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Fossil Fuel and Food Security

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1. Introduction

The ongoing growth of global population, projected at about 9 billion by mid-century, has prompted increasing attention to the challenge of adequate nutrition. Food production outpaced population growth during the late 20th century, owing to increases in land devoted to food production, large increases in fertilizer use and irrigation, and notably the introduction of high yielding strains of major grain crops. Even so, roughly 1 billion people, primarily in developing countries, remain undernourished, while comparable numbers, mostly in rich nations, have become obese.

Fossil fuels play critical roles in the contemporary global food system, yet potential limitations in fossil fuel supplies receive scant attention in current discussions of food security. This chapter reviews elements of food security that depend on fossil fuels, highlights the potential instability of fossil fuel supplies, and considers the corresponding impact on food security over the coming decades as the human population increases.

The narrative proceeds as follows. Many authorities acknowledge food security as a global challenge for the coming decades (Section 2). These narratives highlight the enormous success of the Green Revolution in expanding food supplies in the late 20th century, but underplay the reliance of this success on the widespread availabilty of inexpensive fossil fuels (Section 3). Climate change, which is driven primarily by fossil fuel burning and by deforestation to expand agricultural lands, increases the food security challenge (Section 4). Finite supplies and increasingly difficult access to fossil fuel resources already have impacted fuel and food prices; their impact is virtually certain to grow in the coming four decades that form the primary focus of food security discussions (Section 5). Sustainable agricultural methods, particularly including reduced dependence on fossil fuels, are essential to meet growing human nutritional needs in a stable way, and sustainability in the food system also requires attention to other dimensions of food security (Section 6). Increasing fossil fuel costs will prompt evolutionary changes in the movement of food from farm to fork in different parts of the world (Section 7). Addressing the food security challenge in the face of fossil fuel scarcity is a critical element in the transition to a sustainable human economy based on renewable energy resources (Section 8).

2. Food security

The United Nations Food and Agriculture Organization (FAO) provides a definition of food security that was formulated at the 1996 World Food Summit (FAO, 2008):

Food security exists when all people at all times have access to sufficient, safe, nutritious food to maintain a healthy and active life.

The FAO document identifies four dimensions of food security: (1) availability—food supply from production, stocks, or trade; (2) access—the ability of individuals to purchase food at local market prices; (3) utilization—household processing and physiological intake of adequate nutrition; and (4) stability—continuity over time of availability, access, and utilization. More recent discussions of food security at the local level have added a fifth dimension: cultural appropriateness (Community Food Security Coalition, 2011).

Since the 1980s, food production has only kept pace with population growth, as shown in Figure 1. Consequently, recent discussions of food security (e.g., Worldwatch, 2011; *Science*, 2011) focus on expanded food production. They identify multiple challenges.

- Limited availability of additional lands for cultivation
- Low productivity in regions, especially sub-Saharan Africa, largely untouched by the Green Revolution
- Declining soil fertility, particularly owing to population pressure undermining traditional practices of fertilization with manure and regular fallowing of fields
- Soil erosion under intensive cultivation
- Declining water resources as surface flows become fully appropriated and aquifers are mined unsustainably
- Losses of both agricultural and wild biodiversity as intensive production of a limited number of crops and application of agricultural chemicals affect natural ecosystems
- Substantial losses of crops to pests or spoilage, as well as consumer waste
- Land use competition between food production and other uses, especially biofuel production
- Climate change, with projected increases in temperature and variations in water availability

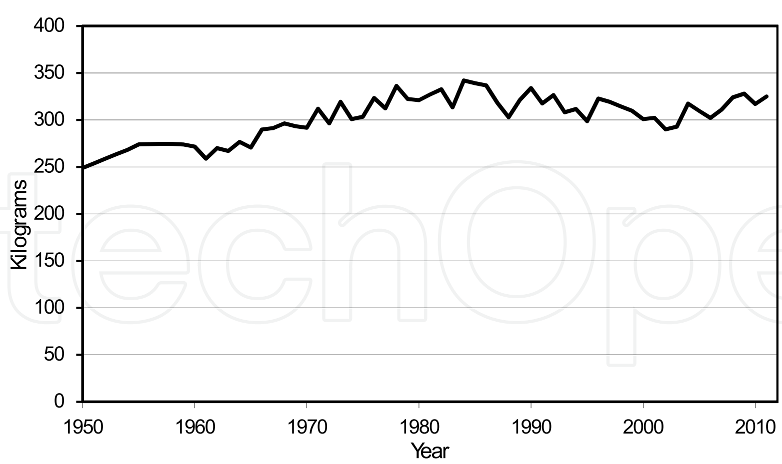

Fig. 1. Grain production per capita, 1950-2011 (Earth Policy Institute [EPI], 2008, 2011a; U.S. Census Bureau, 2011).

Although these reviews include stress on agricultural methods that can be sustained over long time periods, they scarcely mention the dependence of global agriculture on fossil fuels. As detailed in Section 5, a high probability exists that in the coming decades, even apart from policies to mitigate climate change, energy supply limitations will lead to much higher costs for these non-renewable resources. This will impose an additional challenge to meeting global food security needs.

Fossil fuel limitations primarily impact the availability and stability dimensions of food security. The Worldwatch (2011) and *Science* (2011) reviews also address food access as a critical dimension of food security, a point revisited in Section 6.

3. The green revolution

Increasing food supplies, together with improved medical care, made possible the explosive growth of world population from 2.5 billion in 1950 to 7 billion today.

Much of the spectacular improvement in agricultural production is rightly attributed to development of high-yield strains of the major cereal crops, rice, maize, and wheat (Evenson & Gollin, 2003). Dwarf varieties allowed plants to bear more fruit without collapsing, enabling mechanized application of fertilizer (Figure 2), as well as pesticides and herbicides, greatly enhancing the productivity of land while reducing farm labor (Freebairn, 1995). A great increase in irrigation (Figure 3) further improved productivity and brought addidtional, mostly marginal, lands under cultivation (Figure 4). Notably, however, irrigated area per person has been constant within a few percent since 1960 (EPI, 2011b).

The level of fossil fuel dependence differs significantly between developed and developing countries. Although total primary fossil energy input into farm production is comparable between developed countries and developing countries, as illustrated in Figure 5, developed countries use more than four times the energy per capita (8.0 gigajoules/capita/year) than developing countries (1.7 GJ/capita/year). Moreover, Figure 5 further reveals very different distribution of energy use across agricultural inputs. For developing countries, nitrogen fertilizer accounts for more than half the energy inputs, with fuel and irrigation forming the next largest inputs. By contrast, in developed countries, fuel and machinery account for more than half the inputs, with nitrogen accounting for about one quarter.

Primarily as a consequence of this disparity, the farm inputs alone in developed countries average about 2 units of fossil fuel energy inputs for every unit of food energy, whereas in developing countries, the ratio is less than 1 to 2 (Giampietro, 2004, Table 10.7). These figures illustrate the heavy fossil fuel dependence of industrial agriculture.

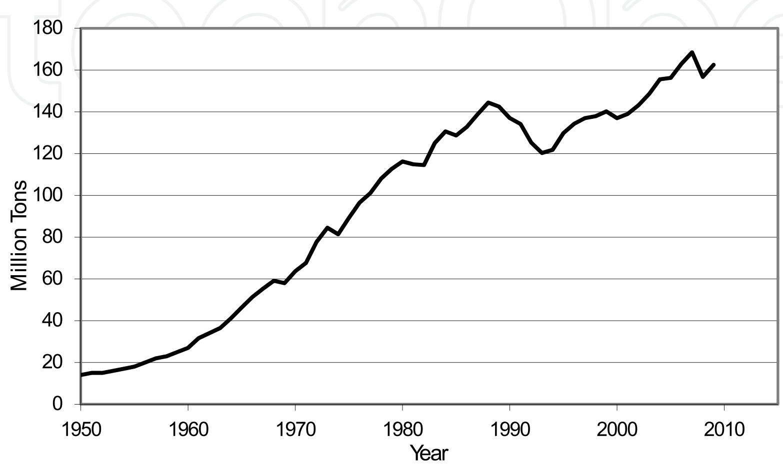

Fig. 2. Global fertilizer use, 2009 (EPI, 20011c).

