CHAPTER 10: FOOD SECURITY

I. Sustainable Food Supply & The End of Hunger

One of the most complicated unsolved problems of sustainable development is how the world will feed itself. This problem is an ancient one. Yet many people thought it had been solved with great breakthroughs in food productivity based on scientific advances. Especially after the Green Revolution of high-yield crop varieties that took off in the 1960s, it seemed very likely that food production would inevitably stay ahead of the growing world population. Now we have some serious doubts. Not only are we coming to realize that a large portion of humanity is poorly fed, but also we are also realizing the seriousness of the threats to global food security that lie ahead.

We cannot say we have not been warned. The warnings have been with us for more than two centuries, starting in 1798 with Thomas Robert Malthus who, in *Principles Of Population*, posed the basic challenge of food security for a growing population. Malthus' basic point was that any temporary boost in food production enough to relieve food insecurity would cause a rise in the population to the point that humanity was once again reduced to a condition of food insecurity. Malthus would look at our current overall global food surplus and warn, "Yes, that's all fine and good, but what will happen when the population surges from 7.2 billion people today to more than 10 billion people by the end of the century?" He would also note that many people even today live in chronic hunger.

When Malthus posed the challenge of feeding the world population, there were around 900 million people on the planet. Since then, the population has increased by a factor of eight. With 7.2 billion people on the planet, and with the global population continuing to grow by around 75 million people per year, the challenge of feeding the planet is with us again. The problem is even more complicated than Malthus could have imagined, for four main reasons:

(1) A significant share of the world population today is malnourished;
(2) The global population continues to grow;
(3) Climate change and other environmental changes threaten future food production;
(4) The food system itself is a major contributor to climate change and other environmental harms.

Let us look first at the issue of malnutrition. Malnutrition is a pervasive problem: around 40% of the world's population is malnourished in one form or another. One major component of malnutrition is *chronic hunger*, or under-nourishment. The Food and Agriculture Organization (FAO) defines chronic hunger as the insufficient intake of energy (calories) and proteins. Hundreds of millions of people are afflicted by chronic hunger, and have the energy for mere survival. The FAO estimated the number at 870 million people for the years 2010-12.

There is another kind of malnourishment that is less visible, and is sometimes called "hidden hunger," or micronutrient insufficiency. The calories and proteins may be sufficient, but micronutrients like vitamins or particular fatty acids are not adequately present in the diet. Such micronutrient deficiencies result in various kinds of ill-health and vulnerability to infection and other diseases. Key micronutrient deficiencies prevalent in many low-income countries include Vitamin A, Vitamin B12, zinc, iron, folate, omega-3 fatty acids, and iodine.

The third kind of malnutrition, which is now at epidemic proportions in many parts of the world, especially the richest countries, is the excessive intake of calories leading to *obesity*, meaning weight is far too high for height. Technically, obesity is often defined as a Body Mass Index (BMI) greater than 30, where BMI equals the weight in kilograms divided by the height squared measured in meters. Overweight is defined as a BMI greater than 25. It is estimated that roughly one-third of all adults in the world are overweight, and around 10% to 15% are obese.

Adding it all up, the numbers are staggering. Around 900 million people are chronically hungry. Perhaps another 1 billion more have enough macronutrients (calories and proteins) but suffer from one or more micronutrient deficiencies. Roughly 1 billion more are obese. In total, around 3 billion people are malnourished out of a world population of 7.2 billion people, meaning that a staggering 40% of the world is malnourished.

This is not exactly where we would want the world to be more than 200 years after Malthus warned us about the chronic crisis of food insecurity. We do indeed have a crisis of food insecurity. Sometimes it is hunger; sometimes micronutrient deficiency; and sometimes excessive caloric intake with unhealthy diets, such as diets too heavy in sugars and carbohydrates. Any serious focus on a sustainable and secure food supply for the world has to view the nutrition crisis in all its dimensions, from those who lack the basic caloric intake to those who suffer from obesity and the ill effects that come from that condition.

Figure 10.1 shows where these problems are distributed. Chronic hunger is heavily concentrated in tropical Africa and in South Asia. More than a third of the population in tropical Africa, especially Central and Southern Africa, is undernourished. In South Asia, between 20% and 33% of the population is chronically undernourished. When young children are undernourished, their physical development may be irreparably damaged, leading to adverse health consequences that last through their lives. Such consequences can include impaired brain development and vulnerability to various kinds of non-communicable diseases (such as cardiovascular disease or metabolic disorders) as adults.

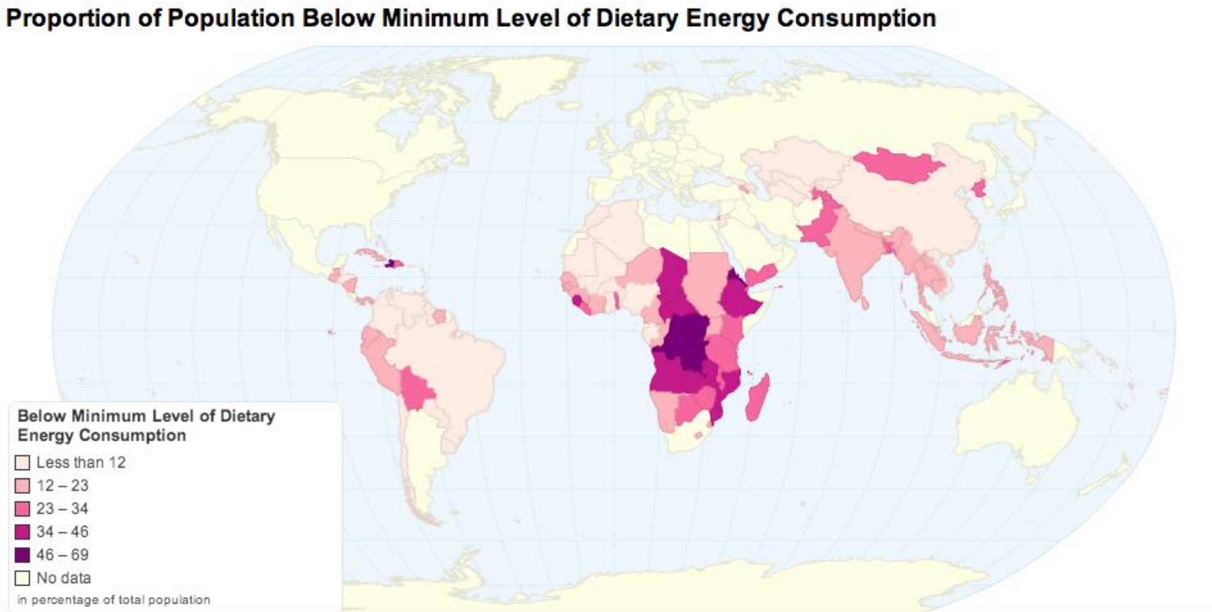


Figure 10.1. Global Chronic Hunger

Chronic undernourishment of young children is measured according to various indicators of severity. The first is *stunting*. Stunting means that a child has a very low height for their age. Specifically, children are assessed relative to a standard population distribution of height for age. Children who are more than two standard deviations below the norm are considered stunted. Stunting reflects the inadequacy of dietary intake, but can results both from a poor diet and from chronic infections, such as worm infections. As Figure 10.2 shows, the most severe stunting is normally found in tropical Africa, and the highest stunting rates in the world are in South Asia, especially India.

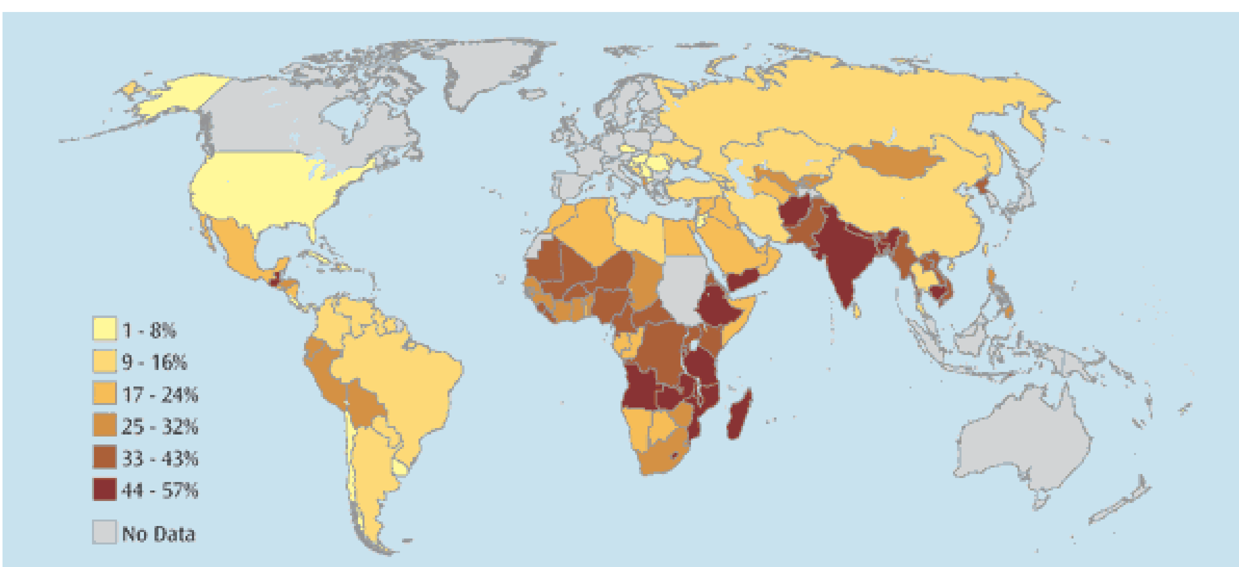


Figure 10.2. Percent Stunting by Country

The second condition is even more urgent, and that is *wasting*. While stunting is a chronic condition where the child does not grow, wasting is a low weight for height. Figure 10.3 illustrates the physical differences between the conditions. Wasting it is often a sign of acute life-threatening under-nutrition; the kind of under-nourishment that one often sees in a famine. In those cases, the child may require an urgent rescue through therapeutic foods (high-intensity nutritional foods designed to combat acute under-nutrition) and emergency procedures to help keep the children alive.

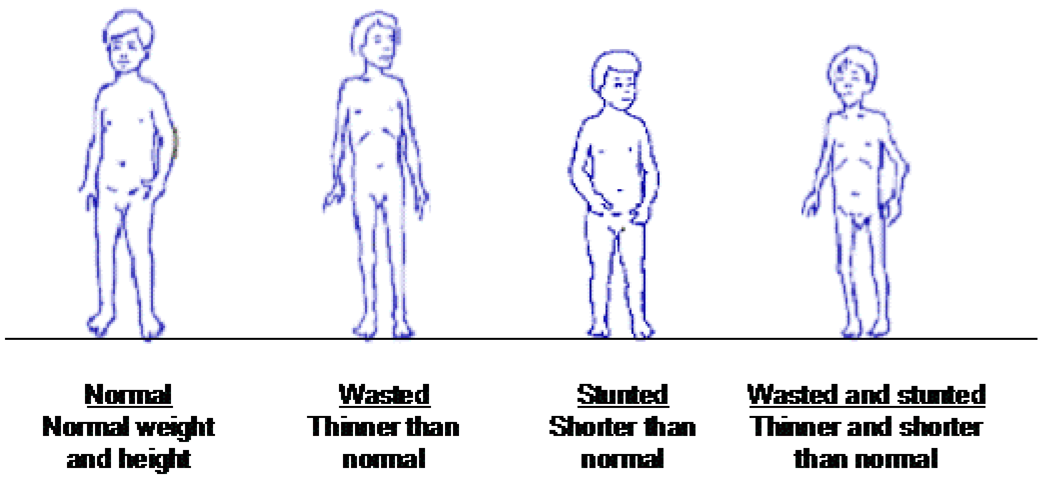


Figure 10.3. Illustration of Stunting and Wasting

There is a key distinction between chronic under-nutrition (chronic insufficiency of calories and proteins) and acute under-nutrition that may arise from wars, disasters, droughts, and displacement of populations. When those acute episodes occur, there is not only massive suffering but also the risk of a massive loss of life from starvation and disease.

