CHAPTER 6: PLANETARY BOUNDARIES

I. Planetary Boundaries

The previous chapters have covered the key questions of modern economic growth: how it began; how it has diffused across time and place; how a "checklist" of factors can help to account for the differences in economic growth across countries; and how countries still trapped in poverty can spring free of the poverty trap. Economic growth is complicated, but sustainable development is even more complicated. To achieve sustainable development, countries need to achieve *three goals* simultaneously: economic growth, broad-based social inclusion, and environmental sustainability. While many countries have "solved" the growth puzzles, few have succeeded in achieving all three aspects of sustainable development.

Indeed, we can go further. Since many of the environmental challenges – such as climate change, ocean acidification, and the extinction of species – are global-scale crises, and since all countries are feeling the effects of these crises, we can say that no country is actually on a path of sustainable development. Even when individual countries are making maximal efforts on their own part, they are still vulnerable to a world economy that has failed to take adequate actions to head off environmental calamities.

The problems are getting harder, not easier. The main problem is one of scale. The world economy has become very large relative to the finite planetary resources. Humanity is pushing against the limits of the environment. In the words of world-leading ecologists, humanity is exceeding the "planetary boundaries" in several critical areas.

Let's review the global circumstances very briefly. Back in 1798, Thomas Robert Malthus wrote the seminal work *An Essay on the Principle of Population*, warning humanity that population pressures would tend to undermine improvements in living standards. If humanity were able to raise its living standards, wrote Malthus, then the population would expand accordingly, until the rise of population would put strains on the food supply and thereby reverse the gain in living standards. Malthus's vision was decidedly pessimistic about sustainable development!

We now know that Malthus was too quick to assume that population pressures would automatically reverse the gains of economic development. Certainly Malthus could have had no idea about the dynamism of science-based technological advances that would occur after his essay. Certainly he could not foresee the Green Revolution in particular, which would dramatically expand the capacity to grow more food to feed a larger global population. Nor could Malthus have foreseen the demographic transition, by which richer households would choose to have fewer children, so much so that populations are already stabilizing or even declining in some of the world's richest places.

Yet Malthus had many things right. When he wrote, the world's population was around 1 billion people. It has since risen more than 7 times. Population has indeed increased sharply alongside the long-term rise of productivity. And there is more to come: perhaps up to 10.9 billion people by 2100 (according to the “medium” fertility variant of the UN Population Division).

To gauge the scope of human impact on the environment – the pressures that humanity is putting on the earth’s ecosystems – we need to combine the sheer numbers of people with the increased resource use per person. For that, we can look at rough estimates of the world output per person. In 1800, the Gross World Product per capita was around $330 USD in 2013 prices. Now it is around $12,600 per capita. That means that per capita income has increased by around 38 times.

Since total world output (GWP) is the product of Population and GWP/Population, we find that the total world product has increased by around 275 times, roughly from $330 billion for the entire world in 1800 to around $91 trillion. Of course these are very rough estimates, but they do give us a sense of order of magnitude of the increase of global production. Alas, that production has also translated into an increase in the adverse human impact on the physical environment.

Humanity has become so numerous and so productive that we can say that we are “trespassers” on our own planet. By that I mean we are crossing boundaries of the earth’s carrying capacity, thereby threatening nature and even our own species survival in the future. The concept of **planetary boundaries** is an extremely useful one. When the world-leading environmental scientist Johan Rockström brought together other leading Earth systems scientists, they asked: what are the major challenges stemming from humanity’s unprecedented impact on the physical environment? Can we quantify them? Can we identify what would be safe operating limits for human activity, so that we can urgently begin to redesign our technologies and our economic growth dynamics to achieve development within the planet’s limits?

They came up with a list of “planetary boundaries” across nine areas, shown in Figure 6.1.

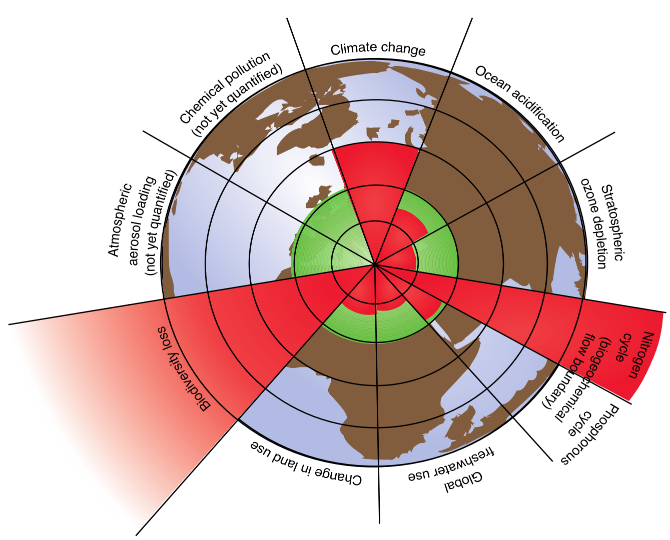

Figure 6.1. The Planetary Boundaries

The first and most important of the planetary boundaries relates to human-induced climate change. We will study human-induced climate change in detail in a later lecture. For now we should note that human-induced climate change is the result of the rising levels of greenhouse gases (GHGs) in the atmosphere. The GHGs include carbon dioxide, methane, nitrous oxide, and a few other industrial chemicals. These GHGs have a shared property: they warm the planet. The greater the concentration of GHGs in the atmosphere, the warmer on average is the planet Earth. Because of industrial activity, the GHG concentrations have risen dramatically in the past century, and the earth has already warmed by around 0.9 degrees C (centigrade) compared with the temperatures before the Industrial Revolution. On current trends, the Earth will warm by several degrees C by the end of the 21st century.

Greenhouse gases allow the incoming solar radiation, in the form of ultraviolet radiation, to pass through the atmosphere to Earth, thereby warming the planet. The earth, in turn, re-radiates that heat as infrared radiation. The earth warms to the point that the incoming (ultraviolet) radiation is exactly balanced by the outgoing infrared radiation. The GHGs, however, trap some of that outgoing infrared radiation, thereby making the earth warmer than it would be without an atmosphere. (With the GHGs in the atmosphere, the earth would be like the moon, considerably colder.) So far, so good. The problem is that with rising concentrations of the GHGs, the earth is becoming warmer than it was before industrialization began. And those rising temperatures are pushing the planet to a new climate, one that is different from the climate that has supported human life during the entire period of civilization. This change of climate is deeply threatening (as we will note more later). It threatens the global food supply; it threatens the survival of other species; it threatens to cause much more intense storms; and it threatens a significant rise in the ocean level, which could disrupt life in many parts of the world.

The most important of the greenhouse gases is carbon dioxide. The main source of human-induced CO2 comes from burning coal, oil, and gas. (The other major source we will study is land-use change, such as deforestation.) The release of energy in the fossil fuels results from the combustion of carbon in these energy sources. The carbon atoms combine with oxygen to release energy plus CO2. In this way, CO2 is the inevitable byproduct of burning fossil fuels. Fossil fuels have created the modern economy. Without them, the world would be poor, as it was for the millennia until the Industrial Revolution. Yet now the CO2 emissions from fossil fuels pose an unprecedented threat. We need to find news ways to produce and use energy, so that we can enjoy the benefits of the modern economy without the dire threats of human-induced climate change.

The second of the planetary boundaries, ocean acidification, is closely related to the first. The oceans are becoming more acidic as the atmospheric concentrations of CO2 increase. The carbon dioxide in the atmosphere dissolves in the ocean, producing carbonic acid (H_2CO_3). Carbonic acid dissociates to an H^+ ion and a HCO_3^- ion (bicarbonate). The rise of H^+ signifies the increased acidity of the oceans. This rising acidity threatens various kinds of marine life, including corals, shellfish, lobsters and very small plankton, by making it hard for these species to form their protective shells.

The pH of the ocean has already decreased by 0.1 unit on the pH scale, which runs from 0 (most acidic) to 14 (least acidic). A change of 0.1 in the pH of the oceans might not seem like all that much, but the scale is logarithmic, so a decline of .1 signifies an increase of protons in the ocean of 10 to the power 0.1, or about .26 (= $10^{0.1}$), a 26% increase of acidity in the oceans, with a lot more acidification to come as the atmospheric concentration of CO2 continues to rise. The map of the ocean in Figure 6.2 shows that the changes in the pH scale are already being noticed in different parts of the world. The oceans are not uniformly becoming more acidic; the local effects depend on ocean dynamics and on regional economic activities. Yet the pH map in Figure 6.2 shows that we are already on a trajectory of dangerously rising ocean acidity.

