delivery system. Food production on a small scale is also a way for people to work towards harmony with nature on a daily basis in our cities and towns.

Urban Agriculture

We should remember that while money does not grow on trees, food actually does grow on trees! Simply by replacing some of the inedible, ornamental species of trees and plants in our cities today, we may be able to produce food and habitat with no more effort than we put into landscaping now. While it may seem that space in our cities is extremely limited, there are a lot of small patches that add up to significant space – the strips of grass between streets and sidewalks, front yards, back yards, porches and patios, containers, rooftops, and basement LED light setups. Imagine if urban people produced even 5-10% of their own food supply worldwide; this would provide a cushion of resilience to the system in case of a catastrophic interruption in our industrial food system. Meanwhile, gardening and tending trees is a wonderful way for urban children and adults to "get back to nature" without having to travel far from their homes. For the more adventurous, chickens, rabbits, even sheep and goats are an option.

Larger-Scale Agriculture

There is a middle ground between the plowed field and the untouched wild ecosystem. The idea of "Permaculture" provides a model of agriculture modeled after natural systems such as forests. Food production systems designed in this way use more tree crops and perennials than conventional agriculture or even conventional backyard gardens. A "food forest" is designed in several layers, from a canopy to a ground cover layer, to mimic a natural system while providing food to people with relatively little effort. Aboriginal human beings in both the Americas and Australia harvested large amounts of food from semi-cultivated, semi-wild ecosystems, providing a model we may be able to adapt even to urban areas.

Permaculture devotees have also experimented with ways of grazing livestock at high densities, but for short periods of time in any given area, that help to build better soil and more diverse ecosystems, even in arid areas. We often think of meat eating as being high-impact and less sustainable than grain-eating. This is true when prime cropland is used to grow grains that are then fed to animals. In a world where this is the dominant paradigm, moving towards vegetarianism will provide large net ecosystem benefits, and of course, to some, this is the only ethical choice. However, there are many areas in the world that do not support crops but can still support grazing animals. If animals can be grazed in these areas in ways that do not require food and water to be brought in, and actually enhance the ecosystem, the system can be sustainable and provide a net ecosystem benefit.

The consumer-driven movement towards "organic" agriculture holds promise. A few studies have suggested that it can be as productive as conventional agriculture, while many others have reached the opposite conclusion. At a minimum, we need to make sure farmers are rewarded for efforts to conserve and build soil. Innovative and creative people need to keep working on high-yield yet ecologically sensitive forms of agriculture. At the same time, conventional high-tech agriculture has managed to feed the masses of humanity so far so let us not discount it. Many promising technologies have been developed and could be taken further, such as drip-irrigation, automated watering based on soil moisture monitoring, plants tended by robots, and even laboratory-derived meat. Like it or not, genetically modified foods and other advanced technologies are probably here to stay, so creative, ethical people need to get involved in guiding the beneficial aspects of the technology while developing safeguards against any potential hazards.

Neighborhoods, Streets, People and Transportation

Now that we have discussed a vision of ecologically, hydrologically, and even agriculturally functional landscapes in our urbanized areas, it is time to add the final two layers to the vision – the infrastructure that people depend on in modern, urbanized, industrialized society, and finally, the layer of people ourselves.

Urban Form and Transportation at the Neighborhood- and City-Scale

The way neighborhoods and streets are laid out matters greatly both to human lives and to the environment. People expend energy in the process of going from their homes to shops, schools, and businesses. Much of the energy we expend currently is derived from fossil fuels, so that the amount of energy we expend is linked directly to air quality and to greenhouse gas emissions. Public transportation vehicles such as bus and subway systems are more efficient than private automobiles in terms of energy used and pollution produced for a given distance traveled, and they certainly waste far less space compared to private vehicles – space that can otherwise provide ecosystem services, economic production, or simply space for relaxing and socializing. However, there is an even lower impact and more socially beneficial way of getting around, and that is getting around under our own power. I believe strongly that the single most important thing we can do both to reduce our environmental impact and to improve our lives is to locate our homes, businesses, shops, and schools close enough together so that most trips can be made by foot or bicycle.

The development patterns of our cities, towns, and transportation systems are an example of institutional dysfunction on a large scale. I won't say exactly what I think towns and cities should look like or exactly how they should be laid out, although I have my preferences on the subject. I do believe strongly, however, that we need to design towns and cities so that people can get around under their own power for the majority of trips they take on a daily basis - such as work, school, shopping, and socializing - between the squares of the city-scale chess board on which most our economic and social lives play out. Instead, many urban areas spread people out at low densities where only private automobiles are seen as a feasible way of getting around, spending enormous amounts of money and losing large amounts of useful land to roads, streets, and parking lots. We assume that concentrating more people in a smaller area would lead to crowding, but in reality it can lead to much less wasted space. In more compact cities, less space is wasted on parking, and people can get around by walking, biking, and public transportation incorporated in safe multi-modal street designs or in spaces that accommodate pedestrians, cyclists, and motor vehicles together at very low speeds. Even vehicles themselves can be shared, keeping them in service more of the time, parked less of the time, reducing the total number of cars required to support a given population (though not necessarily the amount of traffic), and decreasing the amount of space that must be devoted to parking. The space saved can be repurposed to provide a combination of housing, natural habitat, food, and commerce.

