Food security and sustainable resource management

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Key Points:
- Available natural resources are sufficient to meet 2050 global demand for food
- Low-income populations remain vulnerable to limitations in local resources
- Sustainable increases in food production will require major infrastructure and research investments

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Food security and sustainable resource management

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Abstract The projected growth in global food demand until mid-century will challenge our ability to continue recent increases in crop yield and will have a significant impact on natural resources. The water and land requirements of current agriculture are significantly less than global reserves but local shortages are common and have serious impacts on food security. Recent increases in global trade have mitigated some of the effects of spatial and temporal variability. However, trade has a limited impact on low-income populations who remain dependent on subsistence agriculture and local resources. Potential adverse environmental impacts of increased agricultural production include unsustainable depletion of water and soil resources, major changes in the global nitrogen and phosphorous cycles, human health problems related to excessive nutrient and pesticide use, and loss of habitats that contribute to agricultural productivity. Some typical case studies from China illustrate the connections between the need for increased food production and environmental stress. Sustainable options for decreasing food demand and for increasing production include reduction of food losses on both the producer and consumer ends, elimination of unsustainable practices such as prolonged groundwater overdraft, closing of yield gaps with controlled expansions of fertilizer application, increases in crop yield and pest resistance through advances in biotechnology, and moderate expansion of rain fed and irrigated cropland. Calculations based on reasonable assumptions suggest that such measures could meet the food needs of an increasing global population while protecting the environment.

1. Introduction

The connections between water and land resources, climate, and food production continue to receive considerable attention in the scientific literature [*Foley et al.*, 2005, 2011; *Godfray et al.*, 2010; *Kearney*, 2010] and in the popular press [*Lomborg*, 2001; *Brown*, 2006; *Diamandis and Kotler*, 2012]. Despite all this attention, there are still substantial disagreements about the current food situation and even more about prospects for the future. On a global scale, food production and quality of life measures such as per capita caloric intake, infant mortality, and life expectancy have improved substantially over the last few decades [*United Nations*, 2014]. Some analysts suggest that the projected global population could be readily fed if yields everywhere were brought up to levels currently attained in the developed world [*Mueller et al.*, 2012; *West et al.*, 2014]. On the other hand, concerns about the sustainability of current production levels, stressed ecosystems, and climate change have prompted some observers to predict an impending crisis in food production [*Schade and Pimentel*, 2010; *Ehrlich and Ehrlich*, 2013].

Access to the resources needed to grow food varies greatly over time, space, and income level. Birth rates have fallen dramatically and diets have improved in many countries in southern and eastern Asia. On the other hand, populations in parts of Africa are increasing rapidly while food production stagnates or even declines. Although food security seems to have improved in global average terms, the number of people considered to be chronically undernourished remains around 800 million [*FAO et al.*, 2014]. Many more are highly vulnerable to micronutrient deficiencies (e.g., iron, iodine, and vitamin A) and to fluctuations in climate and crop prices. Income-related health problems are especially serious among children [*Gibson*, 2012; *Gómez et al.*, 2013; *FAO et al.*, 2014].

Given the controversial nature of the food security discussion, it seems especially important to clarify the current situation and to move closer to a consensus on prospects for the future. Without this it will be difficult to prioritize investments and to agree on effective policy measures. In this paper, we explore the

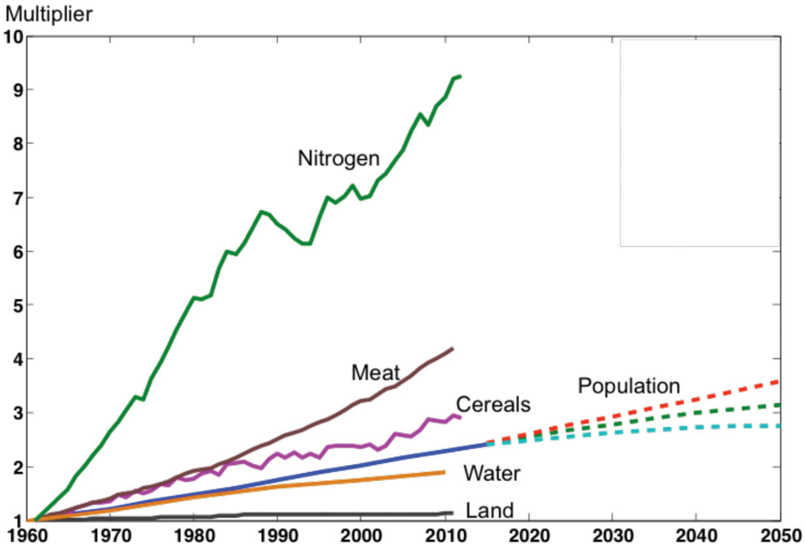

Figure 1. Trends in global population, crop land, irrigation water diversions, cereal and meat production, and nitrogen fertilizer consumed.

question “Do we have enough land and water resources to feed the Earth’s population?” We consider the current situation, examine projections for the future, and look at the environmental implications of increasing food production. The picture that emerges emphasizes the importance of regional diversity in the context of uncertain changes in trade, technology, and climate. There are significant opportunities for water resource professionals to contribute to the conversation on food security and to develop solutions that improve the outlook for the future.

2. Food and Natural Resources

2.1. Global Demand and Supply

Over the last few decades, food security at the global scale has been characterized by large increases in population, production, and trade. Production and trade increases have been able to satisfy the nutritional demands of much of the global population, but by no means all. The historical context for the current situation is shown in Figure 1, which compares 1960–2012 relative increases in global population, cereal and meat production, and crop area (*FAO*, data from http://faostat3.fao.org/home/, accessed 31 January 2015) as well as agricultural water diversions [*Shiklomanov*, 2000] and agricultural nitrogen use (*FAO*, data from http://faostat3.fao.org/home/, accessed 31 January 2015). High, median, and low-population projections to 2050 are also plotted for comparison (*UN, Dept. Economic and Social Affairs*, data from http://esa.un.org/unpd/wpp/index.htm, accessed 31 January 2015).