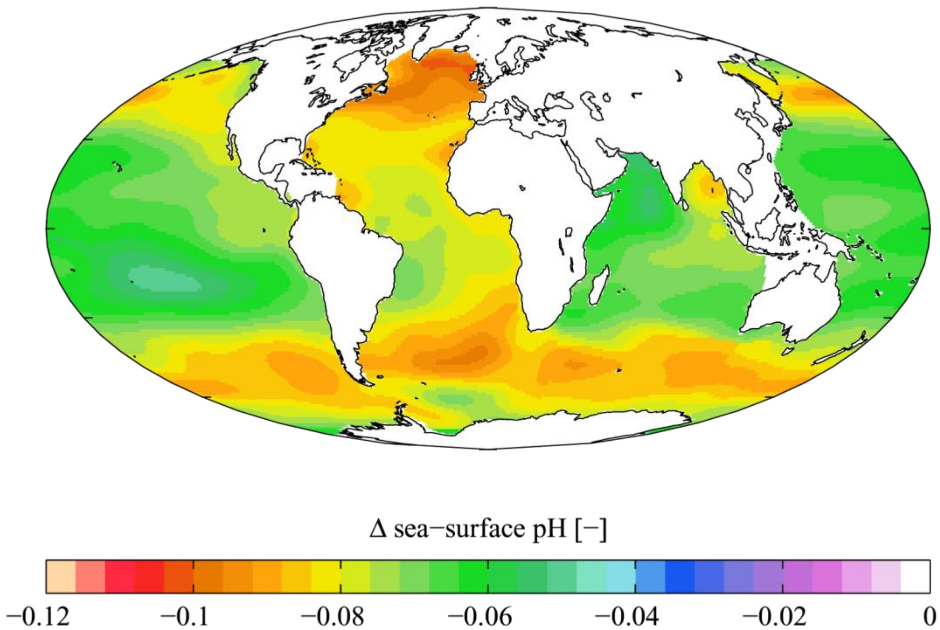

Figure 6.2. Ocean pH Changes

The third planetary boundary is ozone depletion. Brilliant atmospheric scientists in the late 1970s discovered that particular industrial chemicals called chlorofluorocarbons (CFCs), which were used mainly for refrigeration and aerosols at the time, tended to rise into the upper atmosphere and dissociate (that is, split up into smaller molecules). The chlorine in the CFCs, when dissociated from the rest of the molecule, attacked the ozone (O_3) in the upper atmosphere (the stratosphere). By chance, a new NASA satellite was in place to take pictures from space of the ozone layer, and shockingly, the pictures (shown in Figure 6.3) in the mid-1980s demonstrated a huge ozone hole (site of ozone depletion) over the South Pole.

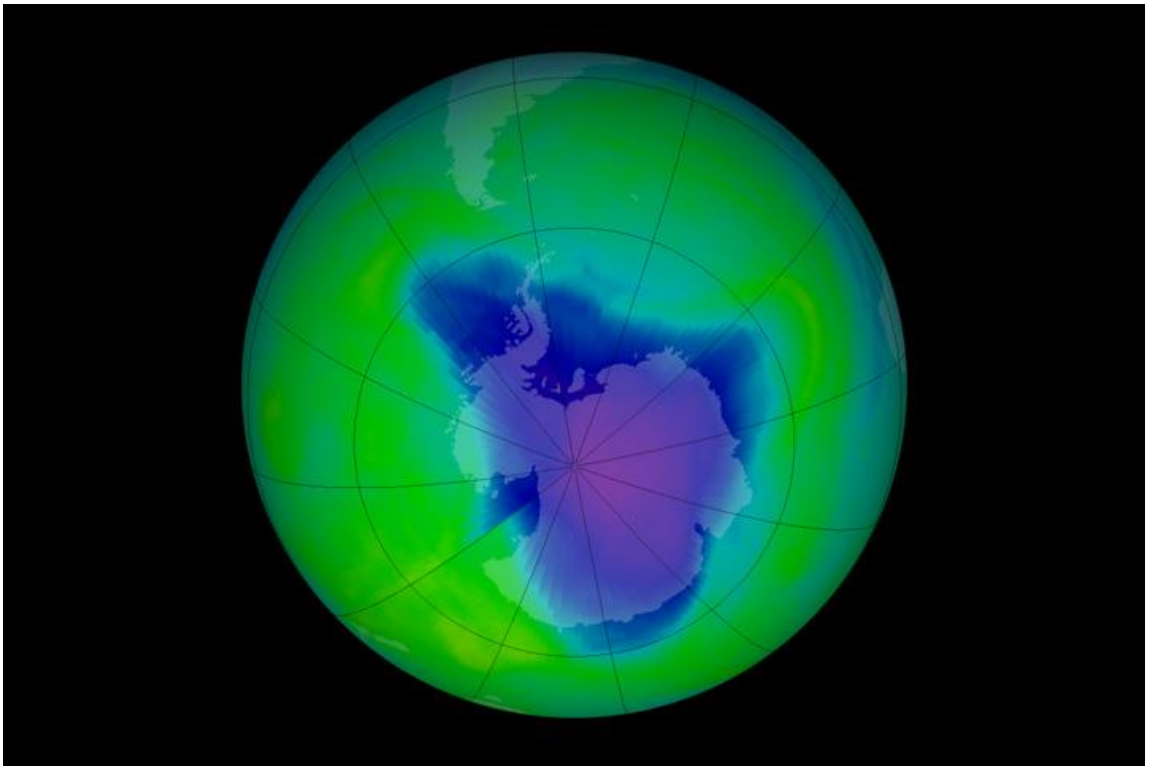

Figure 6.3. NASA Satellite Image of Ozone Layer (1985)

This was a dramatic discovery. The ozone level in the upper atmosphere protects human beings from receiving too much ultraviolet radiation from the sun. Ozone depletion was suddenly a newly recognized, very dire threat to human survival. The real fear was that skin cancers and other disorders would soar as the ozone level faced depletion.

Fortunately, because of great science and technology, humanity was spared the worst. The public was informed in the nick of time that industrial chemicals that were thought to be harmless were in fact a grave threat to public health. The CFCs needed to be eliminated before they caused a catastrophe. The good news is that the world has acted on this one, introducing a new treaty to phase out CFCs from the industrial systems, and to replace the CFCs with safer chemicals. This is now occurring step by step. Without the scientific discoveries, technological insights, and global agreements, ozone depletion would be a grave threat to humanity. Yet we are not yet fully past the threat: we still need to ensure the full elimination of the CFCs and to ensure that the replacement chemicals are indeed fully safe.

The next planetary boundary shown in Figure 6.1 (moving clockwise around the circle) is pollution caused by excessive flows of nitrogen and phosphorous, especially as the result of the heavy use of chemical fertilizers by the world's farmers. Here too, something of profound benefit for humanity – chemical fertilizers – turns out to have a hidden and serious danger. Farmers must put nitrogen, phosphorus, and other nutrients into the farm soils in order to ensure decent yields on their crops. Without fertilizers, yields would still be around 500kg to 1 ton per hectare, rather than the 3-5 tons or more that farmers can achieve on their grain production. Without chemical fertilizers, it would not be possible to feed 7.2 billion people on the planet. It has been estimated that perhaps 4 billion people today are fed as a result of chemical fertilizers.

The problem is that much of the nitrogen and phosphorous is not taken up by the crops. Much of it actually returns to the air and is carried downwind to other locations. Much of it enters the groundwater and rivers, with heavy concentrations of nitrogen and phosphorous reaching the estuaries where rivers meet the oceans. In turn, the heavy influx of nitrogen and phosphorous leads to dangerous ecological changes in the estuaries. The nutrients give rise to "algal blooms," which are massive increases in algae in the estuaries that grow as a result of the high availability of the nitrogen and phosphorous nutrients. When these algae die, they are consumed by bacteria, which in turn deplete the oxygen in the water, giving rise to hypoxic (low-oxygen) dead zones and killing the fish and other marine life. This process of "eutrophication" (high nutrient concentrations leading to algal blooms and then hypoxia) is already occurring in more than 100 estuaries around the world. Figure 6.4 shows a young boy swimming in an algal bloom off the coast of Shandong, China.

Figure 6.4. Young Boy Swimming in Algal Bloom in Shandong, China

The fifth planetary boundary arises from the overuse of freshwater resources. Humans and other species need freshwater every day to stay alive. Of the total amount of freshwater that humanity uses, about 70% is used for agricultural production; about 20% is used by industry; and the remaining 10% is for household use, meaning cooking, hygiene, and other household uses. Humanity is now using so much water, especially for food production, that in many parts of the world societies are depleting their most critical sources of freshwater. Farmers around the world are tapping into groundwater aquifers, taking water out of the ground faster than it is being recharged by rainfall. The result is that these aquifers are being depleted. When they are depleted, the farmers depending on this groundwater will suffer massive losses of production, and food scarcity will result. Groundwater depletion is now a worldwide phenomenon, including the US Midwest, northern China, and the Indo-Gangetic plains of Northern India and Pakistan.

Freshwater scarcity will be exacerbated by countless other problems: growing populations, industrial use of water (e.g. for mining and power plants), changing rainfall and soil moisture conditions due to human-induced climate change, and the loss of meltwater from glaciers as glaciers retreat and eventually are eliminated as a result of global warming. All in all, the planetary boundary of freshwater will pose a major crisis for many regions of the world in the decades to come.

The sixth planetary boundary is land use. Humanity uses a massive amount of land to grow food; graze animals; produce timber and other forest products (e.g. palm oil); and for our expanding cities. Humanity has been converting natural lands such as forests to farmlands and pasturelands for thousands of years. Many regions of the world that were once dense forests are now farm lands or cities. The resulting deforestation not only adds CO_2 to the atmosphere (as the carbon in the plants and trees returns to the atmosphere), thus adding to human-made climate change, but it also destroys the habitats of other species. Human land use change, whether for farms, pastures, or cities, is causing a massive disruption to ecosystems and species survival in many parts of the world.