Increased physical activity in such a system leads to better health, and the safer street designs reduce deaths and injuries. Reduced vehicle use reduces energy use and emissions of air pollutants. Surprising research in the United States indicates that urban dwellers are subject to better health and fewer dangers than their suburban and rural counterparts, even when crime is factored in.[103] Such an urban design can also support an innovation ecosystem of creative businesses and other institutions, further accelerating innovation and can-do spirit in a virtuous cycle. Perhaps we should let people express their preferences through the marketplace rather than forcing them into denser communities, but at a minimum we need to provide choices and look carefully at any hidden subsidies and incentives that are encouraging people to choose urban forms tailored to cars rather than people.

One encouraging trend is the “complete streets” movement in North America, where cars, public transportation, pedestrians, and cyclists are all given equal consideration in street design. These designs have already been nearly perfected in the Netherlands, where cyclists have their own protected lanes and signals. Walking, cycling, and public transportation are the overwhelming choice of citizens, and pedestrian and cyclist deaths are extremely low. While the Dutch have perfected street designs with separate driving, cycling, and walking lanes, they have also successfully implemented shared spaces where pedestrians, cyclists, and cars are all allowed in the same space, but cars are given the lowest priority and required to yield at all times to pedestrians. The Dutch designs are almost perfect – once other parts of the world decide they want to make safe, multi-modal streets a reality, there is very little need to reinvent these concepts rather than just copy the Dutch designs.

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[103] Myers et al., 2013

On a trip to Amsterdam, what really struck me was that when a city no longer has a lot of fast traffic on the streets, the streets begin to take on the character of public gathering places rather than just transportation corridors. At lunch time on a nice day, people just flow out of buildings and onto the street, where they find things to eat and places to sit and enjoy the free time. Streets melt seamlessly into little parks and plazas and public spaces, sometimes just created out of the odd spaces where streets meet at an angle. Simply providing chances for people to sit in public places almost seems too obvious and easy a strategy to mention, but this is often not done, at least in American and Asian cities I am most familiar with. William H. Whyte memorably made an appeal to provide simple movable seats as a way of livening up public spaces.[104]

Once we recognize the value of urban open spaces for commerce, socializing and providing ecosystem services, the oceans of pavement currently devoted to parking in many cities start to seem like an incredible waste of potential. We can begin to shift these areas to more productive uses through market-based means. If the space used for parking can be put to many other more productive economic uses, there is a clear argument that the opportunity cost to society is high and that taxes and fees are appropriate to transfer this cost to the people who are demanding the parking. This has the double effect of better managing the supply and demand for parking in the short term, and gradually encouraging the transfer of land to more productive economic uses over time (but not necessarily more socially or ecologically beneficial uses, unless this is a conscious goal of local planners, residents, and businesses.)[105]

Larger-Scale Transportation Systems

If bicycling is such a great way to get around, why has it not caught on outside a few countries in Western Europe? Risk of death and injury is the most obvious explanation that comes to mind. However, this cannot possibly be the explanation in developing countries considering the widespread use of motorcycles by all levels of society, and the massive carnage they cause. Motorcycles are seen as sexy. Bicycles are not. So one strategy to encourage more bicycling is to figure out how to give them more sex appeal, either through their design or through advertising or both.[106]

Even if safety is not the main selling point for getting out of our cars, we need to agree as a society that the carnage caused by motor vehicles, currently on the order of one million human beings worldwide killed per year, and many times more serious injuries, is completely unacceptable. Cars are serial killers in our midst, especially serial killers of children and healthy young adults, and we need to decide that this is unacceptable and solvable. Sweden, for example, has adopted a “Vision Zero” to completely eliminate road deaths through better road design. This is an important point – although trying to improve driver education and behavior is certainly worthwhile, the best way to improve the safety and livability of our streets is through better, safer designs. These better, safer designs do not have to be invented. They already exist and just need to be adopted. If state and local transportation agencies in

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[104] Whyte, 1980

[105] Also see the work of Donald Shoup, *The High Cost of Free Parking*, on proposals to manage parking supply, parking demand, and land use through appropriate pricing of parking.

[106] The bicycle industry could learn from the condom industry. The successful condom advertising strategy is the one that emphasizes sex, not disease and death.

other countries are unwilling to adopt similar goals, perhaps we should prosecute them for the murders of the children they have the power to save but choose not to. Developing countries, in particular, are choosing to ignore the superior European designs and repeat all the North American mistakes with suburban sprawl, low-density development, loss of farmland and loss of ecosystem services. The scale of development in Asian and African cities is massive, and cynical choices there have the power to overwhelm choices made elsewhere in favor of green innovation, pushing civilization closer and closer to the cliff of that first crash.

Returning to public transportation, expensive subway systems and ugly, smelly old buses are not the only possible choices these days. There are a range of innovative systems that can be considered, and that can be more flexible and adaptable and integrated with the urban fabric. Buses themselves don't have to be ugly and smelly. Just as with bicycles, their sex appeal can be elevated with better design and more creative advertising, not to mention regular disinfection and fresh air. Bus rapid transit systems have been tried successfully in many cities around the world – these provide many of the features of subway systems at a much lower cost, and are lower tech and more flexible and adaptable if conditions change in the future.