Figure 2 shows the parallel growth in per capita daily caloric and protein consumption for different national groups (*FAO*, data from http://faostat3.fao.org/home/, accessed 31 January 2015). The dashed lines indicate recommended minimum caloric and protein intakes compiled from the USDA, WHO, and EU [*Gibson*, 2012]. These are about 2100 kcal d^{-1} and 60 gm d^{-1}, respectively. The recommendations from the three agencies are similar and are aggregated over gender, weight, and activity level. Since individual consumption varies over a reasonably wide range (typically described by a log normal distribution), the mean per capita caloric and protein production values need to be higher than the minimum dietary values if the incidence of malnutrition is to be kept low [*Alexandratos and Bruinsma*, 2012; *FAO et al.*, 2014].

These figures provide some important background for a discussion of global food security. They show that global cereal and meat production have grown faster than population, providing a 40% increase in global per capita cereal production since 1960. This has translated to comparable increases in per capita caloric and protein intakes, which are closely correlated with cereal production. Average cereal yields (production per unit crop area) have also increased, largely reflecting the effects of a moderate increase in water diversions and a dramatic increase in the use of nitrogen fertilizer [*Mueller et al.*, 2012].

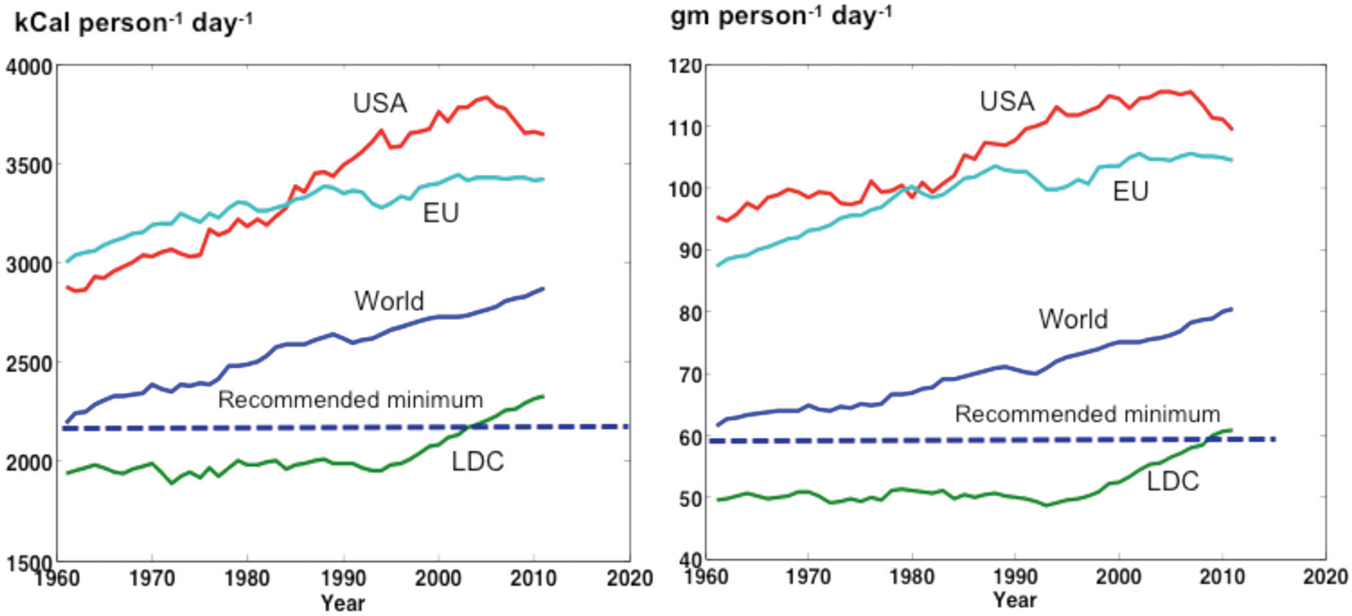

Figure 2. Global energy and protein trends with nutritional thresholds.

Figure 2 indicates that average caloric and protein consumption in the UN's Least Developed Country (LDC) category have already reached the WHO/USDA/EU minimal requirements. This rather surprising result contrasts with the FAO data cited above that indicate that approximately 11% of the global population and 24% of the population in sub-Saharan Africa remain chronically undernourished [*FAO et al*., 2014]. Global production increases have been more than enough to eliminate undernutrition but the most vulnerable populations have not fully benefitted from these increases [*Alexandratos and Bruinsma*, 2012; *Gómez et al*., 2013]. Clearly, average production statistics do not tell the whole story.

The population projections plotted in Figure 1 suggest that food production will have to increase substantially for the rest of this century. The projected rate of increase depends primarily on the assumptions made about population growth and dietary change. The 2012 UN median population projection for 2050 is 9.5 billion, which is an increase of about 38% above the 2010 value of 6.9 billion [*Cleland*, 2013]. The current global average per capita calorie level of 2850 kcal d^{-1} (which is comparable to current consumption in Japan) is well above the recommended minimum caloric intake of 2100 kcal d^{-1} mentioned above. If the average diet stays near 2900 kcal d^{-1} and the distribution of caloric intake over the population is changed sufficiently to insure that everyone has at least 2000 kcal d^{-1}, the projected 2050 population could be adequately fed with about a 40% increase in total crop production. If, on the other hand, the average calorie consumption in 2050 increases to today's U.S. diet of 3600 kcal d^{-1}, there will need to be a 70% increase in production [*Alexandratos and Bruinsma*, 2012].

These estimates assume that the percentages of various foods in the average human diet will remain the same as today. If there are significant changes in dietary composition or in the fractions of total production diverted to animal feed or allocated to nonfood uses the production growth will differ from these estimates, moving either up or down [*Tilman et al*., 2011]. In particular, if the percentage of crop-fed meat in the average diet increases, the total crop production will need to be larger than the estimates given above, due to the low efficiency of converting calories from crops to animal products [*Brown*, 2006].