The seventh planetary boundary is biodiversity. The evolution of life on Earth has created a remarkable diversity of life, somewhere between 10 million and 100 million distinct species, most of which have not yet been catalogued. That biodiversity (biological diversity) not only defines life on the planet, but also contributes in fundamental ways to the functions of ecosystems, the productivity of crops, and ultimately to the health and survival of humanity. We depend on biodiversity for our food supply, our safety from many natural hazards (e.g. coastal flooding), countless construction and industrial materials, our freshwater, and our ability to resist pests and pathogens. When the biodiversity is disrupted, ecosystem functions change markedly, usually in an adverse way (e.g. the productivity of crops diminishes).

Humanity is massively disrupting biodiversity. We are doing so in countless ways, including through pollution, land-use change such as deforestation, human-induced climate change, freshwater depletion, ocean acidification, and nitrogen and phosphorus flux. Many species are in decline in numbers, genetic diversity, and resilience. Figure 6.5 gives some broad sense of the decline of populations of major groups of species. Indeed, countless species face the risk of complete extinction, and prevailing science holds that humanity is now causing the earth's Sixth Great Extinction wave. As summarized in Figure 6.6, the other five extinctions in the earth's history resulted from natural processes, such as volcanoes and meteorite, as well as the internal dynamics of Earth itself. This sixth mega-extinction is not natural. It is the result of one species – humans – damaging the planet so severely that we are putting millions or even tens of millions of other species at risk. Since humanity depends on those other species, we are of course gravely endangering humanity as well.

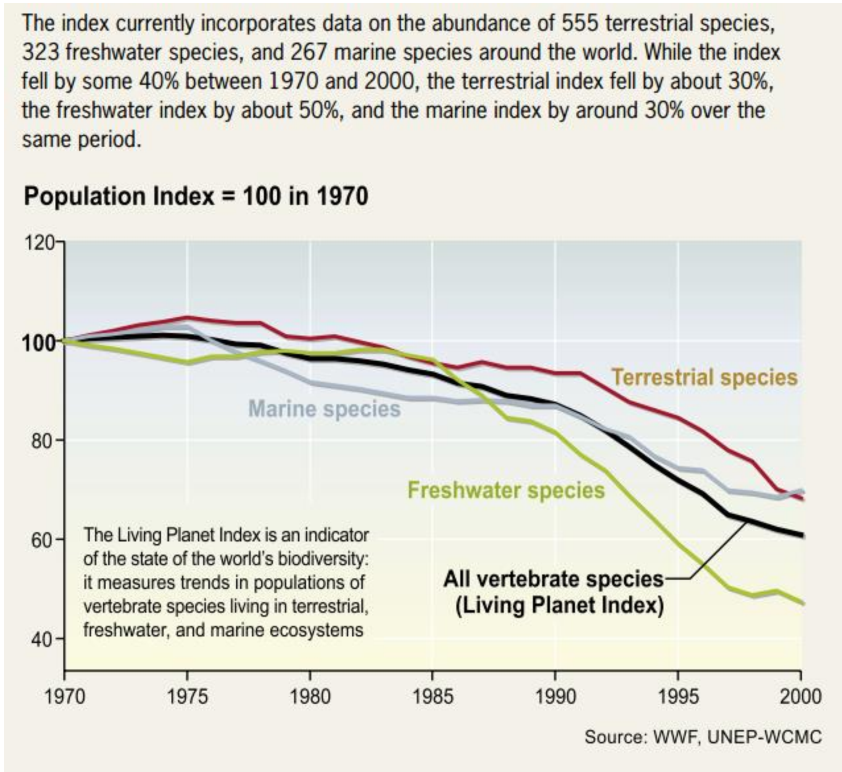

Figure 6.5. The Living Planet Index of Biodiversity

Five of the great extinctions took place long ago--MYA means "millions of years ago."

	end of Ordovician	440 mya	Enormous glaciation and lowering of sea levels. 60% of species disappeared
	end of Devonian	365 mya	Glaciation and falling sea levels again. Maybe meteorite too. 70% of species wiped out.
	end of Permian	225 mya	Huge volcanic eruptions. Earth became winter. . 90% to 95% of all species extinct.
	end of Triassic	210 mya	Maybe a comet shower. Most ocean reptiles extinct. Many amphibians extinct.
	end of Cretaceous called the KT extinction	65 mya	Meteorite struck Earth. Dinosaurs, marine reptiles, ammonoids and many species of plants were wiped out. Mammals, early birds, turtles, crocodiles and amphibians less affected.

Figure 6.6. The First Five Great Extinctions

The seventh planetary boundary is called aerosol loading. When we burn coal, biomass, diesel fuels, and other sources of pollution, small particles called aerosols are put into the air. A tremendous amount of air pollution is created that is very damaging for the lungs; claims many lives per year; and has a significant impact on changing climate dynamics. Very fine particles of diameter less than 2.5 micrometers (written as PM 2.5) can cause life-threatening lung disease. China's major cities have been experiencing catastrophic levels of aerosol pollution, leading to urban smog that is so thick that on some days it is dangerous to venture outside. Figure 6.7 shows such a smoggy morning in Beijing in January 2014.

Figure 6.7. Smog in Beijing (2014)

The next (very broad) category is chemical pollution. Industries such as petrochemicals, steel, and mining not only use a huge amount of land and water for their processing, but also add a tremendous load of pollutants back into the environment, many of which accumulate. They can be very deadly for humans as well as for other species. China, the world leader of economic growth over the past 30 years, has also become the leader of polluted waterways of its major cities because of the extent of its heavy industrial processing, a major environmental problem it will have to deal with.

When humanity trespasses on these planetary boundaries, meaning that human pressures on the environment become greater than the ability of the earth's natural systems to absorb those human pressures, the result is a major change in the function of the earth's ecosystems. Those changes, in turn, threaten human wellbeing, and even human survival when the shocks occur in places where populations are very poor and do not have the buffers of wealth and infrastructure to protect them. When fisheries die, fishing communities die with them. When groundwater is depleted, farming collapses. When the climate changes, regions can be thrown in turmoil and even war, as has increasingly occurred in the dryland regions of Africa, the Middle East, and Western Asia.

Human-induced climate change is already having such dire impacts in many parts of the world. The most direct manifestation of human-induced climate change has been the rise of temperatures, and the rising frequency of extreme heat waves. World-leading climate scientist Professor James Hansen has analyzed the extreme heat events on the planet from the 1950s till now, with the results shown in Figure 6.8. The red spots on the world map indicate occurrences of extreme heat waves. Note the years for the nine maps, starting in 1955 and ending in 2011. We see clearly that the numbers of red blotches on the map – signifying extreme heat waves – have increased dramatically between 1955 and 2011. Indeed, events that only occurred one or two times per 1,000 days in the 1950s are now occurring at a frequency of 50-100 times per 1,000 days in our time.

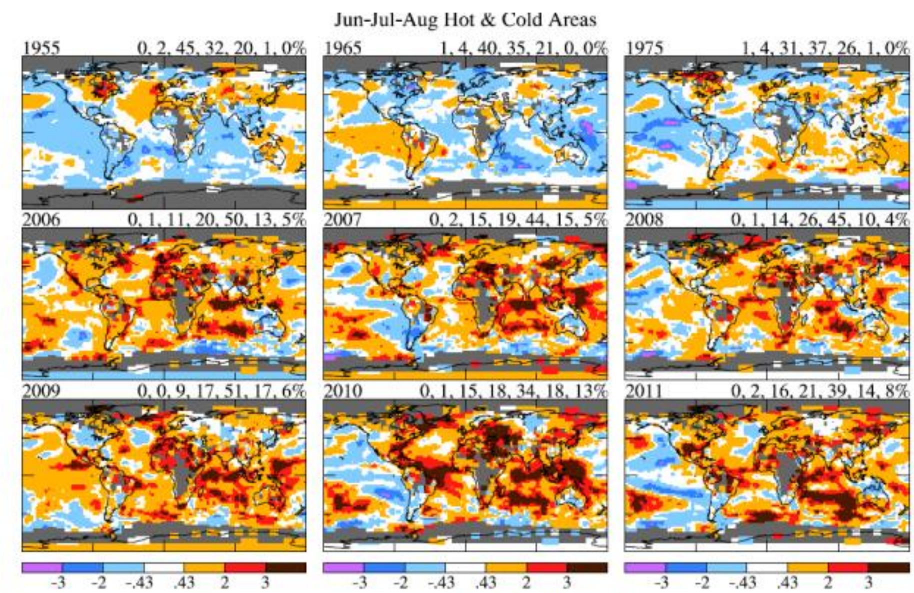

Fig. 3. Jun-Jul-Aug surface temperature anomalies in 1955, 1965, 1975 and in 2006-2011 relative to 1951-1980 mean temperature in units of the local standard deviation of temperature. The numbers above each map are the percent of surface area covered by each of the categories in the color bar.

Figure 6.8. Changes in Extreme Temperatures (1955-2011)

II. Growth Dynamics

It is a stunning reality that humanity is already pushing against the limits of the earth's planetary boundaries. Yet the pressures are likely to increase in the future, not decrease. That is because the world population and GDP per capita both continue to grow. And indeed, we are interested in the success of poor countries in raising their living standards. We are therefore faced with the most important challenge of sustainable development: how to reconcile the continued growth of the world economy and the sustainability of the earth's ecosystems and biodiversity?