One way conditions are very likely to change in the near future is the widespread advent of computer controlled vehicles. The concept of personal rapid transit has existed for decades, but the technology is just now catching up to make it a reality. With personal rapid transit, people "call" a transit vehicle at a station and tell it where they would like to go, analogous to calling an elevator and entering the destination floor. If multiple people are going the same direction, they can go in the same vehicle. Vehicles chosen and routes can be flexible and adaptable to move the largest number of people door-to-door at lowest cost. Originally, these systems were envisioned running on rails. But now computer controlled vehicles have the possibility to revolutionize our entire transportation system. Now a car, van, or bus can pick you up at your doorstep and take you to the doorstep of your destination. Just like the original personal rapid transit vision, groups of people can be taken in the same vehicles along the same routes to maximize efficiency.

Computer controlled vehicles have the potential to drastically reduce the amount of space dedicated to motorized traffic in cities, because these vehicles need much less space to start, stop, maneuver, and park. On the other hand, by reducing the pain and wasted time of commuting, automated vehicles could lead to more and longer trips taken and people choosing to live even further from where they work, shop, and socialize. Engineers, planners, and politicians should begin anticipating the benefits and unanticipated consequences of this major trend now, rather than being caught off guard.

High speed rail seems like the right way to make regional, inter-city trips. This yields environmental benefits compared to air or road travel and reduces road congestion. But the larger, and more difficult to quantify, benefit may be in knitting together several cities in a region into a larger economic and social unit, potentially boosting growth and innovation (including green innovation, if we make that our goal). From both a safety and an environmental standpoint, it makes sense to move most of our freight from trucks to rail too. With fewer cars, buses, and trucks on our highways, and with the remaining vehicles computer controlled and requiring drastically fewer lanes, space will open up along our transportation corridors. This is the place to put the high speed rail lines, high voltage electric lines, pipelines, and other infrastructure needed by the economy of the future. But in the United States, let's not assume that the best we can achieve with high speed rail is the same technology successfully built by the Japanese 50 years ago. Let's innovate and think a few decades ahead and decide what the best technology might be. Perhaps computer controlled buses with wings gliding just a few inches above (porous) pavement?

So am I completely against air travel? No, when Junior does his semester abroad in China he will get there through air travel. That semester abroad has benefits for innovation, cultural understanding, and peace that outweigh the environmental impact of the air travel. In fact, let's have a vision that we can go a lot faster. It shouldn't take Junior 30 hours of travel to get to China. Let's get him there in a couple hours through super-sonic or orbital means, continue to knit our species and civilization closer together, and solve our problems together.

Materials, Efficiency, and Closing the Loop

This section is about our lifestyle and all the "stuff" and energy it requires.

Clean Chemistry

First, we need to establish a vision and policy that all chemicals and materials that come in contact with people and the environment can be completely safe and non-toxic. Then we commit to work toward this vision in government, university and corporate R&D labs.

First, we ban chemicals that are useless at best and harmful at worst. Antibacterial soap is an example of a consumer product that has no known benefit, may actually be toxic, and has been cynically marketed to consumers using fear-based marketing techniques. The bar can be set very high for chemicals used in consumer products - they should be proven safe for both people and the environment before they are allowed on the market.

Next, we turn to chemicals that, while not proven to be completely benign, are actually useful. Examples are substances used to increase agricultural yields, preserve foods, and disinfect drinking water. Drugs also fall in this category. We probably don't want to ban these overnight, but we should work hard to find completely safe substitutes.

Closing the Loop on Materials

We can design products from the very beginning with full recovery and recycling in mind. One example of closing the loop, given in the book *Cradle to Cradle: Remaking the Way we Make Things*[107] is the idea of fully recyclable clothes. With the advent of synthetic fibers, and the faster and faster fashion cycle causing people to treat clothes as essentially disposable, there is an opportunity to design clothing materials and manufacturing processes so they can be recovered and recycled into new clothes. In this way, people get the "utility" of new fashions, entrepreneurs and large corporations make money, and both the amount of raw materials being used and the amount of waste that must be disposed of are reduced (as long as we are being visionary, ultimately approaching an ideal of zero). This is a great

[107] Braungart and McDonough, 2002

example of potential dematerialization of the economy, but dedicated, creative chemists and engineers need to work on it to make it happen.[108] This basic model could be extended to virtually any consumer product that is not actually destroyed in the course of its use.

Reusable containers are an old, and somewhat obvious, idea that we need to bring back. For example, reusable glass bottles used to be much more common, but the economics in recent years has favored disposable plastic packaging. Perhaps the economics will change again. For example, if automated shopping and deliveries become common in cities, perhaps sterilizable and reusable containers will begin to make sense again. Yes, I'm talking robots! A robot won't mind returning your dirty container to a central facility where it can be sterilized, then taken back to a warehouse ready for the next customer's order.

The "sharing economy" is an old idea made practical and exciting by new technology. Most of the things we own sit idle most of the time. Examples are cars, tools, and spare bedrooms. We are willing to pay a high price to keep these things sitting around, just so we have access to them when we need them. Information technology now makes it much easier to share many of these items and keep them in use much more of the time. By sharing these items, we can get the same amount of use out of them while needing fewer of them around. It means less materials used, less manufacturing of the same items over and over, less solid waste, and less wasted space.

Finally, we need to stop accumulating stuff unless it makes us happy! If we choose to acquire an object, it should be because it makes us happier than we were before. To reduce the use of raw materials, we can share, rent, and buy gently used stuff as much as possible.

