Chapter 15
Food and Energy

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Abstract There is nothing more critical to human existence than food. While a proper climate and water are arguably as important as food, they are usually present, but food shortages from population expansion, climatic extremes, conflict, and concentration of output in the hands of the powerful are a nearly constant characteristic of one part or another of the world's human population for as far back as we have records—and probably far before that. For example, huge famines occurred in China in the sixth and twentieth century AD, and many centuries in between, most of Europe in the fifteenth century, Ireland in the middle of the nineteenth century, Bosnia, Philippines, and Sudan during this past century and countless other locations all over the world. But we in most of the developed world live today in a situation of incredible food affluence, and famine seems to have left much of the world except for areas of political-military conflict. How has this come to be? The most general answer is the application of fossil fuel technology and its ancillary technologies, most notably the production of nitrogen fertilizer and substitution of mechanical work for human and draft animal labor, to food plant production. This has allowed an enormous expansion of food production and has allowed us to think about food from many other perspectives, including aesthetic, moral and political. We examine human food production over millennia with a particular focus on energy: the quantity and quality of the energy of the food and also of the energy required to produce it.

15.1 Introduction: Food as a Global Issue

For most of humanity's existence, extreme hunger and starvation have been constant companions. There are records of millions of people starving in China, India, Egypt, Russia, and elsewhere, as recently as the twentieth century. In many smaller

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nations and city-states, starvation has occurred periodically since human settlement began. Today, however, mass starvation is rare. There are two general ways to view this reduction in food shortage: from the “BigAg” perspective, which consists of industrial food producers, synthetic pesticide and fertilizer developers, and large food corporations, or, in the alternative, from the perspective of concerned consumers, environmental conservationists, and sustainability advocates.

From BigAg’s one-sided point of view, the collective ability of today’s farmers to meet—for the most part—the food demand of some seven billion people is allegedly a triumph of technological advances and human ingenuity. Artificial fertilizers, pesticides, novel cropping methods, and bioengineering have seemingly tripled yields of staple and commodity crops in the past half-century. This increase has increased per capita food availability by about 25 % from the 1960s to 2009[1]—despite the fact that these statistics play out differently around the world. Although agricultural output has increased during a period when the total area in farms has decreased[2] and per capita wheat, rice, and coarse grain production has risen over the last decade in all regions except Oceania (Australia and the South Pacific), food shortages continue to persist in many parts of the world. Despite this, the United Nations Millennium Development Goal to halve the proportion of the population that is chronically hungry and malnourished by 2015 may be within reach.[3] But the same advances that are publicized as agricultural breakthroughs are also the culprits of many challenges of the modern food system. The fact that anyone remains hungry in 2016 is more a consequence of resource distribution, politics, and a preference for higher animal protein diets and a high level of wastage in the food distribution, peparation and disposal systems, rather than intrinsic limits to agricultural production. Therefore, the alleged limits of agricultural production need not be resolved through biotechnology and synthetic pesticides or fertilizers alone. Instead, policy changes and a careful look at resource use and distribution may yield much more promising solutions.

From a biophysical and ecological perspective, however, modern farming has become increasingly unsustainable and is pushing the planetary boundaries. Perhaps most importantly, each kilogram of food produced through industrial agriculture is less and less a function of sunlight, soil, water, and labor inputs, as it should naturally be; instead, it is the product of fossil fuel inputs, chemicals, and biotechnology. These fossil fuel inputs can be either direct, in the form of diesel to run tractors, or electricity to pump irrigation water; or indirect, through petrochemical fertilizers and pesticides, as well as energy embodied in farm machinery and other infrastructure. Because of this dependence on petroleum, access to food markets, along with the price of food, is tied directly to changes in energy prices—especially oil.[4] Thus, the question “will we be able to produce enough food to meet the

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[1] Food and Agriculture Organization (2013), p. 124.

[2] Food and Agriculture Organization (2013), p. 124.

[3] Food and Agriculture Organization (2013), p. 67.

[4] Baffes and Dennis (2013), p. 2.

demands of a growing and urbanizing population?" becomes, instead, a question of whether humanity will be able to continue to find and extract increasing amounts of oil and natural gas at a low cost.

The paradigm shift of asking another question entirely alters our view of the food production system. Furthermore, other issues associated with this heavy industrialization include growing pest resistance to pesticides, fertilizer saturation, soil depletion and toxification, and reduction of cultivar diversity and crop ecosystems. The collective long-term effects of the "new conventional" farming system, relying on oil, biotechnology, and industrialization of food production are difficult to predict but allude to a dangerous future. Rapid urbanization has changed how we produce and consume food. Since more than half of people around the world live in urban areas, humanity's dependence on petroleum for transporting food has increased. As cities grow, some of the most fertile land is being paved over with impermeable surfaces and is no longer available for food production. Moreover, as people move increasingly from rural areas to cities, their diets change. Greater income usually leads to higher protein demand and the transition to a more "global" diet that eschews locally produced food for cheaper, more processed imports and higher amounts of dairy, eggs, and meat. China, for example, has seen a four to tenfold increase in meat and milk consumption from 1980 through the 2000s.[5] The production of dairy and meat products is much less efficient than for staple grains such as rice and wheat. In fact, the former requires a much larger energy input for the amount of food produced, and this increases pressure to expand agricultural output. Consequently, rapid urbanization contributes to starvation and malnutrition when energy-intensive farming is the method of producing food.

15.1.1 Starvation and Malnutrition

The most important requirement for food production is to sustain our growing population. Large-scale starvation, while once common, is now relatively rare due to improved efficiencies in transporting food from areas of abundance to scarcity. This approach has historical precedence: for example, while starvation once occurred frequently in India, the completion of the national railroad system essentially eliminated the problem in the 1880s. Starvation still occurs in contemporary societies, but it tends to be linked to war, political instability, or strife rather than actual crop failure.[6] In other words, the planet can produce enough food to avoid human starvation, but it is not always distributed to where it is needed. This contradicting relationship is due to the industrialization of agriculture (and warfare) and increased urbanization.

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[5] Food and Agriculture Organization (2009), p. 11.

[6] See Riley (1993); Devereux (2007).

Malnutrition, as opposed to starvation, is much more common and pervasive than starvation. Malnutrition, occurs when there is enough food, but not enough of the kinds that humans require to be healthy. Most fundamentally, malnutrition occurs when there are enough calories to survive, but not enough calories or nutrients for the body to do all the functions required for optimum well-being. A secondary issue to malnutrition is lack of protein: in general, plant—and especially animal—protein tends to be more expensive, both monetarily and energetically, than carbohydrates. This is because, ultimately, it is much more expensive for plants or humans to fix (take out of the air) nitrogen than carbon.[7] Paradoxically, a portion of the population in developed nations are over-fed and malnourished, with many people consuming up to 3700 kcal in protein-rich diets that lack sufficient potassium, calcium and vitamin D.[8] Thus, malnutrition can occur even when obesity becomes a problem. Thus, the sociological and environmental shifts must be considered in examining the problems of food security.

15.1.2 Food and the Environment

It is easy to look upon agroecosystems and see green, sustainable environments in harmony with nature; indeed, that is how they are often portrayed in the popular press. Yet at the most basic level, agriculture and the natural environment are intrinsically at odds. The very purpose of agriculture is to redirect the land's energy flow from diverse, sustainable ecosystems to simplified monocultures that require continual inputs of human and fossil energy to maintain their highly productive state. Natural ecosystems, on the other hand, usually maintain or build soils, are in carbon balance with the atmosphere, and retain nutrients. Agroecosystems, in contrast, typically lose soil and nutrients while adding carbon to the atmosphere. Depending upon local geography and cultural practices, agriculture also has a detrimental impact on water, air and soil quality: fresh and salt water bodies become eutrophied by excessive nutrients from farmland runoff; changes in land use increase greenhouse gas emissions; livestock and crop production contribute to global climate change; and tilling, fertilizers, and pest control lead to soil erosion and degradation.

Industrial agriculture also disrupts traditional farming systems that have developed over millennia and are tied to local environmental conditions and social structures. Perhaps most significantly, erosion from industrial agriculture is reducing our one-time allotment of arable soils.[9] Net soil losses under industrial farming are one to two orders of magnitude greater than soil production or erosion under

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[7] On the most basic level, nitrogen fixation is required for the production of plant protein, while carbon fixation is part of the process of producing sugars and other carbohydrates.

[8] United States Department of Agriculture (2010), p. 8.

[9] Pimentel (2006).

native vegetation.[10] Excess fertilizers enter fresh water bodies and eventually end up in the ocean, leading to eutrophication and disruption of biogeochemical nutrient systems. These ecological impacts have energy costs, too, as nutrient-poor soils require increasing inputs of energy-intensive fertilizers. They also disrupt fresh and salt-water fisheries, leading trawlers to fish more intensively in order to maintain catch levels.

The water required to produce various food and forage crops ranges from 500 to 2000 liters (L) per kilogram of crop produced. A hectare of US corn, for instance, transpires more than 5 million L of water during the 3-month growing season. If irrigation is required, more than 10 million L of water must be applied to this crop.[11] It is possible that water, as opposed to energy, will limit agriculture in the future. Agriculture places enormous demands on global water resources, and climate change may further alter the distribution and amount of precipitation received in the current arable lands. Today, however, energy is still a limiting factor of production: water-pumping infrastructure and desalinization, for example, require significant energy inputs. Nonetheless, it is beyond the scope of this chapter to examine the potential impacts of climate change on agricultural production, other than to say that they are large, controversial, and act to increase some crops while decreasing others.