The FAO per capita calorie figures given above are obtained from net production after preconsumer losses have been deducted [*Parfitt et al*., 2010; *Gustavsson et al*., 2011]. Additional loss, generally referred to as food waste, occurs at the consumer end. Production losses tend to be higher in developing countries, where infrastructure for food storage and transportation may be limited, while consumption losses are greater in developed countries [*Hodges et al*., 2010]. Overall, food loss and waste together remove about 30% of harvested food [*Gustavsson et al*., 2011]. This implies that the per capita caloric consumption values estimated above are somewhat higher than actual caloric intake, especially in developed regions where food waste must be deducted from consumer purchases. It also implies that up to 30% more people could be fed with existing production if food losses were significantly reduced. However, it is not clear if infrastructure investment to reduce producer food loss is the most cost-effective way to satisfy rising demand, especially in developing regions.

2.2. Resources for Future Food Production

A number of studies have attempted to assess the water, land, and nutrient resources needed to support expanded crop production. *Postel et al*. [1996] estimate that the global renewable freshwater supply (terrestrial precipitation going to evapotranspiration and accessible runoff) is about 82,100 $km^3 \ yr^{-1}$. This total supply can be viewed as an upper bound on the amount available for agriculture since some of it is distributed in areas unsuitable for crops. It compares to global evapotranspiration rates (consumptive use) of 5500 $km^3 \ yr^{-1}$ for rain fed cropland, 5800 $km^3 \ yr^{-1}$ for pasture, and 6800 $km^3 \ yr^{-1}$ for forest products (total "green water" consumption) [*Postel et al*., 1996]. The additional evapotranspiration originating from river and groundwater diversions is about 1900 $km^3 \ yr^{-1}$ for irrigated cropland and 400 $km^3 \ yr^{-1}$ for other human activities ("blue water" consumption). *Rost et al*. [2008] use a model based on 1971–2000 data to obtain 7874 $km^3 \ yr^{-1}$ for total crop consumption (green plus blue) and 8791 $km^3 \ yr^{-1}$ for total pasture consumption (green plus blue) but do not distinguish consumption for forest products. The *Postel et al*. [1996] and *Rost et al*. [2008] estimates are compatible with those reported for circa 1995 by *Shiklomanov* [2000], by *FAO* for the same period (data from http://www.fao.org/nr/water/aquastat/main/index.stm, accessed 31 January 2015), and by *Siebert and Döll* [2010].

Overall, there is remarkable agreement on recent global water use, considering the different methods used to construct the estimates of different researchers. These estimates give a range for human consumptive use of 20,000–25,000 $km^3 \ yr^{-1}$, which is less than 30% of the 82,100 $km^3 \ yr^{-1}$ upper bound on water available for agriculture. Based on these figures, global accessible renewable water resources appear to be significantly greater than needed to satisfy the projected demand of food, presuming that agricultural water requirements will increase in proportion to production (e.g., 40%–70%). However, the water supply actually available for expanded agriculture is probably considerably less than the upper bound. A more detailed analysis is needed to determine the magnitude of the global reserve.

Additional insight can be obtained by examining the availability of land, which is the second critical input to be considered in a food security assessment. There are various definitions, sometimes conflicting, of the global area devoted to cropland and pasture. In addition, there are different ways to assess the land area suitable for crops but not necessarily cultivated. In a detailed analysis of global agricultural land, *Ramankutty et al*. [2008] give estimates of 15 million km^2 for cropland and 28 million km^2 for grazing land in 2000, out of a total land area of 149 million km^2. *Siebert and Döll* [2010] use different methods to obtain an estimate of 13 million km^2 for the sum of irrigated and rain fed cropland. These figures suggest that human agricultural activities have appropriated roughly 30% of the land on the planet.

The potential for increasing agricultural land above the circa 2000 level of 15 million km^2 is addressed in a study by *Ramankutty et al*. [2002], who estimate that the total land suitable for some type of rain fed crop (used for one or more rotations) is 41 million km^2. This is close to the value of 45 million km^2 obtained independently by *Fischer et al*. [2010], who include irrigated land in their assessment. Much of the uncultivated land considered to be suitable for crops in these studies is located in tropical forests.

Estimates of suitable grazing land for ruminants are complicated by the fact that the same land may be used for crops and/or grazing, either simultaneously or at different times [*Ramankutty et al*., 2008]. Grazing is an essential source of nutrition in regions where crop production alone cannot satisfy dietary needs. However, it only contributes about 9% of global meat production [*de Haan et al*., 2002]. Generally speaking, the water, soil, and terrain conditions that must be satisfied for suitable grazing land are less stringent than those for cropland. Considering that the total noncrop land area is a factor of 4 larger than current grazing land of about 28–34 million km^2, it seems unlikely that grazing for human use will be land limited in the foreseeable future [*Ramankutty et al*., 2008].

Figure 1 shows that food production has been increasing much faster than demands on global water and land resources. Nitrogen fertilizer has probably been the single largest contributor to the dramatic increase in global production [*Vitousek et al*., 1997; *Mueller et al*., 2012]. *Erisman et al*. [2008] estimate that 30–50% of the crop yield increase obtained over the twentieth century was due to nitrogen fertilizer application. The supply of fixed nitrogen for agricultural use is limited only by the energy needed for the Haber-Bosch process, which converts atmospheric nitrogen to ammonia for fertilizer [*Erisman et al*., 2008].