Violence and conflict often break out in hungry regions. Figure 10.4 depicts food insecurity in the spring of 2012. In West Africa there was drought and food crisis in the Sahel, covering Mali, Chad, and Niger; in East Africa, there was drought and food crisis in the Horn of Africa, covering Ethiopia, Somalia, Northern Uganda, Northeast Kenya, and Djibouti. In both cases, the drought and resulting famines led to large population movements, and resurgent violence as migrants clashed with local populations. In Mali, regional conflicts and local conflicts combined to produce a massive and devastating civil war.

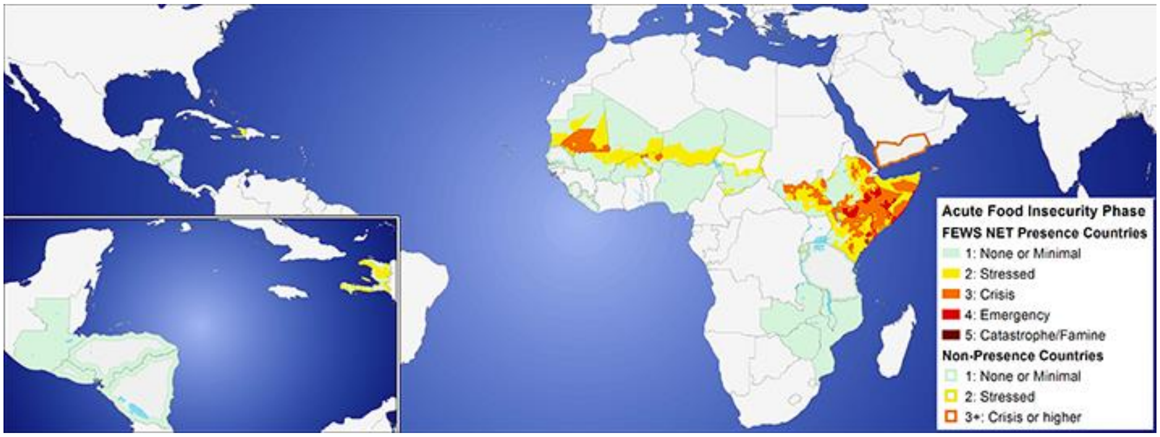


Figure 10.4. Acute Food Insecurity (Spring 2012)

Hidden hunger afflicts not only those with chronic under-nutrition but also another billion or so people who have an adequate caloric intake but an inadequate variety of nutrients in the diet. Figure 10.5 shows estimates of three particular micronutrient deficiencies (iron, vitamin A, and zinc). We note the especially high rates of micronutrient deficiencies in South Asia, West and Central Asia, much of tropical Africa, and the Andean region. Unfortunately, the data on hidden hunger are themselves hidden. There are no precise estimates of micronutrient deficiencies around the world.

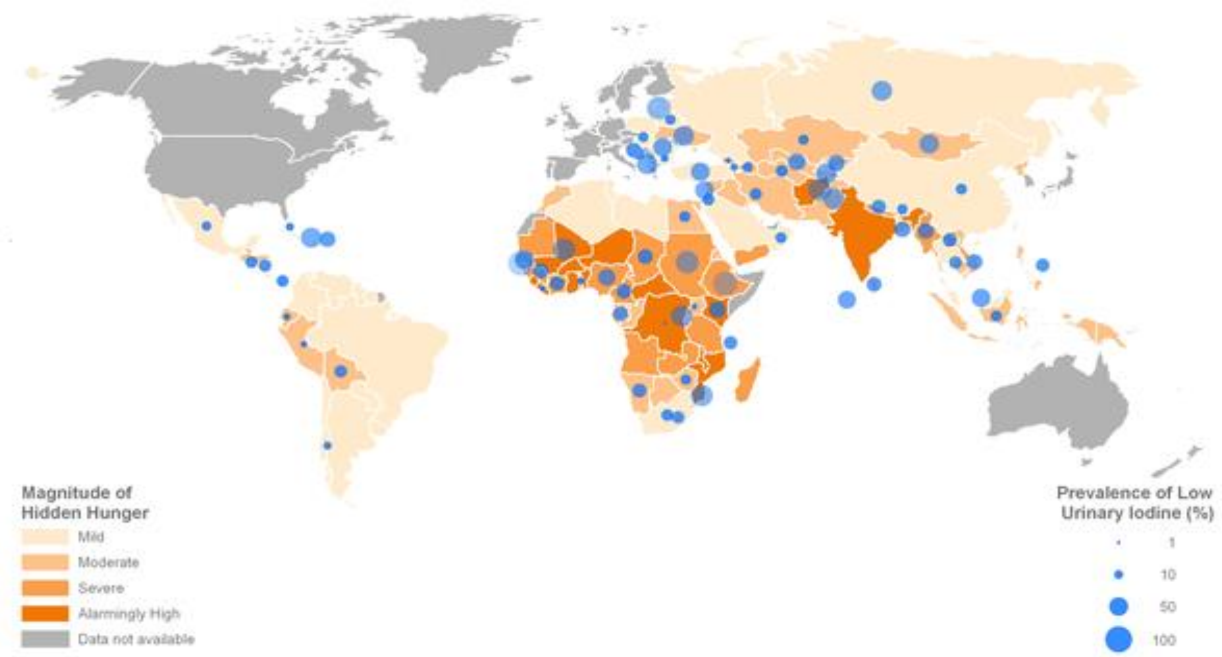


Figure 10.5. Hidden Hunger Index (Zinc, Iron, and Vitamin A deficiencies)[1]

[1] http://www.plosone.org/article/info:doi/10.1371/journal.pone.0067860

Obesity marks the other end of the malnourishment spectrum, and also causes a tremendous amount of disease and premature mortality. As we see in Figure 10.6, the United States, Mexico, Venezuela, and several countries in the Middle East and North Africa, Libya, Egypt, Saudi Arabia, South Africa, and a few others, have an obesity rate above 30%. Several more countries, notably in Europe and the former Soviet Union, have an obesity rate between 20% and 30%. Why are we facing this obesity epidemic?

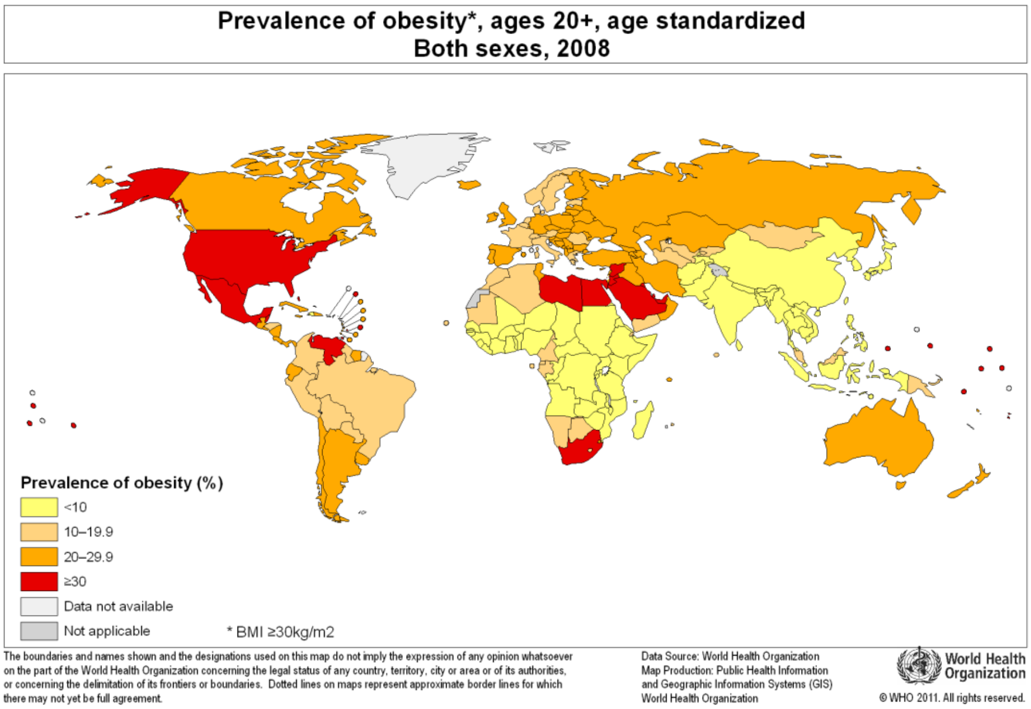


Figure 10.6. Global Prevalence of Obesity

The fundamental causes of the obesity epidemic are still not fully clear. Part of the cause is the total caloric intake, and part is the result of relative inactivity in the urban environment. The high caloric intake may also result from the *kinds of highly processed foods* that people are eating, notably foods with a high "glycemic index." The glycemic index measures the rate at which a food raises the level of blood sugar. Foods with high glycemic indexes include soda drinks, potatoes, rice, and many baked goods. Foods with low glycemic indexes include whole grains, fruits, and vegetables. It is hypothesized that high-glycemic-index foods give rise to a sharp rise in blood sugar followed by a sharp rise in insulin, which in turn lowers the blood sugar and raises the appetite. Satiety is therefore reduced, and over-eating may result.

In short, the obesity epidemic most likely results from a combination of too many calories, the wrong kinds of calories, and the extreme physical inactivity of urban life. There is no doubt, as the map in Figure 10.6 indicates, that a global epidemic is underway. It is already spreading from high-income countries to middle-income countries, and poses a rising threat to health and wellbeing.

To counteract this epidemic, dietary changes combined with more physical activity will be key. Breakthroughs in nutritional science are giving us guidance on improved diets. One of the leaders of modern nutrition is Professor Walter Willett, Chair of Harvard University's Department of Nutrition. He proposed a "healthy eating pyramid" (Figure 10.7) that depicts the kinds of foods, and the relative frequency and amounts that should be eaten, in a healthy and well-balanced diet. A healthy diet includes whole grains (with low glycemic indexes), vegetables, fruits, and plant oils. Meats and foods with a high glycemic index (e.g. potatoes and rice) should be eaten sparingly. At the base of the pyramid is daily exercise. Unfortunately, actual diets in the United States and other countries with obesity epidemics are quite different, with very high intakes of processed grains, rice, potatoes, soda drinks, red meats, and unhealthy fats (trans fats) used in baked goods and fast foods.