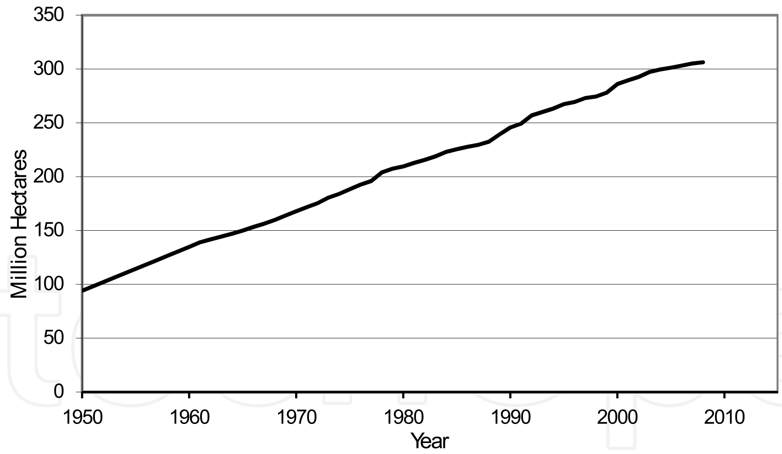

Fig. 3. Global irrigated area, 1950-2008 (EPI, 2011b).

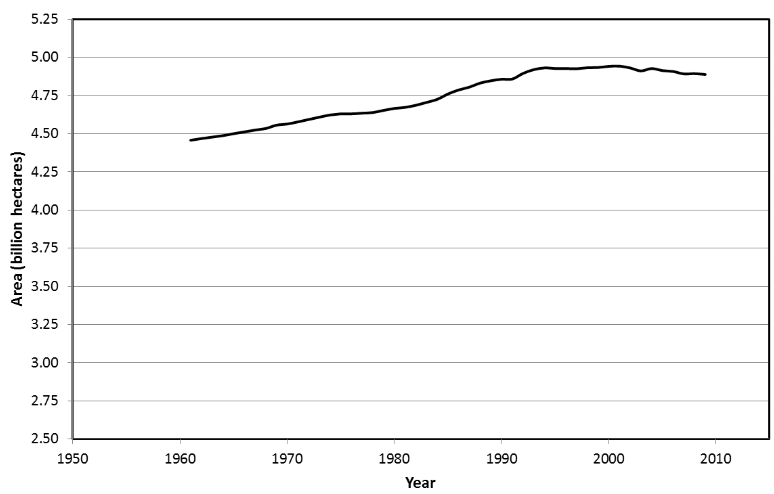

Fig. 4. Global agricultural area, 1961-2009 (FAO, 2011a).

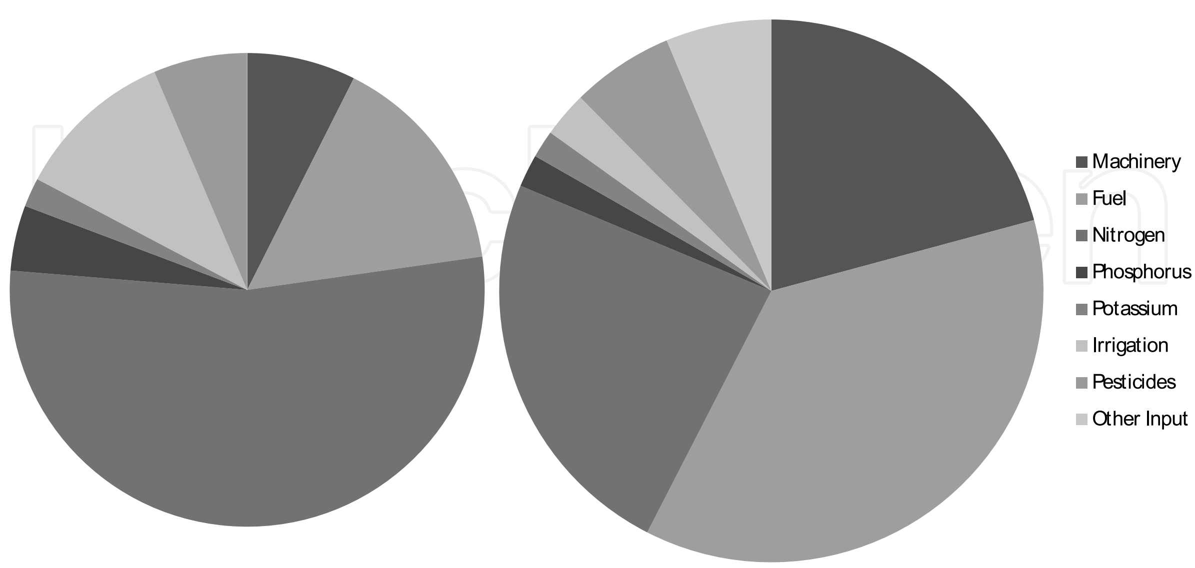

Fig. 5. Distribution of farm energy inputs in developing countries (left) and in developed countries (right) (Giampietro, 2004, Table 10.2). The areas are proportional to total energy use: 8 EJ/year and 10 EJ/year, respectively. Successive input sectors appear clockwise from the top.

Pimentel et al. (2008) have assembled case studies of cultivation of a variety of crops in both developed and developing countries. In general, their data indicate that developed countries achieve much higher yields with much less human labor, with the difference coming from fossil energy. Consequently, developed country production is more expensive and less energy efficient. In most cases the output energy is less than the input, whereas the opposite is true in developing countries (with the few exceptions probably coming from animal energy—which is provided by forage unavailable for human consumption). To cite an extreme example, apple production in the United States achieves 9 times the yield per hectare, but with overall energy efficiency of 40% compared to India and nearly 100 times the economic cost.

The fossil fuel dependence of the food system in developed countries, however, is much larger still, because farm production accounts only for about 20% of the total system inputs. Indeed, the largest single contribution comes from food preservation and preparation in the home, with additional substantial contributions from transportation and food processing (Figure 6).

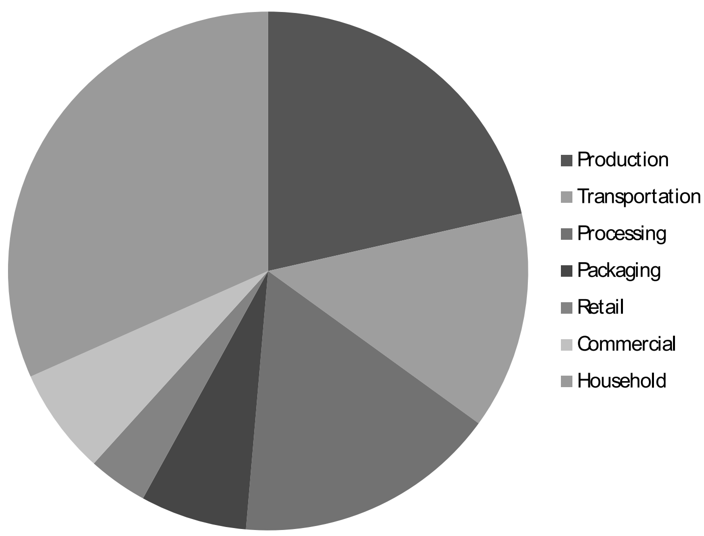

Fig. 6. Distribution of energy inputs in the U.S. food system (Heller & Keoleian, 2000, p. 41). Successive input sectors appear clockwise from the top.