The more we close the loop by reducing, reusing, and recycling materials, the less we need the concept of "waste". San Francisco has set the visionary goal of zero waste. Let's achieve this vision all over the world and banish the word "waste" from our thinking.

Closing the Loop on Water

At the scale of the Earth, the hydrologic cycle is of course a closed loop. Water is transferred from the atmosphere to the ground, where it runs off into bodies of water (of course, a lot of rain just falls right on bodies of water.) We withdraw the water, treat it, and "use" it for something. "Using" it of course doesn't actually destroy it - it either transfers it to the atmosphere (for example, if we used it to water a farm field or operate a steam turbine), or it pollutes it, after which we treat it again and put it back in a body of water. From the body of water it can evaporate to the atmosphere, and the cycle beings again. At the human scale, "closing the loop" means that we begin to separate the human water cycle from the natural bodies of water. We use water as efficiently as possible and just keep cycling it in an endless loop without impacting natural ecosystems. When we lose some of it to the atmosphere, we replace it by catching some rain directly.

[108] If you invent this, please make the clothes truly wrinkle free. Not wrinkle resistant, but truly 100% wrinkle free. It is time for humanity to finally escape the tyranny of ironing and put the effort saved to better use.

We can begin with a vision of moving beyond the flush toilet. This technology is accepted today as the unchallenged standard worldwide, but its widespread adoption has occurred only in the last 100 years or so. Cities up until at least the 18th century were filthy places, with all manner of household, animal, and human wastes simply dumped into the streets. The development of sewer systems was a wonderful advance in terms of reducing the unsanitary and unsightly conditions in cities. Yet sewer systems came about long before running water. Waste was simply dumped in the sewer system, and the next rain would wash it away into the nearest stream or river where it could be carried away. For urban dwellers, this system of dumping waste underground and letting rain wash it away was a big improvement over dumping it in the street and letting the rain wash it away. When the flush toilet was invented, it became convenient to flush into those same sewer systems, and this became the practice everywhere. Gradually, we began using more and more clean, drinkable water to wash away our wastes. Today we dilute our waste with large amounts of clean drinkable water, cleaned in an industrial factory (a water treatment plant). Then we use that water to transport the waste just a short distance, then deposit it in another factory (a wastewater treatment plant) which uses a complicated, chemical- and energy-intensive process to separate the waste from the water again (but never completely - carbon, nitrogen, and phosphorus compounds that could be used as fertilizers are instead discharged into rivers, streams, and estuaries, where they cause ecological and economic damage. Meanwhile, nitrogen fertilizers are derived from fossil fuels and phosphorus fertilizers from enormous phosphate rock mining operations. Phosphorus is a limited resource that may run out in a few decades at the current rate of usage, and it is such a fundamental requirement for all plant growth that there is unlikely to be any substitute.)

So, the reason we use water to flush our toilets is not necessarily to reduce the smell or unsightliness of human waste, as many may now assume, but because it is an expedient way of transferring waste from buildings to sewer systems. Once this polluted water is transferred to a sewer system, most modern societies have decided that it must be transported and treated before it can be discharged back to the natural environment. The inventors of the flush toilet almost certainly did not consider this future need for costly and energy-intensive transport and treatment. There was never a decision made that this system was the best of all possible systems, to be implemented worldwide. It simply happened step by step, more or less by accident, and now our entire society accepts it as the only possible way.

Much more efficient systems have been conceived that are able to recover the nutrients and energy in the waste products onsite without mixing them with so much clean water, and some efforts are being made to bring these to the mass market. Examples are composting toilets, urine-separating toilets, and research on a high-tech energy- and nutrient-recovering toilet funded by the Gates Foundation. There is enormous resistance to these alternative approaches simply because most people alive today assume flush toilets have always existed, and cannot imagine any alternative. A better toilet is not a trivial problem, but nor is it a problem of the scale and complexity of oil refining, central banking, developing nuclear weapons, putting a man on the moon, or even putting a computer in everyone's pocket. We simply need a few more smart engineers and business people focused on the problem and it can be solved, to enormous benefit.

Better sewer systems go along with better toilets. For example, vacuum sewer systems require little water and do not have to flow downhill. At the end of the sewer system will still be some kind of treatment plant, but now instead of separating a small amount of "waste" from a large amount of water, it can process a concentrated stream of materials into forms that can be reused. For example, phosphorus can be recovered from urine and processed for use in fertilizer as a substitute for phosphate rock. Organic wastes, such as "biosolids" (a nice name for feces), farm waste, yard waste, and food waste can all be combined and digested anaerobically, generating methane which can be piped to homes and industries, burned to generate electricity, or used in fuel cells. Vacuum sewer systems make it easier to collect all these materials and bring them to a central location (most homeowners and businesses will not be willing to keep their feces and food waste sitting around in cans for the weekly garbage truck pickup.)

Not all uses of water require highly purified, pristine drinking water. We can reuse the lightly soiled water from showers and clothes washers for toilet flushing (if our toilets still use any water!), car washing, and watering our green infrastructure. Remember that from our clean chemistry program all our soaps, shampoos, and detergents are now completely benign and fine to use on the garden. In this way we use every drop of water more than once.