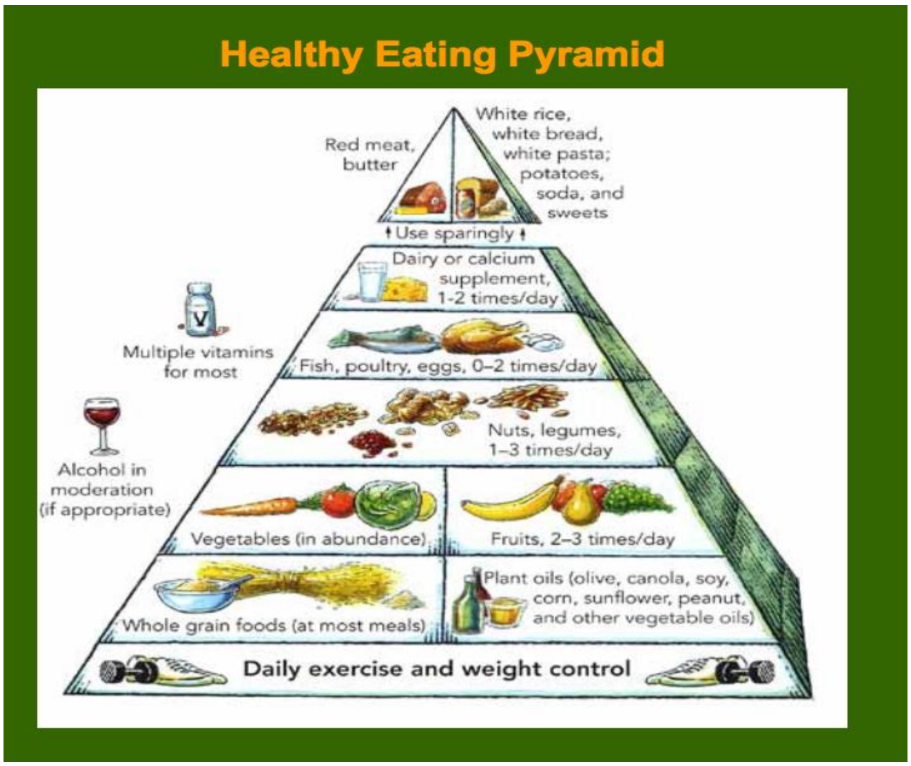


Figure 10.7. The Healthy Eating Pyramid

Global food insecurity is already bad enough, but is likely to get worse before it gets better. Not only is around 40% of the world malnourished, but the global food supply is also becoming destabilized by climate shocks and other environmental ills (e.g. freshwater depletion, threatening irrigation of crops), even as the world population continues to increase. Moreover, the global demand for grains is rising even faster than population. Countries like China with rising incomes are also shifting to diets with more meat products. Since each kilogram of beef requires 10-15 kilograms of feedgrain to grow the cattle, there is a multiplier effect of higher incomes on the global demand for grains. The combination of unstable food production (due to climate change) and rising food demand (due to rising population and meat consumption) is resulting in upward pressure on global food prices.

Figure 10.8 shows food prices since the late 1970s. From 1970 to the early 2000s, real food prices were falling: the rise of food production was outpacing the growth of food demand. Yet since the early 2000s, food prices have been soaring in real terms (that is, food prices have increased much faster than average inflation). Indeed the rise of food prices during the period since 2000 marks a major reversal of an even longer trend of falling real food prices throughout the 20th century.

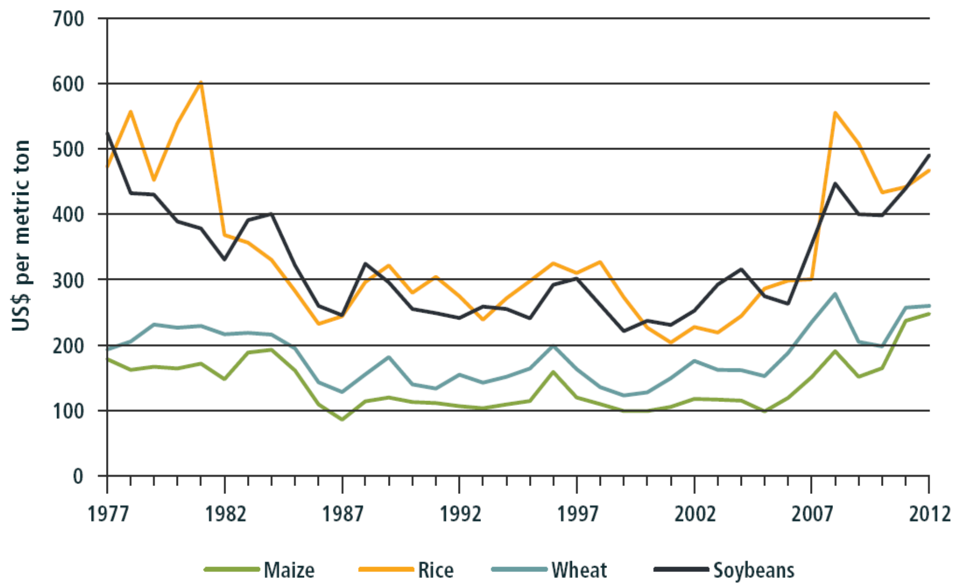


Figure 10.8. World Prices for Key Commodities (1977-2012, $2005 USD)

For wealthy people, the rise in food prices is an inconvenience. As we see in Figure 10.9, only around 6% of the US household consumption is for foodstuffs. Yet for poor people, diets consume a large percentage of the family income, as much as 45% of the household budget in the case of Kenya, as shown in the figure. This inverse relationship of total consumption per person and the share spent on food is known as Engel's Law, and it is one of the most robust patterns in the economy. Because of Engel's Law, the recent rise of global grain prices is more than just an annoyance or a hindrance for the poor, especially the urban poor. It is often a profound threat to their wellbeing, one that pushes many people into abject poverty, hunger and desperation. Of course for farmers who are net sellers of grain on the market, the rise in food prices can be a blessing, not a curse, as it may raise the farmer's income by more than it raises the household's cost of the food consumption.

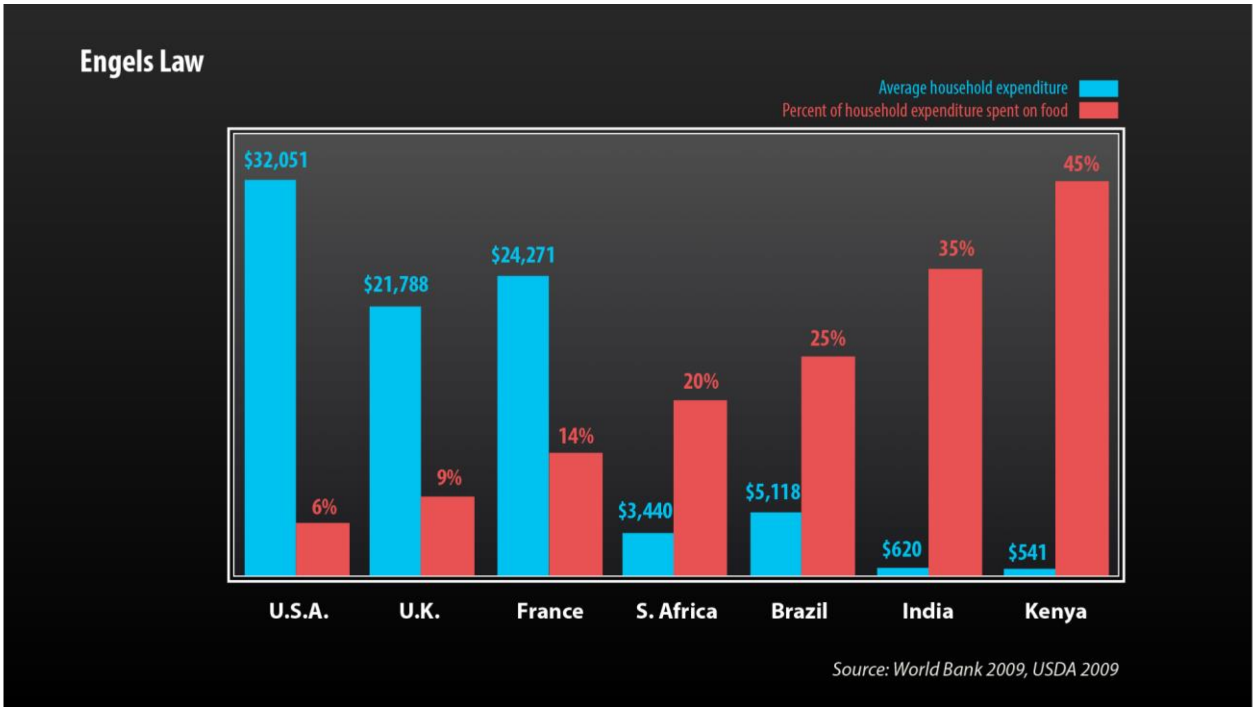


Figure 10.9. Engel's Law: Proportion of Income Spent on Food

In summary, we have around 40% of the world still not properly nourished, a food supply already under stress, rising food prices, and increasing demand for food production. What can be done? We now turn to the supply side: how food is grown, where it is grown, and what might be the prospects for sustainable and nutritious food production in the future, especially in the era of climate change and water scarcity.

II. Farm Systems, Ecology & Food Security

One of the challenges of addressing global food security is the remarkable variation in farm systems around the world. There is no "one size fits all" when it comes to farming, or to methods to increase farm yields. This enormous diversity should not be surprising. Farmers differ incredibly in what they grow; how they grow it; and the challenges of climate, soils, water, topography, pests, biodiversity, and transport costs that they face. These variations in turn have an enormous effect on farm systems and strategies. As a result there is no single or simple answer as to how farmers can become more productive and more resilient to environmental risks. Part of the proper diagnostics and solutions for a global sustainable food supply depends on thoroughly understanding how farm systems differ around the world.

There are about 130 million square kilometers of land on Earth and of that, a remarkably large proportion is already taken for human needs. Agriculture constitutes around 50 million square kilometers, roughly 40% of the world's total land area. Roughly 14 million square kilometers are arable land (land that can be used for agricultural crops), and roughly 34 million square kilometers are meadows and pasturelands. Farmland itself accounts for a little over 10% of the world's land area.

Pastures are much bigger, around a quarter of the total land area. Another 39 million square kilometers are forests, covering about 30% of the earth's land area. A modest proportion of the forests, perhaps around 15-20% of the total, are managed for pulp, paper, timber, logging, etc. The remainder of the earth's land is about 41 million square kilometers, roughly 30% of the total, much of which is uninhabitable land such as deserts and high mountains. Only a few percent of the world's land areas is in cities, where half the world's population lives. Recent estimates put the urban landscape at around 3% of the total, and rural households and businesses at another 3%.

Figure 10.10 maps where the agricultural land is, both for cropland and grazing land. The green shaded areas, where cropland is greater than 50% of the total, include the US Midwest, parts of Western, Central and Eastern Europe, Russia, and much of China and India. In Africa and South America, the grazing land and cropland are mixed. The drier areas tend to be places where food crops cannot be grown with high productivity, and so are used more for animal grazing. In semi-arid environments, one finds nomadic populations that move herds of livestock across large areas in pursuit of the grasslands watered by the seasonal rains. In Africa, these pastoralist environments are found in the semi-desert regions of the Sahel in West Africa, the Horn of Africa, and the deserts (like the Kalahari of Botswana) in Southern Africa.