The supply situation is different for phosphorous, an important component of fertilizer that has also contributed to recent yield increases. Phosphorous is obtained primarily from animal manure and nonrenewable mineral (phosphate) reserves. Agriculture has distributed phosphorous from a few localized mineral sources to soil and water throughout the planet, making it relatively difficult to recycle. Although mineral reserves are uncertain, some researchers believe that the sources of mineral phosphorous of acceptable quality could essentially disappear before the end of the 21st century [*Smil*, 2000; *Cordell et al*., 2009]. However, it is possible that agricultural demand can still be met if application efficiencies are improved and existing technologies for recovering and reusing phosphorous gradually replace phosphorous mining [*Cordell et al*., 2009]. The final major crop nutrient contained in fertilizer is potassium, which is obtained from extensive mineral (potash) reserves. Most investigators believe that these reserves are sufficient for the foreseeable future [*Fixen*, 2009].

The discussion above implies that there are enough water, land, and nutrient resources to meet aggregate global food demand until the middle of this century, when the median global population is predicted to peak [*Buringh and Dudal*, 1987; *Alexandratos and Bruinsma*, 2012]. More specifically, the resource reserves identified above could support a global production increase of 30–70% if water, nutrients, and food could be readily moved from place to place. In reality, such free movement is often not feasible, especially for water. Food insecurity can be a problem, even when global supply exceeds demand, because local resources may not be sufficient to support local food needs.

2.3. Variability Across Space, Time, and Income

In order to obtain a more complete view of current and future food security, we need to look at variations in resource availability and at global food trade. Many efforts have been made to assess spatial variations in land, water, and nutrient resources. *Gleick* [2002] and *Rijsberman* [2006] describe spatially distributed water scarcity indices that quantify stress on water resources. *Ramankutty et al*. [2002], *Fischer et al*. [2010], and *You et al*. [2014] identify areas that meet both the climatic (precipitation and growing season) and landscape (soil and terrain) conditions needed to support agriculture. Such integrated climate-landscape studies address food security more directly than research that considers only water or only land scarcity.

The basic issues can be adequately illustrated by examining the global distributions of annual average precipitation over 1961–1990 [*Mitchell et al*., 2004], soil suitability [*Fischer et al*., 2010], rain fed cropland density in 2000 [*Ramankutty et al*., 2008], and current population (Center for International Earth Science Information Network, data from http://www.ciesin.org/, accessed 15 January 2015), all plotted in Figure 3. Precipitation is a surrogate for water availability, the soil suitability index considers both soil conditions and terrain, current cropland density is a surrogate for crop production, and population is a surrogate for food demand [*Alexandratos and Bruinsma*, 2012]. The current cropland plotted here resembles most published maps of suitable (or potential) cropland, with cultivation taking place in many of the same grid cells but over a greater fraction of available cell area [*Ramankutty et al*., 2002; *Fischer et al*., 2010].

A comparison of the plots in Figure 3 reveals several points. Crops are grown extensively in northern midlatitudes where both water and soil conditions are favorable, but less so at high latitudes, where the growing season is short, and in the humid tropics, where soil weathering and other environmental factors tend to limit agricultural production [*Ewel*, 1986]. The crop production map is very similar to the "water footprint" map described in *Hoekstra and Mekonnen* [2012] since water use tends to be high where crop production is also high, either for local consumption or for export. Figure 3 also reveals that parts of sub-Saharan Africa, South America, and southern Asia have high population densities but relatively low cropland densities, suggesting a mismatch between food demand and supply at local and regional scales. The failure of supply to meet demand will likely continue over the next few decades in sub-Saharan Africa, where projected population growth rates are especially high [*Alexandratos and Bruinsma*, 2012]. The situation is the opposite in the plains of North America and Eurasia, where crop production exceeds local demand and the land and water resources consumed by agriculture support income-earning exports.