15.1.3 The Politics of Food

Since the agricultural revolution, higher incomes and social statuses have been linked to a higher quality and higher calorie diet. As nations become economically wealthier, their diets—and especially those of their richest populations—become much more protein-dense. Consequently, these diets became more energy intensive to produce. Still, while relatively affluent middle class Chinese urbanites dine on pork, or American workers lunch on hamburgers from the drive-thru window, countless poorer people around the world subsist on rice or sorghum mixed with a few scraps of vegetables. The evolution of agriculture has not brought positive impacts to the global population across the planet and continues to show discrepancies in terms of food safety and food security world-wide.

That this inequity in access to high-quality foods persists would likely surprise few readers. The world's poor, however, also face disproportionate environmental impacts from the shift to a "Western" diet by a growing middle class. Subsistence farmers in tropical nations, for example, have been forced from their traditional lands and their customary agricultural practices (such as *swidden*, or "slash and burn" farming). These techniques are replaced by large monocrop systems with outputs destined for export, such as soybean farming in Brazil.

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[10] Montgomery (2007), p. 13268.

[11] Pimentel and Pimentel (2003), p. 660S.

The replacement of traditional century-old farming practices with intensive crop-monocultures is driven by economic incentives. During the 1980s, international financial institutions implemented neoliberal policies in the global south to provide development loans. However, their policies also eliminated trade barriers and flooded local markets with cheap, subsidized grains from the U.S. and Canada, which destabilized local production systems.[12] Many developing nations continue to rely on agricultural exports to generate income in order to run their economies and pay the interest on longstanding development loans. All of this has implications for each nation's food security and self-sufficiency.

Fad diets and changes in taste in Western countries also affect distant ecosystems and cultures. A recent example of this is the introduction of quinoa as a high-status food and healthy substitute for processed grains in the United States. Traditionally consumed as a staple food in Peru and Bolivia, Americans now import nearly 68 million pounds of quinoa per year.[13] Some scholars consider this an economic boon to poor farmers in the region who now have access to lucrative health food markets in the U.S. Yet others decry the disruption to local markets and the inability of the local poor to afford this once ubiquitous crop–the price of which has increased sevenfold from 2012 to 2014.[14] While the debate continues over costs and benefits to local farmers in Peru and Bolivia, it is clear that voluntary (or perhaps marketing-influenced) changes in Western diets have real implications for the diets and economies of far-flung cultures.

15.1.4 The Morality of Diet

What, then, should a moral person eat? Worldwide, an estimated two billion people live primarily on a meat-based diet, while an estimated four billion live primarily on a plant-based diet.[15] For some, this is a purely economic decision: they would consume meat if it were available and affordable. Yet, for others, the decision to eschew meat stems from religious, cultural, or moral beliefs. About one third or more of the 1.2 billion people living in India exist on a vegetarian diet. Another tenth of the population eats only grains, vegetables and some eggs. Certainly, there are also millions of relatively affluent people who are vegetarian for moral and environmental reasons, such as a desire to reduce resource consumption or concern about the welfare of animals raised for food. Other considerations for a moral diet include: the environmental impacts of food production (including, but not limited

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[12] See, e.g. Costa Rica as described in Hall et al. (2000).

[13] Washington Post (2013).

[14] World Bank (2014).

[15] World Bank (2014).

to, greenhouse gas emissions, eutrophication, and pollution of water bodies); health impacts to humans, such as antibiotic resistance in bacteria; the often cruel treatment of livestock; the wages paid to farmers for their labor; and the protection of non-renewable and renewable resources, such as soil erosion.

The decision about what to eat is ultimately complex and nuanced; the growing global population, resource constraints—especially from peak petroleum production—and the increasing inability of the ecosphere to assimilate the wastes from our economy all complicate this process. Notably, however, the number of children one chooses to have, and at what age, may impact the food production system far more than what foods one decides to eat for a multitude of reasons explained hereinafter. Throughout this chapter, the goal is to educate the reader on the relation between fossil and natural energies and the contemporary food system, and provide insight for those looking to reduce the energy impact—and greenhouse gas emissions–of their diet. Ultimately, the morality of diet lies within one's food choices and the large-scale consequences of the accumulation of an individual's dietary decisions on the market and the planet. In other words, this chapter provides an outline that connects food choices with one's environmental footprint.

15.2 Food as Energy

Human bodies are, at their essence, biological machines. To operate well, these machines require daily inputs of water, fuel, and the essential chemical compounds that they cannot synthesize alone. Thus, whether one is rich or poor, the "work" one must do each day requires securing sufficient resources of fuel (food energy), water, and nutrients. Government agencies, intergovernmental organizations (such as, the United Nations), and non-governmental organizations (NGOs) research and provide suggestions about the amount and variety of food that humans should consume to meet dietary needs. These usually take the form of recommended daily allowances of calories,[16] along with macro- and micro-nutrients. They can also be presented as informal food-based dietary guidelines, such as "eat a variety of fruits and vegetables each day." It is telling that in our age of relative abundance, these guidelines often *warn* against overconsumption of calories,[17] rather than providing minimal daily energy consumption requirements. This oddity, especially in light of the problems associated with starvation and malnutrition, seem illogical. However, upon deeper reflection about the connections between the current food industry and the rising numbers of malnutrition, the links fall into place.

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[16] Measured in kcal, where 1 kcal = 4.184 kJ.

[17] United States Department of Agriculture (2010), p. 8.

15.2.1 How Food Is Measured

Macronutrients provide the bulk energy content of food. These chemical compounds are grouped into three major classes: carbohydrates, proteins (and their amino acid components), and fats. The total combustible energy in food can be measured by using bomb calorimetry. Simply put, the food is combusted in a chamber full of oxygen submerged in a known volume of water, and the resulting increase in water temperature is measured. Although there are slight differences in the amount of energy per unit of mass for different compounds, it is generally accepted that 1 g of carbohydrates or protein contains about 4 kcal, while fats contain about 9 kcal of available energy. However, not all of the ingested chemical energy in food is available to the body. Insoluble fiber, for example, is combustible, but it passes through the digestive tract without being metabolized. More complex adjustments must be made to bomb calorimetry results to determine the energy available to humans in foodstuffs.[18]

The unit of energy typically used to measure the available energy in food is the kilocalorie. A calorie is defined as the amount of heat needed to raise 1 g of water by 1 °C at 15 °C. A kilocalorie is 1000 cal. One kilocalorie (kcal, dry weight) is equivalent to approximately four BTU, or 4.18 kJ (10^3 J—note Joules are the SI standards for energy and should be used for ALL energy calculations and representation, but calories are entrenched for food). A British Thermal Unit (BTU) is approximately equivalent to the energy found in the tip of a matchstick. Thus the digestion of each kcal of food liberates the energy contained in four matchsticks. There are usually about 4 to 9 kcal per (dry) gram of food, or 112–255 kcal per ounce, with the lower values characteristic of carbohydrates and proteins, and the higher values of fats. Using these metrics, a person needs roughly half to 1 kg of food per day, including food wasted. Thus, in a deeply simplified model, the planet must produce nearly 1 kg of food for per person per day. Some of this food will be wasted and some additional energy and water is needed to prepare and process the food. Thus, energy goes into producing food and food is, in turn, used to produce energy. The vast complexities within this seemingly simple equation, however, give rise to a universe of considerations that are crucial to understanding the modern food system.

15.2.2 The Fate of Ingested Food: Food as Physiological Energy

Due to incomplete digestion, not all of the gross energy available in food is available to the body. For every 100 units of gross energy ingested, approximately

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[18] Food and Agriculture Organization (2003), p. 5.

three-quarters are assimilated into the blood in the form of simple sugars, amino acids, and fatty acids. The remainder of the energy is lost through egestion as feces and combustible gases. Other energy losses occur through the urine, as well as through the catabolism (breakdown) of protein and evaporation from the body's surface.[19] Metabolizable energy (ME) is the energy that remains after accounting for these important losses. Of this metabolizable energy, some must be used to run the processes of digestion, absorption, and intermediary metabolism, and is thus unavailable for other metabolic processes. The digestive tract is home to some 800 species of bacteria, which are important for the metabolism or generation of several vitamins, in addition to helping ferment indigestible carbohydrates. Additionally, the bacteria recirculate compounds excreted in bile from the liver.[20] The gut flora, in turn, uses some of the metabolizable energy in these processes. Correspondingly, the net metabolizable energy (NME) accounts for losses due to the aforementioned processes, while the remaining energy—that which passes from the gut into the bloodstream—becomes available for basal metabolism, active metabolism,[21] growth, and reproduction. About one percent of ingested energy is used for growth and reproduction.[22]

15.2.3 Human Energy Requirements

Today, humans require on average 2000–2500 kcal[23] for proper nutrition.[24] Depending upon their weight, sex, level of activity, and other factors, they can require as little as 1000 kcal (for children 2–3 years old) and up to 3200+ kcal (for active male adults) per day. This energy requirement is appreciably lower than the 3000 kcal/day estimated by some academics for modern and historical hunter-gather populations.[25] The notably higher levels of kcal for hunter-gatherers can be attributed to their greater levels of activity and higher resting metabolic rates. A modern human would have to walk nearly 19 km (12 miles) per day in addition to their current daily activities in order to expend the energy used by their typical !Kung or Ache counterpart.[26] The fact that the average human requires one-third less food energy than our Paleolithic ancestors (and modern hunter-gathers) can be attributed principally to our present use of fossil fuels for labor, transportation, and air-conditioning. Nonetheless, the variations in diet also change how much

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[19] Food and Agriculture Organization (2003), p. 5.

[20] O'Keefe (2008) p. 51; Flint et al. (2012), p. 577.

[21] For example, locomotion and work.

[22] Hall et al. (1986), p. 12.

[23] Or approximately 8400–10,500 kJ.

[24] United States Department of Agriculture (2010), p. 8.

[25] United States Department of Agriculture (2010), p. 8.