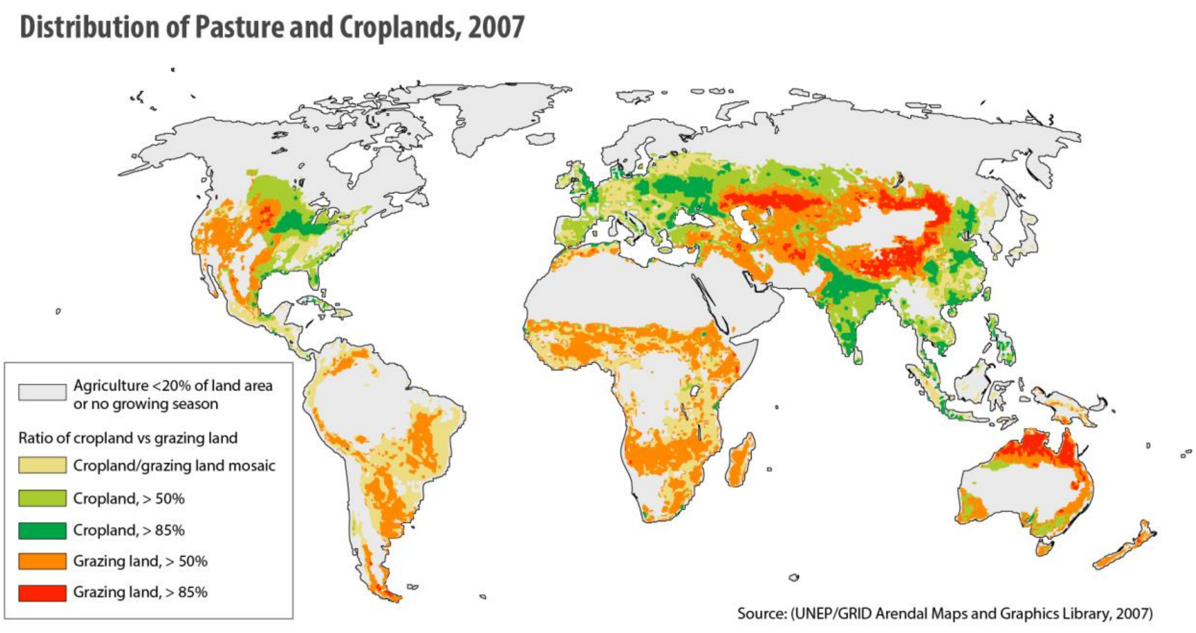


Figure 10.10. Distribution of Pastureland and Cropland (2007)

There are two major forest areas to study in the map of the world's forests in Figure 10.11. First are the rainforests around the equatorial belt. The earth receives the highest solar radiation per m^2 at the equator. The intense solar radiation warms the equatorial land, and causes the humid equatorial air to rise and cool. The water vapor condenses and gives rise to massive precipitation at the equator (and descending dry area at around 25-degrees north and south latitude, giving rise to deserts north and south of the equator). The equatorial rainfall and warm year-round temperatures produce the three great equatorial rainforests of the planet: the Amazon in South America, the Congo Basin in Africa, and the great rainforests of the Indonesian archipelago in Southeast Asia. This rainforest band circles the planet at the equator. The other major forest regions are in the high latitudes, like the boreal forest across the vast Eurasian land mass and Canada. Unlike the forests that once stood at mid-latitudes in North America, India, China, and Europe, but have since been cut down, the boreal forests remain standing today in large part because the land under the forests cannot be used profitably for farming as the temperatures are too low and the potential growing seasons are too short. Otherwise, human settlers would likely have deforested the high-latitude regions just as humans long ago deforested the temperate mid-latitude regions.

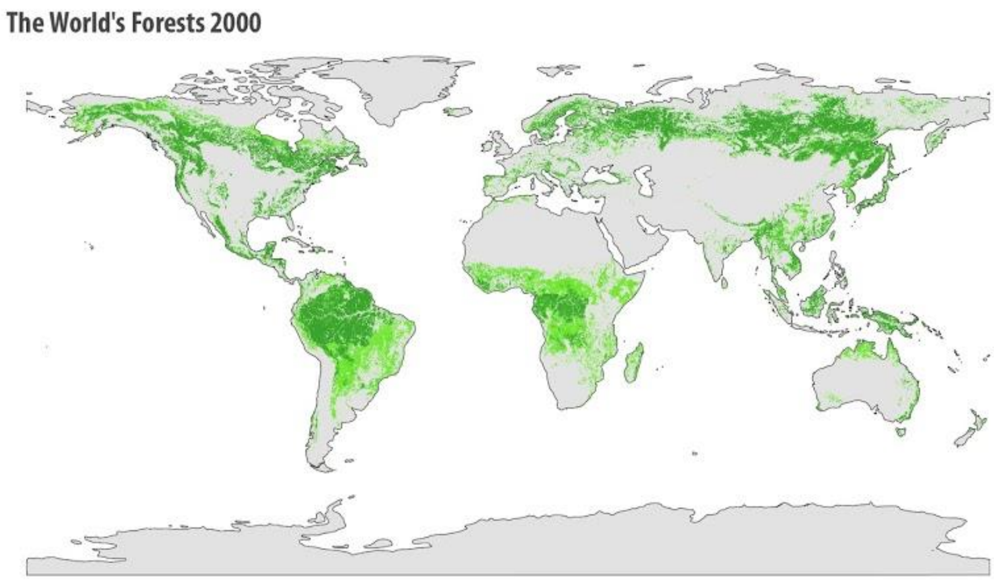


Figure 10.11. The World's Forests (2000)

We see therefore that the locations of cropland and forests are deeply rooted in the ecological conditions, including temperature, rainfall, topography (e.g. if the land is too steeply sloped it may be impossible to farm), whether irrigation is feasible, and more. All of these patterns shape the farm systems and shape the location of human populations. Population densities are nearly zero in the deserts and tundra, and low in the near-deserts and areas in high latitudes just lower than the tundra. Population densities and farmlands are prevalent in temperate mid-latitude zones that are well watered, with good soils, moderate temperatures, and therefore good growing conditions for crops. These areas were heavily forested in pre-history, but humanity began deforesting them long ago to make way for croplands and pasturelands.

Many of the forests today are being threatened with deforestation, especially the equatorial rainforests. Populations are encroaching on these areas for a variety of reasons, including to make way for pastureland and cropland, or to get fuel wood and other goods and services. The pace of deforestation is currently unsustainable in all of the great equatorial rainforests. Some of the forests are over-logged for tropical hardwoods, which are highly valued but used in an unsustainable manner around the world. Rainforests are also being cut down and replaced by massive tree plantations; for example, to grow high-demand products like palm oil, a problem that is particularly intense in Indonesia, Malaysia, and Papua New Guinea.

It is worthwhile to take a deeper look at one part of the world to illustrate how the geography shapes the farm systems and the society. In Africa, there are distinctive characteristics of climate that cause distinctive farm systems and distinctive economic results as well. Figure 10.12 maps the various farm systems in Africa – the 14 major agro-ecological zones, each with a specific kind of farm system adapted to the particular ecology.

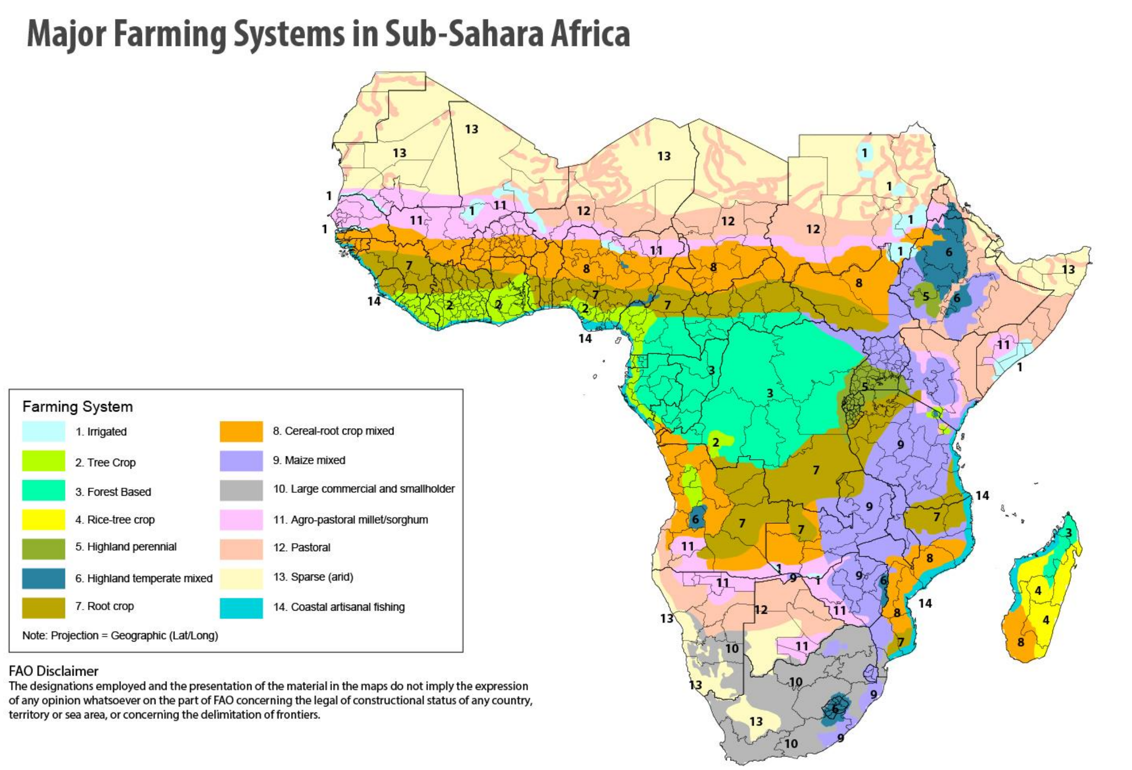


Figure 10.12. Major Farm Systems in sub-Saharan Africa

Start at the equator. There the year-round high temperatures and high rainfall give rise to a rainforest ecology. The Congo Basin rainforest (show as the bright green area 3) is not especially productive for annual crops (the soil nutrients are rapidly washed away by the intense rainfall), so the forest is mainly used for tropical forest products (tropical logs and tree crops such as rubber, palm oil, and cocoa). A similar situation applies in the tree-crop ecology of the coast of the Gulf of Guinea (green area 2) in

West Africa, stretching from Liberia in the West to Cameroon next to the Congo Basin. This area too is given over to massive tree-crop plantations.

As one moves poleward (meaning towards the North pole in the northern hemisphere and towards the South pole in the southern hemisphere), the rainfall diminishes and becomes more seasonal. In general the rainfall is greatest in the summer months (e.g. in May-September in the northern hemisphere, such as Nigeria and Kenya, and September-March in the southern hemisphere, such as Malawi and Tanzania). Instead of growing tree crops, these regions grow annual crops. Maize growing is especially prevalent in East Africa (in purple zone 9). Root crops like cassava are grown in the brown zone 7. As one continues poleward in both hemispheres, the rainy season becomes shorter still. Only short-season crops, well adapted to temporary dry spells, such as sorghum and millet, can safely be grown. These dryland crops are found in the purple zone 11 in both hemispheres. Continue the poleward journey (northward in the northern hemisphere, southward in the southern hemisphere) and one arrives at the arid regions, where the rainfall is too low to grow crops, but just enough to water pasturelands for nomadic livestock. Thus the ecological zone 12 in both hemispheres is home to the pastoralists of Africa, such as the Tuareg and Fulani of West Africa, and the Khoikhoi of Southern Africa. Finally, take one more step poleward and we are in the deserts of the northern Sahara and the southern Kalahari.