This challenge is profoundly significant and profoundly challenging. We want economic development, and we need environmental sustainability. The two seem contradictory, though I will argue that they are in fact compatible if we follow smart policies. Still, making growth and environmental sustainability compatible will be no easy feat. To put in another way, **we need to learn to achieve economic growth that remains within planetary boundaries.**

To get a quantitative sense of the extent of this challenge, let us first consider the amount of "pent-up growth" that is now in the world economic system. By pent-up growth, I mean the amount of economic growth that we might expect as the result of poorer countries catching up with richer countries even if the richer countries do not grow rapidly in the future.

We are now a world of around $91 trillion dollars a year (the IMF's estimate for 2014) when measured in US dollars at international (PPP) prices. There are 7.2 billion people with an average output per person of approximately $12,000. The average income in the high-income countries is roughly three times the world average, meaning that high-income countries have an average per capita income of around $36,000. The average income of the developing countries (low-income and middle-income countries) is roughly $7,000. Suppose that the poor countries successfully catch up with the rich world. That catching-up process would raise the income of the developing countries to $36,000, and would raise the world average income to that level as well. Since the average income would rise three times, total world output similarly would increase by three times, from around $91 trillion to around $275 trillion.

That is a stunning increase for a world economy that has already trespassed major planetary boundaries. Yet is understates the potential impact, since the three time increase is what would happen with today's population. Now let us factor in future population growth. Today's world population of 7.2 billion people is projected to rise to around 9.6 billion by mid-century, and 10.8 billion by the end of the century. Just the rise to 2050 is an increase of 33% by mid-century. With full catching up, the world economy would therefore grow to 9.6 billion people at $36,000 per person, or a total world income of $346 trillion, nearly four times today's Gross World Product.

It is true that convergence of income levels is not likely to occur by 2050. Today's developing countries are not likely to close *entirely* the per capita income gap with the high-income countries by mid-century. Yet our calculations also assumed that the rich countries would stay in place at $36,000. But they are likely to achieve continued economic growth. So our calculations must adjust for two factors: incomplete catching up, and continued economic growth in the high-income countries. We need a statistical model of future growth in order to make an educated assessment about possible outcomes.

Here is one simple rule of thumb. Compare the growth rates of the US and countries with lower per capita incomes. Generally speaking, a country at half of the per capita income of the US (that is, at $25,000 per person) will tend to grow roughly 1.4 percentage points per year faster than the US in per capita GDP. If the US grows at 1 percent per year in per capita terms, the country at $25,000 per capita would tend to grow at around 2.4 percent per year. A country at half the level of $25,000 (that is, at

$12,500 per capita) would tend to grow *another* 1.4 percent per year faster, or at a rate of 3.8 percent per year (= 1% + 1.4% + 1.4%). Using this principle, we find the following typical growth rates:

Country	Per capita Income (PPP)	Growth Rate (tendency per year)
Least Developed	1,613	8.0
Low income	3,125	6.6
Lower middle-income	6,250	5.2
Upper middle-income	12,500	3.8
Lower high-income	25,000	2.4 (=1 + 1.4)
US	50,000	1

The poorer the starting point (assuming no poverty trap or other fundamental barriers to growth), the greater the head room for rapid catching up. Over time, the poorer countries narrow the gap with the richer countries by growing faster. As the income gap narrows, so too does the growth rate of the poorer country. There is a gradual convergence of living standards gradually over several decades, as well as a convergence of growth rates to the long-term growth rate of the technological "leader" (in our example, to the 1 percent growth of the US). The poor country starts out growing very fast, and then as it becomes richer and closer to the technological leader, its growth rate also slows down and eventually gradually converges with that of the technological leader.

The convergence theory helps us understand why the developing countries are indeed achieving faster economic growth than the high-income countries. If we trace this out for the next 40 years from 2010 to mid-century, assuming that the high income world averages 1 percent per year and the poorer regions catch up gradually with the high-income region along the lines of the convergence formula, the result is the kind of graph shown in Figure 6.9 (shown with a logarithmic scale for the vertical axis). While the high-income and developing countries start out quite far apart, basically a five-fold advantage of the high-income countries, the gap between the two groups narrows significantly, to the point where the high-income countries are only two times, not five times, larger than the developing world by the middle of the century.

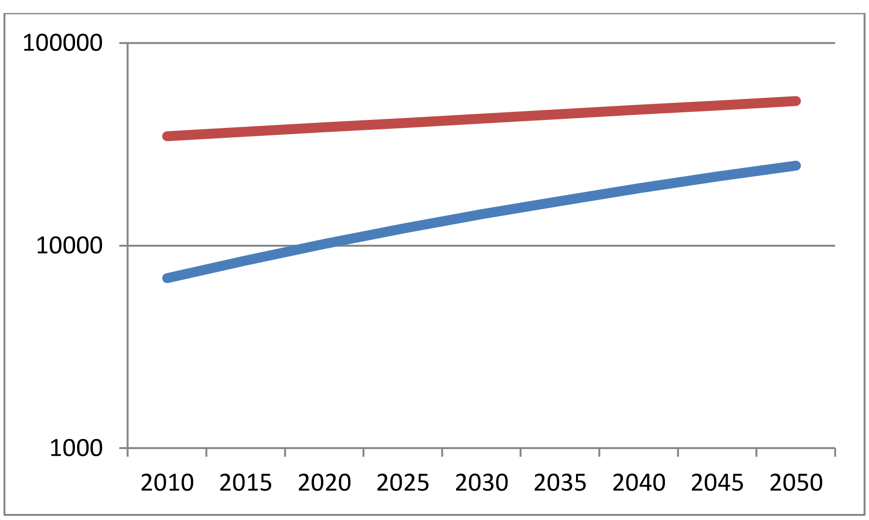

Figure 6.9. High Income vs. Developing Country Growth

What would this gradual convergence imply for total world production and the resulting planetary pressures? To answer this question, we need to now add in the population dynamics as well. As noted, today's population of 7.2 billion people will reach 8 billion people around 2024 and 9 billion by around 2040. By the end of the 21st century, in the medium-fertility variant of the United Nations, the world will reach almost 11 billion people. This is shown in Figure 6.10, again using a logarithmic scale for the vertical axis. With the logarithmic scale the *slope of the curve tells us the growth rate of the world population*, so that when we see the curve leveling off by the end of the century, it also means that the growth rate of the world population is slowing to a low number. By the end of the century the population is projected to stabilize, as signified by the flattening curve. Combining population forecasts with the convergence theory, and assuming the scale of the planetary boundary challenge can be met so that convergent growth can continue, the world economy would rise from around $82 trillion dollars in 2010 to around $272 trillion dollars by the middle of the century, more than a three-time increase, but slightly lower than our previous calculation based on the full convergence of the developing countries.

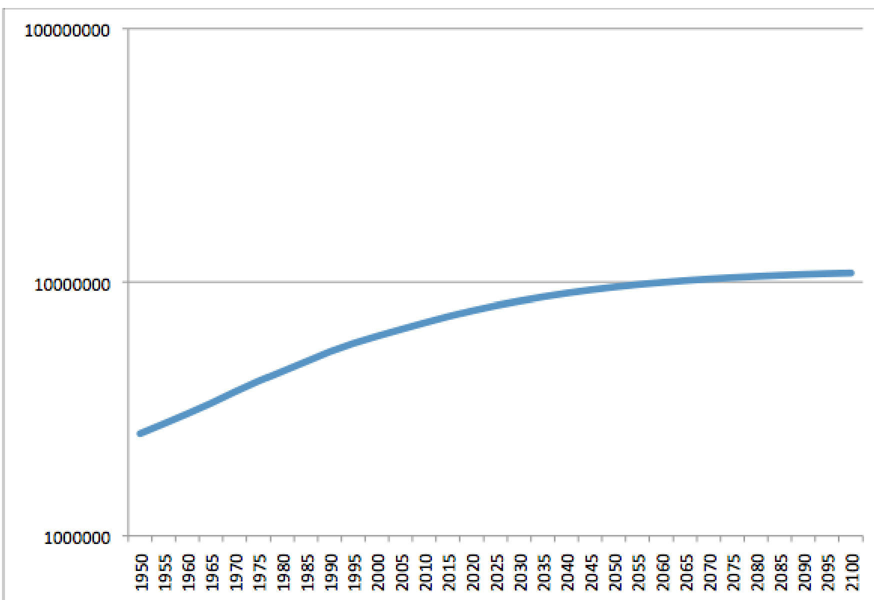

Figure 6.10. Global Population on a Semi-Log Scale

We live in a world already bursting at the seams, with humanity pushing against planetary boundaries. We also live in a world where the developing countries seek to close the income gap with the rich world, and have the technological means to do so over time. Yet if this continued economic growth is pursued using today's technologies and business models, humanity will completely burst through the planetary boundaries, wreaking havoc on the climate system, the freshwater supplies, the ocean acidity, and the survival of other species. In order to reconcile the growth that we would like to see with the ecological realities of the planet Earth, we are going to need the world economy to develop in a fundamentally different way in the future.

III. The Case of Energy

Of all of the problems of reconciling growth with planetary boundaries, probably none is more urgent and yet more complicated than the challenge of the world's energy system. The world economy has developed (one could say "grown up") on the basis of fossil fuels, starting with the 18th century steam engine, and then the 19th century internal combustion engine, and then the 20th century gas turbine. Indeed, until James Watt invented the improved steam engine in 1776, there was no realistic way to achieve sustained economic progress. Fossil fuels allowed the breakthrough to the era of modern economic growth, and that history reminds us of how deep the challenge is of moving away from fossil fuels in the 21st century. The energy sources that have been central to global economic development for more than two centuries are now a clear and present danger to the world, because of the CO_2 that they emit.