[26] Kious (2002), p. 1.

nutrition a person can actually get from his or her diet. Arguably, an organic, locally-sourced, whole-foods plant based diet will provide more nutrients and more food for a certain amount of calories than a comparatively unsustainable processed-food animal-protein based mainstream meal that is not locally sourced. Thus, energy quality and nutrition also play a major role in the considerations at the heart of this chapter.

15.2.4 Energy Quality and Nutrition

Not only do humans need energy, they need the right kind of it. Thus, adequate nutrition depends on proper food safety and security—and vice versa. Centuries ago, when hunter-gatherers obtained their food, the hunters had to be good animal trackers, and the gatherers had to know where to search according to the season. Essentially, these populations got their food through their own energy investments. Similarly, early farmers had to understand many things about where and when to plant, cultivate and harvest. By contrast, with contemporary and intensive agriculture, food producers need not just human labor energy outputs and accumulated knowledge, but energy in the form of petroleum for tractors and transport, natural gas to fix nitrogen for fertilizer, and electricity for pumped irrigation. In addition, farmers seek affordable energy, i.e. energy that does not require a lot of energy to produce, such as in the form of fuels with a high-energy return on investment (EROI).[27]

The bulk of human food needs are met through the production and consumption of staple crops, mainly corn, wheat, and rice–all highly productive grasses. While cultivars vary by geographic region and culture, their structure and function—high carbohydrate (high energy) and high yield per effort (high efficiency)—vary little. Protein requires more energy per gram to produce, often substantially more. Vegetables, necessary for good nutrition, are more energy intensive than grains. Thus a complete diet requires a mix of both high efficiency staple crops, as well as higher quality foods that need a greater energy investment for production. If we were to eat the most energy efficient diet, it would probably still not be sufficiently nutritious. On the other hand, a modern diet too rich in proteins and fats is also energy intensive and early agriculture probably decreased the nutritional status of humans. Academic and scientific opinions vary greatly, and there is no consensus at this time about the optimal diet that combines good nutrition along with a low energy cost. Progressive thinkers suggest that a locally-sourced organic whole-foods plant-based diet may be the best approach for public health and environmental integrity[28] although further quantification of this is needed.

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[27] Lambert et al. (2014), p. 153. For impact of early Agriculture see Angel (1975).

[28] T. Colin Campbell and Jacobson (2013).

Thus far, this chapter focused mostly on the nutritional requirements of the individual. Now, however, the focus shifts to a larger, more comprehensive, question: how should we look at food and energy for an entire country, or region, or the world? Nearly everyone asking this question goes back to the first important paper on this topic by Thomas Malthus.

15.2.5 Thomas Malthus's Question

A discussion of the resource versus population issue always starts with Thomas Malthus and his 1798 publication *First Essay on Population*:

> I think I may fairly make two postulata. First, that food is necessary to the existence of man. Secondly, that the passion between the sexes is necessary, and will remain nearly in its present state…., increases in a geometrical ratio. Subsistence increases only in an arithmetical ratio. Slight acquaintances with numbers will show the immensity of the first power in comparison of the second.[29]

Malthus continues with a very dismal assessment of the consequences of this situation for humans including even more disheartening and inhumane solutions that disadvantage poorer populations. Most people agree, however, that Malthus' premise has not held up between 1800 and the present, as the human population has expanded by about seven times along with concomitant increases in nutrition and general affluence—albeit the latter occurred only recently. In *The End of Food*, Paul Roberts (2008) reports that malnutrition was quite common throughout the nineteenth century. It was only in the twentieth century that cheap fossil energy allowed a sufficient level of agricultural productivity to avert famine. Many scholars have made this argument—that humans' exponential escalation in energy use, including that used in agriculture, is the principal reason that the food supply has grown parallel to the human population. Since Malthus' time, therefore, we have avoided wholesale famine for most of the Earth's people due to the expansion of fossil fuel use. This was something that Malthus could not have foreseen.

The first twentieth century scientists who argued consistently with Malthus' concern about population and resource distribution were ecologists Garrett Hardin and Paul Ehrlich. Hardin's essays in the 1960s on the impacts of overpopulation include the famous *Tragedy of the Commons*, in which he discusses how individuals tend to overuse common property to their own benefit even when it is disadvantageous to all parties involved.[30] Hardin wrote other essays on population, coining such phrases as "freedom to breed brings ruin to all" and "nobody ever dies of overpopulation," the latter implying that overcrowding is rarely a direct cause of

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[29] Malthus (1798).

[30] Hardin (1968).

death, but rather it leads to disease or starvation or living in dangerous areas such as periodically hurricane-flooded deltas, which, in turn, kill people as a result of overpopulation. This idea is exemplified in an essay about the thousands of people in coastal Bangladesh who drowned in typhoons over the past centuries. Hardin argues that the residents knew this region would be inundated every few decades, but they lived there anyway because they had no other place to go in such a crowded country. The typhoon pattern recurred in 1991 and 2006, thus supporting Hardin's argument that overpopulation causes other problems, which then lead to death.

In *The Population Bomb* (1968), ecologist Paul Ehrlich argues that continued population growth will wreak havoc on food supplies, human health, and nature, and that Malthusian processes (such as war, famine, pestilence, and death) will sooner rather than later bring the human populations "under control" and down to the carrying capacity of the world. During the time of Ehrlich's work, agronomist David Pimentel and others,[31] ecologist Howard Odum, and environmental scientists John and Carol Steinhart quantified the energy dependence of modern agriculture and showed that technological development is almost always associated with increased use of fossil fuels. Other ecologists, including George Woodwell and Kenneth Watt, discuss in depth how people negatively impact ecosystems.[32] Kenneth Boulding,[33] Herman Daly and a few other economists begin to question the very foundations of economics,[34] including its dissociation from the biosphere necessary to support it and, especially, its focus on both growth and on infinite substitutability—the idea that something will always come along to replace a scarcer resource.[35] More recently, Lester Brown and others provide convincing evidence that food security is declining, partly because of distributional issues and partly because of declining soil fertility, desertification, and a decrease in the availability of fossil-fuel derived fertilizers.[36]

On another note, Jay Forrester is the developer of a series of interdisciplinary analyses and thought processes, which he calls system dynamics. He describes the impending difficulties posed by continuing human population growth in a world of finite resources. His analysis became known as the Limits to Growth model.[37] His computer models were refined and presented to the world by Forrester's students Donella Meadows, Dennis Meadows, and their colleagues in 1972.[38] They showed

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[31] Pimentel et al. (1973, 2005).

[32] See Charles A.S. Hall, Kent A. Klitgaard, Energy and the Wealth of Nations: Understanding the Biophysical Economy (Springer 2012).

[33] See a list of Kenneth Boulding's work at http://www.nasonline.org/publications/biographical-memoirs/memoir-pdfs/boulding-kenneth-e.pdf.

[34] Hall and Day (2009).

[35] Hall and Day (2009).

[36] *See generally* Brown (2009a, b).

[37] Also known as the "Club of Rome" model, after the organization that commissioned the publication.

[38] Meadows et al. (1972)

that exponential population growth and resource use, in combination with finite resource and pollution assimilation, will lead to serious global economic instabilities, eventually resulting in a large decline in the material quality of life and the overall human population.[39] Around the same time as Forrester's writing, geologist M. King Hubbert predicted in 1956, and again in 1969, that oil production from the coterminous United States would peak in 1970 before declining. Although his predictions were dismissed at the time, U.S. oil production in fact peaked in 1970, and natural gas did so in 1973.[40] These predictions provided frameworks for an understanding of past and future food production challenges.

Before considering the present and future possibilities with respect to food, one must examine food production from the widest possible perspective. This analysis begs the questions: How has the present human food situation developed? Are Malthus' ideas still valid? Has the temporary availability of fossil fuels delayed the implementation of the "Malthusian dilemma," or have technological conditions changed the limits of food production? How can we understand the relation of human population and food over a long period of time? The following sections explore some of these issues.

15.3 History of Humans and Food

15.3.1 The Prehistory of Human Society: Living on Nature's Terms

Agriculture, by its definition, is a manipulation and cultivation of nature's abundance of foods. It is, therefore, important to understand the relationship between human evolution and food system evolution. In fact, people sufficiently similar to the modern human have been on Earth for roughly half a million years and have benefitted from nature's supply of food. Yet, scholars understand very little about how these people made their living, what they did day to day, or how they interacted with each other. The only existing evidence of their lives consists of human bones, the bones of their prey, and an occasional tool. Scientists are relatively certain that these early humans survived by hunting and gathering, i.e. by exploiting whatever food nature provided along with what could be obtained using relatively simple tools such as spears and baskets. Most of what we know about our hunter-gatherer ancestors is derived principally from anthropological studies of remaining hunter-gatherer cultures such as the !Kung, a group that still lives in the Kalahari desert of Southern Africa, as well as in towns and cities.[41] Nonetheless, all of those who examine what life must have been like for our ancestors, are indebted to the work of

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[39] Hall and Day (2009), p. 220.

[40] Hall and Day (2009).

[41] Lee (1969)

Richard Lee, who studied the !Kung while they were relatively unaffected by modern civilization. Many academics believe that modern hunter-gatherers are the best mirror in which to see what life must have been like for our ancestors over the half million years between the evolution of our species and the development of agriculture.

Life for a hunter-gatherer is essentially about taking nature as it is found and finding ways to support oneself on those resources. Since most early human hunter-gatherers lived in tropical environments, the key issue was gaining needed energy from food. For the !Kung, this meant that women predominantly gathered mongongo nuts while men hunted. Mongongo nuts were a critical and abundant resource; today, they still provide the largest portion of energy and protein for the !Kung, in addition to nutrition from game. Life was good for the !Kung, at least before their major contact with outside civilizations.