Countries naturally straddle several of these zones. A country like Ghana has tree crops in the humid south near the Gulf of Guinea and maize and dryland crops in the north. Mali has irrigated rice in the south and pastoralism in the North. Kenya is a mosaic of farm systems, as is Ethiopia with deserts, pastoralism, lowland and highland crops (crops are graded by elevation as well as by latitude). These distinct ecologies also are home to distinct ethnic, racial, and religious groups, leading to remarkable social and cultural diversity, as well as the potential for clashes, such as the age-old tensions that can arise between sedentary farm communities and migratory nomadic livestock herders.

People living in food-secure, well-watered (and often irrigated) croplands of the temperate regions often have little feel for the complexity of food production and the potential for food insecurity in seasonal tropical environments, especially those of low average rainfall and high vulnerability to drought. When the rains fail in dryland regions, populations may face hunger and may be forced to migrate in desperation, often bringing them into contact with other ethnic groups competing for scarce land and water. The result can be an explosion of violence, as in Darfur, Ethiopia, and Northern Mali. (Ecological tensions are generally one factor among several that give rise to such violence, so complex phenomena such as inter-ethnic violence typically have many drivers, not one factor alone.)

The world has especially failed to grasp the deep crises of the hyper-arid regions, such as the Horn of Africa (including parts of Ethiopia, Kenya, Somalia, and other neighbors) and the Sahel (including parts of Senegal, Mali, Niger, Chad, and others). These are agro-pastoralist regions, or in some cases solely pastoralist regions. They tend to be very poor, utterly dependent on rainfall, and suffering under the burdens of climate change, instability of rainfall, rising populations, falling trends in total precipitation, increasing hunger, and resulting instability and violence. However, the long-term drivers of crisis – including climate change and rising populations – have been too slow-moving to be recognized by most policymakers in Washington, London, and other rich-country capitals. When violence breaks out in these impoverished and vulnerable places, the rich countries have tended to respond with military approaches (e.g. to fight terrorist groups in the Sahel and coastal pirates in Somali) rather than to address the underlying problems of poverty, climate change, and unsustainable population increases (e.g. for lack of access to family planning). The military strategists in Washington or NATO fail to see the human and ecological dimensions of the crises.

III. How Environmental Change Threatens the Food System

Yet the problems are even deeper. Not only are massive numbers of people currently food insecure; farm systems almost everywhere are under tremendous stress, unable to ensure healthy diets and nutrition in economical and sustainable ways to meet the needs of the populations locally and globally.

There are some enormous challenges ahead that will make these problems even tougher than they are now. The most direct of these challenges is the fact that the world's population continues to grow relatively rapidly, even in absolute terms. Every year, another 75 million or so people are added to the world population. By 2025, the world will reach 8 billion people. The current medium-fertility variant of the United Nations puts the world's population at 10.9 billion people by 2100, though the number could be even larger than that. (With a faster fertility decline than in the UN medium variant, the world population would stabilize at perhaps 8-9 billion.)

At the same time that the world will be grappling with the challenge of feeding more people, the current food supply, already under so much stress, is going to be even further stressed by another couple of features. One that I noted earlier is the tendency of countries with rising incomes to add more meat to the diet, amplifying the demand for feedgrains. The second major challenge is the environmental threats that will make it harder to grow food in many places in the world. These environmental threats and changes come in many shapes and forms. Climate change is the biggest of all. As the climate changes in complex ways under the force of human emissions of greenhouse gases, for many parts of the world these changes will be highly adverse for food production.

Higher temperatures in general are going to be harmful for food production in today's warm environments. (The very high latitudes of the world, such as in Canada and Russia, could experience a rise in food productivity as very cold places become a bit less cold.) Especially in the poorest, tropical parts of the world, crops are likely to face temperature-related stresses. At high temperatures, crops may not develop at all, seeds may become infertile, and plant respiration at higher temperatures may mean a net reduction of yields of farm crops. Higher temperatures mean faster evaporation of water in the soils, and more transpiration of water through the stomata of the leaves of plants (the combination of evaporation and transpiration is called evapotranspiration). Climate change threatens the soil moistures, and threatens the productivity of crops as a result.

Warming also will be accompanied by changes in regional and global precipitation patterns. Many parts of the world will become drier, and many dry parts of the world will find it extraordinarily difficult, perhaps impossible, to continue to grow crops. It is a general principle that today's dry places in the tropics and sub-tropics will tend to get drier, while today's wet places closer to the equator will tend to get wetter and with more intense episodes of precipitation. Dryland places that today are on the very edge of crop growing may find themselves in a new climate that is too dry for food production. Wet places may find a great increase of flooding and extreme tropical storms.

Climate change will also mean rising sea levels. Coastal lowlands that are farmed right now will be threatened. Places like Bangladesh, which are on the deltas of the great rivers, may be inundated by floods or even permanently submerged.

In addition to climate change, CO2 emissions are having a direct effect of acidifying the oceans. Ocean acidification has serious implications for another part of our food supply: marine life. Figure 10.13 illustrates the effect on shellfish of increasing acidification (from the top pictures to the bottom pictures in each column). A higher concentration of atmospheric carbon dioxide will lead to greater ocean acidity, which in turn will lead to smaller and damaged shellfish, as the acidity impedes the formation of the calcium carbonate shells. Many highly aquatic environments for marine life will be undermined, with a consequent threat not only to biodiversity but to human nutrition as well.

SHELLFISH GROWN UNDER ALTERNATIVE CONCENTRATIONS OF CO2.

36-DAY OLD HARD CLAM LARVAE ON LEFT, 52-DAY BAY SCALLOP LARVAE ON RIGHT

SOURCE: WASHINGTON STATE BLUE RIBBON PANEL ON OCEAN ACIDIFICATION, 2012

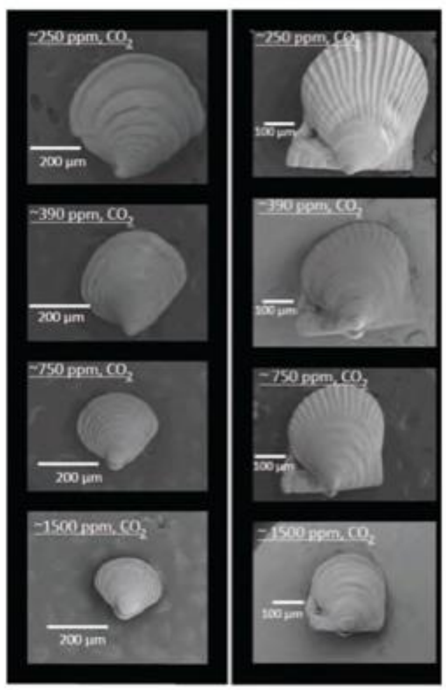


Figure 10.13. Impact of CO2 on Shellfish

In addition to climate change and ocean acidification, many other environmental changes are already degrading farmlands and threatening agricultural productivity. Farmers use large amounts of pesticides and herbicides to grow crops, but these chemicals can poison the soils and the environment, and take a major toll on biodiversity in the farm regions. For example, pollinators like honeybees are vital for crop productivity, e.g. for growing fruits and other kinds of flowering crops. Yet the pollinator populations are plummeting. While the reasons are not clear, and perhaps include several factors, chemical pollutants are likely among the culprits.

Invasive species are another issue. This is when animal or plant species are deliberately or accidently relocated from one environment to another environment, which can derange the entire ecology. The new species might be introduced without any natural predators in the new setting, and therefore its population may run wild and overtake the native species. In this way there may be a rapid overgrowth of new super-weeds, rodents or other kinds of pests and pathogens that overtake the ecosystem where they have newly arrived.

Environmental stress also threatens the world's irrigated lands, which provide a disproportionate amount of the world's grain production. Crop production obviously depends on water availability, both rainfed and irrigated. Irrigation is the farm system of choice for farmers when they can afford it, because it offers the chance of a high degree of water control and even multiple crops during the year (including during the dry season). The problem is that our current global irrigation depends on fresh water sources – rivers, glaciers, and groundwater – that are all under threat from overuse and human-induced climate change. Glaciers are retreating as they melt under the warming climate. This melting can give rise to a temporary increase of river flow and crop production based on that flow. Yet when the glaciers finally disappear, the meltwater flows will swing from excess to zero. The result of the loss of glacier meltwater could prove to be a devastating and dramatic loss of food production.

Many major rivers have been so overused at this point that they are not even flowing to the sea. This, added to the pressures of climate change, will mean less river flow overall. The Nile, which hundreds of millions of people depend on, will most likely have a significant decline of river flow due to climate change. Those who depend on the vital Yellow River in North China are experiencing the consequences of declining river flow and a river that no longer reaches the ocean. So too with the Rio Grande, shared by the US and Mexico and now the cause of deep contention as water supplies are facing grave stresses in the drought-prone regions of Northern Mexico and the Southwestern US.

Groundwater pumping for irrigation, such as in the American Midwest, the Ganges plains, and the North China planes, is now far faster than the natural recharge of those aquifers. The groundwater aquifers are thereby being depleted. The shocking reality is that hundreds of millions of people depend on irrigated crops where the underlying water source – groundwater, rivers, glaciers – are already under tremendous stresses that are very likely to intensify in the future.

Rapid land degradation, soil loss, and depletion of soil nutrients are other results of intensive agriculture, when farms have encroached upon land areas with topographies not really suitable for farms, such as the steep slopes on mountainsides. The consequences are very high. There is likely to be deforestation, the loss of habitat of other species, a significant emission of carbon dioxide into the atmosphere as the forests are cut down and burned, and then the habit of abandoning the farm areas after the farm productivity quickly diminishes.

All of these environmental threats – climate change, ocean acidification, chemical pollutants, invasive species, retreating glaciers, over-abstraction of groundwater and river flows – emphasize the fact that farm systems, more than any other human activity, are dependent on the climate and environments we know and have had for the past centuries. Our food supplies are dependent on the known hydrologic patterns, ocean chemistry, and patterns of biodiversity, all of which are now undergoing enormous and rapid human change. The human pressures on the planet – the Anthropocene – are creating a new world, and it will be a dangerous one from the point of view of food security.

Of course there are possibilities for adaptation and far more efficient resource use. But the current inertia in habits, and the instability, crises and conflicts that result from the collision of nature and our current systems, needs to be addressed. We must realize how big the challenge will be. It has been hard enough feeding the planet – a challenge we have not even met for our current population in today's environment. When we consider the rising populations and the growing environmental stresses, we realize the magnitude of the food challenges that lie ahead.

IV. How the Food System Threatens the Environment

The problem with the food supply is further complicated by the fact that while the food supply is threatened by environmental change, today's agricultural systems are also the single largest source of human-induced environmental change! In other words, the agricultural systems themselves are a source of the threat to future food production. The arrows of causation run in two directions. On the one side is environmental change that threatens food production. Yet at the same time, agriculture as it is currently practiced gravely threatens the natural environment.

The damage of agriculture to the physical environment adds yet another dimension to the challenge of feeding the planet in a sustainable way. Our problem is not only about how to feed more people, and how to feed the growing population more nutritiously than today. It is not only how to maintain farm yields in the face of environmental threats. It is also the challenge of changing current agricultural practices in order to stop inflicting so much environmental damage from the agricultural sector itself. Yet because farm systems differ so much around the world, there will have to be distinctive, localized problem-solving in order to make local farm systems compatible with conservation of ecosystem functions, the preservation of biodiversity, and the reduction of human impacts on the climate system and freshwater supplies.