A simple solution might seem to be simply to use less energy. But this is not actually so simple, because energy means the ability to do work. Any useful work in an economy depends on access to high-quality energy. Yes, energy efficiency must clearly be part of any solution for sustainable development, as we waste a lot of energy in the form of driving unnecessarily large cars, living and working in poorly insulated buildings, and so forth. Yet the world needs energy resources, and the use of energy, even with a substantial gain of efficiency, is likely to increase in total as the world economy grows. So we have a basic problem. More energy will be needed in the future, but the traditional forms of fossil fuel energy cannot do it for us because they would create a massive intensification of human-induced climate change.

The graph in Figure 6.11 shows on a logarithmic scale the income of different countries and their primary energy use. Total energy use combines fossil fuels, wood burning, hydroelectric power, geothermal energy, wind and solar power, nuclear power, and biofuels (other than wood). This graph shows the total output compared with the total primary energy use. The graph of the total output of an economy versus its energy consumption is close to a straight line, signifying that a doubling of the size of an economy tends to be associated with a doubling of primary energy use. As the economy grows, the energy use tends to grow alongside it, though of course with energy-saving efficiency gains over time as well.

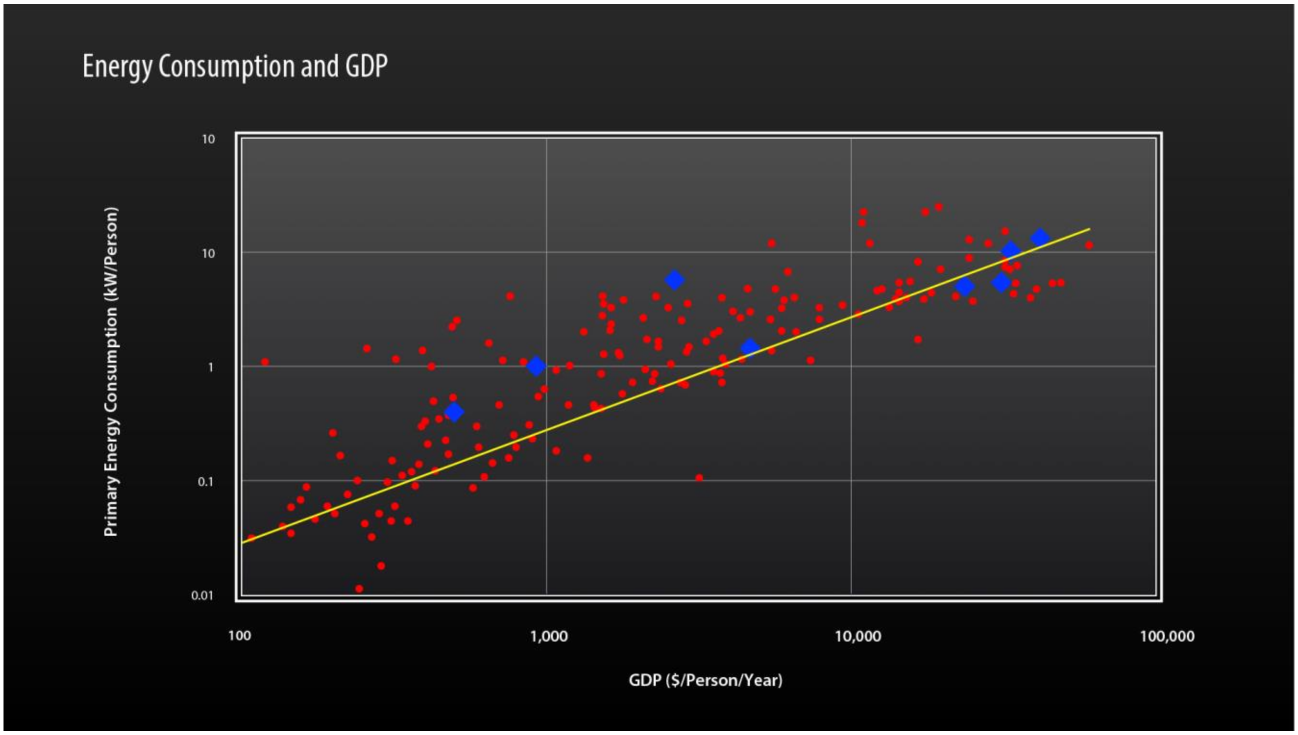

Figure 6.11. Energy Consumption and Gross Domestic Product

It is useful to quantify how much energy we use, how much carbon dioxide we therefore emit into the atmosphere, and what that implies for how much climate change we are causing. On average, for every $1,000 dollars of total production (expressed in 2005 dollars) in the economy, the economy use (expressed in metric tons of oil equivalent energy) tends to be 0.19 tons of oil equivalent energy. One metric ton is 1,000 kilograms, so .19 of a metric ton is 190 kilograms; therefore, for each $1,000 dollars of production we use approximately 190 kilograms of oil or its equivalent in energy content.

Every ton of oil equivalent energy used in the world releases 2.4 tons of carbon dioxide emissions. The exact amount of CO2 depends on the energy source. Since nuclear power is not a fossil fuel, for example, it does not by itself create carbon dioxide emissions. On the other hand, coal is almost all carbon (with some impurities), so it creates the most carbon dioxide emissions per unit of energy of any fuel, about 4 tons of CO2 for an amount of coal equal in energy units to 1 ton of oil. 1 ton of oil itself creates about 3.1 tons of CO2 emissions. The amount of natural gas equivalent to 1 ton of oil creates about 2.4 tons of CO2. And hydroelectric power, solar power, and wind all release zero CO2, and so are clearly highly desirable from the point of heading off climate change.

Let us now put the pieces together. The world economy in 2010 (measured in 2005 dollars) was about $68 trillion dollars (remember that in 2014 it's $91 trillion in today's prices). Multiplying $68 trillion by .19 tons of oil equivalent per $1,000 dollars, and then by 2.4 tons of carbon dioxide per ton of oil equivalent energy (please do the calculation!), results in the 31 billion tons of CO2 that the world released into the atmosphere in 2010. Humans also put CO2 into the atmosphere in some other ways, such as by chopping down trees and releasing the biologically sequestered carbon previously stored in the trees. Approximately 46% of every ton of CO_2 released stays in the air. The other 54% is typically stored in what are called “natural sinks,” the oceans, land, plants, and trees. That means if we put 31 billion tons into the air in one year, a little over 14 billion of those tons stayed in the air.

Now comes the next question. How much is 14 billion tons of CO_2 compared with the entire atmosphere? To answer that we can look at the total volume of the atmosphere (how many molecules are in the atmosphere) and how many molecules of CO_2 are in those 14 billion tons. Doing the calculations, we find that for every 7.8 billion tons of carbon dioxide released into the atmosphere, the carbon dioxide in the atmosphere rises by one molecule per million molecules. This gives us a translation factor: each 7.8 billion tons of CO_2 in the atmosphere raises the CO_2 concentration by 1 molecule per million. Scientists speak of “parts per million” instead of molecules per million, and use the abbreviation ppm. In 2010, the 14 billion tons of CO_2 in the atmosphere therefore raised the CO_2 concentration by around 1.8 ppm (parts per million).

Is that a big increase for one year? Yes. Should we be frightened by it? Yes. Figure 6.12 shows a graph of the concentration of CO_2 in the atmosphere measured over hundreds of thousands of years. The concentration of CO_2 fluctuates over geological times (1,000s of years) as a result of normal Earth processes such as changes in the earth’s orbital cycle. The graph shows the peaks and declines of CO_2 in the earth’s geological history over the past 800,000 years, driven mainly by natural changes of the earth’s orbital cycle until the most recent 200 years.

Look at the graph all the way to the right, which is the present age. During the past 200 years, and especially the past 100 years, the CO_2 concentration has shot straight up, breaking out of the natural range of the past 800,000 years. This is the result of humanity discovering how to use fossil fuels in huge quantities. For 800,000 years, the concentration of CO_2 fluctuated between roughly 150 and 280 parts per million. Then suddenly, in the blink of an eye in geological time, humanity has caused the CO_2 to soar way above 280 parts per million. Within just 150 years, the CO_2 concentration has soared from 280 ppm to 400 ppm. We have reached a level of CO_2 in the atmosphere not seen for the past 3 million years!