According to Lee's studies, the !Kung spend far fewer hours working each day than most people living in industrial societies, and a lot of their time is spent in leisure activities. Life for the !Kung is not quite that simple however. Desert living is constrained by the need for water and food. In their homeland of Botswana, there are relatively few waterholes and it is essential to set up camp near one of these. As a result, the !Kung periodically exhaust the food resources near their present waterhole and must move to a new water source and establish a new camp. Mongongo trees are spread around part of the Kalahari desert and initially the !Kung have a relatively easy time obtaining the food they need from relatively short excursions from their camp. As time goes on, however, they deplete the nuts within easy reach so that each day they have to make a longer and longer trip to gather enough mongongo nuts to feed their families. At some point when they have gathered all the mongongo nuts within a day's hike, they have to make a much further overnight trip to get them. This has the effect of greatly increasing their energy expenditure and lowering their energy return on investment (EROI). Their energy investment is much greater because they need a lot of food both going and coming back, and may end up eating a substantial portion of the food they set out to gather. At this point, it is usually desirable to make the investment of moving to a new water hole.

It is becoming clear that our stone-age hunter-gatherer ancestors, just like hunter-gatherers today, were truly remarkable hunters. This had the net effect of drastically reducing the populations of the large birds and mammals of the earlier world. As humans spread about the world, they encountered, in each new place, large and presumably tasty herbivorous animals of the sort that no longer exist anywhere on Earth today. For example, the new arrivals to North America roughly 12,000 years ago found giant beavers, rhinoceros, two species of elephants, camels, and many other now unfamiliar creatures. Likewise, human arrivals in Australia found giant flightless birds, while the first humans in what is now contemporary Italy encountered enormous turtles. None of these large animals are there today. Furthermore, with the exception of those in Africa, there are few animals left larger than 100–200 kg—although such sizable animals were abundant prior to human contact.

There are two competing hypotheses for what caused the extinction of those large animals. First, since the climate was warming rapidly 10,000 years ago, it is possible that they succumbed to some effect of climate change. The second hypothesis is that humans hunted these animals to extinction. These large animals had no previous reason to be afraid of anything as small and seemingly weak as a human being. The first humans could simply walk up to these animals and stick a spear into their side. Africa still has many large herbivorous species, likely because these animals coevolved with humans as they became more proficient hunters with better weapons. Wherever humans migrated, most or all of the animals larger than 100–200 kg disappeared within 2000 years, lending support to the idea that *Homo sapiens* caused these animals' extinction.[42] In addition, the fact that these same animal species had survived many previous climate changes lends considerable—but not absolute—support to the human-caused extinction theory. Thus, significant environmental impact is hardly a new phenomenon of the human species, but rather something that has been occurring for millennia.

15.3.2 African Origin and Human Migrations

All available evidence suggests that humans and their predecessors evolved in Africa. It is the only place where scientists have found human fossils and evidence dating back to 1.7–1.8 million years ago. Take a mental time trip to East Africa about 2 or 2.5 million years ago: you will be at the epicenter of human evolution. What is remarkable, however, is that you will find not one, but perhaps half a dozen types of early humans (or hominids); each group as distinct from one another as chimpanzees are from gorillas. Most of these protohominids were found in small migratory bands more or less at the transition of forests to drier savannas. In the 1990s, scientists announced that they had found what appears to be the ancestor of humans; a being who lived some 4–6 million years ago. This discovery is cause for great excitement amongst those who are determining our lineage. The creature, named *Ardipithecus ramidus* (Ardi for short), walked more or less upright but still spent a significant portion of its time in trees, similar to chimpanzees.

The Ardis had several interesting characteristics. Recent research has found that a human uses only about one quarter the energy that a chimpanzee uses to walk 100 m., so there has clearly been a tradeoff of more energy-efficient walking for the ability to both walk and climb trees well. Probably most of the Ardis made, or at least used, tools of some sort. Studies show that even chimpanzees have a rather astonishing ability to make many different types of tools, including stone anvils. Most of the Ardis' tools were made from organic materials and were, therefore, not well preserved. Hence, scientists know little about the evolution of early protohominid tool-making. It seems clear for humans, however, that by about 2.5

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[42] Sandom et al. (2014), p. 2, Martin (1973).

million years ago, they had developed skillful methods for making stone knives and spear points, such as by striking one rock on another in repeated, often sophisticated, patterns. There are even a number of ancient "industrial complexes" in, for example, Kenya's Olduvi gorge, which has become a rich hunting ground for information about our ancestors.

The development of tools is one of the factors setting Ardis and chimpanzees apart. Spear points and knife blades are energy-concentrating devices that allow the strength of a human arm to be multiplied many times. This, in turn, allowed humans to exploit many new animal resources, and eventually colonize cooler lands. Human ancestors were using stone tools for roughly two and a half million years, which is equivalent to about 100,000 human generations. By contrast, humans have been using metal tools for roughly 8000 years, or about 400 generations. Most of human history, therefore, has been without metal tools. Early copper and bronze tools were probably not much more effective than well-made rock or bone tools. In time, however, these tools became much more effective as their design and technology improved. An important reason behind the slow transition to metal tools is that stone tools could be made with a small energy investment (essentially human muscle power). Metal tools, on the other hand, required heat, which meant a much larger human investment of cutting trees, making charcoal, and finally making the tool itself.[43] Early smelting was probably technically inefficient, but it had the advantage, at least initially, of the availability of very high grades of ore. Thus, the development of tools became increasingly sophisticated. These stone spear points and knife blades were more or less the first in a long series of technological advances that helped increase the flow of energy to humans. The consequence of these tools is that they greatly expanded the ability of humans to exploit various plant and animal resources in their environment. They also diversified the climates in which humans could live by enabling them to kill large animals and use their skins for clothes.

Another important new energy technology was that of fire. While it naturally allowed people to stay warm in cooler climates, it more importantly increased the variability and utility of plant foods: cooking broke down the tough cell walls of plants, for example, and made them more digestible.[44] Following the discovery of this "technology" a little less than two million years ago, many humans left the relatively benign climate of Africa. Before long, the remains of both humans and their tools ended up in present day Middle East, Georgia and Indonesia. By one million years ago, human remains were common all throughout Asia. However, humans did not colonize Europe until roughly 500–800 thousand years ago. The first humanoid colonists of Europe are likely not our direct ancestors, for morphologically modern humans[45] appear to have left Africa in a separate migration only about 100,000 years ago. There are very strong debates in anthropological literature

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[43] Perlin (1989), Ponting (1991).

[44] Wrangham (2009).

[45] Popularly known as "Cro-Magnons," and distinct from the earlier "Neanderthal" stocks.

as to whether all of these groups of people are the ancestors of modern humans or just the "Cro-Magnon" variety, but modern DNA analysis seems to favor the separate stock concept. For whatever reason—perhaps interracial warfare, climate change, or some indirect result of competition—the Neanderthal stocks were eliminated from Europe by 35–40,000 years ago, along with many other protohominid variations, leaving, it seems, a few of their genes with those of European stock. In sum, the evolution of humans is an important precursor to understanding how agriculture evolved.

15.3.3 The Dawn of Agriculture: Increasing the Displacement of Natural Flows of Energy

Some time roughly 10,000 years ago, in the vicinity of the Tigris and Euphrates valleys of present day Iraq, a momentous thing happened. Humans, previously completely constrained by their limited ability to exploit natural food chains (due to the low abundance of edible plants in natural systems), discovered that they could increase the flow of food energy to themselves and their families by investing some of the seeds that might otherwise be eaten into more food for the future. How this happened can never be known for certain.

The implications of agriculture development for humans were enormous. The first, seemingly counterintuitive, consequence of agriculture is that human nutrition declined. Studies of bones of people buried over the past 10 thousand years in Anatolia, which is the area roughly encompassing the border region of modern day Turkey and Greece, revealed the height and general physical condition, as well as their nutrition status of the people who used to live there. The data indicates that the people actually became shorter and smaller with the advent of agriculture, indicating a *decrease* in nutritional quality (see footnote 27). In fact, the people of that region did not regain the stature of their hunter-gatherer ancestors until about the 1950s. Therefore, although agriculture may have given the first agronomists an advantage in terms of their own energy budgets, that surplus energy was translated relatively quickly into more people with only an adequate level of nutrition as human populations expanded. Or perhaps, as outlined below, more of the farmers' net yield was diverted to artisans, priests, political leaders, and war, leaving less for the farmers themselves. One of the clear consequences of agriculture was that people could settle in one place, so that the previous pattern of human nomadism was no longer the norm. As humans occupied the same place for longer periods of time, it began to make sense to invest their own energy into relatively permanent dwellings, often made of stone and wood. This start of the construction of the durable human structures have left significant artifacts for today's archeologists and show some of the implications of agricultural development.

Another significant consequence of agriculture was the enormous increase in social stratification, which took place as economic specialization became more and more important.[46] For example, if one individual was particularly skilled at generating agricultural yield or understood the logic and mathematics (i.e. best planting dates) of successful farming, it made sense for the farmers of the village to trade with him some of their grain for knowledge, thereby initiating, or at least formalizing, the existence of markets. From an energy perspective, relatively low-skilled agricultural labor was being traded for the high-skilled labor of the specialist. The work of the specialist could be considered of higher quality in terms of its ability to generate greater agricultural yield per hour of labor. Considerable energy had to be invested in training that individual through schooling and apprenticeships. The apprentice had to be fed while he or she was relatively unproductive, in the anticipation of greater future returns. The energy return on investment (EROI) of the artisan was higher than that of the farmer (even if less direct), and as a result, so was his pay and status. Thus, social stratification was directly linked to agriculture and changed ancient societies tremendously.