The agricultural sector is in fact the most important sector from the point of view of human-induced environmental change. Many people imagine the automobile or perhaps coal-fired power plants to be the biggest source of human-made environmental damage. And they are indeed major causes of global environmental unsustainability. Yet it is food production that takes the dubious prize as the most important single driver of environmental harms.

What are the kinds of pressures generated by agriculture? The first is greenhouse gases. The farm sector (including deforestation to make room for new farms and pasturelands) is a major emitter of all three of the major greenhouse gases: carbon dioxide, methane, and nitrous oxide. This means that farm practices will need to be re-designed to help the world move to lower greenhouse gas emissions.

The second major impact is on the nitrogen cycle. Our atmosphere is 79% nitrogen in the form of N_2 (di-nitrogen). That form of nitrogen is inert, odorless, without taste, and not very useful for us. However, nitrogen in the *reactive* forms of nitrates, nitrites, and ammonia is absolutely vital for living species, because nitrogen is the backbone of amino acids and proteins. Reactive nitrogen is absolutely core to our metabolism and to every aspect of our lives, including the ability to grow food. It is for that reason farmers put nitrogen on the soil in the form of chemical-based fertilizers and green manures. The nitrogen is a critical macronutrient for the crops. Nevertheless, the heavy use of nitrogen fertilizers (both green and chemical-based) causes major damage to ecosystems by changing the intensity of nitrogen fluxes in the environment.

The third major way that the farm system impacts the planet is the destruction of habitats for other species. This is not entirely surprising considering that an estimated 40% of the total land area of the planet is agricultural land. Humanity has already grabbed a huge amount of the land area, but it is still grabbing more. It is especially grabbing more in the forest areas, and the rainforests at risk right now are places of incredible and irreplaceable biodiversity. One of the major reasons that the earth is vulnerable to a sixth great extinction wave of species is this process of habitat destruction at human hands.

There are many other ways in which the environment is damaged by farm activity. These include the pesticides (shown in Figure 10.14), herbicides, and other chemicals that are used in farm production and that are a major threat to biodiversity. The overuse of freshwater for crop irrigation is another. Around 70% of the total human use of freshwater goes through agriculture, with only 10% going through household use and the remaining 20% or so for industrial processes. Agriculture is a voracious user of water, and that water itself is under threat.

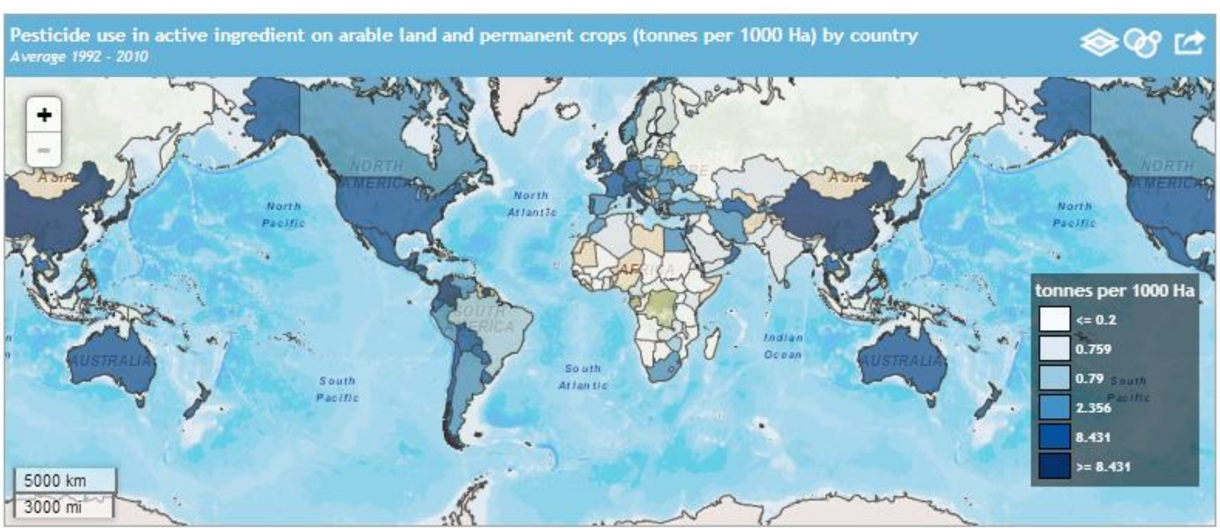


Figure 10.14. Global Pesticide Use (1992-2010 average)

For all of these reasons, the agriculture sector is a key driver of anthropogenic environmental loss. There is a strong need to change farm technologies, processes and patterns of land use to make the food system compatible with a sustainable planet.

The pie chart in Figure 10.15 shows us the estimated total amount of greenhouse gases that are emitted, according to the key sectors of the economy. The power sector, through the burning of coal, oil and gas, is responsible for a massive amount of CO2 emissions and for an estimated 24% of the total greenhouse gas emissions. The transport sector, with the internal combustion engine in automobiles, is responsible for an estimated 14% of total emissions. Industrial processes, such as steel production or petrochemical production, account for around 14% of total greenhouse gas emissions. In total, the direct and indirect use of fossil fuels accounts for around two-thirds of the greenhouse gas emissions.

The non-energy sphere is therefore responsible for around one-third of the total greenhouse gas emissions. These include CO2 emissions, methane, nitrous oxide and chemical pollutants from specific chemicals like hydro-fluorocarbons. Within the broad category of non-energy greenhouse gas emissions, agriculture plays by far the predominant role, both in the direct impacts of farming and the indirect impacts of deforestation and land-use change to make way for farming and livestock management. Of course agriculture also emits CO2 through energy use, for the planting, harvesting, storage, and transport of agricultural products.

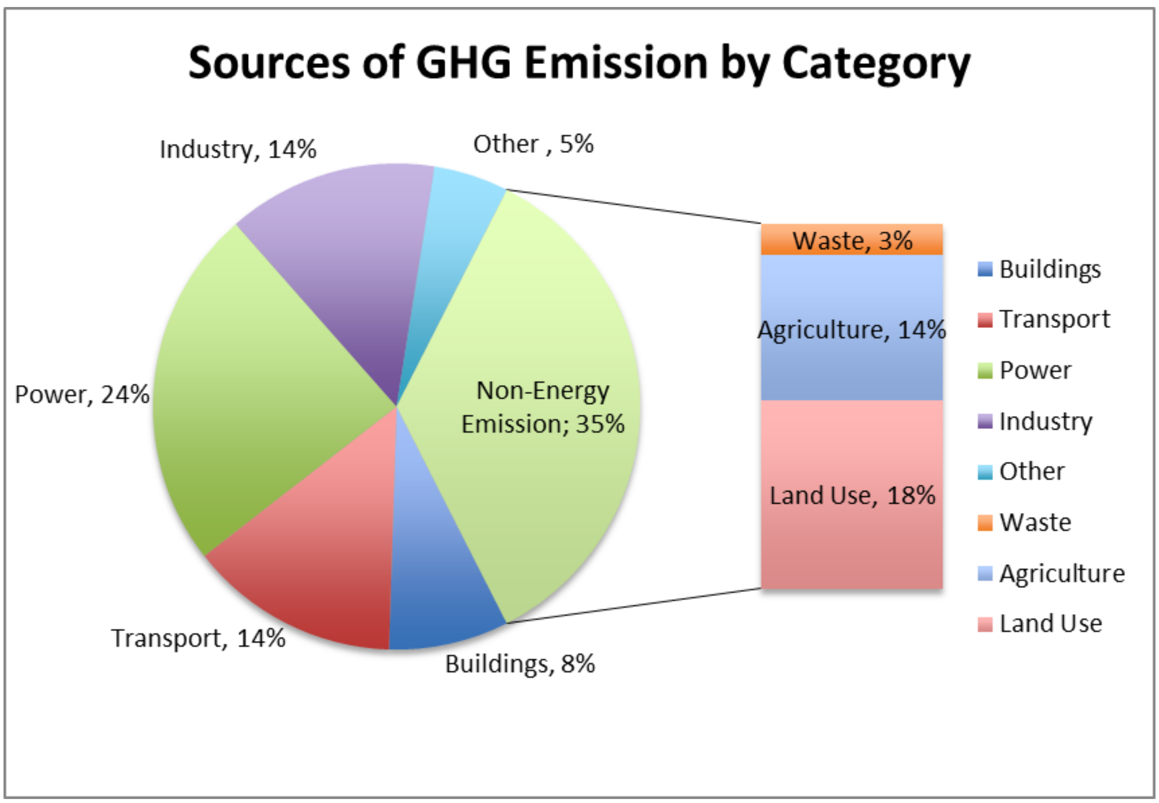


Figure 10.15. Sources of Greenhouse Gas Emissions

Agriculture is a major source of CO2 emissions through land use, but also a major source of the second and third-ranking greenhouse gases. Methane (CH_4) is emitted in the production of certain crops, notably paddy rice, and by livestock, through the natural processes of their digestion. Nitrous oxide (N_2O) is also emitted from agriculture, for example through the chemical changes to nitrogen-based fertilizers. Instead of being taken up by the plants, the nitrogen in the fertilizer volatilizes (evaporates) and also goes into the water supply. Livestock and fertilizer use thereby emit nitrous oxide in large amounts.

Indeed, the natural nitrogen cycle has now been overtaken in quantity by humanity. In nature, the N_2 molecules in the atmosphere are converted into reactive nitrogen through various biological processes of nitrogen-fixing bacteria, as well as by lightning. Yet now humanity is converting more N_2 into reactive nitrogen than even nature itself. Humanity does it through industrial processes that convert atmospheric nitrogen into ammonia and other forms of reactive nitrogen. Back in the early years of the 20th century, two great chemical engineers, Fritz Haber and Carl Bosch, developed a process that some consider to be the 20th century's single most consequential industrial innovation. The Haber-Bosch process is a way, through the application of high amounts of energy and the use of various identified catalysts, to break that N_2 triple bond and create ammonia in a large-scale industrial process. This ammonia can then be used to provide the base stock for urea and other nitrogen-based fertilizers. This process, developed between 1908 and 1912, solved the scarcity problem of nitrogen nutrients needed to increase global food production. Up until the Haber-Bosch process, nitrogen deposited on soils came either from the manures of farm animals or from the mining of bird and bat excrement (guano), largely off the coasts of Peru and Chile. But those guano deposits were being quickly depleted, and there was a nitrogen crisis developing at the end of the 19th century. Along came the Haber-Bosch industrial process, which spurred production of nitrogen-based fertilizer. What was then a world population of fewer than 2 billion people could thereby become a population of more than 7 billion people one century later.

It was the advent of nitrogen-based fertilizer, along with high-yield seed varieties of the Green Revolution and other agronomic advances, that made it possible to produce enough food to support 7.2 billion people (recognizing that a large number of those 7.2 billion are not well nourished!). Yet, with all that nitrogen now being converted from N_2 into reactive nitrogen, there is a huge problem, shown the complicated flow chart in Figure 10.16. What happens to that all that chemical nitrogen when it is used in the farms? It runs off into the water supplies, and volatilizes into the air, to be carried by the winds to land and water downwind. When reactive nitrogen enters the water supply as nitrates, it creates major dangers to the water supply and ecology. Some of the reactive nitrogen runs into the rivers and the sea, which leads to algal blooms and nitrification in downstream estuaries. Some of it enters the atmosphere, not as N_2, but as N_2O, nitrous oxide, a greenhouse gas. Some of it enters the atmosphere not as N_2O, but as NO_2 (nitrogen dioxide), which causes smog and local pollution.