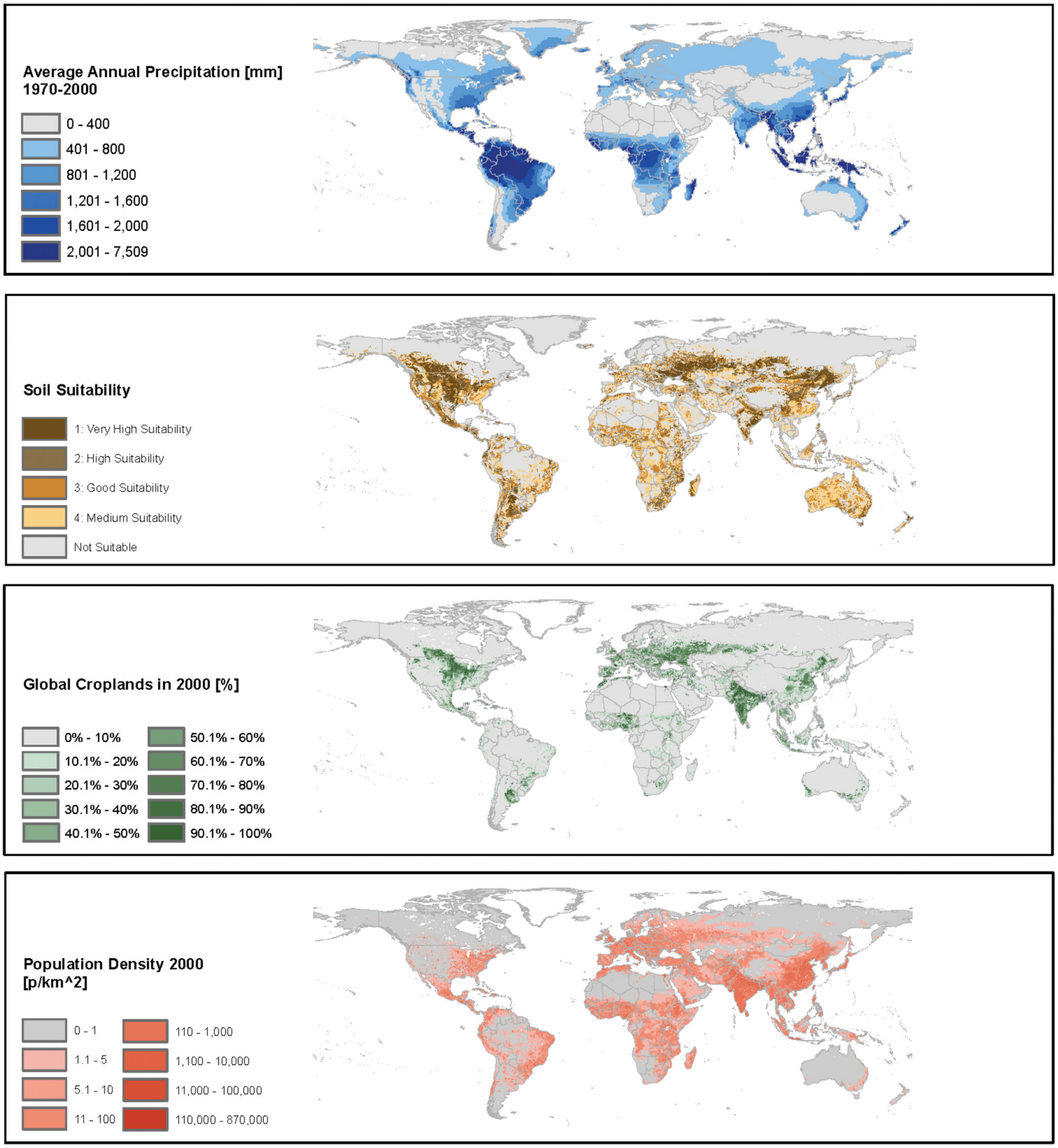

Figure 3. Global distributions of precipitation, soil suitability, cropland, and population density.

The effects of spatial imbalances in food demand and supply have been mitigated, to some extent, by rapid increases in global trade. Transfers of food between different regions effectively move crop inputs, such as water and land, from areas with excess resources to areas with shortages [*Fader et al*., 2013]. *Dalin et al*. [2012] indicate that international virtual water transfers have increased substantially in recent years, effectively moving water from South America to Asia and Europe and from North America to Asia.

Virtual land transfers are less frequently discussed but are also an implicit part of global food trade. *MacDonald et al*. [2015] provide a good review of both virtual land and water. Virtual resource transfers explain the high caloric consumption observed in richer countries with limited water or land. However, such transfers have had relatively little impact on the approximately 1.4 billion rural people earning less than US$1.25 per day [*Ortiz and Cummins*, 2011]. These people are largely left out of the international trade system and are still dependent for survival on locally grown crops and the local resources that sustain them [*IFAD*, 2011].

3. Environmental Implications of Current and Expanded Food Production

Our discussion of food and natural resources leads naturally to a consideration of environmental impacts. These impacts are important in a general sense because of possible adverse effects on the global ecosystem. They also are important for their influence on crop production. The adverse environmental impacts of agriculture can affect food production by threatening agricultural water supplies (e.g., salinization), crop yield (e.g., soil degradation), and valuable ecosystem services (e.g., pest predators). Agriculture can also have adverse impacts on human health (e.g., drinking water and atmospheric contamination). Any balanced discussion of food security must consider the environmental impacts of current and future agriculture as well as the availability of water, land, and nutrients.

We begin with an assessment of the options for increasing production since these determine, to a large extent, the environmental processes to be examined. Although we distinguish impacts on water and land resources, many of the processes discussed here affect entire ecosystems. A thorough analysis needs to consider connections between water, land, and atmosphere, and the critical roles of particular organisms and habitats.

3.1. Options for Increasing Food Production—Expanding Land and Increasing Yield

It is likely that projected increases in global food production will be driven, as they were in the recent past, by a combination of expanded agricultural land area and increased yield or "intensification" [*Tilman et al*., 2011]. *Alexandratos and Bruinsma* [2012] estimate that yield increases will account for 80% of the global crop production increase to 2050, and as much as 100% in some developing countries. The relatively small contribution of land expansion reflects the fact that the most productive lands are already cultivated, making future expansion more expensive and less effective. Much of the crop-suitable land that remains uncultivated today will require careful management if converted because of its vulnerability to climatic variability, soil degradation, and pests as well as the risk of adverse impacts on fragile ecosystems [*Young*, 1999]. On balance, cropland expansion will continue when and where local conditions make it attractive but it is not likely to have as large an impact on global production as intensification [*Lambin and Meyfroidt*, 2011].

Historic crop yield increases have been achieved primarily through fertilizer application and irrigation but also through the use of pesticides, biotechnology, and improved equipment and infrastructure[*Matson et al*., 1997]. Yield-related increases in meat production have been obtained by feeding stock with crops that require greater inputs of water and/or nutrients than grazing on rangeland. *Steinfeld et al*. [2006] estimate that about 30% of the global cereal harvest is used for animal feed. It is important to qualify this observation by noting that, although crop-based meat and dairy production are common in the U.S., China, and areas with readily available maize, it is less common in much of the developing world, where many animals are still fed on rangeland, mixed-use land, or with domestic and agricultural waste [*Bradford*, 1999; *Bouwman et al*., 2005].

Crop yields vary greatly with location, even when soils and climate are similar. The attainable or potential yield for a given crop in a given climate is generally defined to be the highest observable yield obtained under realistic growing conditions for the same climate [*Mueller et al*., 2012]. This ideal yield is determined by solar radiation, temperature, atmospheric CO_2, and genetic traits that control growing period and canopy light interception [*Van Ittersum et al*., 2013]. Actual yields are less than the attainable yield primarily because of water or nutrient deficiencies or the effects of pests. These can be at least partially overcome through the use of irrigation, fertilizer, and pesticides. A number of researchers have compared actual yields to attainable yields in order to identify areas where yield gaps provide the greatest opportunity for increasing production (see *Van Ittersum et al*. [2013] for a review and critique).