We might be able to approach the ideal of completely closing the loop on water used within homes and businesses. However, we will still need significant amounts of water to grow food and to nurture our green infrastructure, and most of this water is ultimately returned to the atmosphere. So we will need to capture some rainwater to balance out what is lost. Rainwater from roofs can be captured in small cisterns for household use and gardening. Rainwater falling on our streets and other pavement can be directed to our green infrastructure.

None of the technologies I mention here contradicts the laws of physics, but all present logistical and institutional issues. This just means we need to get to work!

Wise Use of Energy

Of course the indisputable laws of physics do not allow us to "close the loop" on energy. It might seem strange to talk about energy conservation in a book where I propose increasing energy use as a measure of the long-term progress of our human civilization. Indeed, I believe that in the far future we will be able to increase our energy consumption enormously with little or no environmental impact. But our current sources of energy are simply too expensive and dangerous to allow any significant increase without devastating environmental consequences. There are two avenues we can pursue at the same time: first, large energy efficiency gains in the short run and second, advances in truly clean, cheap energy for the medium and long run. Both avenues require vision.

Bold visions have been proposed to increase energy efficiency in the relatively near term. "Factor 10" is such a bold vision to set a target of one order of magnitude reduction in resource use within 30 to 50 years. The "2000 Watt society" is another vision for society to consume only an average of 2000 Watts of power per person, a level the originators of the concept (who were from Switzerland) believe would be sustainable. The "passive house" program, originally from Germany, is an example of an existing construction standard proven to result in an order of magnitude (around 90%) reduction in energy use for residences.

I do not pretend to know which technologies are likely to supply us with truly clean, cheap energy in the long run. Two that have sparked my imagination are solar energy technology and advances in our understanding of the subatomic world.

In the medium term, new materials may allow us to cover many more areas of the Earth's surface with much more efficient solar cells. Of course, there is a theoretical point of coverage where the sheer area of solar cells would be competing with natural ecosystems and with human agriculture, but we are far from that today. We can figure out how to cover all our buildings (roofs and sides), roads and streets, and parking lots with solar cells before we begin to worry about this competition. The next logical step would be to consider relatively unproductive ecosystems like deserts, although deserts are not completely lifeless and the ethics should be carefully considered. Longer term, space-based solar technology is intuitively appealing because it avoids the problem of competing with Earth's ecosystems, and ultimately allows us to collect more solar energy than just what strikes the Earth.

Subatomic physics may still hold many surprises. Safer fission reactor designs, safer fissile materials such as thorium, and fusion reactors all may hold promise, although of course they present risks too. We may be forced into a renewed focus on nuclear energy if we do not find another substitute for fossil fuels on a large enough scale.

Education

Education is clearly the key to developing human beings who are both ethical and able to take a systems approach to solving problems. System thinking can be the central organizing principle of all education from an early age. The MIT school of "system dynamics" modeling is one approach to teaching system thinking from early grades all the way to adult professionals. MIT has provided a series of free online "Road Maps" that provide guidance on incorporating dynamic system thinking and computer modeling in education. Another way to teach system thinking may be through games rather than through more traditional lecture and memorization. Children are willing to concentrate hard and solve complex problems in games, so there is an opportunity to make games more educational or even the primary way we learn. Games also provide an opportunity to repeat key concepts over and over, a key to long-term learning.

Ethics also can be embedded in education from an early age. Children can learn about the principles of ethics that have been studied and developed in the past, but also need to be challenged daily by ethical dilemmas so they learn to examine their values and make choices consistent with what they think is right and wrong.

Educational institutions need to give the study of human institutions and behavior patterns equal consideration alongside science, technology, and business. This does not mean dividing and isolating students within natural science, social science, and economics departments – it means embedding the study of human institutions in all these disciplines, and helping scientists and engineers understand that getting things done requires an understanding of other human beings.

Social science itself needs to become less observational and more operational – psychologists, sociologists, and anthropologists need to reclaim their seats at the decision making table alongside economists, engineers, and others. The field of planning (urban and regional planning, economic development planning, environmental planning, water resources planning, etc.) has much to contribute here. Well-trained planners can be the glue that holds together engineers, architects, landscape architects, scientists, urban designers, developers, politicians, and members of the public.

In many countries, there is a renewed focus on science and mathematics in education. Mathematics is a critical tool for solving problems. However, mastering the logic of mathematics does not guarantee ethical thinking or system thinking. A person who is amoral, narrow-minded, and good at math is useless at best and dangerous at worst. A creative system thinker who is bad at math can still be useful if there is someone around to help with the math. But this is not an excuse for laziness. There might be a few creative geniuses out there who are "just not wired to do math", but very few. Most people can learn math. Let's create a world full of ethical, mathematically adept system thinkers!

Finally, I think school is just too boring for many children. We can teach important principles using examples that are naturally interesting to most children – plants, animals, dinosaurs, machines, vehicles, robots, stars, planets, and water to give a few examples.[109]

Government and International Relations

I have left this section until last, and debated including it at all. I have done my best to include very little in this book that could be seen as politically controversial. Now I will relax a bit and perhaps betray some of my personal views. The point of the discussion below is to illustrate a range of ideas and policies we could discuss and debate and consider and experiment with. In the end that is the whole point - not to limit ourselves to a very narrow range of thinking, but to open our minds, examine our values, then discuss and debate and try some new things and improve our world. So with that said, let's dive right into the deep end and tackle perhaps the most controversial issue of all, taxes!