4. Climate change

The Intergovernmental Panel on Climate Change (IPCC, 2007) has summarized the evidence for climate change, its likely impacts, and possible mitigation and adaptation measures. Heat-trapping by so-called greenhouse gases, most importantly carbon dioxide (CO_2), is warming the global climate (IPCC, 2007, p. 2). Most emissions (57%) of these gases come from fossil fuel burning, with an additional 17% contribution from deforestation, decay of organic matter, and peat (IPCC, 2007, p. 5). Deforestation is largely driven by expanding populations bringing additional land under cultivation. A breakdown of emissions by sector attributes nearly 14% to agriculture and another 17% to forestry, although these figures do not include other post-farm contributions from the food system. Agriculture accounts for roughly 50% of methane emissions (mostly from rice paddies and ruminant animals) and 70% of nitrous oxide emissions (mostly associated with nitrogen fertilizer) (IPCC, 1996, pp. 49-53).

Climate change will have significant impact on agricultural productivity and consequently on food security (Table 1).

Agricultural systems have long adapted to slow variations in climate and it is likely that they will do so under the projected warming of the 21st century. Nevertheless, climate change impacts on global agriculture already have had demonstrable negative effects on agricultural output (Lobell, Schlenker, & Costa-Roberts, 2011). Beyond such impacts, a growing rate of extreme events promises to be especially disruptive. The correlated events of the 2010 drought in Russia and flooding in Pakistan (Lau & Kim, 2011) had global consequences through their impact on food prices. In particular, high food prices in the Middle East, which resulted in part from unavailability of Russian grain, along with other obvious social and political factors, contributed to the political unrest that unseated several governments (Lagi, Bertrand, & Bar-Yam, 2011). Although no individual weather event, much less individual civil events, can be attributed solely to climate change, models consistently predict increasing frequency of extreme weather events (IPCC, 2007, p. 13). Together, both cumulative slow impacts and severe local events will exacerbate the challenge of achieving global food security.

Phenonomenon & Trend	**Estimated Likelihood**	**Agricultural/forestry/ecosystem Impact**
Over most land areas, warmer and fewer cold days and nights, warmer and more frequent hot days and nights	Virtually certain	Increased yield in colder environments; decreased yields in warmer environments; increased insect outbreaks
Warm spells/heat waves. Frequency increases over most land areas	Very likely	Reduced yields in warmer areas due to heat stress; increased danger of wildfire
Heavy precipitation events. Frequency increases over most areas	Very likely	Damage to crops; soil erosion, inability to cultivate land due to waterlogging of soils
Area affected by drought increases	Likely	Land degradation; lower yields/crop damage and failure; increased livestock deaths; increased risk of wildfire
Intense tropical cyclone activity increases	Likely	Damage to crops; windthrow (uprooting) of trees; damage to coral reefs
Increased incidence of extreme high sea levels (excludes tsunamis)	Likely	Salinisation of irrigation water, estuaries, and fresh water systems

Table 1. Projected impacts of climate change on agriculture, forestry, and ecosystems (IPCC, 2007, p. 13)

Global diplomatic action to mitigate climate change has stalled. Most nations that ratified the 1997 Kyoto Protocol have made significant progress toward reducing greenhouse gas emissions, as have individual states in the U.S. and many cities around the world. With the two largest emitters, China and the United States, at loggerheads, current negotiations seem likely to remain stalled (Bodansky, 2011). In the absence of a wide-ranging international agreement, business as usual prevails, with emissions rising even faster than most earlier projections by the IPCC (Figure 7).

Climate change clearly will afflict agriculture and overall human well-being in the 21st century. Along with other challenges to food security, climate impacts on agriculture will exert upward pressure on food prices. Policy action to mitigate climate change by putting a price on greenhouse gas emissions, especially from fossil fuel combustion, will increase fossil fuel prices and further impact food security. Yet another complication is diversion of cropland to biofuel production, which has forged a tight link between the prices of oil and of biofuels (Figure 8). As shown and discussed in Section 6 (Figure 11), this linkage extends to food prices. Further discussion of the impact of biofuels appears in Section 6.4.

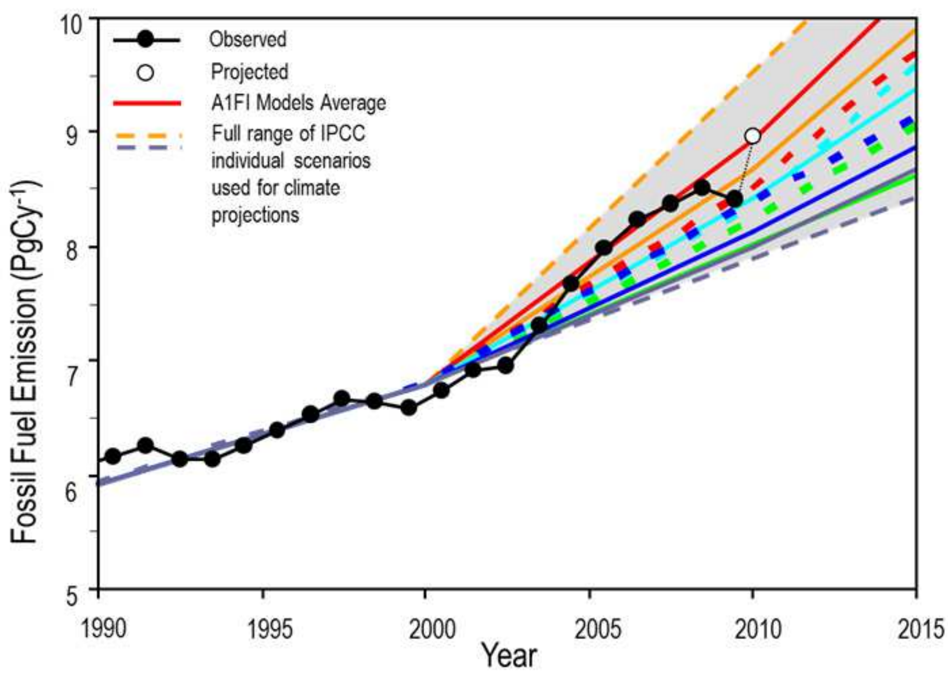

Fig. 7. Comparison of actual and projected emissions with multiple emission scenarios from the IPCC (2000, solid lines). The outer dashed lines show the full range of projected emissions. The highest solid line represents the fossil-fuel intensive scenario (Raupach, 2007, updated by Canadell, 2011).

Fig. 8. Linkage between gasoline and ethanol prices (FAO, 2011b, p. 80).

5. Peak hydrocarbons

The great abundance of easily accessed fossil fuels and the correspondingly low price of energy that fueled the Green Revolution were temporary phenomena. Consequently, impending maxima in production of oil and coal, and eventually natural gas, combined with the dependence of global food production on fossil fuels and novel demands for agricultural production of biofuels, pose a daunting challenge for food security.

Agriculture around the world depends to varying degrees on gasoline and diesel for mechanized farm machinery, for transportation of supplies to farm and ranch and deliveries of products to market, and for off-grid energy to power irrigation pumps. It depends critically on natural gas to create ammonia-based nitrogen fertilizers. In many areas, especially in developed countries, agriculture depends on coal-fired electricity for irrigation, food processing, preservation, and cooking (see sector for "Other Input" in developed countries in Figure 5). In addition, fossil fuel inputs also contribute to energy-intensive mining of phosphorus, a critical nutrient with limited mineable resources (Elser & Bennett, 2011). The fossil oil, natural gas, and coal that power modern society, in particular contemporary global agriculture, were deposited by geological processes over millions of years. Large-scale human exploitation of coal has occurred for little more than 200 years; for oil and gas the timescale is little more than 100 years. Evidence is accumulating that production of these non-renewable resources will reach a maximum in the coming decades during which humankind must meet the challenge of food security. Peak production could come much sooner.