Generally, yield gap studies find that the largest gaps for major cereals are in Africa, China, and the Eurasian plains (for maize), parts of India (for rice), and in parts of North America, India, and Eurasia (for wheat), with significant gaps for particular crops in a few other locations [*Licker et al*., 2010; *Mueller et al*., 2012]. *Licker et al*. [2010] estimate that 50% more maize, 40% more rice, and 60% more wheat could be grown globally if yields for these crops were universally increased to 95% of the attainable values. This could conceivably satisfy the 40–70% mid-21st century increase in global calorie demand mentioned earlier.

The relative importance of nutrient application and irrigation for increasing yield depends greatly on location and crop. In many areas, a combination of increased nutrients and irrigation is probably needed to close yield gaps. Looking at a global scale, *Mueller et al*. [2012] estimate that 73% of the areas experiencing yield gaps in cereal crops could approach attainable yield with nutrient application alone while only 16% could produce at this level with irrigation alone. They indicate that yield gaps on existing cropland could be greatly reduced with nutrient increases of about 30% and an irrigated land increase of about 25%. Although these numbers are uncertain, they give a feeling for the intensification required to bring crop yields close to attainable levels. Unfortunately, very few yield gap studies provide quantitative estimates of the environmental consequences of closing gaps or of the cost of preventing adverse impacts. It is possible that environmentally acceptable methods for increasing yield could be economically unattractive when compared to other options such as waste reduction, dietary change, and expanded trade. One of the primary challenges of increasing food production in the coming decades will be to find cost-effective ways to close yield gaps without adverse environmental consequences that could ultimately reduce rather than increase production.

Climate change can affect crop yields through (1) increases in growing season length and atmospheric CO_2 concentrations, which can have positive effects (up to a point), (2) increases in peak growing season temperature, which can have negative effects, and (3) changes in precipitation spatial distribution, timing, and volume, which are all highly uncertain. *Lobell et al*. [2011] use a statistical analysis of historic data to conclude that growing season temperature and precipitation trends since 1980 have had a slightly detrimental effect on maize and wheat yield. Other model-based studies give mixed results, depending on crop and on the climate change effects included [*Ramankutty et al*., 2002; *Deryng et al*., 2011; *Lobell and Tebaldi*, 2014; *Rosenzweig et al*., 2014].

There is large uncertainty about the effects of increased atmospheric CO_2 concentrations on crop yield. Moderate increases can facilitate photosynthesis, which implies that plant stomata need not stay open as long so less water is lost through transpiration. This could lead to a net reduction in terrestrial evapotranspiration and perhaps a resulting increase in water availability. The overall effects of climate change will depend most on what happens to temperature and precipitation in the major producing areas of North America, the Eurasian plains, India, and China. Drawing on a large set of model simulations, the Intergovernmental Panel on Climate Change [*IPCC*, 2013] predicts that temperature, precipitation, and evaporation will all gradually increase over most of these areas, with modest decreases in soil moisture and runoff. However, these predictions are much too uncertain to assess the net impact of climate change on global crop production. For purposes of our analysis, the effects of climate change on food security in 2050 appear to be secondary compared to other factors such as growth in demand and the impacts of agricultural intensification.

3.2. Impacts on Water Resources

The water resource impacts of expanded crop production are considerably different for rain fed and irrigated agriculture. The water required for new rain fed agriculture comes from a relatively large pool of "green" water previously consumed by natural vegetation. Generally speaking, a transition from natural vegetation to rain fed agriculture does not have a major impact on evapotranspiration from the landscape and it often increases recharge to groundwater. Irrigated agriculture, almost by definition, consumes more water than rain fed agriculture and effectively diverts "blue water" from the landscape to the atmosphere, changing the hydrologic cycle.

Irrigation has played an important role in recent increases in food production, particularly in semiarid areas where opportunities for rain fed agriculture are limited but surface or subsurface water may be available from upstream sources. A number of investigators have estimated that the 16% of cultivated land that is equipped for irrigation (3 million km^2) accounts for about 44% of all crop production [*Alexandratos and Bruinsma*, 2012]. This implies that irrigated agriculture has about 4 times greater yield than rain fed agriculture. Such statistics provide a somewhat oversimplified characterization of irrigation, which is often used to supplement rain fed agriculture during dry spells or at particularly vulnerable times, such as planting. In any case, irrigation provides a more reliable supply of water than purely rain fed agriculture and generally improves crop yields [*Mueller et al*., 2012]. *Alexandratos and Bruinsma* [2012] estimate that land equipped for irrigation could expand by about 60% to around 5 million km^2, although they caution that this figure provides only a rough indication of actual irrigation potential. *FAO* [2011] forecasts a much smaller increase of only 6%. A more precise estimate must be based on site-specific assessments that identify areas where irrigation water can be provided reliably, without jeopardizing riparian ecosystems or reserves held in wetlands and groundwater aquifers. *Wada et al*. [2012] estimate that 20% of current global irrigation water (accounting for nearly 10% of global food production) is nonrenewable. *Doell et al*. [2014] give a value of about half this size.

Groundwater is particularly attractive for irrigation since it is available all year round at the point of use. *FAO* [2011] estimates that about 40% of all irrigation water is obtained from groundwater. Sustainable use of groundwater requires that pumping does not exceed the aquifer's safe yield, which can be defined as long-term recharge less downstream commitments. Groundwater is an open access resource prone to the "tragedy of the commons," which arises when each user pumps to maximize his or her own benefit, knowing that others are doing the same but with the ultimate result that the resource stock is depleted to the point that everyone loses. A notable example is the southern High Plains aquifer in the U.S., where well yields have diminished dramatically due to falling groundwater levels [*Scanlon et al*., 2012]. Eventually, farmers will have to return to rain fed agriculture, which lowers yield, limits the choice of crops to be grown, and makes the agricultural system more vulnerable to climatic variability.