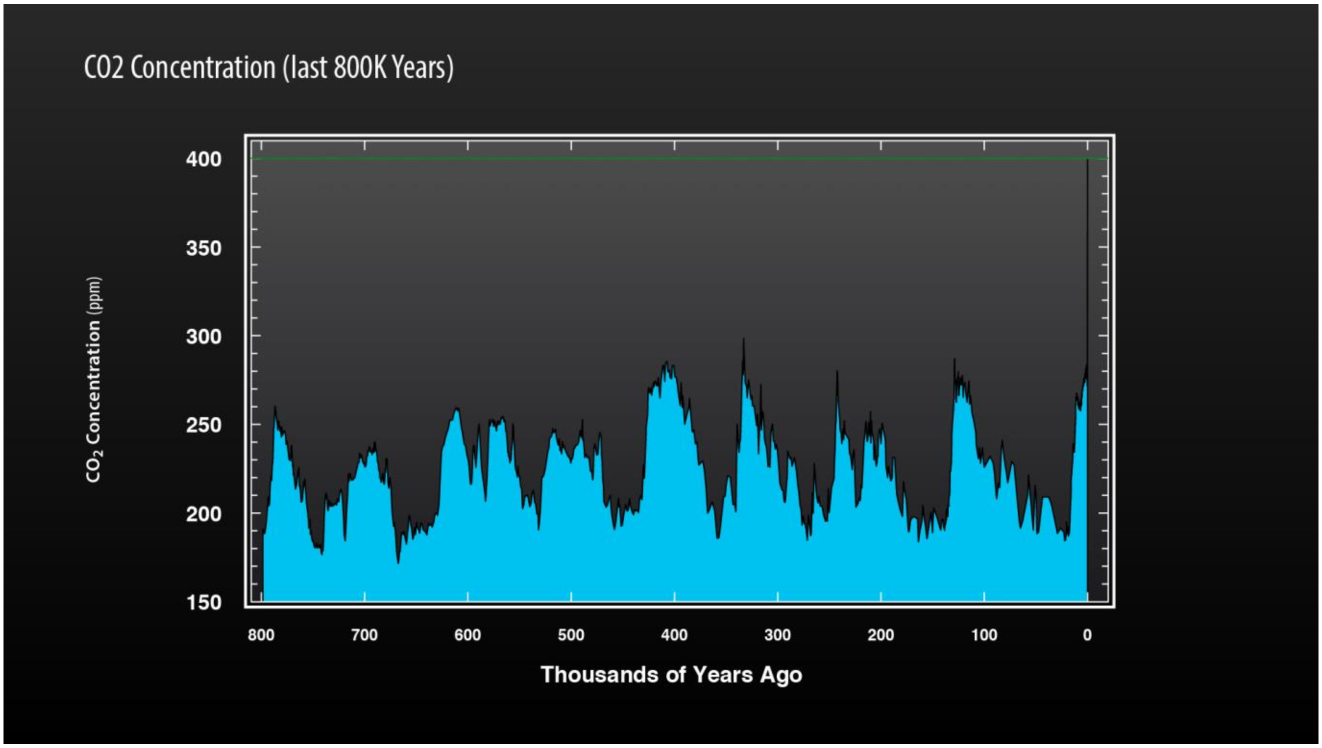

Figure 6.12. CO2 Concentration (800,000 Years Ago-Present)

What the climate scientists tell us is that this kind of change is consistent with a significant rise of temperatures on the planet. Indeed, if we reach 450-500 ppm of CO2, as we soon will likely do, humanity will very likely be living on a planet that is on average 2 degrees centigrade warmer than before the Industrial Revolution. A 2 degrees centigrade rise in the global average temperature might not sound like much, but it implies even larger increases of temperature in the higher latitudes and also massive changes of the earth's climate system, including patterns of rainfall, droughts, floods, and extreme storms. Moreover, the sea level will rise significantly, perhaps by 1 meter during the century, and with bad luck (such as the disintegration of part of the Antarctic or Greenland ice sheets) by much more than 1 meter. We are talking about changes in CO2 concentrations that, when translated into climate change and environmental change more generally, are unprecedented in human history; large; dangerous; and happening now.

How fast are these changes occurring? If we are at 400 ppm today, and the CO2 concentration is rising by around 2 ppm per year, we will reach 450 ppm just 25 years from now and 500 pm in 50 years. If economic growth leads to an even faster rate of CO2 change, we might reach the range of 450-500 ppm even earlier. Indeed, if the world economy were to triple, and energy use were to triple alongside it, then CO2 would be rising around 6 ppm each year rather than 2 ppm.

In other words, if we do not dramatically change course quickly, we are on a path of extraordinary peril. Because of our fossil fuel reliance, we would be seeing a great increase in frequency of the heat waves already evident in the maps by Professor James Hansen (Figure 6.8). We would mostly likely be seeing mega-droughts, mega-floods, more extreme storms, more species extinction, more crop failures, a massive sea level rise over time, and a massive acidification of the oceans as that CO2 dissolves into the ocean and produces carbonic acid. Some regions will be more vulnerable than others. Not every place on the planet will experience each kind of disruption. But in a world that is 3 degrees warmer (or even more) in temperature than now, the disruptions will be widespread. And we could well be on our way to 4 degrees warmer or even more by the end of the 21st century according to the best evidence.

The solutions, which we will study later on, involve a "deep decarbonization" of the energy system, meaning a way to produce and use energy with far lower emissions of CO2 than now. There will be at least three main "pillars" of deep decarbonization. The first is energy efficiency, using much less energy per unit of GDP than now. The second is electrification, meaning that we shift from petroleum to electricity to drive cars, and from fossil fuels to electricity to heat and cool buildings. The third is low-carbon electricity, meaning that we produce power with wind, solar, nuclear, or carbon capture and storage technologies, so that emissions of CO2 per megawatt of electricity are drastically reduced. Every part of the world will need to join in this process.

We must indeed change course on energy and we must do it quickly – far more quickly than what the politicians are telling us. But there is some good news. There are powerful low-carbon technologies available at sharply declining prices, for solar power, wind power, energy efficiency, electric vehicles, and more. These technologies will be crucial to a low-carbon future.

IV. The Case of Food

Intuitively, fossil fuel use (and the mining that goes along with it) would seem to be the dominant means by which humanity impacts the physical planet. Energy use is everywhere, in transport systems, power generation, industry, offices and homes. Yet there is actually an economic sector with comparable or even greater environmental impact than the energy sector: agriculture.

Perhaps this is not entirely surprising. Agriculture is, of course, key to our very survival. We must eat. And since the beginning of civilization, most of humanity has been engaged in farm life. Even now, in the early 21st century, half of the world's population resides in rural areas, with some fairly direct connection with agriculture. Yet the extent of agriculture's impact on the environment is even bigger than it appears. Think of the planetary boundaries – almost every one of them is related to agriculture.

Consider each of the planetary boundaries in turn from the point of view of agriculture.

<u>Climate change</u>. When land is cleared for farmland and pastureland, the resulting CO2 emissions contribute to climate change. So too does the energy use on farms and in the transport and preparation of foods; the methane released in rice production and by livestock; and the nitrous oxide that results in part from the volatilization of nitrogen-based fertilizers.

<u>Ocean acidification</u>. Agriculture contributes to the CO2 emissions that in turn are the main culprit in ocean acidification.

Ozone depletion. CFCs used in food production and storage (e.g. refrigerants) are the drivers of ozone depletion.

Nitrogen and Phosphorous Fluxes. The use of chemical fertilizers is the main source of anthropogenic nitrogen and phosphorous fluxes.

Freshwater depletion. Agriculture, we have seen, is by far the greatest user – and therefore cause of depletion – of freshwater resources.

Biodiversity. The grand tradition of agriculture, unfortunately, is to "simplify" the biodiversity of a given landscape. A complex natural ecology is replaced by a human-managed ecology that often involves a single genetic variant of a single crop such as rice, wheat, or maize. Monoculture farming can cause a sharp decline in biodiversity that eventually reduces crop productivity as well as other ecosystem functions. Agriculture can reduce biodiversity in other ways as well, for example through the application of pesticides and herbicides that end up poisoning the local environment, or through the introduction of non-native species that disrupt local ecosystems.

Aerosols. Agriculture can contribute to aerosols through many pathways: dust, burning of crop residues, combustion of diesel and other fossil fuels, and so forth.

Chemical Pollution. Agriculture in high-income settings is often highly chemical intensive, involving chemical fertilizers, pesticides, herbicides, and other soil treatments. Pollution may also arise from food processing, waste management, use of antibiotics in animal feeds, and so on.

In addition to crossing these planetary boundaries, the global agriculture system has other important adverse impacts. One issue is that the food system is also giving rise to new pathogens. For example, the industrial breeding of poultry causes recombination of genes of bacteria and viruses. When livestock and poultry mix with wild species, there are further viral re-combinations. The interaction of the food industry with wild-type pathogens has probably given rise to several emerging infectious diseases, most likely including the frightening outbreak of the SARS virus in 2003.

All of these huge, and unsustainable, environmental consequences of farming are deeply ironic. They recall Malthus's warning about the physical limitations of growing food on the planet. Malthus noted that population tends to increase geometrically (at a given growth rate) while the ability to grow food, he believed, increases only arithmetically (that is, by a given quantum, not a given growth rate, per year). He noted that geometric growth would necessarily overtake arithmetic growth, so the growth of the human population would necessarily overtake the ability to grow food. At some future point, warned Malthus, there would be so many people that hunger would necessarily ensue, with devastating feedbacks, such as war, famine, disease and other scourges that would push the population back down. Malthus argued that in the long run, humanity would therefore not break free of the physical constraints on the ability to grow food.

Figure 6.13. Thomas Malthus

Malthus did not anticipate the scientific advances of the 19th and 20th centuries. He did not anticipate the science of soil nutrients, founded by the great German scientist Justus Von Liebig in the 1840s. He did not anticipate the science of seed breeding made possible by the science of modern genetics, founded by the Silesian monk Gregor Mendel in the 1860s. He did not anticipate the invention in the 1900s-10s of human-made nitrogen fertilizers in the Haber-Bosch process. And he did not anticipate the great synthesis of these advances in the Green Revolution of the 1950s-80s. For these reasons, most economists and others have long scorned Malthus. Modern science indeed allowed a geometric growth of food production in line with a geometric rise of the world's population.