5.1 Oil

Global production of oil reached a plateau in about 2005 and did not increase even during the extreme price rise in 2007 and 2008. Hamilton (2009) has analyzed the price spike and concluded that it resulted primarily from growing demand and inelasticity in oil supplies. Some analysts and even oil executives have asserted that the production plateau indicates the arrival of Peak Oil, the time when the global production of this finite resource reaches its maximum value (Post Carbon, 2011). Although roughly half of the global recoverable resource remains available, ability to accommodate increased demand is limited at best. Consequently, continuously escalating demand from the rapidly developing economies, especially those of China and India, which represent roughly 1/3 of humanity, promises higher prices. The oil price rise early in 2011 surely had political roots in "Arab Spring," especially the revolution and civil war in Libya, but constrained supplies already had caused rising prices before the political events unfolded (Hargreaves, 2011).

Strong differences of opinion exist about the probable timing of Peak Oil. Prominent oil analysts such as Daniel Yergin (Smil, 2011) and Vaclav Smil (2003) remain very skeptical that Peak Oil will occur in the near future. On the other hand, Fatih Birol, chief economist for the International Energy Agency (IEA) has stated, "[I]t will be very challenging to see an increase in the production to meet the growth in the demand, and as a result of that one of the major conclusions we have from our recent work in the energy outlook is that the age of cheap oil is over. We all have to prepare ourselves, as governments, as industry, or as a private car driver, for higher oil prices" (Williams, 2011). Also, military establishments have begun to include Peak Oil in their contingency planning (e.g., Bundeswehr, 2010).

The 2010 IEA World Energy Outlook projects slowly increasing oil production (less than 1% per year) to about 96 million barrels per day (Mb/d) in 2035, with falling production in producing fields compensated by oil fields yet to be developed and others yet to be found (Figure 9). The projected growth is insufficient to meet escalating demand from developing countries, especially China and India. Furthermore, successive IEA projections have been declining: 121 Mb/d in 2004, 116 Mb/d in 2006, 102 Mb/d in 2008, and 96 Mb/d in 2010. Moreover, IEA projections have been criticized by the Association for the Study of Peak Oil and Gas. For example, Aleklett et al. (2010) project just 76 Mb/d in 2030, 26 Mb/d less than the 2008 IEA projection for 2030.

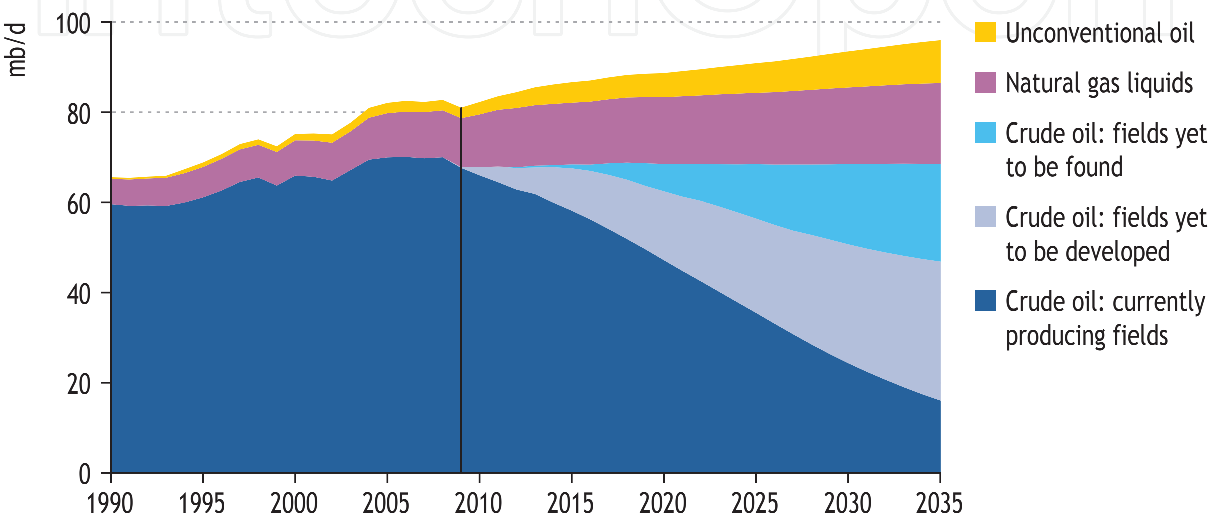

Fig. 9. Oil production by type in the IEA preferred New Policies scenario (IEA, 2010).

A major issue here is the lack of transparency about oil reserves by national oil companies, especially in Saudi Arabia. To what extent does excess capacity exist to stabilize oil prices in the coming decades? Beyond that, to what extent can unconventional sources, such as deep water fields, tar sands and shale oil raise future production and defer sharp price increases and limit volatility? One characteristic of these resources is that they yield less energy returned in sale product for the energy invested in discovery and production (Guilford et al., 2011). Consequently, they require greater energy investment and therefore greater capital investment to produce. As a result, the future—even the relatively near future—will hold higher oil prices. Besides direct impact on the cost of agricultural production, higher oil prices will increase pressure to divert cropland from food to biofuel production, raising food prices even more. Both trends will exacerbate difficulties for the poor to maintain food access.

5.2 Coal

Coal produces 48% of electricity in the United States (Energy Information Administration [EIA], 2011a) and approximately 42% in the world (EIA, 2011b, Table 66) Many utilities promote coal-burning as a low-cost alternative, but recent studies suggest that the often quoted 200 years of coal supply, both globally and in the US, is a serious overestimate.

Heinberg (2009) reviewed several available investigations and concluded that exhaustion of high quality coal reserves and infrastructure limitations on development and marketing of lower quality resources will advance the timing of Peak Coal into the relatively near future (one to two decades, not one to two centuries). Independently, Rutledge (2011) has analyzed the patterns of coal development and concluded that actual developed reserves typically are about ¼ of the early reserve estimates of the geological resource. He concludes that the world will consume 90% of producible coal by 2070. Although he refrains from discussing peak production, his analysis again points to a time no more than a few decades into the future. Patzek & Croft (2010) project a peak already in 2011, with a production decline to 50% of the peak by 2037.

Glustrom (2009) provides a bottom-up analysis of coal reserves, focusing primarily on the western United States. Analyzing the production potential of individual mines, especially in the Powder River Basin of Wyoming and Montana, which accounts for about 40% of U.S. coal production, she finds that extant surface mines on the basin perimieter have 10-20 year production horizons. Expanding production by development of new surface mines faces regulatory and infrastructure obstacles; mining of deeper deposits faces these, as well as additional energetic and economic costs. She does not analyze the coal resources of other countries in detail, but citing Rutledge and one of the same studies as Heinberg, she infers that the issue is global. Although the existence of vast coal resources is clear, the energetic and economic viability of production from lower and lower quality formations in less and less accessible places renders increasing rates of production problematical.

Consequently, expanded reliance on coal-powered electricity to meet agricultural needs faces economic challenges. These challenges apply also to post-farm components of the food system, implying an overall rise in household food expenditures, especially in developed countries where these components account for a much larger share of food system energy.

5.3 Natural gas

The situation for natural gas, the primary energy and hydrogen source for creation of synthetic nitrogen fertilizer, is more promising but still uncertain. Technological developments of hydraulic fracturing (fracking) and horizontal drilling have begun to unlock oil and natural gas from extensive shale formations. This has led to sharp increases in estimates of U.S. natural gas reserves (EIA, 2011c), as well as large increases in drilling activity in formations such as the Barnett Shale in Texas and the Marcellus Shale in Pennsylvania. The broad distribution of comparable shale formations around the world suggests that similar initiatives will lead to an abundance of natural gas potentially lasting many decades into the future. However, doubt has been cast on the most optimistic projections.

First, fracking is controversial because of its potential environmental impacts. The process involves injection into the target formation at high pressure of a large volume of water mixed with sand and a brew of chemicals, some of them toxic. The major concern is the potential for contamination of surface or groundwater. This could occur through failure of well linings intended to isolate deep wells from shallower geological strata, though spills of concentrated fracking fluids, or through inadequate treatment of fracking fluids released into local streams. An additional concern is the potential for resource conflict associated with the sheer volume of water required for fracking. As a result of such concerns, France has banned the technology (Patel, 2011). In the United States, the potential impact on drinking water prompted a Congressional mandate to the Environmental Protection Agency (EPA) to study the issue. Preliminary results are due in 2012 and a final report in 2014 (EPA, 2011, p. *x*). Fracking has been widely used for production of coalbed methane in the western U.S. and the potential energy resource is exceedingly valuable, so that the practice will continue in most countries, possibly under greater regulatory scrutiny.