Groundwater extraction has tripled over the last 50 years, and severe overpumping of aquifers has become common [*WWAP*, 2012]. *Doell et al*. [2014] identify areas where serious groundwater overdraft has occurred. Some of these contribute significantly to global food production, such as the Ganges basin, the North China Plan, and the U.S. high plains region. One of the attractive aspects of groundwater as a water source is its ability to serve as a bank, with reserves drawn down in times of need and replenished in times of plenty. This important benefit is lost when the aquifer is consistently pumped above the safe yield.

Groundwater regulation generally lags well behind regulation of surface water supplies. As a rule, groundwater problems show up with a delay relative to surface water problems, given the large time scales of aquifers. China is only now drafting a comprehensive groundwater law to amend the general water law (J. Liu et al., unpublished manuscript presented at 2011 AGU Fall meeting, H11F-1131). In 2015, California reacted to the prolonged drought with new groundwater legislation (State of California Assembly Bills AB 1739 (Dickinson), SB 1168 (Pavley), and SB 1319 (Pavley), 2014). In India, groundwater legislation is inadequate, with essentially no enforcement in the agricultural sector [*Prasad*, 2008]. Perhaps this is to be expected, considering that the control of withdrawals from large numbers of wells is much more challenging than the control of a surface reservoir release. In any case, regulation and monitoring will be needed to achieve sustainable use of groundwater resources.

While concerns about water quantity are often the focus of sustainability discussions, the deterioration of groundwater quality due to overpumping is possibly an even more serious long-term threat. In coastal aquifers, overpumping leads to seawater intrusion while inland it mobilizes saline water contained in adjacent strata [*Van Weert et al*., 2009]. These effects are difficult to reverse and can jeopardize the long-term viability of affected agricultural systems.

Present global groundwater extraction is about 1000 km^3/yr, of which 67% is used for irrigation, 22% for domestic water supply, and 11% for industry [*WWAP*, 2012]. *Wada et al*. [2012] estimate that unsustainable groundwater depletion is about 280 km^3/yr (in 2000), up from 126 km^3 yr^{-1} in 1960. Assuming that agricultural groundwater use is responsible for 67% of overpumping, withdrawals need to be reduced by around 190 km^3 yr^{-1} to be sustainable. The equivalent loss of grain production is about 150 million t yr^{-1}, or 10% of global wheat and corn production [*FAO et al*., 2014]. This aggregate estimate gives a sense for the importance of groundwater in the overall food security picture.

Another important water resource impact is the effect of irrigated agriculture on riparian ecosystems and wetlands. Agricultural diversions can intercept the water needed to replenish and preserve these ecosystems. In addition, irrigated agriculture can concentrate salts in drainage water that flows downstream to other users as well as to aquatic ecosystems that are sensitive to salinity levels [*Williams*, 2001]. The global area of wetlands has halved since 1900, largely as a result of agricultural appropriation of both land and water [*Zedler and Kercher*, 2005]. This process is ongoing. River flows have been diminishing in the last few decades—20% of the 143 rivers surveyed in *Dai et al*. [2009] show a decreasing flow tendency.

The impact of agricultural diversions has been recognized in national regulations that prescribe the minimum flow needed to preserve riparian and wetland systems. In Switzerland, this amount is the 95-percentile value from flow duration. *Tennant* [1976] proposed a low flow requirement of 10% of mean annual flow. Although the ecological benefits of ephemeral rivers are not adequately captured by such low flow requirements these limits do give a sense of the problem. When the [*Tennant*, 1976] 10% figure cited above is applied globally, the result is that about 1500 km^3 yr^{-1} of the river and groundwater flow currently withdrawn for human use would need to be reserved. If taken seriously, these requirements increase water scarcity considerably.

The major increases in fertilizer use that have driven the rise in global crop production have also had major impacts on water and land resources as well as the atmosphere. The impacts of agriculture on the global nitrogen cycle and on the accumulation of reactive nitrogen in water, soil, and the atmosphere are well documented [*Galloway and Cowling*, 2002; *Galloway et al*., 2004; *Erisman et al*., 2007; *Robertson and Vitousek*, 2009]. These changes have led to eutrophication of fresh and marine waters, contamination of groundwater, changes in greenhouse gas composition and atmospheric ozone levels, and soil acidification [*Vitousek et al*., 1997; *Erisman et al*., 2008]. Fertilizer use has also gradually increased the stock of phosphorous in soil and aquatic reservoirs [*Smil*, 2000]. The environmental impacts of phosphorous application include eutrophication of inland and coastal waters, most notably the spread of “dead zones” near the mouths of major rivers, and contamination from radioactive and heavy metal byproducts of phosphate processing [*Cordell et al*., 2009]. By comparison, the adverse environmental impacts of potassium appear to be much less than those associated with nitrogen and phosphorous [*Arienzo et al*., 2009].

Since nutrient augmentation is a major component of the agricultural intensification process, it is likely that total fertilizer applications will increase rather than decrease. In light of this, it is particularly important to insure that agricultural practices minimize biologically active nitrogen and phosphorous residuals not utilized by crops. A useful measure of sustainable use is the nitrogen use efficiency (NUE), which measures the fraction of applied biologically active nitrogen that remains in the crop system (harvested biomass, recycled crop residues, and soil). A similar concept can be applied to phosphorous. *Cassman et al*. [2002] cite NUE values for major cereals that range from 20 to 40%, depending on crop and location. The remaining 60–80% of reactive nitrogen leaving the farm adds to stocks in the natural environment. Although much of this reactive nitrogen is eventually denitrified to molecular nitrogen, it has significant effects as it travels through the environment. Also, an increasing amount of this nitrogen appears to be accumulating as production outstrips natural denitrification capabilities [*Robertson and Vitousek*, 2009].