I am going to make a different point, though. Malthus really had a stronger case than we recognize, and we should thank Malthus more wholeheartedly for pointing out a deep conundrum that continues to this day. First, when Malthus wrote his famous text, the world population was one-seventh of what it is now. Malthus was correct to worry. Second, when economists claim that Malthus neglected the potential for technological advance, we can note that economists on their part neglect the environmental damage caused by modern farming. Yes, the global farm system feeds the planet (though not necessarily very well, as I emphasize below), but it does not do so in an environmentally sustainable way. Until global farming itself is a sustainable activity, we should not be too quick to brush Malthus aside. We don't want Malthus to have the "last laugh" (that indeed would be a tragedy for humanity), but we do want to correct the farm system before it does irreversible damage to the global environment.

Just as we are going to need to find a new energy pathway based on energy efficiency and low carbon energy supplies, we are also going to need to find new farm systems, adapted to local ecological conditions and causing much less ecological damage. What is common to nearly all of the world's major farm regions is that the farm systems are still not sustainable. We have yet to prove Malthus wrong! His specter will loom large until the world population is stabilized (or declining) and our production methods are environmentally sound. The challenge of a sustainable global food supply is therefore a fundamental part of any 21st century agenda of achieving sustainable development.

V. Population Dynamics and Sustainable Development

A major part of our ability to achieve sustainable development will depend on the future dynamics of the world's population. The more people there are on the planet, the more challenging it will be to reconcile the economic objectives of rising living standards per person and the planetary boundaries. The more rapidly population is growing in a particular country, the more difficult it will be to combine economic growth, social inclusion, and environmental sustainability in that place.

Poor countries with high fertility rates (with more than 3 children per woman, and in some countries reaching 6 or 7 children per woman) are often stuck in a "demographic trap." Because households are poor, they have many children. Yet because they have many children, each child is more likely to grow up poor. These societies end up in a vicious circle in which high fertility and poverty are mutually reinforcing.

Facing the question of high fertility (and the rapid population growth that accompanies it) is therefore crucial for breaking free of poverty. When poor families have large numbers of children, they are not able to provide the necessary investments for each child in the human capital – health, nutrition, education, and skills – the child needs to be healthy and productive as an adult. Moreover, governments are not able to keep building the infrastructure – roads, power, ports, and connectivity – needed to keep up with the growing population. And the country's fixed natural capital such as land and depleting natural capital such as hydrocarbons must be subdivided among an ever-growing population. Reducing the fertility rates voluntarily, while respecting human rights and family desires, is therefore essential to sustainable development and the end of poverty.

The world's demographic future is still up for grabs, depending on the fertility choices that households (especially low-income households) make in the future. Figure 6.14 shows the four fertility scenarios produced in 2012 by the United Nations Population Division. The single line between 1950 and 2100 shows the actual change of population from 2.5 billion to 7.2 billion in those years. There are four scenarios after 2010 depending on alternative assumptions about fertility rates between 2010 and 2100.

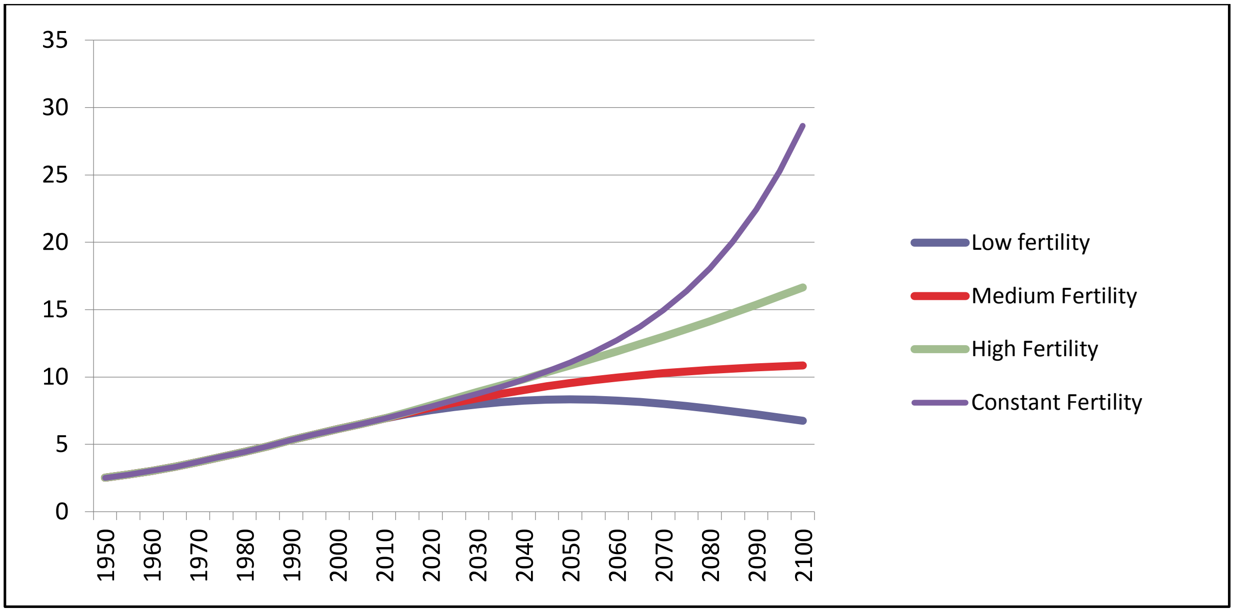

Figure 6.14. World Population Projections (1950-2100)

The "medium" fertility variant shown by the red line reaches about 10.8 billion people in the year 2100. This would signify a net increase of another 3.6 billion people by 2100, roughly half again of today's population. The medium scenario is the one that the UN regards as the most plausible continuation of current trends.

The purple line at the top shows something unthinkable, but still very interesting. Suppose fertility rates do not change at all from their current levels. In each country and age group, the fertility rate would remain as it is currently. Simply running the clock forward based on the current fertility rates, the world population in 2100 would be 28.6 billion, four times higher than today! The earth could not sustain this, so it will not happen. Yet this scenario does tell us that fertility rates must decline from their current levels.

The green line is called the high-fertility variant. It is a bit more plausible than the constant-fertility variant, and yet still pretty frightening. It says that if women were to have on average just *one-half child more* (as a statistical average, or 5 children more per 10 women) than on the medium variant, the world would reach 16.6 billion. A small change in the fertility rate, of 0.5 children per woman, has an effect of nearly 6 billion more people on the planet by 2100. Fertility rates matter!

The low-fertility variant is the blue line below the other three. This last scenario is preferable to the others from a sustainable development standpoint. In this variant, each woman has on average 0.5 children fewer than in the medium variant (or to put it another way, every 10 women have 5 children fewer than in the medium variant). The population would peak around 2050 at 8.3 billion, and then gradually decline to 6.8 billion by 2100, fully 4 billion people fewer than in the medium variant! Such an outcome, with the population at the end of the century less than now, would make it much easier to meet the social, economic, and environmental needs and goals of humanity.

These scenarios show that *small changes of fertility rates* will have big changes of outcomes. They suggest that if steps are taken to help facilitate a faster reduction of fertility in today's high-fertility regions, for example by helping girls to stay in school through age 18 rather than marrying young, the positive impacts from the household to the planetary scale could be huge.

Figure 6.15 shows the annual rate of change of population in the medium scenario for different groups of countries. The solid blue line is the world average, which shows the world's population growth peaked at about 2% around 1970. At that time the world population was about 4 billion people, so with a 2% growth rate the world was adding about 80 million people per year.