Taxes

I won't try to tell the reader how much tax is the right amount. I do think that people would support taxation more if they had a better understanding of how governments spent their tax money. One simple idea that should be entirely uncontroversial is a taxpayer receipt. This would just tell each taxpayer exactly how much they paid and what the government spent their money on. Many people have strong ideological beliefs about the proper magnitude of industrial subsidies, environmental regulation, scientific research, and space exploration, to give just a few examples of controversial topics. But before we can begin having reasoned debates on these topics, it would help to understand how much of our government's budget is currently spent on these programs. In the United States, for example, government expenditures on basic scientific research and renewable energy subsidies are small, while military and weapons spending are large. Understanding the magnitude of these numbers would put us in a better position to make up our individual minds whether we agree with how the money is being spent, then work together through our messy political process to spend it better.

[109] Well, these are interesting to most little boys, anyway. Having never been a little girl, never had a sister, and not being the parent of any little girls so far, I am not really sure what little girls like.

Because urban areas are where most economic and innovation activity occurs, we should make sure tax revenues are not being shifted disproportionately to less productive areas. This does not mean that no tax revenues collected in urban areas should be spent to help rural people. This is a policy question that every country needs to work out through a democratic process. The United States, however, has a system particularly designed to favor rural areas to an extent that may stifle investment in critical infrastructure and services in population centers, ultimately hurting the whole economy.

Two possible approaches to taxation are to focus more on fairness or to focus more on efficiency. To maximize fairness might mean asking those with higher incomes and more wealth to pay a higher percentage than those with lower incomes and less wealth. To maximize efficiency might mean avoiding taxes on income and capital, which may counteract incentives to be productive and innovative. It may not be possible to maximize both fairness and efficiency. [110] However, there is one type of tax that seems to be both efficient and fair, and that is a tax on external costs. Costs are external if they are created by parties in a given transaction, but imposed on parties outside that transaction. For example, without regulation the costs of pollution (for example, ill health) are borne by society at large, while the benefits (for example, profits from sale of a good produced by a polluting factory) are enjoyed only by a few individuals or businesses. When a tax is imposed on the polluter, the polluter can choose to pay the tax (reducing the need for taxes on income or capital), to pollute less, or some combination. A portion of the profit the polluting firm would have made is now converted to some combination of better health and a more vibrant economy for the larger population.

Unsustainable depletion of natural capital enriches some parties in the short run while imposing long-term external costs on everyone else. Herman Daly's original proposal was to prevent depletion of natural capital by determining how much of each type of natural resource can be extracted and used sustainably in the course of a year (in our bank account analogy, the annual interest on our natural capital), then auctioning permits to limit extraction to that amount. While this may sound politically difficult, the same outcome could be approximated by revenue-neutral taxes on resource withdrawal. In principle, the idea of such a revenue neutral tax on external costs could be supported across the political spectrum. People focused more on the environment would get to see progress toward a steady state with no net draw down of natural capital, while people focused more on economic matters would see the advantage of shifting from less efficient taxes to more efficient ones.

If done very gradually and carefully, for example by retiring a small fraction of permits each year, Daly's system could spur the innovation needed to eventually increase human activity without increasing environmental impact. For example, if fuels were taxed on the basis of carbon content, the energy and electricity industries would have a financial incentive to pursue carbon-free energy sources. Greenhouse gases, air and water pollutant emissions are obvious examples of pollution that could be taxed with benefits to both the environment and society. Cars could be taxed for the deaths and injuries they

[110] In the best of all possible worlds, we would tax in the most efficient possible way, then decide through a democratic process how to spend or distribute the money in the fairest possible way. In the real world, this is difficult because those with more political power can use efficiency arguments to encourage policies that minimize their own taxes (for example, no tax on capital gains or corporate profits), then later refuse to take part in discussions on a fair distribution of the proceeds.

cause. We could tax materials such as chemicals not thoroughly tested for safety, forestry products not certified as sustainably produced, and cement (a big carbon emitter, and perhaps the building material most implicated in disturbing the hydrologic cycle and water quality in urban areas). We could consider taxing pollution at the end of the pipe or smokestack, rather than natural resource extraction at the source as Daly proposed. Taxing many small emitters of pollution would be administratively difficult, but more politically feasible because political power is diffused widely among all the parties involved. Conversely, taxing a few large extractors of raw materials would be administratively easier but politically more difficult, because such industries have concentrated political power, often intertwined with political and military elites in many countries.

When an external cost is taxed, it is no longer external but now must be paid by parties who otherwise would have imposed that cost on someone else. This can begin to shift peoples' decisions in a direction that maximizes benefits for the environment and society at large, including decisions in favor of many technologies and practices I have mentioned in this section, from green infrastructure to walkable towns to energy efficiency to closing the loop on materials and water. Properly done, taxing external costs is not social engineering or taking away any individual's economic choices, other than the choice to unfairly enrich oneself by hurting others.