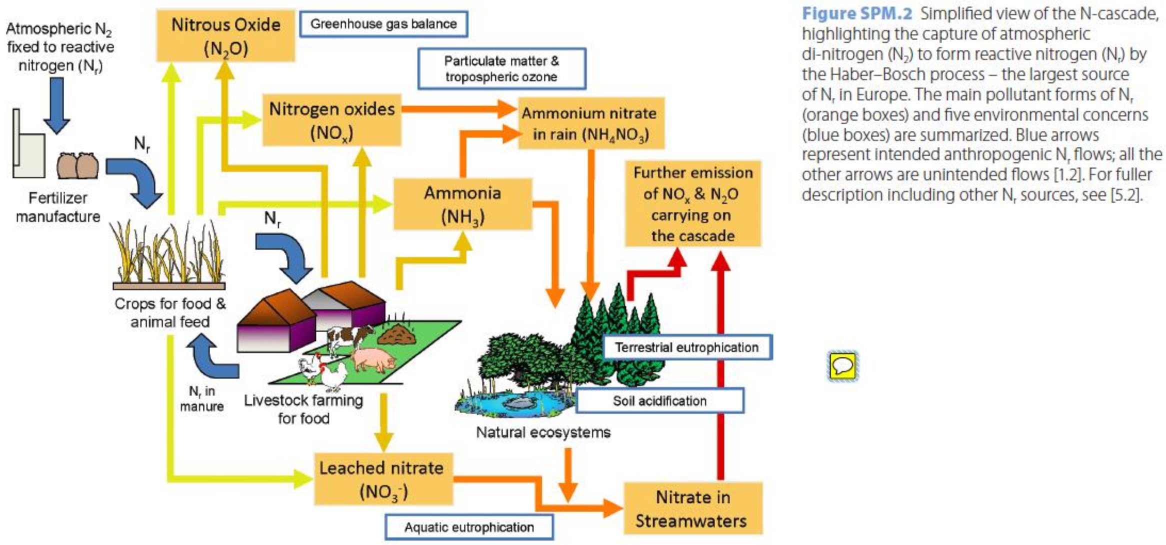


Figure 10.16. The Nitrogen Cascade

The graphic from a European Union study in Figure 10.17 shows the host of problems arising from the heavy use of fertilizers: there are more greenhouse gases released; soil acidification; threats to water quality from nitrates and the nitrites in the water supply; the eutrophication of the downstream estuaries; and the fall of air quality as the NO_2, NO_3, and other nitrogen-based molecules enter the urban atmosphere to create smog, tropospheric ozone, and massive health hazards in our cities.

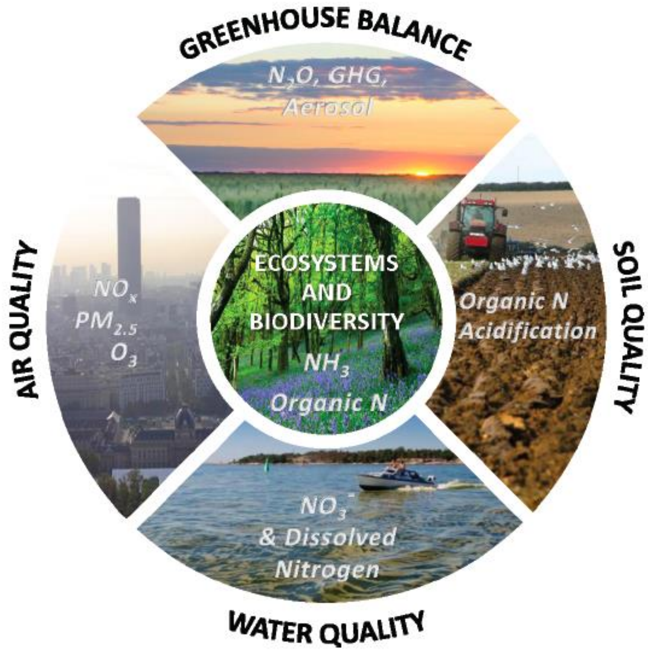


Figure SPM.7 Summary of the five key societal threats of excess reactive nitrogen, drawn in analogy to the 'elements' of classical Greek cosmology. The main chemical forms associated with each threat are shown [5.4]. *Photo sources*: Shutterstock.com and garysmithphotography.co.uk.

Figure 10.17. Key Threats of Excess Nitrogen

Here then is a major dilemma that is rarely discussed in our day-to-day life. We absolutely need the nitrogen including the chemical fertilizers for our global food production, and yet the multiple negative impacts of nitrogen on the physical environment, from climate change to eutrophication to urban smog, are serious and growing. The map in Figure 10.18 comes from a study showing estuaries around the world suffering from eutrophication, particularly from nitrogen and phosphorous-based fertilizers off the coasts of the economies with high rates of fertilizer use. The zones in red are "dead zones" in the coastal areas, where eutrophication (excess nutrient loading) has been followed by algal blooms and then by the bacterial decomposition of the algae leading to the depletion of oxygen in the water and a killing off of marine life. The problem is growing and is likely get worse unless we address how to use the needed nitrogen in a more responsible way, for example through far more precision use of chemical fertilizers to reduce the runoff and volatilization of the reactive nitrogen.

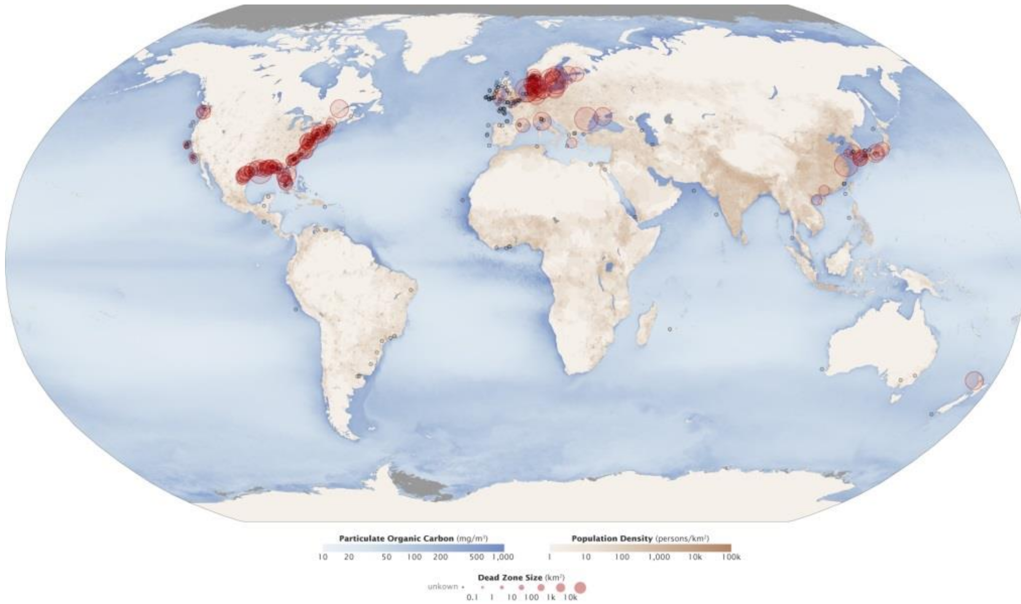


Figure 10.18. Marine Dead Zones

Another key area of heavy agricultural impacts is on the forests. Forest loss is occurring in all of the great rainforest regions, including the Amazon, the Congo Basin, and the Indonesian archipelago. In the Amazon, the clearing of the rainforest to make way for new pastureland, farmland, and construction of infrastructure accounts for most of the deforestation. Fortunately, there has been some reduction of Amazon deforestation in recent years. In Southeast Asia, tropical hardwoods are in huge demand for the booming economies of Asia, especially China. Logging and clearing of the rainforests to grow tree crop plantations also account for a major part of the destruction of original rainforest.

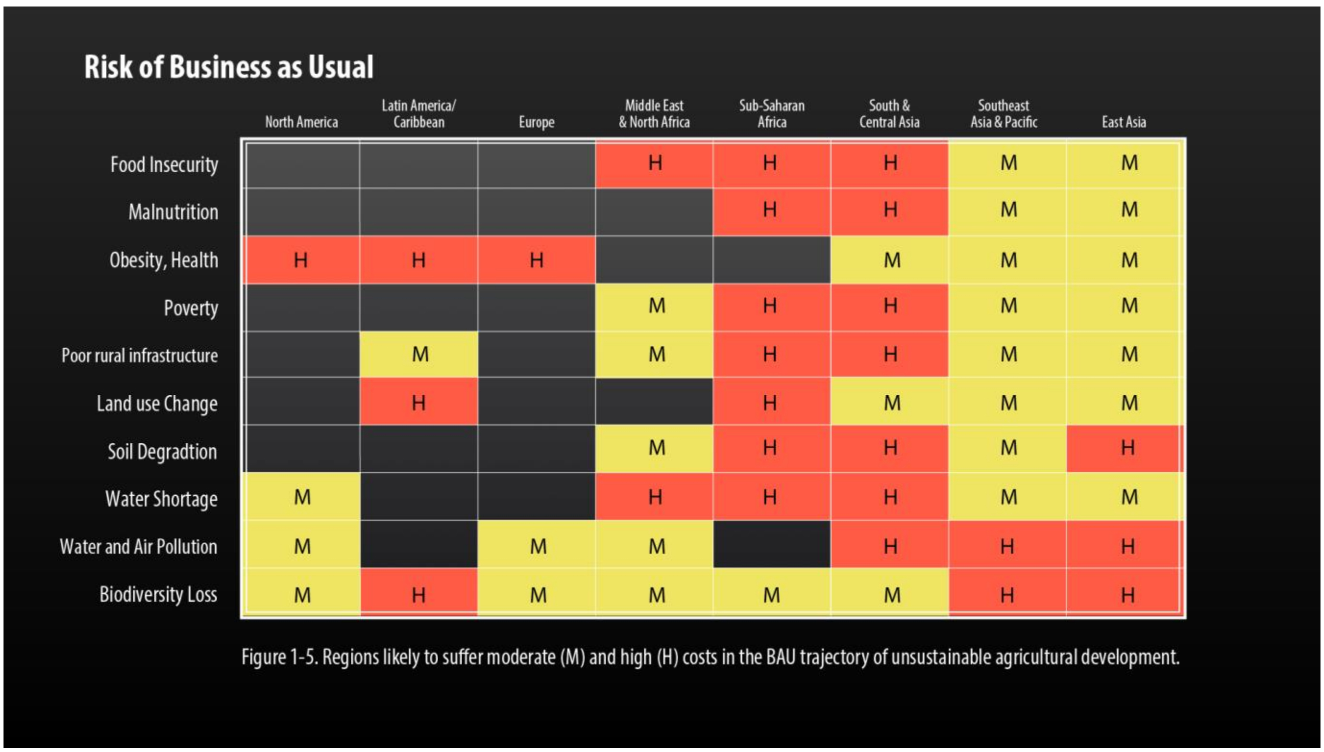
In Africa, there is yet another driver: peasant smallholder agriculture. This is not for large-scale clearing for logging, but the spread of smallholder farmers into the forest margin. Often there is significant deforestation from the use of the forest for fuel wood (e.g. to make charcoal). In the wealthier rainforest regions of the Amazon and Southeast Asia, the fuel wood problem is typically not as severe because there are alternative energy sources. But in the Congo Basin and other forest areas of Africa where populations are very poor and alternative fuel sources are not available, charcoal is used in such large amounts that it is an important driver of the deforestation and habitat loss of other species.