Eventually, the concept of agriculture spread around Eurasia and Africa but resource depletion followed shortly thereafter. Another new phenomenon appeared with the development of agriculture: cities and other manifestations of urbanization. The first area this occurred appears to be in the Tigris Euphrates valleys in one of the first cities ever known, Ur.[47] This was roughly 4700 years ago, and there were many great cities in that region, including Girsu, Lagash, Larsa, Mari, Terqa, Ur and Uruk. These cities grew up in heavily forested land, as signified by the massive timbers in remaining ruins. Today we call that ancient civilization Sumeria and the people Sumerians but there are essentially no trees or cities left in that region. In fact, the forests were gone by 2400 BC, the harbors and irrigation systems were silted in, the soil became depleted and salinized, and barley yield dropped from about 2.5 tons per hectare to less than 1 ton. By 2000 BC, the Sumarian civilization was no longer extant. The world's first great urban civilization used up and destroyed its resource base and disappeared over a span of 1300 years.[48] Consequently, resource depletion turned out to be one of the reasons why entire civilizations and cities became extinct.

The interaction of people with cultivars,[49] in turn, greatly changed the plants themselves. Notably, all plants are in constant danger of being consumed by herbivores, ranging from bacteria, to insects, to large grazing or browsing mammals. In the planet's history, herbivorous dinosaurs predated today's mammals. Thus, the evolutionary response of plants to this grazing pressure was to develop various defenses, such as the physical protection of spines, which are especially abundant in desert plants. More common, however, was chemical protection in the form of alkaloids, terpenes, and tannins. These compounds place a heavy burden on

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[46] Diamond (1999).

[47] The word "urban" is actually derived from the ancient city Ur.

[48] See Perlin (1989), Michener (1963), and Tainter (1988), who tell these stories in fascinating detail.

[49] Cultivars are plants that humans cultivate.

herbivores (or potential herbivores) by discouraging consumption or by requiring a high-energy cost to detoxify poisonous compounds. Humans do not like these frequently bitter, poisonous compounds either. For thousands of years, humans have been, therefore, preferentially saving and planting the seeds from plants that taste better or have other appealing characteristics. Partial exceptions include mustards, coffee, tea, cannabis, and other plants, that provide bitter alkaloids which would be poisonous if they were all that humans consumed, but present curious, interesting, or otherwise alluring dietary supplements in small doses to those humans who like them. Consequently, however, cultivars have poor defenses against insects and often require the use of external pesticides—a technology that has complex environmental and biological consequences. Many cultivars would not survive in the wild now, and have coevolved with humans into systems of mutual dependency. Meanwhile, all kinds of pests are themselves adapting to the concentration of humans, often with disastrous impacts to humanity. Humans have nevertheless survived, prospered, and multiplied, especially since the industrial revolution. Thus, the co-dependency of plants and humans is another aspect of the evolution and development of agriculture.

Other highly impactful energy-related events occurred during these prehistorical times. The domestication of animals may be one of the most significant developments. While some aspects of animal domestication predate agriculture, most domestication occurred more or less simultaneously with the inception of agriculture. Animal domestication and the increased sophistication of animal husbandry were critically important in increasing energy resources for humans in at least two important ways: First, for the reason that these animals ate plant material that humans did not eat, this greatly increased the amount of energy that humans could harvest from nature, especially in grasslands. Second, oxen and horses markedly increased the power output of a human.

The story of how the use of animal technology passed throughout Eurasia was critical in facilitating this transference. In fact, the majority of domestic animals came from Eurasia and could be moved East to West much more easily than North to South. Humans' most important animals included sheep, cows, horses, pigs and chicken. They were "corralled" in Eurasia by virtue of the area's geography, and consequently evolved into today's domestic animals. The increasing familiarity with beasts of burden, along with the development of roads and caravan technology, in turn, allowed for the expansion of long distance trade. Humans refined and passed on sailing and navigational skills, enriched agricultural knowledge and the biotic resources of many human groups.

As agriculture, settlement, and commerce expanded, a greater need for maintaining records arose. Some time around 3000 BC, humans developed formal writing, seemingly simultaneously in Egypt, Mesopotamia, and India. Writing had many societal implications, but perhaps most importantly, it allowed for agricultural and other technologies to be passed from one generation to another and transferred among cultures. These old records have also allowed scientists to estimate earlier patterns of human population changes and they suggest that the pattern of human population is hardly one of continuous regular growth; rather, it is one of periodic growth followed by decline. Sometimes this is manifest as a catastrophic drop in, and disappearance of, a particular population; or, more commonly, the demise of the political structure that once held them together. Edward Deevy suggests that there were three main historical increases in human populations: first, the corralling of animals; second, the development of agriculture; and third, the industrial revolution. We are still experiencing the last phase as global human population growth continues strongly, although at a lower rate than in earlier times. Commerce, nonetheless, continues to shape agriculture and international trade in an increasingly globalized world may have some of the greatest impacts on food law and policy.

15.3.4 Human Cultural Evolution as Energy Evolution

Most of the major changes in terms of humans' ability to exploit natural resources are associated with increased use of energy. Spear points and knives are, for example, energy concentrating devices; fire allows greater availability of plant energy to humans; agriculture significantly increases the productivity of land for human food; and so on. The evolution of humans' ability to control energy—such as through the harnessing of wind and water power—is best described in Fred Cottrell's book *Energy and Society*, which was published more than half a century ago.[50] Cottrell's focus was on the development of what he called "converters," i.e. specific technologies for exploiting new energy resources. As Cottrell shows, technological change is usually associated with an increase in the quantity or quality of exploited energy.

Cottrell's early chapters focus on herding as a means of exploiting biotic energy,[51] water power, and wind power. He shows the historical importance of situating cities downstream on a river so that the natural flow of the water allows citizens to easily exploit all upstream resources such as, timber, agricultural products, game, and ore. Through the use of barges, humans' carrying capacity upstream and downstream increased.[52] Likewise, the development of sailing ships increased the energy efficiency of a human porter enormously, and, according to Cottrell's calculations, the early sailing ships generally increased the load that a human could carry by a factor of 10; and by late Roman times it was as much as 100. The Romans needed to import large quantities of grain from Egypt,[53] in part because they had

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[50] Cottrell (1955).

[51] Biotic means living parts of an ecosystem. In contrast, abiotic mean chemical or physical, non-living.

[52] The Nile is an exception, for the winds tend to blow north to south while the water flows south to north, so dhows could go both ways.

[53] Contrary to popular belief, Caesar and Mark Anthony were not in Egypt for Cleopatra—the real target was grain from continuously replenished flooding soil.

depleted their own soil. According to Cottrell, however, they were not the only ones who coveted grain and, initially, the Romans lost a lot of their supply to pirates. This required the Romans to transport the grain in heavily guarded narrow warships, while the soldiers on board consumed a significant portion. Therefore, another energy investment had to be made by the Romans, namely clearing the Mediterranean of pirates. With this accomplished, they adopted the use of wide-beamed merchant vessels, and Egypt became a significant net energy source for the Romans. Cottrell gives many other examples of the increasing use of energy by humans over time, including noteworthy chapters on the rise of industrial agriculture, steam power, and railroads in England. What all of these examples and developments have in common is humans' dependence on energy and the central role it plays in human development.

15.3.5 Industrial Agriculture

The next great leap forward in agriculture came in the twentieth century, when an increasing use of cheap fossil fuels, along with technological advancements, brought about a dramatic transformation of agriculture. It was the enormous surplus energy derived from fossil fuels (coal, oil, and natural gas), that made this development possible while 20–100 or more units of energy could be returned per unit invested. The high EROI (Energy Return on Investment) allowed surplus energy to be invested in agriculture and other industries, thus generating surplus wealth and boosting profit margins.

Between 1900 and 1970, the western world's shift from human and animal labor to predominantly mechanized labor changed the EROI of agriculture. In traditional cultures, 5–50 kcal of food were obtained for each kcal invested; by 1970 just one kcal of food was obtained for every 5–10 kcal of total invested energy (fossil and human labor), including transport and processing.[54] White hypothesized that the development of human societies is constrained ultimately by their ability to generate surplus energy, including food. This ability is a function of the quality of available energy and energy transformers (technology). Over the long run, the quality of available energy is determined by the amount of energy needed to return the next unit of energy. During this period, fossil-fuel-driven tractors and other machines replaced the labor of humans and draft animals. In the nineteenth century, up to 75 % of the U.S. labor force worked on farms. By the end of the twentieth century, it was less than 2 %. Astonishingly, far fewer Americans were working on farms in 2000 than in 1840, even though the American population is so much larger today. The increase in agricultural productivity is due primarily to the use of fertilizers and pesticides, along with the development of new varieties of crop plants. All of these shifts in energy use were made possible through the use of fossil fuels.

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[54] Steinhart and Steinhart (1974), p. 307.

Perhaps the most important change in energy production is the development of the industrial Haber-Bosch process, which converts atmospheric nitrogen gas into ammonia. Up until 1908, crop plants were severely limited by the availability of nitrogen. This is true even though 80 % of the atmosphere is nitrogen (N_2). This nitrogen, however, is very difficult for most plants and humans to access due to the triple bonds in the di-nitrogen molecule ($N{\equiv}N$). Until Fritz Haber developed the Haber-Bosch process, only the tremendous energy of lightning or some very select algae and bacteria could break these bonds. Haber, in one of the most important scientific discoveries ever made, found that by heating and compressing air mixed with natural gas and using the right catalyst, the N_2 molecule could be split and turned into ammonia (NH_3). This, in turn, could be combined with nitrate (itself created by oxidizing ammonia) to generate ammonium nitrate, which is the basis for both gunpowder and fertilizer. The Haber-Bosch process requires significant energy input, but its development freed humans from the limits of natural processes such as manure fertilizing. Arguably, this freedom led to dangerous environmental consequences that may have been averted but the abuse of fertilizers through the industrial agricultural industry is beyond the scope of this chapter.