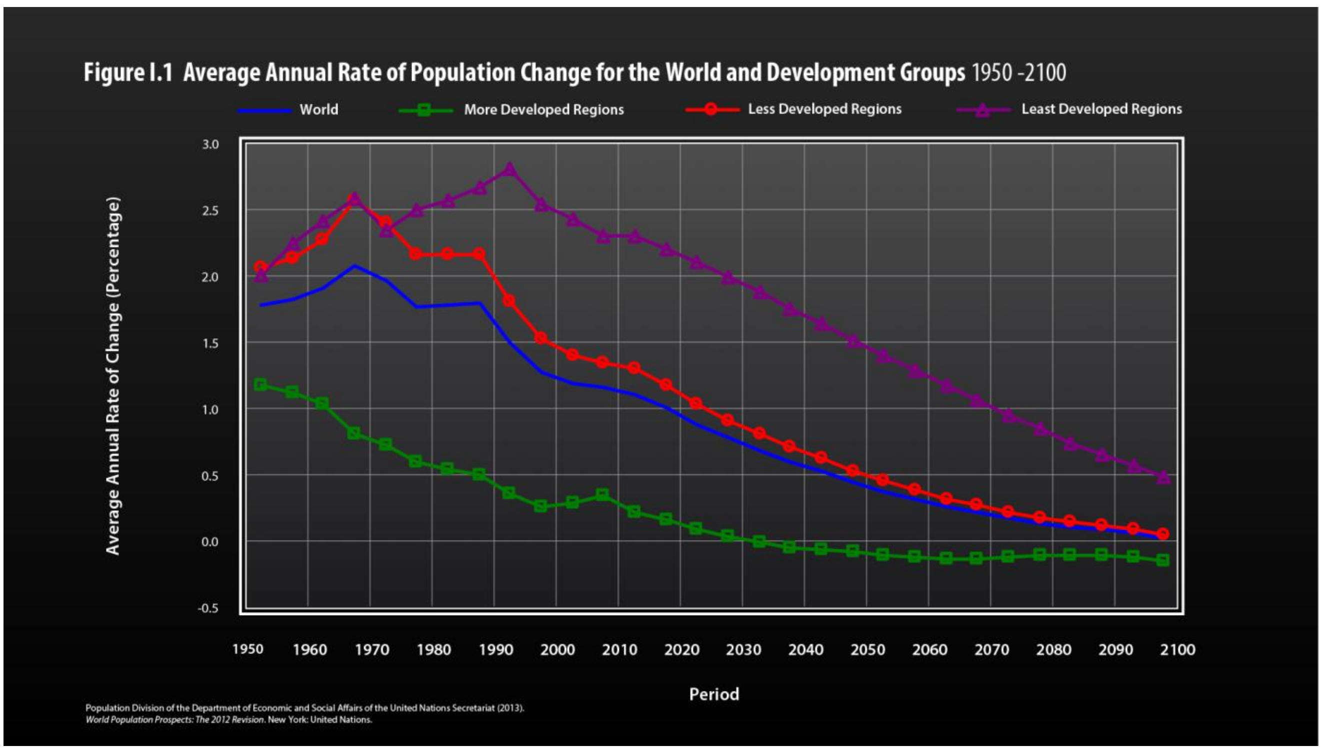

Figure 6.15. World Population Changes by Region (1950-2100)

In the year 2010, the growth rate dropped to 1.1% to 1.2% per year, but now the base on which that percentage growth is occurring is twice as large as back in 1970. Multiplying 1.1% by 7.2 billion people, and there is still the same 80 million increase as of 40 years ago. This says that while the *proportionate* growth rate of population has slowed, the *arithmetic* increase each year remains around 75 to 80 million people.

In the medium-fertility variant, the world's population growth rate tends to decline to almost zero by the end of the century because fertility rates basically come down to replacement. The replacement fertility rate means that each mother has two children, one daughter and one son, so each mother is replacing herself with a daughter who will become the mother of the next generation. This keeps the population stable in the long term. (The replacement rate, technically, is a little bit above 2.0 to take account of the early mortality of children who do not reach adulthood.)

Figure 6.15 shows clearly that the least developed countries have the highest population growth rate. In the poorest places, there are many regions where family planning is not used; girls are pulled from school very young; and women face massive discrimination and are not in the labor market. In these circumstances, fertility rates tend to be extremely high, for example more than 6 children per woman. It is these countries where a rapid, voluntary transition to the replacement rate is most important.

The graph in Figure 6.16 shows the actual total fertility rates between 1950 and 2010, and then shows the medium-variant projections by the United Nations to the year 2100. As of 2010, the more developed countries, at the bottom of the curve, are already below replacement rate. If their fertility rates continue to be so low in the years ahead, their populations will decline. The highest fertility rates at the top of the graph are the least developed countries. For the less developed regions as a whole, and for the world on average, the fertility rates are a bit above replacement but not as high as in the least developed countries.

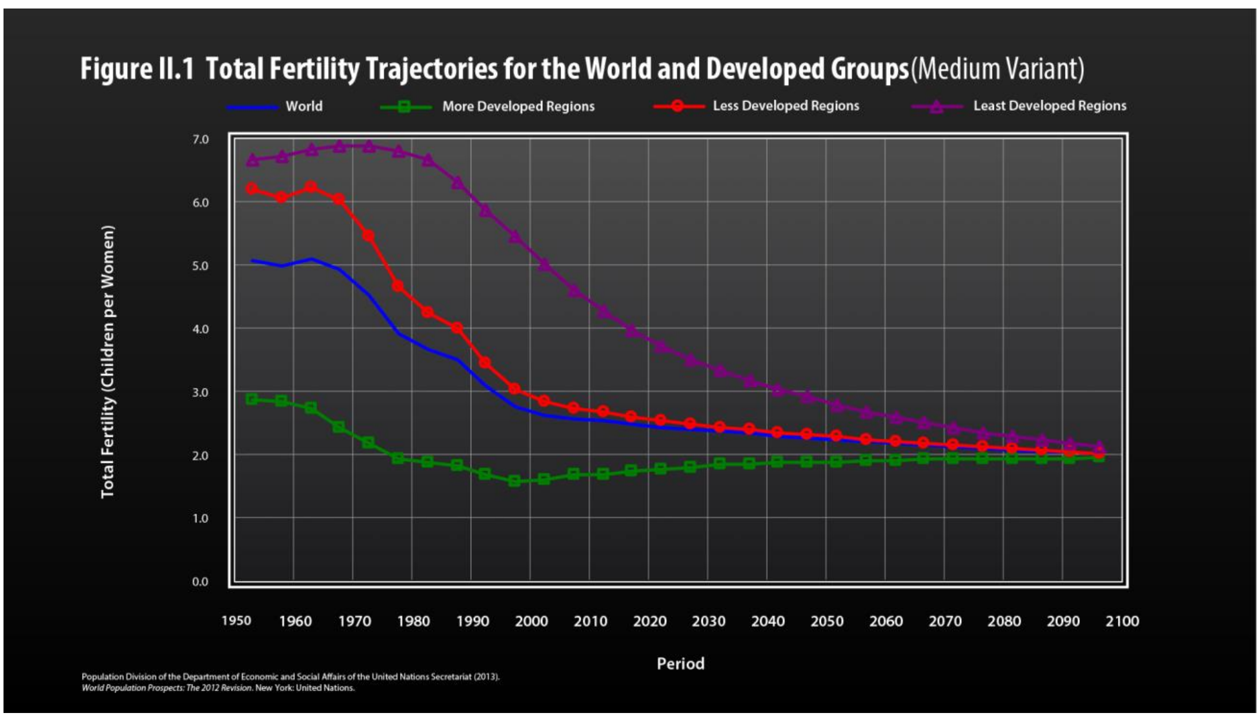

Figure 6.16. Medium Fertility Projections (1950-2100)

What could lead to a faster transition to a replacement fertility rate in today's high-fertility regions? There are many determinants of the fertility rate. Age of marriage is key. In traditional societies girls are often not schooled at all or leave school and marry very early, sometimes as young as age 12, perhaps for economic or cultural reasons. Child bearing starts very soon thereafter, and these young girls remain without economic, political or social empowerment, and often end up giving birth to 6-8 children or even more. A second determinant of fertility is the access (or lack of access) to modern contraception and family planning services. Places where contraceptives are widely available, where clinical services work, where there is culturally sensitive advising of households, tend to have lower fertility rates. Family planning programs that are culturally sensitive and operating effectively in low-income countries can dramatically lower fertility rates on a wholly voluntary basis. A third determinant of the total fertility rate is the woman's role in the labor force. In some countries, women are not allowed to work, or are restricted to working in the home or in just a few occupations. Fertility rates in these settings tend to be high. When women are working outside the home, the fertility rates are much lower. There is a direct "opportunity cost" of foregone earnings when women are home raising many children.

Another possible factor is the urban versus rural location of the household. In farm households, parents often view their children as "farm assets." Children do farm work, such as milking the cows, carrying fuel wood, and fetching water. In an urban setting, by contrast, children are much more likely to be in school and not working in a formal way (though there are of course painful exceptions). This means that on average, families in urban areas see the net cost of raising children to be higher than do families in rural areas. When families migrate from rural to urban areas, their fertility rates thus tend to come down.

Child survival is another key determinant of fertility. If most children survive to adulthood, families may choose to have few children; but if the parents worry that many children will die early, they will likely have more children to ensure the survival of at least some children. One of the keys to a quick voluntary reduction of fertility therefore is to lower the mortality rate of children, thereby giving confidence to parents to have fewer children as well. The legality of abortion also plays an evident role as well. Different societies have widely divergent views about abortion, but the data suggest that those countries with legal abortion tend to have lower observed fertility rates than countries where abortion is illegal.

Public leadership also plays a big difference, because the choice of family size is also influenced by social norms. In most traditional societies, the cultural norm was to have as many children as possible. But when economic, social, and health conditions change, fertility rates also change. And public policy can speed or slow that change depending on the messages sent by leaders in the community and government. Role models also influence fertility rates. Sociologists have found that when television broadcasting arrives in a poor area, fertility rates tend to come down, often quickly. One hypothesis is that people watch role models on TV with small families, and therefore choose to emulate these examples.

Population dynamics are very important for sustainable development. The chances for sustainable development will be very different if the world population reaches 10.8 billion at the end of the century or instead peaks by 2050 and declines to 6.8 billion by 2100. The latter trajectory would be much easier from the point of view of achieving a higher quality of life, greater poverty reduction, higher income per capita, and environmental sustainability. There is also good reason to believe that lower fertility rates would be the truly preferred choice of most households if they have affordable and convenient access to family planning; education for their girls; child survival; and decent jobs and the absence of discrimination for women. When those conditions exist, most likely households would take the opportunity on a voluntary basis for a sharp reduction of fertility rates, helping to move the world more quickly to a peak and then gradual decline of the world population. This would enormously help to put the world on a sustainable development trajectory, where living standards can be raised while respecting the planetary boundaries.