Second, questions have surfaced concerning the magnitude and potential cost of shale gas production, as reviewed by Hughes (2011a). Evidence exists that shale gas wells deplete rapidly, so that the ulimtate resource is smaller than conventional projections (Figure 10). Morever, the technology-intensive drilling process (even apart from environmental concerns) requires elevated prices to be profitable—higher than present prices and higher than EIA projections for a decade or more. Consequently, either shale gas resources will prove to be smaller than early optimistic estimates or prices will rise so that shale gas can profitably accommodate growing demand.

Finally, doubt has arisen over the life-cycle carbon emissions of shale gas, particularly compared to coal, and therefore over the potential of natural gas to reduce emissions by displacing coal and thus to serve as bridge fuel in a transition to a renewable energy economy. Hone (2011) reviews this issue and Hughes (2011a) also compares two discordant shale gas-coal comparison studies. Shale gas probably would reduce total emissions, especially as best-practices evolve to minimize fugitive emissions (methane, the principal component of natural gas has roughly 20 times the heat-trapping effect as CO_2), but perhaps not by the 50% projected by the most optimistic estimates.

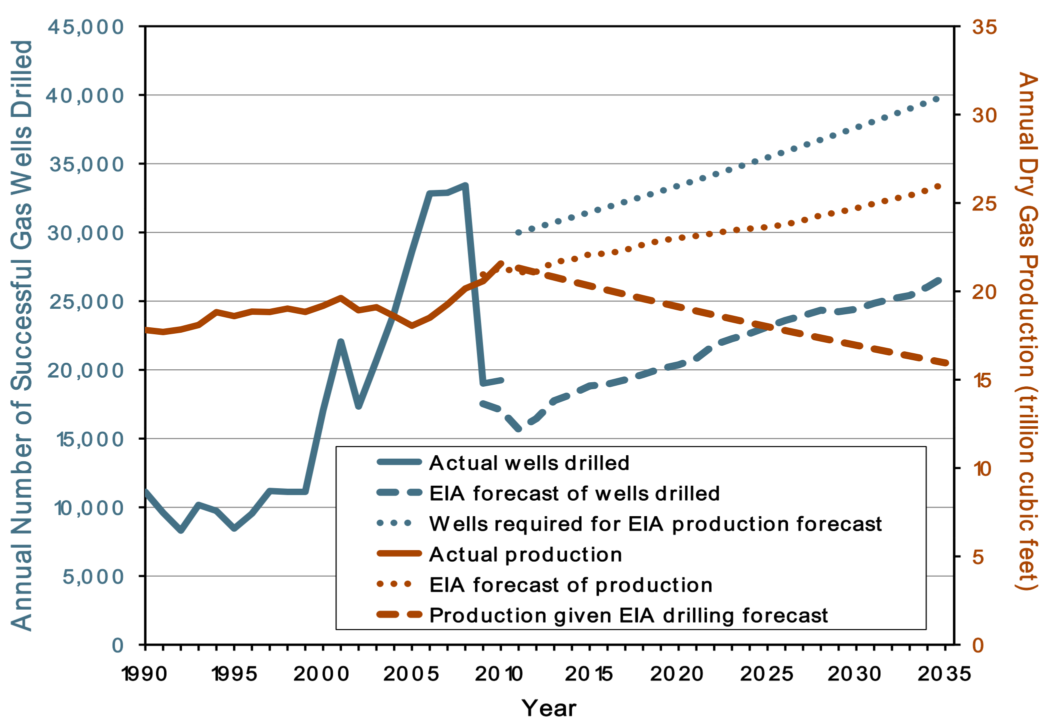

Fig. 10. Shale gas drilling rates (blue) and production (red)(Hughes 2011a). Solid lines represent historical data. Red dashed line and blue dotted line represent Hughes' alternatives to EIA projections.

No one doubts the existence of a vast geological shale gas resource, but, as for coal, conversion to producible reserves depends as much on energetics and economics as on technology. Such considerations about shale gas production will determine the ultimate magnitude of global natural gas production. Given the importance of natural gas for synthesis of nitrogen fertilizer, the evolution of shale gas production in the coming decades will have a direct impact on the cost of conventional efforts to maintain soil fertility.

In this regard and as mentioned above, the dependence of global agriculture on mined phosphorus also is a relevant concern. To the extent that fossil fuel availability contributes to the cost of mining, it will impact the price of this other critical soil nutrient.

5.4 Fossil fuels and climate change

On a marginally hopeful note, Rutledge (2010) concludes that actual fossil fuel consumption will be less than projected in *any* of the emissions scenarios considered by the IPCC (2000), yielding a peak atmospheric CO_2 concentration of 455 parts per million. If he is correct, the world has already experienced roughly half of the maximum temperature rise that will occur from fossil fuel burning—although impacts such as rising sea levels and vanishing glaciers will continue to unfold beyond 2150.

It is unlikely that the possible stabilization of long-term climate will greatly relieve stress on agricultural systems by mid-century—especially compared to the associated direct challenge of rising fossil fuel prices.

6. Sustainable agriculture

The vulnerability of the world food system and hence global food security to fossil fuel prices, as illustrated in Figure 11, renders critical the need for a transition to sustainable agricultural systems.

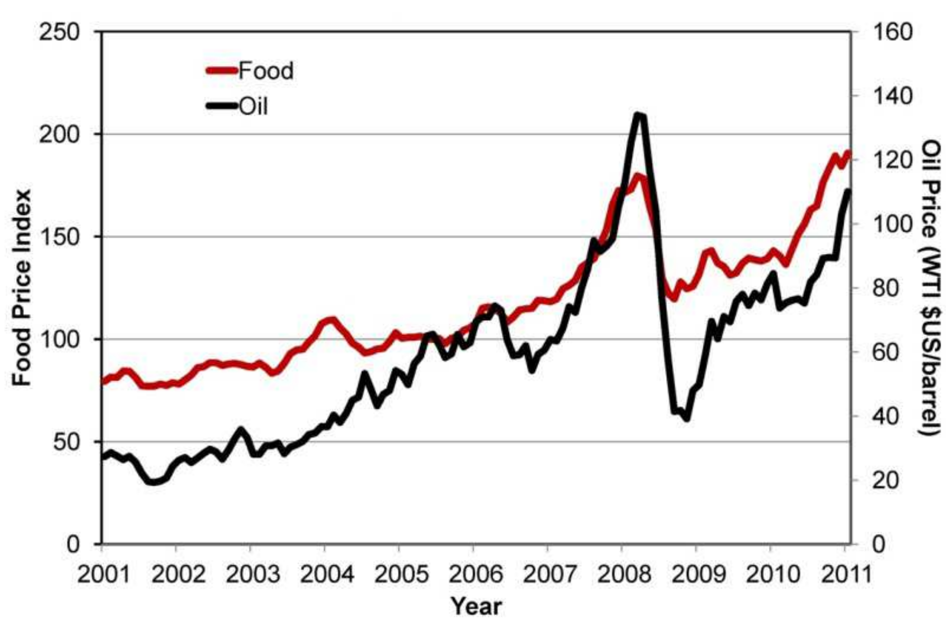

Fig. 11. Coupling of oil and food prices (Hughes, 2011b). The red line represents the FAO food price index; the black line represents the cost of West Texas Intermediate crude oil.