Greener Growth Accounting

Pursuit of economic growth (meaning more human activity, knowledge, and information processing ability in the long run, but more resource consumption and waste production in the short to medium term) is the path our civilization is on and will continue to be on for the foreseeable future. It is the dominant paradigm of our time, a near consensus bordering on religious faith. I do not think discussions of an "anti-growth" stance or a "steady state economy" are the right rhetoric to employ at this point in history, and in fact are likely to be politically counterproductive. We can sit in Europe and perhaps even North America and theorize about a gradual acceptance of these concepts, but my experience in Asia has convinced me that leaders of a majority of the world’s people believe that economic growth, heavy industrialization and urbanization are the unquestioned destiny of human civilization. I am concerned that only a crisis may be capable of shaking that belief, and a crisis is what we are trying to prevent. However, I believe it is possible that a better end point can be targeted without resort to inflammatory anti-growth rhetoric. If our society can find ways to improve human wellbeing in ways that have less environmental impact over time, in other words if all growth is green growth, we will have reached the equivalent of a steady state material economy.

There have been some proposed indices of growth and progress that could one day either replace GDP or provide additional information alongside GDP. GDP is a good measure of the amount of economic activity. However, because it simply measures the amount of money changing hands each year, it does not distinguish between spending on activities that are good for civilization and those that are not. For example, it counts all spending on consumption, resource extraction, and waste disposal equally whether those activities cause pollution or not. One example of an alternative, the Index of Sustainable Economic Welfare (ISEW), is intended to better distinguish between true benefits on the one hand, and environmental and social costs on the other. Governments could initially adopt measures like the ISEW alongside traditional GDP measures, providing additional information that might direct choices in more sustainable directions.

The final policy I will mention in this section is to improve and extend ways for richer countries to pay poorer countries to preserve biodiversity-rich forests, wetlands, and coral reefs. There are some programs in place, but we need to find ways to make sure these programs are successful. They will ultimately benefit everyone on Earth for many generations to come.

Promoting Green Innovation

Now that we are done with taxes, my suggestions may start to get even more controversial. We have established that the pace of green innovation needs to increase by at least one order of magnitude, and we have established that human capital is necessary for innovation. We have established that the right kind of education can produce the right kind of human capital (ethical system thinkers). To invest in this necessary human capital, governments should find a way to make a university degree free for everyone. This can be done with new tax revenues or with savings from reduced war costs.

To boost innovation, we need to create a level playing field that does not favor big business over small business and startups. One reason is that small business can be innovative. However, we learned from Schumpeter that big business (and I would add, big business-like government, quasi-government and nonprofit entities) will innovate too when it faces the threat of disruptive innovations coming from outside players. Big business certainly has the resources to innovate when it is motivated to do so. Government's role is first to remove barriers to entrepreneurship, second to limit the political access of big business so it is not able to buy elections and influence politicians to write the rules unfairly in its favor, and third to make sure big business does not have an unfair advantage in the legal system simply due to its deeper pockets.

War, Weapons, and Peace

Finally, I will throw caution to the wind and state some strong personal opinions. It is my strong personal opinion that nuclear weapons are a moral abomination. First we need to believe that a world free of nuclear weapons is possible, then we need to make it happen. The United States, the only country to ever engage in nuclear warfare, should have the moral courage to lead this effort.

As nuclear weapons continue to proliferate and even worse weapons may be within reach, a focus on peace is more important than ever. We need to figure out how to extend and enforce the international conventions banning development of biological weapons, and figure out how to deal with emerging threats like nanotechnology as they arise.

It is not just advanced weapons that are a threat - it is war itself. We should remember that there was a sense of optimism in Europe at the turn of the 20th century. Almost nobody anticipated World War I. Today we may have a similar sense that global-scale conflict is unlikely. But as I write, potential conflicts are brewing in Asia between China on the one side and Japan, the Philippines, Vietnam, and Taiwan on the other. India, China, and Pakistan are all uneasy, and nuclear armed, neighbors. The geopolitics of the Middle East and North Africa is as unstable as ever. The United States and other countries could easily be drawn into any armed conflict that erupts.

Some countries set peaceful examples. Costa Rica has had no standing army since 1948, despite instability and militarism in its region. New Zealand does not allow ships carrying nuclear weapons or even nuclear reactors in its territorial waters, a stand unpopular with many allies including the United States. Norway of course awards the Nobel Peace Prize.

Governments could agree to all limit defense, security, and espionage spending to a certain percentage of GDP (for example, 1% compared to the current 4-5% in the United States). In any year when spending exceeds this amount due to emergency, governments could agree to collect the necessary funds through an explicit "war tax", which works like a sales tax and shows up on every receipt every time a person buys something. This way all citizens would understand how much they are paying to support war, and what they are giving up as a result.

The U.S. and other countries could transform their Departments of Defense (i.e. War) into Departments of Global Stability.[111] The mission would be to prevent both conflicts between states and conditions within states that lead to development of civil conflict and terrorism. An even broader mission would include risk management and resiliency in the face of war, famine, plague and disaster. A similar idea is to establish a Department of Peace[112] alongside the Department of Defense.

We need to figure out a level of surveillance we can all live with. As we enter a world where individuals, small groups, and corporations can be as dangerous as nuclear-armed governments were in the 20th century, we may have to accept some degree of surveillance and reduction in privacy. Perhaps the best we can hope for is a world where it is hard for anyone to keep secrets, including governments. Perhaps we can agree on a set of rules, on what types of biotechnology are off-limits for example, and rely on self-policing by professions and governments to an extent. But when it becomes clear that an individual, group, corporation or government represents a serious threat, some form of police action by an international body or even a single country may be necessary. This sounds depressingly like the "global war on terror" pursued by the United States after the 2001 terrorist attacks in New York City. Unfortunately, we may be headed for many more conflicts of this sort with many more participants. It is best to think about it now and decide on the best form it could take.