Clearly in each of these areas, in order to preserve habitat, protect biodiversity, and reduce the greenhouse gas emission consequences of deforestation, actions need to be introduced that are responsive to the particular challenges in those areas and the particular needs of the local populations. This will not only play an enormously important role in helping to reduce the rate of climate change, but will also be absolutely vital if we are to succeed in heading off the massive loss of biodiversity.

V. Towards a Sustainable Global Food Supply

Creating a sustainable farm system around the world is absolutely vital. The farm system must simultaneously feed a growing world population and reduce the tremendous pressures that our current systems are placing on the earth's key ecosystems. And the farm systems need to be made more resilient to climate change and other environmental changes that are already underway. We need to think about what will happen if we continue with business as usual, and contrast that with what we really need to do, which is reshape our own behavior with regards to food. We must reshape farm systems and create an alternative trajectory of sustainable development.

What are the threats of the business as usual path? The chart in Figure 10.19 attempts to summarize those risks and give an expert assessment of how serious the particular risks are in particular regions of the world. The boxes that are shaded red are major alerts – these are places in the world where the challenges are of the first order of significance. The boxes that are yellow are like yellow warning signs; things could get bad in these areas with regard to these particular threats.



	North America	Latin America/ Caribbean	Europe	Middle East & North Africa	Sub-Saharan Africa	South & Central Asia	Southeast Asia & Pacific	East Asia
Food Insecurity				H	H	H	M	M
Malnutrition					H	H	M	M
Obesity, Health	H	H	H			M	M	M
Poverty				M	H	H	M	M
Poor rural infrastructure		M		M	H	H	M	M
Land use Change		H			H	M	M	M
Soil Degradtion				M	H	H	M	H
Water Shortage	M			H	H	H	M	M
Water and Air Pollution	M		M	M		H	H	H
Biodiversity Loss	M	H	M	M	M	M	H	H

Figure 10.19. The Risks of Business as Usual

Business as usual will mean increasing food insecurity in some parts of the world. The places at greatest threat are sub-Saharan Africa and South Asia, the two epicenters of under-nutrition. But one should also note the rising to North Africa and the Middle East, because these are places where all of the climate evidence suggests there will be significant drying in the future, and therefore crop production will be under even greater threat than it is today.

Certainly the business as usual course also means considerable dangers for East Asia and Southeast Asia, because these regions will be places of tremendous water stress, and places where higher temperatures will wreak havoc on the food supply. Malnutrition from deep under-nourishment will continue to have its epicenter in sub-Saharan Africa and South Asia. On a business as usual path the other kind of malnutrition, obesity, is likely to worsen in North America and many parts of Latin America. It is already at epidemic proportions in Mexico. There are serious risks in Southeast Asia, East Asia, India and in other parts of South Asia as well.

Land use change will have huge costs, especially in the rainforest regions. That means costs in Latin America, sub-Saharan Africa, and parts of Southeast Asia. Soil degradation is already a major crisis in parts of sub-Saharan Africa and South and East Asia, where the land has already eroded. The soils often have been swept away due to farmers trying to grow crops on steep slopes or in places where the winds blow the topsoil away, as is occurring in many parts of China. Biodiversity loss is also a moderately or acutely high threat in every region of the world.

While there are a few regions that escape some of these risks, there are no regions that will escape all of them. Today's poor regions are at extreme peril because they are already living on the edge. They already have people living in fragile environments, such as in tropical or dryland ecosystems. Part of their poverty has come from the fact that the natural environment is already fairly inhospitable. With environmental change, what is currently a difficult environment can quickly become an impossible environment to support human life. When that happens, people will suffer, die, have conflict, and migrate. There will be environmental refugees created by the millions, possibly even hundreds of millions. In a world not often open to migration, poor newcomers forced to move can face a very hostile environment when they arrive. We are in for a lot of trouble if we maintain the business as usual trajectory.

How do we move to a sustainable development trajectory? Because of the complexity of the food system, and the inter-linkages of land use, nitrogen use and chemical pollutants, and the vulnerability of crops to higher temperatures, the kinds of responses that are needed will have to be varied, holistic in nature, and carefully tailored to local contexts. This is among the toughest sustainable development challenges that we face, because the world is in crisis and the problems will tend to get worse. It is not easy to say that one region will bail out the others, because all regions will have stresses. There will be no magic key that will suddenly make it possible to solve this problem. Each region is going to have to identify its own pathways to sustainable agriculture.

What are some of the things that can be done? The first is to improve the ability to grow food. We should be more productive in terms of higher yields per unit of land area, and more resilient in terms of the ability of food crops to withstand the shocks that we know are already coming. Just as Norman Borlaug and his colleagues M.S. Swaminathan and Minister Subramaniam made the Indian Green Revolution possible, we are going to need another Green Revolution of new crop varieties that will be especially propitious for the environmental challenges ahead.

For some regions this will mean a special importance of drought-resistant varieties because the frequency of serious droughts is likely to become much higher. Certain plants in nature have a high level of drought tolerance. Plant scientists are now attempting to identify those genes and through various means, both conventional plant breeding or advanced genetic modification, to create new crop varieties that also share drought resistance. Natural breeding techniques have already helped to develop new seed varieties that are better able to withstand bouts of low rainfall during the growing season. Genetically modified organisms (GMOs), or GMO crops, have taken the experimental pathway of identifying the gene complexes in naturally occurring drought-tolerant plants and transplanting those gene complexes into crops.

Many people find this idea of genetic modification to be very threatening, risky to the environment and potentially to human health. Whatever is done in this research domain of cutting-edge genomics needs to be tightly monitored and regulated, but I would argue that we should certainly test these technologies to see what they have to offer. It seems very promising that by identifying genes for drought resistance or saline tolerance we can get major advances in food security. We should therefore not dismiss a whole class of technology so quickly. While GMO technologies may pose certain risks, those risks are likely to be controllable and monitorable. The underlying technology itself may offer huge breakthroughs in food security in an age where we will need such breakthroughs.

The second step of what can be done is to make crop varieties more nutritious. Crops should not only grow better in harsh conditions, but also be more nutritious in content. Of course part of an improved diet involves choosing the right crops in the first place, with a well-balanced diet with fruits, vegetables, whole grains, and plant oils. Part of the solution is to make a particular crop (e.g. rice) more nutritious. This is the idea of the so-called “golden rice,” a crop that has been developed by the International Rice Research Institute (IRRI) in Los Baños, Philippines. IRRI helped bring about the Green Revolution in rice. Now its scientists are re-engineering the rice genome to express beta carotene, a precursor for vitamin A, so that children who eat the golden rice will have the vitamin A that they need, helping to combat one of the key kinds of hidden hunger.

The third direction is absolutely essential, and is known as “precision farming” or “information-rich farming.” Such precision farming is already in widespread use in high-income countries. The point of precision farming is to economize on the use of water, nitrogen, and other inputs into production, so that more food can be produced with less environmental impact. In the coming years with the declining costs of information technology, poor farmers will use these techniques too. Precision farming involves, for example, a more precise application of fertilizer, so that there is less volatilization and runoff of fertilizer not taken up by the crops themselves.

Precision agriculture depends on information technologies, on detailed mapping of soil types, and often on global positioning systems (GPS) that can tell a farmer exactly where that farmer is in the field and what is happening in the soil in that part of the farm. This kind of precision farming is on its way to the middle-income and poor countries, and it continues to be developed at lower costs. It is very promising because it efficiently uses scarce resources and enables farmers to cut down significantly on the amount of fertilizer applied on the soil. Farmers can then economize, make a better income, not waste as many resources, and decrease their environmental impact.

More generally, better nutrient management can occur through better soil testing, soil mapping, and localized chemistry. Reading the qualities of the soil on hand-held devices or from satellites makes it possible to get far more detailed resolutions of soil needs. This kind of soil nutrient management offers places with soil nutrient depletion a massive potential boost in yields. Africa is the first in line for this yield boost. It also offers places that use far too much fertilizer, such as China, to cut down very sharply on their fertilizer use.

Another breakthrough ahead lies in improved water management. We need to apply less water to get more "crop per drop," because we are already depleting the scarce water we have and because the water challenges will get tougher in the future. That is not only because of water depletion but also the consequences of climate change. Solar-powered irrigation can play a very important role in micro-irrigation technologies, especially to help smallholder farmers.

Another major breakthrough that offers us a tremendous opportunity will be better harvesting, storage, and transport of crops to avoid the very large losses of foodstuffs that now occur from farm to plate. Such food waste is often estimated to be around 30-40% of total food production. These large losses come from rodents and pests, food rotting, the physical loss of the crops, exposure to rain, and so forth. Simple, low-cost means of more effective storage systems, better incentive systems for food handling, and the empowerment of local farmer cooperatives to invest in community-based storage facilities, offer a tremendous hope for reducing losses in the agriculture value chain in low-income, hungry settings. These improvements will not only lead to large gains in farm incomes, and more food security, but also to less human pressures on the environment.

Better business models for poor smallholder farmers are vital, not only for ending extreme poverty, but also for empowering smallholders to make investments in improved crop varieties, irrigation, water management, and storage, all to raise farm yields and incomes. There are gains to be achieved through the aggregation of smallholders into farmer cooperatives and farmer-based organizations. These new business models can improve value chains and incomes.

Finally, we have to take responsibility ourselves for our personal health and for the way we approach the issues of food as individuals. Massive epidemics of obesity show that something is seriously wrong with prevailing diets. A lot of the problem comes from the fact that our governments have subsidized the wrong kinds of foods. Carbohydrates, trans fats and other kinds of fast foods that are absolutely unhealthy are heavily subsidized and widely consumed. Our economic incentives have often been aligned against the very kinds of foods that are better for our health. We have subsidized, in effect, the feed grains that have led to massive over-consumption of beef in the United States and Europe, to the point where so much meat is eaten that it is detrimental to human health and is exceedingly damaging for the environment. Deploying 10 or 15 kilograms of feed grain for every kilogram of beef that is consumed tremendously multiplies the burdens on the land, on fertilizer use, and on water supplies, which aggravates all of the natural problems.

We are also aggravating these problems more recently by diverting invaluable food production into the gas tank! In the United States, through unjustified subsidies driven more by politics than by any common sense or ecological insight, the US Government has turned a significant part of the annual corn (maize) production into ethanol for automobiles. This is a miserable deal because of the amount of vital resources needed to produce that ethanol. The maize-to-ethanol strategy creates no savings for the natural environment, and diverts a tremendous amount of food production away from the food chain. These subsidies thereby push up food prices and place extra pressures on the natural environment. All this is being done at the behest of a few powerful companies with powerful lobbies in Washington (and comparably in European capitals). This is an example of where behavior and policy have gone awry.

The conclusion is as we have noted time and again. The pathway to sustainable development involves behavior change, public awareness, political and individual responsibility, and the mobilization of new systems and technologies that can dramatically reduce the pressures on the natural environment, and help make our economy and way of life more resilient to the environmental changes already underway. Sustainable agriculture and food security remains a huge unsolved, yet solvable, problem. It is one of the areas that will require the most intensive problem solving at local levels all around the world. For these reasons, sustainable food systems and the fight against hunger will have a major place in the Sustainable Development Goals that lie ahead.