The Haber-Bosch process took off in 1946 at the end of World War II. As there was no further need for massive amounts of war explosives, the U.S. Federal Government asked whether there might be a different use for the weapons factories. The answer came from agricultural colleges: the technology could be used to significantly increase agricultural yield. This "industrialization of agriculture" freed food production from its former dependence upon manure fertilizers. With the concurrent development of machinery, far fewer Americans were needed to grow food. This shift in labor division created an exodus to the cities and led to the growing number of urban industrial jobs. Meanwhile, the increased use of oil, gas, and coal generated greater material wealth for workers. Thus, America changed from a relatively poor, agriculturally-based country into an increasingly industrialized and urban one while becoming enormously wealthy in the process. The net energy required for this economic work was increasing exponentially. The great increase in wealth prompted economists to develop theories to explain the economic forces behind this growth. And yet, interestingly, among those chronicling the process there is essentially no mention of energy as a catalyst for these changes.

The large agricultural yields generated by fossil-fuel-led agriculture allow a large surplus of energy, including food energy, to be delivered to society. In turn, this transfer allows most people and capital to be employed somewhere other than the energy industry. These energy surpluses, in other words, have helped to develop all aspects of our civilization—good and bad. The same can be said for technological advances that enabled the unearthing of phosphate rock deposits. Irrigation became widespread as a result of this industrialization, allowing crops to be grown in arid and semi-arid areas. The Central Valley of California is perhaps the best-known region where irrigation dramatically increased agricultural production. Worldwide, crops became more homogenized and food processing more widespread. All of these changes furnished the development of the globalized industrial food system that characterizes food production today.

15.4 Energy Cost of Food

15.4.1 Energy Production Efficiency for Agriculture in the United States

There are four relevant studies on the energy cost of food production in the United States. Each of these studies uses slightly different methodologies but express energy cost in terms of caloric output versus caloric input. Carol and John Steinhart,[55] for example, calculated energy use in the entire U.S. food system using data from governmental sources between 1940 and 1970. Output in the Steinhart and Steinhart study was based on the caloric requirements of the U.S. population, rather than actual crop production. The output amounts also excluded U.S. food production exports. Inputs included direct fuel and electricity use, energy used to create fertilizer, agricultural steel and farm machinery, and energy used to run irrigation systems. Steinhart and Steinhart concluded that U.S. agricultural energy efficiency declined by about threefold from 1940 through 1970, as tractors replaced animal power and farmers used more commercial fertilizers. In the end, agriculture was providing a return of less than one energy unit of food for one energy unit of fuel (even at the farm gate), and less than one unit of food for three units of fuel by the time the food reached the plate.

In another study, Cutler Cleveland examined the energy efficiency of food production in 1995.[56] Cleveland derived energy inputs and outputs from economic data and was thus able to make calculations from as far back as 1910. He determined the energy content of agricultural inputs by converting the dollar value of fossil fuel and electricity consumption, along with other farm input expenditures[57] to physical units at extant prices. Then, he converted these physical units to energy units using a dollar to energy conversion factor for the embodied energy in fuels using the energy intensities (kcal per dollar) derived by the energy research group at the University of Illinois.[58] Cleveland calculated agricultural output using two data sources: first, with the USDA index of total agricultural output, which includes dollar estimates of production of crops, fruits and vegetables, and animal products; and second, with the Gross Farm Product, or the value added in the farm sector in dollars. The results of Cleveland's research show that the energy efficiency of U.S. agriculture declined from about 5.5 calories of food energy output per one calorie of fuel in 1910 to a 1:1 ratio in 1980, leaving him in rough agreement with the Steinharts. Thus, the cost of energy to produce food could be estimated about 100 years ago.

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[55] Steinhart and Steinhart (1974).

[56] Cleveland (1995), pp. 111–121.

[57] These include pesticides, fertilizers, machinery, energy used to generate electricity, and agricultural services.

[58] Herendeen and Bullard (1976), p. 383; Hannon et al. (1985).

The authors of this chapter have also summarized the energy it takes to grow food in the U.S. and Canada in recent decades using mainly physical data.[59] This study found that about two percent of all energy used in the United States goes towards growing crops. Pimentel and his colleagues[60] estimated that about 17 % of U.S. energy use goes into the entire food system, including growing, transporting, and preparing food, each sector consuming about one third of this total energy. We also found that the "Edible Energy Efficiency" (EEE) of U.S. agriculture has actually more than doubled from 0.8:1 in 1970 to 2.2:1 by 2000, followed by a slower increase to 2.3:1 by 2009. The energy efficiency of the agricultural sector in Canada has not changed appreciably since 1980, and has remained at about 2:1 from 1981 to 2009. The authors' study found that EEE improvements in the U.S. can be attributed not only to increased crop production *per* hectare and lower direct fuel consumption, but also to the increased use of less energy-intensive corn and changes to the diet of livestock.[61] Increases due to technological progress alone appear small for the last several decades, at less than 1 % a year.[62] In sum, although efficiency initially fell as agriculture was industrialized, technological advances in recent decades mean that efficiency has now stabilized or increased slightly.

Notably, there are several contributors to agricultural energy use. The production of N fertilizer contributes about 40 % of all energy used; on-farm fuel use requires 30 %, followed by K_2O (7 %), lime (6 %), the transportation of inputs (6 %), P_2O_5 (5 %), seed (5 %), herbicide (4 %), drying (2 %), and insecticide (1 %).[63] Energy use is lower for legume crops because they fix atmospheric N, and therefore do not require energy-expensive N fertilizer. How these contributors of energy use affect the food system is described in the following section.

15.4.2 The High (Energy) Cost of Meat, Dairy, and Processed Foods

The production of meat, dairy, animal products and processed foods is significantly more energy-intensive than plant-based food production. It is, therefore, important to appreciate the energy that is invested in producing the various types of foods. Grains, for example, are the most productive agricultural product.[64] Yields can be anywhere from 1 to 10 tons per hectare, and occasionally more. Temperate yields

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[59] See Hamilton et al. (2013), p. 1764.

[60] Pimentel et al. (1989).

[61] For instance, increased use of meals and other by-products, which reduce the grain demand by livestock.

[62] See Hall et al. (2009a), pp. 25–47; Hamilton et al. (2013), pp. 1764–1793.

[63] Camargo et al. (2013) p. 263.

[64] This is due to their efficient photosynthetic pathways.

tend to be higher than tropical, despite the longer growing season that tropical farmers enjoy. This is because the soil has lower nutrient levels and the longer nights consume more energy. Since people need a minimum of 1 kg of food per day,[65] anywhere from around 3 to 30 people can be supported by 1 ha[66] of land producing grains. The number of people fed per hectare of land will be significantly less if the crop is first fed to animals. This is a significant argument why vegetarianism, and even more specifically, veganism, makes for a more sustainable diet and leaves a lower environmental footprint than a diet rich in animal products.

In areas of the world with high human densities, such as India and China, the majority of people eat only grains, such as rice. Indeed, this grain-based diet is similar for poor people around the world. Energy yields per hectare of vegetables or animal products tend to be low; at best between one quarter and one half of energy invested, but more frequently the yields are as low as ten percent of the total invested energy per hectare. The conversion efficiency of plant to animal flesh is in fact only 10–20 %.[67] Despite this poor energy efficiency, animals can use lower quality, less productive land where it would otherwise be expensive or impossible to grow crops. This is readily observed in much of the world where wetter land is used for crops and drier land is used for pastures.

According to Pimentel and Pimentel,[68] farmers in the US raise and care for nine billion livestock in order to meet the animal protein demand by humans each year. Indeed, the total numbers of livestock are estimated to be some five times the U.S. human population. About 124 kg of meat is eaten per American per year. The average meat-eating diet consists of 35 % beef, 25 % pork, 39 % poultry, with the remainder made up of other meats. Americans also consume protein in the form of milk, eggs, and fish. In terms of the energy efficiency conversion, livestock must consume six units of plant protein for each unit of animal protein that they produce.[69] Thus, in terms of producing food for the world, the reliance on animal products reduces efficiency, productivity, and, as a side-note, causes substantial health concerns for human consumers and dangers for the environment.

15.4.3 Energy Distribution and Delivery: Food Miles

Researchers estimate that roughly equal amounts of energy are used in delivering food to the consumer as to grow it.[70] With the globalization of agriculture and other sectors of the economy, this quantity has almost certainly grown. A study at Iowa

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[65] Or 365 kg—roughly one third of a ton—per year.

[66] 1 ha = 2.54 acres.

[67] The conversion is expressed in a “calories to calories” ratio—be careful not to equate this with weight because of varying moisture contents.

[68] Pimentel and Pimentel (2003).

[69] Pimentel and Pimentel (2003), p. 660S.

[70] Pimentel personal communication (on file with the author).

State University estimates that in the U.S. the average food item travels 1500 miles before it reaches the consumer.[71] There is also a growing movement toward locally-sourced food to reduce food miles, although the energy consequences of this movement have not been clearly evaluated yet. Syracuse, New York, for example, has a large and vibrant farmer's market. And yet, we observed that to deliver food locally to the farmer's market[72] would use as much delivery energy per kilogram of food as products delivered to grocery stores from 300 miles away in a full semi-truck[73] which can carry 50 times more food.[74] There are many good reasons to eat locally, but the extent to which transportation energy and overall food miles are actually saved in doing so need to be examined more carefully for conclusive evidence to support any one hypothesis of the sustainability of eating locally.