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[111] I first heard this suggested by Lester Brown.
[112] I first heard this suggested by Dennis Kucinich.

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Appendix: Key Data Sources and Relationships

I have tried to present the scientific, economic, and system concepts in this book in terms accessible to an intelligent reader with no formal technical training. Some readers might feel that the language is too technical. Others might feel frustrated that I do not go into more detail on mathematical relationships. I have discussed the relationships in the book, but in a few cases I felt that a more thorough discussion would interrupt the flow of the story I was trying to tell. I have added this appendix to elaborate on a feedback relationship that is particularly critical to the behavior of the model. This work also required a large number of conversions between various units of mass and energy. I have made the computer code that does the calculations, produces the graphics, and performs the simulations freely available on the internet at this address: https://github.com/rdmyers75/human-enterprise-book.[113] The computer code can be run and modified in the language R.

The most difficult feedback relationship to establish was the effect of natural capital depletion on the growth of human activity. If this relationship were obvious or easy to define, our civilization would not be arguing over whether depletion of natural capital poses a threat and how much of a threat it poses. We would know the exact magnitude and nature of the threat, and we would be able to design a precise course of action to mitigate it. However, the relationship is not obvious or easy to define. It is extraordinarily complex, and it can easily be the subject of decades of research in academia and government. Although I would enjoy being involved in this research, and am monitoring the results as they trickle out, this research is not the main business I am in at this point in my life. As I have throughout the book, I have chosen a simple relationship and some simple assumptions to represent the behavior of the system. My objective is not to be precise about the magnitude and timing of the system behavior, but to correctly capture the nature of the system behavior over long periods of time.

I have used mass of carbon as a proxy for natural capital and energy use (expressed as power, energy over time) as a proxy for human activity. From Grubler (1999), the carbon content of the fuel mix used by civilization was approximately 0.76 kg C per kg of oil equivalent (a unit of energy which can be converted to kJ) contained in the fuel as of the year 2000. Over the past 200 years, the carbon content of fuel per unit of energy has declined on average about 0.25% per year in the United States and 0.30% in the world. I have chosen to use the 0.25% figure in most of my simulations (except where noted) and assumed that it will continue for the long term.

I assume that as long as natural capital is abundant, human activity will continue to grow exponentially. However, as natural capital is depleted, eventually there will come a threshold where a countervailing force will be exerted to slow down, stop, or reverse growth. This force could be exerted by any one or any combination of the "planetary boundaries" discussed throughout the book - for example, collapse of ocean or forest ecosystems that cycle critical nutrients and gases, catastrophic soil loss, severe groundwater depletion, food and energy scarcity causing severe economic recession or even mass starvation, war, or plague. To try to develop a comprehensive mathematical description of all these factors and their effects on human activity would be an extraordinarily complex undertaking, and any answers found would be subject to a high degree of uncertainty.

I have chosen just one feedback relationship to represent this feedback loop. The one I have chosen seems to me to be particularly likely and particularly dangerous - the effect of climate change on tropical agriculture. The idea is that as the concentration of greenhouse gases in the atmosphere increases, temperature will increase, and the yield of grain crops will decrease, particularly in the tropics.

We have already established a link between the magnitude of energy use and the magnitude of carbon emissions. Next we can establish a link between carbon emissions and temperature. Although this relationship is extraordinarily complex, the IPCC (2013) has developed a simple linear relationship to

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[113] I am writing this in 2014. I plan to keep these files available indefinitely, but I don't know what year you are reading this.

characterize it called the transient climate response to cumulative carbon emissions (TCRE). [TCRE] "quantifies the transient response of the climate system to cumulative carbon emissions... TCRE is defined as the global mean surface temperature change per 1000 GtC emitted to the atmosphere. TCRE is likely in the range of 0.8°C to 2.5°C per 1000 GtC." I have chosen 1.0°C/1000 GtC from this range as the basis of my assumptions.

Finally, we need to establish a link between temperature and grain yields. Lester Brown (2009) has proposed the following: "For each 1 degree Celsius rise in temperature above the norm during the growing season, farmers can expect a 10-percent decline in wheat, rice, and corn yields." Brown provides the following references for this claim: Shaobing Peng et al., "Rice Yields Decline with Higher Night Temperature from Global Warming," Proceedings of the National Academy of Sciences, 6 July 2004, pp. 9, 971–75; J. Hansen, NASA's Goddard Institute for Space Studies, "Global Temperature Anomalies in 0.1 C," at data.giss.nasa.gov/gistemp/tabledata/GLB.Ts.txt, updated April 2009; "Summary for Policymakers," in Intergovernmental Panel on Climate Change, Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge, U.K.: Cambridge University Press, 2007), p. 13.

It is not important for these relationships to be precise. In fact, they are highly uncertain. This uncertainty means that the precise magnitude and timing of the simulation results cannot be relied on as a precise prediction of the future. However, the simulation results can be relied on as a prediction about the nature of the future. The relationships above are logical and capture the nature of the feedback relationships that exist between natural capital and human civilization. Human beings will continue trying to grow our technology and level of activity if nothing prevents us from doing so. Depletion of natural capital cannot continue forever without exerting a negative force on our potential growth rate. The balance of these forces, along with some degree of good or bad luck, will determine our future.