The great success of the Green Revolution in expanding food production faster than population during the second half of the 20th century depended on multiple developments in plant genetics, expanded use of synthetic fertilizer, increased irrigation, mechanization, petroleum-based herbicides and pesticides, and policies at the national and international levels (Smedshaug, 2010, pp. 219-222). Many of the innovations depended on low energy costs, especially for oil, that are unrepeatable. Particularly in developed countries, cheap energy has led to widespread intensification, indeed, industrialization of agriculture, with capital and fossil fuel inputs producing very high yields (e.g., in kg/ha) with very low inputs of human labor (Pimentel & Pimentel, 2008, Chapter 10). A social consequence of this has been disruption of agricultural communities and migration to cities where unemployment has been a common outcome (Berry, 2010).

For all its success, industrial agriculture is unsustainable (Tilman, 1998; Kimbrell, 2002), owing to its diverse negative effects on the environment and on social systems, which include the following.

- Reduction of agricultural biodiversity through monoculture plantings of a small number of crop cultivars
- Reduction of wild biodiversity through habitat destruction and pesticide poisoning
- Contamination of groundwater with pesticide runoff
- Eutrophication of waterways from runoff of excessive nutrients
- Reduction of soil fertility through loss of soil organic matter
- Soil erosion far in excess of natural replenishment
- Increased incidence of crop and animal diseases
- Pollution from concentrated animal wastes
- Release of greenhouse gases
- Disruption of agricultural communities
- Health impacts of agricultural chemicals, antibiotic residues in human food, and poor diets
- Opportunity costs of public agricultural subsidies

All of these impacts threaten the stability of global food production, and hence threaten food security. In addition, for all its productivity, industrial agriculture has failed to provide adequate food access to roughly 15% of the global population. Consequently, discussions of food security increasingly stress the need for agricultural systems to move to methods that can be sustained over generations (Pimentel & Pimentel, 2008, Chapter 23; Science, 2011; Smedshaug, 2010, pp. 222-225; Smil, 2010; Worldwatch, 2011). The coupling of food prices to rising prices of fossil fuels compounds this need.

The following subsections highlight proposed approaches to sustainable agriculture. Owing to the complexity of the global agricultural system, including huge differences between developed and developing countries, as well as linkages to economic and social policy, it can only provide a sampling of available information. Topics include agroecology; organic cultivation; crop breeding, including both genetically modified organisms (GMOs) and perennial crops; competition with biofuels; and proposed broad strategies.

6.1 Agroecology

The central theme of evolving global agriculture in the 21st century is “sustainable intensification,” which FAO (2011c, Chapter 1) has defined as “producing more from the same area of land while reducing negative environmental impacts and increasing contributions to natural capital and the flow of environmental services." A key element of this is agroecology, particularly practiced by small producers in developing countries, as advocated by the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD, 2009). De Schutter & Vanloqueren (2011) provide a brief for agroecology with the following definition. "Agroecology is the application of ecological science to the study, design, and management of sustainable agriculture. It seeks to mimic natural ecological processes, and it emphasizes the importance of improving the entire agricultural system, not just the plant." Following ecological principles, agroecology seeks to recycle biomass and nutrients; enhance organic matter deposition to build soil; carefully manage resources of sun, water, and nutrients; enhance biological and genetic diversity; and encourage beneficial biological synergies while minimizing pesticides. De Schutter and Vanloqueren provide sample cases of successful implementation in the developing world, identify obstacles to wider implementation (including marginalization of the targeted small-scale farmers by past policies), and articulate policies for scaling up these innovations. By following ecological principles, agroecology seeks to minimize inputs and recycle nutrients, thus greatly reducing fossil fuel inputs and improving sustainability.

6.2 Organic agriculture

In the developed world, which already practices intensive agriculture, a popular alternative to conventional methods is organic cultivation. In a major comparison between organic and conventional cultivation, Gomiero, Pimentel, & Paoletti (2011) provide the following definition. "Organic agriculture refers to a farming system that enhances soil fertility through maximizing the efficient use of local resources, while foregoing the use of agrochemicals, the use of GMOs, as well as that of many synthetic compounds used as food additives. Organic agriculture relies on a number of farming practices based on ecological cycles, and aims at minimizing the environmental impact of the food industry, preserving the long term sustainability of soil and reducing to a minimum the use of non-renewable resources."

Some commentators flatly state that organic agriculture cannot feed the world. Gomiero et al. (2011), however, offer a more complex picture, which is framed by the difficulty in making apt comparisons between conventional and organic agriculture. Studies differ in how they define system boundaries, e.g., including or excluding indirect energy costs, leading to wide divergence in resulting estimates. Further, most such studies focus on single crops and analyze data for just a few years. Whereas conventional agriculture increasingly relies on monocultures, organic agriculture flourishes by rotating and varying crops over multi-year cycles. Moreover, long-term trends, especially on soil fertility—in which the two systems exhibit opposite effects—do not emerge in short-duration investigations. The authors document that organic agriculture is superior on virtually every aspect of environmental performance, particularly energy efficiency. Productivity data are mixed, with yields generally higher for conventional agriculture by perhaps 20%, but with differences between developed countries, where organic yields tend to be lower, and developing countries, where they tend to be higher. Given what is now decades of research and investment in conventional agriculture, the likelihood that organic yields could become equal or better given comparable investment of resources deserves serious consideration.

The Rodale Institute, long a leader in research on organic agriculture, recently issued a report on its 30-year study comparing conventional and organic cultivation (Rodale, 2011). The report documents comparable yields between the two systems, with fewer inputs, lower carbon emissions, and higher profitability from the organic fields. While some of the higher financial returns depend on the market premium paid for organic crops, the large profit disparity (organic: $224/ha/year; conventional: $60/ha/year) implies that much of the difference comes from the much lower cost of inputs. Although the contribution of organic agriculture is growing rapidly, critics point out that organic cultivation still accounts for only about 1% of U.S. production. Moreover, as pointed out by Pollan (2006, p. 184), "Big Organic" cultivation (eschewing synthetic fertilizer, pesticides, and GMOs, but not industrialized production methods) is not necessarily sustainable or free of concerns about fossil fuel scarcity: "As in so many other realms, nature's logic has proven no match for the logic of capitalism, one in which cheap energy has always been a given. And so, today, the organic food industry finds itself in a most unexpected, uncomfortable, and, yes, unsustainable position: floating on a sinking sea of petroleum."

A case study in agriculture after Peak Oil comes from the Cuban experience in the 1990s following the collapse of the Soviet Union, which eliminated both the source of almost all of its oil imports and also markets for Cuban agriculture. Wright (2009) has studied this example and documented the dramatic shift to organic methods. The example may be imperfect, because Cuba's isolation from global markets and industrial inputs are unique historically, but it does indicate the ability of organic agriculture and ample labor to produce an adequate food supply with minimal fossil fuel inputs.

6.3 Crop breeding

An unquestioned need exists for continued advances in crop breeding to produce cultivars adapted for specific habitats and circumstances, including climate change. Whether these techniques should include genetic engineering is controversial. Acknowledging the challenges of sustainable agriculture, many food security experts, such as Fedoroff et al. (2010), strongly advocate GMOs as necessary to the solution. Goals include breeding grain crops that would fix nitrogen, eliminating the need for synthetic nitrogen fertilizer, the most fossil fuel-dependent agricultural input in the developing world. Others, such as Benbrook (2011) take a more skeptical view, especially for developing countries. To the extent that genetically engineered cultivars depend on fossil fuel-dependent technologies, they will fail to meet the coming challenge of increasing fossil fuel costs. Likewise, the profit-driven choice of cultivars, with restrictions on seed saving, local experimentation, and innovation, appears inadequate to address the essential needs of small-scale agriculture that feeds 80% of the world's people.

Regardless of the resolution of the GMO debate, advances in molecular biology have provided powerful tools for advancing conventional crop breeding. One advocate of this approach is the Kansas-based Land Institute. Consistent with the agroecology approach, Land Institute founder Wes Jackson and his colleagues advocate a sustainable "next synthesis" based on cultivation of perennial grains (Jackson, Cox, & Crews, 2011; Glover et al., 2010). Jackson et al. argue that these crops can reconcile ecological sustainability with the productivity needed to meet human needs, in the process providing both a model and metaphor for the material economy.