15.4.4 The Developing World

In the last decade, scholars have started to examine agricultural energy use in the developing world. For instance, Hamilton et al.[75] reviewed existing studies of agricultural energy efficiency[76] for developing nations. Cao et al.[77] found that the energy ratio for agriculture in China decreased by 25 % from 2:1 in 1978 to 1.5:1 in 2004, largely due to increases in fossil fuel use that outpaced food production. According to this study, for every two units of fossil fuel invested, there is a yield of approximately one unit of food energy although this ratio declined from 1990 to 2004. By contrast, Karkacier et al.[78] found a positive relationship between increasing an index of energy consumption and agricultural output in Turkey, with each additional ton of oil increasing an index of agricultural output by 0.167 units. Other studies looking at edible energy return on investment (EROI) have been conducted on national and international levels for specific crops such as rice. Pracha and Volk (2011) performed an analysis of the edible EROI for Pakistani rice and wheat from 1999 to 2009. The authors found that the average EROI was 2.9:1 for the edible portion of wheat, and 3.9:1 for rice. Going further, Mushtaq et al.[79] calculated EROI values for rice in eight nations and found that the EROI varied from 4:1 to 11:1 (which includes the energy stored in straw), and from 1.6:1 to 5:1 when including only the edible portion. Overall, it appears as though the efficiency of turning

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[71] Pirog and Benjamin (2003), p. 1.

[72] "Local" meaning 30 miles away, and with a truck getting 15 miles per gallon.

[73] Which gets only 7 miles per gallon.

[74] Balogh et al. (2012).

[75] Hamilton et al. (2013).

[76] Kcal of food produced per kcal of input fossil energy.

[77] Cao et al. (2010).

[78] Karkacier et al. (2006).

[79] Mushtaq et al. (2009).

petroleum into food does not vary significantly between more and less developed nations, at least when production is dominated by the use of fertilizers and some machinery. The world is indeed globalized.

15.4.5 Waste

Although the efficiency of delivering food to the consumer has improved slightly in the U.S., waste remains prevalent throughout the food system. Some researchers[80] estimate that 27 % of food produced on American farms ends up as waste and is not consumed. More recent estimates, however, put food waste as high as 40 %, or some 1400 kcal per person per day.[81] Since agriculture requires such high quantities of water, this waste equates to one quarter of U.S. freshwater consumption and approximately 300 million barrels of oil.[82] While the reasons for food waste differ between high-income and low-income nations, post-consumer waste accounts for the bulk of waste in the U.S., while in lower income countries food waste/spoilage tends to occur before it is distributed to the end user.[83] Approximately 1.3 billion tons of food produced for human consumption is wasted globally each year.[84]

15.5 Challenges of Sustainable Agriculture in the US

It is no secret that the US has very high energy demands in its agricultural sector. Certainly, both Howard Odum's 1971 piece, *Potatoes Partly Made From Oil*,[85] and David Pimentel's early studies helped to raise awareness about this issue. Initially, most agronomists paid little attention and were generally dismissive that such problems were important. Nonetheless, there has been a large public response to the environmental concerns about agriculture, although these tend to focus on chemical threats to the health of humans and wildlife. Today, reducing energy use has become the goal of many agronomists.

While the general public response is much too broad to summarize in this chapter, it seems fair to say that the most typical responses are summarized with the word "sustainable." For instance, "sustainable health", "sustainable production systems", "sustainable farming or consuming cultures", "sustainable energy", and other terms, are at the centre of public discussions. Generally, as with most issues

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[80] Kantor et al. (1997).

[81] Hall et al. (2009b), p. 2.

[82] Hall et al. (2009b), p. 2.

[83] Food and Agriculture Organization (2011), p. 10.

[84] Food and Agriculture Organization (2011), p. 10.

[85] See Howard T. Odum, *Environment, Power, and Society* (1971).

that appear in popular environmental literature, there is very little quantitative analysis. Certainly, Hamilton et al.'s findings[86] that U.S. agriculture is becoming somewhat *more* efficient, even as it is dominated by corporate and market forces, would likely surprise many people. Ironically, the largest single barrier to improved efficiency is the large U.S. governmental plan generating ethanol from corn as a replacement for gasoline. This program produces little, if any, net energy by the time the fuel goes into the vehicle,[87] and its existence is clearly based on a political strategies that have trumped current scientific data, which fail to support ethanol as an energy-efficient alternative to gasoline. Problems with the ethanol program include the removal of a substantial amount of food from a hungry world, enormous soil erosion, loss of wildlife habitat, and a net addition of carbon into the atmosphere. Since the land used for ethanol production tends to be the best corn land in the U.S., such as in Iowa, for example, the ethanol crops displace the remaining corn production to sub-optimal habits, such as in Minnesota and Texas. This replacement of crop land results in increased energy costs for American commodity production, such as Cornflakes and bacon. A recent program proposed by the U.S. Navy to fuel a large proportion of its ships and even airplanes with biofuels, nominally to improve energy security and efficiency, has completely flopped based on the enormous price and poor availability of such huge quantities of biofuels, in turn caused by their very low EROIs.

15.5.1 Policy Constraints and Promotion of Sustainable Agriculture

Sustainable agriculture movements, at least from the perspective of protecting soil and water resources, are becoming increasingly common in the US. This is exemplified by the rise of state and county soil conservation districts, agricultural colleges, and young people who are expressing an interest in the agricultural future of America. Probably the largest impact in terms of sustainability comes from the encouragement of no-till agriculture campaigns, whose goal is to disturb the soil cover as little as possible during planting and cultivation.

Certainly there is much popular and governmental lip service toward generating sustainable agriculture, and even some state and local policies that address it directly. And yet, most lawmakers are reluctant to act, resulting in the non-policy of leaving agricultural sustainability decisions to the market. What impact this may have on long-term environmental health is impossible to ascertain but gives many scholars reason to worry about the immediate and long-term consequences of allowing the industry-dominated status quo to continue. Leaving this issue to the market, which searches for the lowest production price as a matter of course, will argue against protecting the soil and continue to deplete the planet's resources.

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[86] Hamilton et al. (2013).

[87] See, for example, Patzek (2004), Murphy et al. (2011), p. 179 and Conway (2007).

Techniques to prevent soil erosion, such as cover crops and erosion barriers, are crucial to maintaining soil health, the foundation of intact agriculture. However, these techniques require money to implement and stand in the way of short-term industry revenues that externalize the cost to the environment beyond market prices. (For more on the externalities of agriculture, see *Textbox: Internalizing Ecological Externalities*).

Another policy with significant environmental impact is the current production of huge amounts of corn-based ethanol. For the reason that corn is a highly soil erosive crop and ethanol production systems are characteristically placed on the best farmland, continued focus on ethanol production will have an enormous impact on the future of agriculture in the United States. How these larger national policies stack up against state and regional programs is impossible to calculate or predict with precision. It is imperative, however, to implement better policy to support sustainable agriculture, to protect the environment, to internalize the negative externalities of industrial agriculture, and to promote diets with lower environmental footprints. While there is much rhetoric on these issues we see precious little quantification of actual results, for example along the line of Cleveland (see footnote 54) and Hamilton et al. (see footnote 57).

15.5.2 Urban Agriculture

The common conception of agriculture is that of a rural enterprise. Indeed, the vast majority of food production comes from rural farms. There are exceptions, however, the most notable of which originated from Will Allen and his colleagues in the city of Milwaukee. Allen is a former professional basketball player from Milwaukee, who, at the end of his basketball career, returned to the city where he sought out his wife’s parents’ farm, which had been the site of many happy childhood memories. In the intervening years, the city had essentially expanded around the farm. Allen came up with an inspired idea: bringing more farms into the city.

Allen created a series of clever approaches, including making new soil, because the old soil in the city was polluted with industrial wastes, by combining old coffee grounds with city-generated wood wastes and discarded supermarket food. He placed this new soil mixture in plastic hoop houses to heat while it evolved into excellent compost; following that, it was used for growing crops on tables. This entire enterprise was coordinated with local residents including children, who were encouraged to grow and sell their own produce. As a result, vacant lots in the inner city started producing affordable and highly nutritious food. This entire effort was propelled by Allen’s enormous charisma in a movement called “growing power”, and it was eventually exported to Chicago and other cities around the U.S. Similar projects are springing up in many places. How much impact all this will have in the future remains to be seen, but it it certainly one of the most exciting new ideas we have seen. How many future farmers of America are now inner city kids? On a smaller scale we recommend Mel Bartholemew’s (2006) book “Square foot gardening" (2nd edition) for another innovative way to personal low energy food production.

The full potential of urban agriculture remains to be seen, but it is certainly one of the most exciting new ideas on the rise. Cities, such as Baltimore, Washington, D.C., Pittsburgh, and New York are also starting to have more and more urban agriculture, including the White House bee hive.[88] Urban agriculture has the potential to create a sense of community, to raise awareness of sustainable agriculture, to reduce inner-city food deserts, to reduce food miles, and to feed populations. Although urban farms are limited in space, their potential exceeds the mere premise of food production and has potential to counter industrialized areas through some positive green space with tremendous potential to have positive impacts on agriculture.

15.5.3 Case Study: Syracuse and Onondaga County

Syracuse and Onondaga County provide an example of a geographic region that could decrease its environmental footprint by switching to a plant-based diet. A 2012 study by Balogh et al. quantified the food demand, production, and footprint for this small city and its surrounding county[89] over the past 100 years. Farms in this region have increased their caloric output since the 1930s despite a consistent decline in the overall area dedicated to farming. This can be attributed to increasing yields and the shift to more productive crops, as well as the increased inputs of fertilizers and energy more generally. They found that, from current farmland, the county could meet only 15 % of its food demand. Each year, the existing farms use energy equivalent to approximately 1.2 million barrels of oil. Furthermore, the county residents would require the equivalent of an 2.5 million barrels of oil per year to feed the local population solely from locally produced food. Transportation alone makes up 11 % of this annual energy demand. If the county were able to produce half of the food demanded by its residents, transportation energy could be reduced by 43 %. Larger reductions in energy consumption could be achieved by a shift to a low meat[90] or vegetarian diet. Two-thirds of county residents could be fed a vegetarian diet from the land that is currently under agricultural production. Despite this potential, it would require an area of farmland nearly twice the total size of the county, given the current meat consumption levels of the area's residents.

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[88] See the White House Bee Hive video at https://www.whitehouse.gov/photos-and-video/video/inside-white-house-bees (last accessed April 7, 2015).