6.4 Competition with biofuels

Demand for alternative liquid fuels has driven diversion of cropland to biofuel production, resulting in close coupling between the prices of oil and agricultural commodities illustrated in Figures 8 & 11. Advocates such as Collins & Duffield (2005) are optimistic about the ability of conventional U.S. agriculture to meet world food needs, as well as to make a significant contribution to biofuel production. Sustainability-minded analysts Giampietro & Mayumi (2009), however, argue that biofuels (at least those produced from agricultural crops) reduce food supply, increase CO_2 emissions, and retard rural development. Addressing the broader question of meeting a large fraction of human energy needs with biomass, Smil (2010, p. 721) dismisses the idea as an insufferable intrusion on the necessary functioning of the biosphere. Smil does not address specifically either crop residues or grasses as possible biofuel sources, but his general energetic analysis underscores concerns that extensive exploitation these non-crop biological resources would undermine necessary nutrient recycling. Acknowledging the impact of energy prices on food prices and the volatility of food markets, Koning & Mol (2009) call for new institutions to balance food and energy markets.

6.5 Proposed strategies

Two recent reviews (Godfray et. al, 2010; Foley, et al., 2011) identify broad strategic approaches to sustainable food security that incorporate to some extent all sides of the issues addressed in Sections 6.1 to 6.4. The suggestions of the two articles overlap to some degree and include the following.

- Stop expanding agriculture. The environmental benefits of preserving sensitive ecosystems would outweigh the marginal loss of increasing production, especially in the tropics.
- Close yield gaps. Improving realized productivity toward what is achievable with locally available genetic material, technology, and management could improve yields in many regions by tens of percent. This is the thrust of the sustainable intensification efforts discussed in Section 6.1, though there are many complexities and necessary local variations.
- Increase agricultural resource efficiency. Careful management of both water and nutrient inputs can avoid both deficiencies and excess applications that produce environmental degradation. Great scope exists for more precise applications in time and space.
- Increase production limits. Greater yields would result from optimizing cultivars for specific conditions, especially those in developing countries, by conventional plant breeding or genetic engineering. Preservation of agricultural biodiversity, especially of locally adapted crops and livestock, is an important component of this effort.
- Increase food delivery by shifting diets and reducing waste. Limiting diversion of crops to uses such as animal feed and biofuel production would increase the amount available for direct human consumption. Likewise, the 30% or more of harvested food lost to pests, degradation, and discard could feed many more people.
- Expand aquaculture. This initiative would continue current trends, but also focus on minimizing environmental impacts.

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Godfray et al. (2010, p. 817) conclude by stating, "The goal is no longer simply to maximize productivity, but to optimize across a far more complex landscape of production, environmental, and social justice outcomes." Figure 12 vividly illustrates the challenge.

Notably, neither of these reviews acknowledges possible fossil fuel scarcity and high costs as challenges to food security.

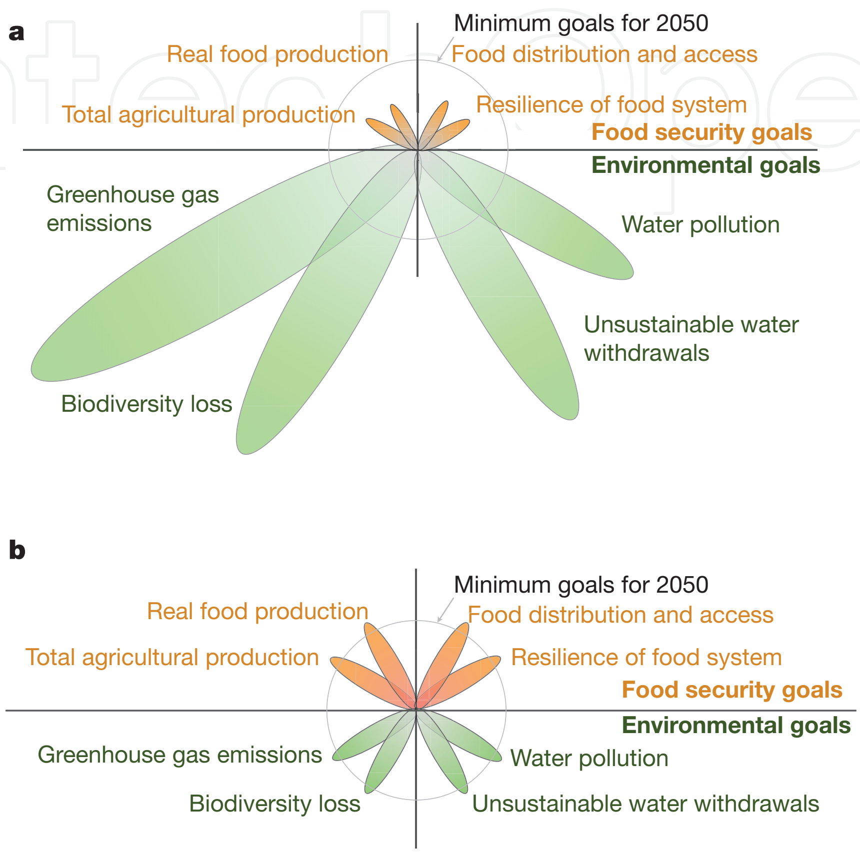

Fig. 12. Qualitative comparison of (a) the present state of global agriculture and (b) projection for meeting food security and environmental goals for 2050 (Foley et al., 2011.)

6.6 Other commentaries

Smil has written extensively on both food (2000) and energy (2003). He is optimistic that fossil fuels will remain abundant for several decades and that the agricultural system has sufficient inefficiencies to accommodate the needed productivity growth while undergoing transition to a renewable energy base. In *Energy at the Crossroads* (2003), he stresses the fact that an energy transition on the societal scale projected in the coming decades will itself require decades, owing to the massive capital investment required and the time needed for these investments to bear fruit. The same consideration clearly applies to the agricultural system as well. As an optimist about energy supply, Smil does not consider the possibility, as does Heinberg (2009), that the upfront energy investment required for renewable energy technologies and potential limits in absolute energy supply could prevent the needed investments. He does, however, stress the need for more equitable distribution of both energy and nutritional resources at levels intermediate between the current consumption levels of developing nations and of the highest consuming nations, particularly the United States.

Bottom-up analyses such as Smil's, typically take little account of institutional inertia that creates significant obstacles to widespread achievement of possible system efficiencies. One such potential obstacle is the disparate influence on agricultural systems and food trade between rich nations and transnational corporations on the one hand, and poor nations and small farmers on the other (FAO, 2003). The new movement for food sovereignty (Wikipedia, 2011) is a grass roots attempt to redress this imbalance, asserting as a human right access to healthy, culturally appropriate, sustainably produced food.

Pimentel and Pimentel (2008, Chapter 23) are less sanguine than Smil about the energy future. They review future food needs, energy requirements for producing the food, constraints on land and water, climate change, and environmental pollution. They stress, as do none of the other sources discussed here, that lowering birthrates is an additional food security and sustainability strategy. They acknowledge the social challenge involved in conveying to parents that having smaller families would serve their interests and those of their children, but do not mention evidence that improving the status and education of women yields multiple societal benefits, including voluntary fertility reduction. The gender gap in world agriculture is highlighted by the FAO (2011b).

Smedshaug (2010) provides a long view of the history of agriculture and the role of national and international policy in regulating food production. He takes as given the constriction of energy resources in this century, but provides no detailed projections of its impact. He does, however, stress the critical role of policy in moderating the fluctuating effects of markets on production and on farm incomes. The history of intermittent overproduction that he documents suggests that providing adequate food supplies will be possible—even as it is today. The question is whether policy makers can achieve a state that meets the broad definition of food security, particularly including not just food availability, but universal access to food on a stable basis.

7. Fossil fuels in the food system

Section 6 focused primarily on the farm and the interaction of the farm system with the environment. This section seeks to articulate likely impacts of rising fossil fuel costs and conceivable adaptions in developed and developing countries, both on the farm and in post-farm segments of the food system.

Because of its annual cycle of production, the food system adapts relatively quickly to altered prices of inputs, leading to optimism that the system will evolve relatively smoothly in a changing cost environment. Price spikes, however, can be more disruptive then gradual increases, although they may also induce long-term adjustment. An example is the radical improvement in energy efficiency of American refrigerators since the oil price shocks of the 1970s. Since then, energy efficiency has improved by a factor of about 3.5, while average sizes have grown about 10%, and real prices have decreased by 2/3 (Appliance Standards Awareness Project, 2011).

7.1 Developed countries

Figures 5 and 6 show the heavy fossil fuel dependence of the agricultural system in the U.S., which should be broadly typical of other developed countries. Increasing energy costs will prompt evolution toward the more sustainable cultivation systems described in

Section 6, in particular, the reduced material and energy inputs and greater labor intensity illustrated by Rodale (2011). Technological inputs from improved crop strains, precision application of water and nutrients, and other innovations will also contribute. Higher energy prices will accelerate the longstanding evolution of agriculture and the larger economy toward higher energy efficiency; they may also reverse the corresponding trend toward greater overall energy use. Because of the significant food system costs to individual households, food and energy price increases will directly impact household budgets, leading to choices of more efficient appliances and possibly dietary changes. Owing to the long life of home appliances, however, evolution will be slow. Fuel costs will directly impact the transport sector, while electricity costs will impact food processing. Possible responses are greater reliance on biofuels, which exacerbate food price increases, reliance on renewable energy resources, and localization of processing and distribution facilities. The evolution probably will include all three, in a variable mix depending on national and regional market forces.

Smil's (2000, 2003) optimism about the adaptability of both the food and energy systems is likely well-placed, unless severe economic shocks of the more pessimistic Peak Oil forecasts disrupt the economy on a large scale and undermine capital investment. Then, the more drastic localization scenario represented by the Cuban experience (Wright, 2009) may be relevant.

Agricultural and energy policy initiatives could either accelerate or inhibit adaptation to an environment of gradually increasing energy prices; they also could reduce or increase vulnerability to price shocks. Unfortunately, politically powerful vested interests in conventional agriculture and fossil fuel production are likely to oppose policy innovations to promote more sustainable systems.

7.2 Developing countries

Figure 5 also displays the distribution of farm energy inputs in developing countries, showing that fertilizer embodies the largest energy cost. Rising prices will make this input increasingly expensive, and probably unreachable for most small farmers, unless subsidized by government policy. The cost of fertilizer will exert pressure to accelerate agroecological innovations, although soil fertility already compromised by reduction in animal nutrients and rotation cyles (Bunch, 2011) may warrant targeted use of synthetic fertilzer as part of a long range plan for land restoration. Scarcity of other fossil fuel inputs will confirm existing patterns of labor-intensive farming. Success in global efforts to raise crop yields on small farms in the developing world will require sustained policy commitments from national and international agencies.

Little information is available about post-farm energy inputs in developing country agricultural systems (Ziesemer, 2007). Organic systems in developed countries may provide a partial model, although these data also are few. Transportation costs will largely confine distribution to local and regional markets, although success in intensifying production may increasingly satisfy local needs and require expansion of regional marketing opportunities. Urban farming should have a role to play (Karanja & Njenga, 2011), as should innovative approaches that simultaneously minimize waste, generate income, and provide food, e.g., cultivating mushrooms on invasive water hyacinths in Africa (Pauli, 1998, Chapter 11). Because the largest population growth rates also occur in countries where agricultural productivity is low, systemically addressing the role of women in agriculture, along with provision of women's health services and educational opportunities, could advance food security both by improving productivity and by reducing human fertility, in addition to providing broader societal benefits.

8. Conclusion

Creating food security for the projected mid-century global population of 9 billion is an enormous challenge. Meeting the challenge will require efficient use of arable land without continued deforestation, efficient use of water, mindful choices between use of agriculture for food and for energy, altering diets for optimum balance of animal and plant protein, supplementing diets with unconventional foods such as mushrooms and algae, attention to global nutrient cycles, restoration of soils, protection of biodiversity, improved crop varieties, and adaptation to climate change.

The goal of this chapter is to demonstrate that over the coming decades this multi-faceted challenge must be met in an economy with increasingly limited supplies of oil and coal, and probably natural gas, with correspondingly rising energy prices. In particular, continuation and expansion of conventional energy- and chemical-intensive agriculture will become uneconomic, even apart from its contribution to climate change and other negative ecological impacts. In the arena of food security, "business as ususal" is unsustainable. Even if conventional agriculture can meet short-term productivity demands, it already fails to provide food access to a billion people, and it simply cannot provide a stable long-term solution to the food security challenge.

The challenge of food security represents just one dimension of the growing conflict between the dominant economic paradigm of unending growth and the finite capacity of planet Earth to supply resources and absorb wastes. Crucial elements of this conflict have been identified in *Limits to Growth* (Meadows, Meadows, & Randers, 2004, p. 178): (1) the cultural acceptance of growth as desirable, (2) the existence of physical limits, such as the land area available for agriculture, which may be erodable by overexploitation, and (3) the existence of delays in the system between signals, such as declining crop yields, and responses, such as altered land management.

To project possible trajectories of human welfare, *Limits to Growth* broadly represents key components of the economy: population, food production, industrial output, pollution, and resource depletion. It further identifies interactions that provide positive or negative feedbacks among them. For example, increasing food production positively impacts population, wheres pollution has a negative impact. Conceptual scenarios explore the possible evolution of the coupled systems. Most of the scenarios exhibit peaks in population and industrial output by mid-century, followed by collapse; only a few scenarios that embody conscious choices acknowledging ecological limits show a relatively smooth transition to sustainability.

Many of global challenges of recent years, such as increases in oil prices, the growing climate crisis, and the continuing economic crisis, can be interpreted as signals of a global economy that has overshot the carrying capacity of the planet. Unfortunately, owing to slow responses in natural systems, if policy makers wait for an unequivocal signal, such as prolonged economic depression caused by declining oil supplies, their belated responses will fail to forestall collapse. Moreover, even with courageous leadership focused on long-term outcomes, slow responses in political systems will delay decisive policy action.

Thus, leaders at every level of government and society face a critical challenge to identify and implement wise policies to build long-term sustainability into the interlinked food, resource, environment, and economic systems. *Limits to Growth* (pp. 259-260) offers a list of guidelines for this effort. Other sources, such as Brown (2011), provide book-length treatments.

Food security requires sustainable agriculture, which in turn requires farsighted leadership to guide evolution away from heavy dependence on fossil fuel inputs and toward the alternatives discussed in Section 6. Failure to achieve food security will take a tragic toll of human suffering through famine and social chaos. The need to act is urgent.

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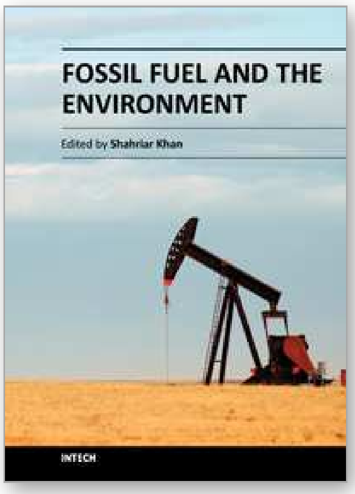

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The world today is at crossroads in terms of energy, as fossil fuel continues to shape global geopolitics. Alternative energy has become rapidly feasible, with thousands of wind-turbines emerging in the landscapes of the US and Europe. Solar energy and bio-fuels have found similarly wide applications. This book is a compilation of 13 chapters. The topics move mostly seamlessly from fuel combustion and coexistencewith renewable energy, to the environment, and finally to the economics of energy, and food security. The research and vision defines much of the range of our scientific knowledge on the subject and is a driving force for the future. Whether feasible or futuristic, this book is a great read for researchers, practitioners, or just about anyone with an enquiring mind on this subject.

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