[89] Total population: 450,000. Based on Balogh et al. (2012).

[90] In this case, consuming meat once per week.

15.5.4 Case Study: Jevons' Paradox

Technology is usually seen as advancing and improving efficiency in different areas, such as food production or healthcare. In the past, most technological advances came from applying more fossil energy to the problem at hand, which ranged from fertilization of exploited soils, pesticide-treatment of GMO monocultures and similar unsustainable practices. Although, more recently makers of technology are attempting to use less energy, agricultural and biotechnology, however, is a double-edged sword, the benefits of which can be substantially blunted by Jevons' Paradox. This paradox centers on the idea that increases in efficiency often lead to lower prices, which, in turn, encourage greater use of the product in question.

Jevons[91] found that more efficient steam engines, which had been designed to use less coal, were cheaper to run and so that people used them more. A contemporary example is that more fuel-efficient automobiles tend to be driven more miles in a year and hence may consume greater energy resources overall. Likewise, Eva Alfredsson[92] found that, in Sweden, those who followed a lower-carbon, less energy-intensive diet saved money and tended to take vacations further away, often emitting as much or more carbon dioxide—essentially, using more energy—than they saved with their "green" diet.

Thus, without clear and distinct data to educate consumers and policy makers about what a truly sustainable diet or lifestyle represents and how it can be achieved, many practices intended to conserve resources will backfire and feed hypocritical greenwashing.

15.5.5 The Need for Quantitative Analysis

The current information gaps and lack of reliable predictions into the future of energy in the food system can be addressed through sound solution-oriented environmental science. There are countless examples of "greener" approaches to agriculture and food production, but on closer quantitative examination the benefits of these methods are ambiguous at best.[93] When it comes to "sustainability," there seems to be a deficit of hard, quantitative analysis in most U.S. national assessments, as well as in the research taking place at American colleges. Much of the authors' work has been to educate young people who think they already know the answers, when, most often, neither they nor their instructors actually have any of the answers. Many of students, for example, are anti-fracking, or anti-coal, or anti-nuclear or anti-something else. How we are going to balance the human

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[91] Jevons (1865).

[92] Alfredsson (2004).

[93] Alfredsson (2004).

population's energy expectations remains to be seen. Nonetheless, in educational institutions, however, whatever the name of the program, it is crucial to teach "environmental science" and not just "environment" so as to properly educate students how to generate and test hypotheses, how to perform quantitative assessments, how the natural and social sciences are connected, and other important skills that will equip them to critically analyze how to best meet their country's future energy needs.

Government agencies and non-government organizations should strive to perform comprehensive systems-based analyses of current food production. These studies should include connections to the larger-scale global system as well as the impact on smaller-scale regional and individual agriculture production. Moreover, the studies should examine economic impacts, but should also be grounded in the biophysical reality in which agricultural systems exist—taking into consideration, for instance, a nation or region's stocks of freshwater and soil, as well as whether and how access to energy resources changes dynamically over time. It is important for the U.S. to have a well-funded National Institute of Agricultural Assessment where these issues can be studied thoroughly, independently, and objectively. Careful and thorough quantitative analyses are, in environmental science, the first step to creating policies that preserve the long-term health of the environment and ensure sustainable agricultural production. Legislation and policy can only yield effective solutions if it is grounded on sound environmental science.

15.5.6 Phosphorus: The Ultimate Limiter?

Plants need more than nitrogen fertilizer to survive and grow—especially in light of the often excessive use of artificial fertilizers in conventional agriculture. Phosphorous and potassium are critical too, as well as smaller quantities of sulfur, molybdenum, and perhaps a dozen other essential plant nutrients. When nuclear scientists Goeller and Weinberg examined the entire periodic table, they found that for all of the elements necessary to civilization, there is a substitute. For example, aluminum wires can substitute for copper; the Haber process can use energy to create substitutes for organic sources of nitrogen. Goeller and Weinberg found one exception, however: phosphorus.[94]

Phosphorus is essential for plant growth and life in general. However, it is somewhat rare and there is no substitute for it in plant metabolism. In the paraphrased words of geochemist Edward Deevey some five decades ago, "there is something peculiar about the geochemistry of the Earth today that life is so dependent upon phosphorus but it is now in such short supply."[95] In other words,

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[94] Goeller and Weinberg (1976).

[95] Deevey (1960), p. 194.

life on earth may have initially evolved when phosphorus was more abundant. Today, most phosphorus comes from mines in Florida or Morocco, or is mined in the Western Sahara. Much of this phosphorous goes on a non-renewable trip from mine, to ship, to fertilizer bag, to crop application, to the crop itself, to animals, to humans, to toilets, to waterways, and finally to the ocean. The chemistry of phosphorus, therefore, is of great concern to modern economies because of its critical importance and non-substitutability for plant growth, indeed for all life. Another reason for its importance are that the main sources (in Florida and Morocco) are being increasingly depleted. Phosphorus now requires more energy to be produced and it also causes undesirable algae growths as a waste product in water bodies. With most phosphorus ending up diluted beyond recovery in the world's oceans, it is vital to invest in a better understanding our dependence on phosphorus and how to best conserve it. This means that the essential pathways of phosphorous use must not only be understood, but should also be explored in search of more sustainable and environmentally-friendly alternatives.

15.5.7 Continuing Population Growth

Thomas Malthus, who was mentioned earlier in this chapter, believed that humans would continue to have about the same number of children per female, and that this constant rate of increase would be applied to an increasing total number of families over time, thus leading to exponential growth. Malthus also believed, however, that food production would grow linearly, ultimately leading to starvation as the population outstripped food availability. Since Malthus' time, in fact, the human population and food production have both increased exponentially, with food production arguably increasing even somewhat more than the human population. The rise in food production tends to be attributed to technology, meaning plant breeding and better farm management, and especially an increased use of fertilizers and machinery. Arguably, the reasons for increased food production are indeed in large part due to industrial agriculture, but perhaps there could have been another way. Kimbrell has hypothesized that a more sustainable, less industrially intensive food production system could possibly bring about yields as great or greater.[96] In the meantime, we seem to be married to industrial agriculture by necessity, which is quite dangerous as human populations continue to grow and petroleum supplies seem less certain.

All of the energy inputs, ranging from water to chemicals, are based on an increasing use of petroleum in industrial agriculture and in the face of globalization. Until recently, petroleum production was also increasing exponentially—this is no longer the case and slowing growth in petroleum production and the substitution of ethanol for gasoline are causing a host of other environmental concerns for

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[96] Kimbrell (2002), pp. 3–36.

modern agriculture. What Malthus' equations lacked, therefore, was a factor for the invention and enormous expansion of petroleum-based agriculture. Of course, if petroleum supplies becomes seriously constrained and good substitutes are not found, then, in the long run Malthus' predictions will prove to be correct. Thus, alternatives must be found that are less petroleum-dependent and more sustainable.

15.6 Conclusion

As long as conventional and intensive agriculture remain largely dependent on petroleum and as long as people fail to see the value in a locally-sourced organic whole-foods plant-based diet, true environmental sustainability cannot be achieved and agriculture will likely remain at odds with nature. In fact, many neoclassical economists, technology supporters, and empiricists argue that technological advancements will allow indefinite growth in agricultural productivity.[97] They postulate that new technologies, such as genetically modified organisms (GMOs) and better irrigation systems, will boost crop yields and crop efficiency. On the other hand, most economists believe that market incentives such as higher fuel prices will generate greater energy efficiency in agriculture through technical and managerial changes.[98] These changes could include reducing the amount of land in cultivation, thereby increasing the average quality of that land left in production, possibly increasing farm size, and reducing rates of energy use through technological improvements. Cleveland[99] concluded that from 1978 to 1990, U.S. agriculture made significant improvements in energy productivity through technical and managerial changes in response to higher fuel prices. By 1990, however, U.S. agricultural energy efficiency had returned to 1950s levels for a variety of reasons beyond the scope of this chapter. We need a much better assessement of energy and agriculture country by country.

Global energy resources face an uncertain future in the current post-peak and climate-challenged oil age.[100] Real crude oil prices have increased at least fourfold in recent decades.[101] As the US stands on the brink of what will undoubtedly be a significant change in how humans obtain and use energy, the uncertain future but certain price hikes (eventually) pose powerful and yet insufficient incentives for increasing energy efficiency. Therefore, it is important to determine the energy efficiency of agriculture using an energetic analysis, rather than a traditional economic cost-benefit analysis. An economically-focused cost-benefit analysis often ignores important factors, such as externalized costs to the environment and social integrity. The objective of a more complete energetic analysis should,

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[97] Jorgensen (2011), p. 276; Minten and Barrett (2008), p. 797.

[98] Cleveland (1995), p. 111; USDA (2011), p. 87.

[99] Cleveland (1995).

[100] Hall and Ramirez-Pascualli (2012).

[101] United States Energy Information Administration (2014).

therefore, be to determine whether the energy efficiency in agriculture has increased substantially by region over the past several decades. Although this chapter focuses solely on human food energy produced by agriculture—as opposed to all energy produced by agriculture, which would include the energy implicit in inedible silage, fiber crops, animal bones and fuels, another objective remains to determine the amount of energy (in joules) used by each major agricultural input and to compare their individual efficiencies, to calculate the output percentage in the form of crops, meat, and livestock feed, to show the environmental impact of crops grown exclusively for biofuels, and to compare the results of this study against the results of two extant studies on the energy efficiency in the U.S.[102] and in other regions of the world. Such an analysis may help to determine the global energy resource availabilities, efficiencies, and vulnerabilities and whether all of the rhetoric about sustainability has obtained any real results that would compensate for depeltion of soils, fertilizers and petroleum and, especially, for increased wastage, affluence and human numbers.

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[102] Hamilton et al. (2013), p. 1764 and Cleveland (1995).

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