Mueller et al. [2012] indicate that nitrogen is overapplied in many important crop production areas, including parts of North America, Europe, China, and India. Phosphorous is overapplied in Europe, China, and South America. Nutrient use efficiencies must be improved in order to obtain yield gains without further increasing the discharge of reactive nutrients to the natural environment. *Cassman et al*. [2002] suggest that the key is to control fertilizer application dynamically to better account for indigenous nutrient sources. These sources vary significantly with time, space, and cropping practices. Better process understanding and monitoring methods will likely be the keys to development of efficiency improvements that are both effective and economically feasible [*Smil*, 2001; *Erisman et al*., 2008; *Robertson and Vitousek*, 2009].

There is a widespread belief that agricultural pesticides have contributed to recent increases in global food production but there is little quantitative information on their long-term efficacy. *Knudsen et al*. [2006] indicate that global pesticide use (measured by imports and exports) grew by a factor of 12 between 1970 and 2000, during a period when fertilizer inputs, irrigation area, and crop production were all increasing. Since yield gaps have not decreased anywhere near as much as pesticide use has increased, additional applications appear to be giving diminishing return. The adverse environmental and human health impacts of pesticides are well documented and it is now reasonable to ask whether the crop production increases obtained from extensive pesticide use have been worth the costs [*Pimentel*, 2005].

The primary challenge for the industry in recent years has been to maintain existing yields by dealing with new pests and diseases. Farmers appear to be "locked in" to continually adopting new pesticides in an effort to prevent declines in yield [*Wilson and Tisdell*, 2001]. Losses due to pests remain quite high, despite widespread pesticide use. *Yudelman and Nygaard* [1998] estimate an overall crop loss of around 40%, and *Oerke* [2006] gives losses of 26–29% for soybean and wheat and 30–40% for maize, rice, and potatoes. These losses are presumably less than those experienced before the widespread introduction of pesticides, although there are few controlled experiments.

Tilman et al. [2002] point out that evolutionary processes insure that the beneficial effects of any particular pesticide will be transitory. They emphasize the value of combining chemical agents with other means of pest control, including crop rotation and more diversity within the field. Considering the diminishing returns cited above, it seems unlikely that increased use of chemical pesticides will provide yield improvements. It seems more likely that pesticides will be viewed as one component of a multifaceted pest management program that includes biotechnology, conservation tillage, and creative land use techniques [*Tilman et al*., 2002]. Such a program could become an important part of a broader agricultural intensification strategy.

3.3. Impacts on Land Resources

One of the primary impacts of expanded food production on land resources is soil degradation, which can reverse the gains obtained from converting forest or grasslands to agricultural use and can threaten yield increases obtained from nutrient enrichment or other means. The estimates of suitable cropland cited earlier are based on simplified descriptions of soil properties and climate that do not explicitly account for the possibility of soil degradation or loss of currently cultivated land. Degradation processes that can be aggravated by agricultural activity include water and wind erosion, physical and chemical weathering, and salt accumulation [*Lal et al*., 1989]. It is difficult to assess how serious a problem soil degradation could be on a global scale [*Govers et al*., 2014]. GLASOD, a widely cited study based on expert judgment, produced a global map of soil degradation that is summarized by *Bridges and Oldeman* [1999]. They estimate that the global area with moderate or worse soil degradation is about 13 million km^2, a value that is comparable in magnitude to total global cropland. Unfortunately, the estimate and associated soil maps have not been verified or reproduced and they represent a single snapshot in time [*Sonneveld and Dent*, 2009]. More recent studies have attempted to quantify soil degradation through surrogates derived from the normalized difference vegetation index (NDVI) but NDVI changes may reflect land use conversion (e.g., from forest to crops) and climatic fluctuations as well as soil degradation [*Bai et al*., 2008]. There is a critical need for quantitative data relating soil degradation to long-term changes in arable land and crop production.

A compilation of more direct site-specific studies suggests that soil erosion is responsible for a 0.3% annual decrease in global crop production [*den Biggelaar et al*., 2003]. *Rengasamy* [2006] reviews soil salinity on a global scale, citing estimates that about 10 million km^2 of the total global land area of 149 million km^2 has saline or sodic soils. It is unclear how much impact this has had on crop production. While soil degradation could be a serious long-term problem if ignored, there is evidence that it can be significantly reduced through improved management practices that are both economically and technologically feasible [*Matson et al*., 1997; *Ruttan*, 1999].

Since tropical forests represent a significant fraction of uncultivated land suitable for crops, the possibility of soil degradation in these areas is particularly important to consider. A number of investigators have discussed the vulnerability of tropical soils, where soil fertility is generally poor due to fast turnover of soil organic matter and nutrient leaching that can be accelerated by agriculture [*Ewel*, 1986; *Ramankutty et al*., 2002; *Lambin et al*., 2003]. Although tropical forests are currently being converted to cropland at a rapid rate, it is likely that soil fertility in the newly cropped areas will decrease over time and that lime and nutrients will need to be added to maintain acceptable yields [*Ramankutty et al*., 2002].

Conversion of forest and savannah to agriculture has an indirect impact on land resources through its effect on habitats and biodiversity. In a survey of habitat conversion, *Hoekstra et al*. [2005] conclude that regions with the greatest loss of natural biomes correspond closely to those with the greatest cropland density. Since native species promote agricultural productivity by regulating pests and maintaining natural nutrient cycles, there is significant benefit to integrating agriculture, as much as possible, with natural habitats [*Tscharntke et al*., 2012]. However, the connections, positive or negative, between management practices in particular locations and ecosystem services from native species are often difficult to quantify. It is generally agreed that adverse impacts will be greater if the agriculture that replaces natural systems puts stress on water resources (more likely if the land is irrigated), degrades soils, or increases the flux of excess nutrients and pesticides into the environment [*Tilman et al*., 2001].

4. Case Studies in China

Although food security problems can occur over a range of space and time scales and at various income levels, they tend to be more severe at the local level, during transient climatic or economic disturbances, and they tend to have a more serious impact on the poor. Any complete assessment of food security needs to include focused studies at scales such as river basins or agro-ecological zones, where it is possible to examine supply, demand, environmental impacts, and income in a site-specific manner. Such studies can identify bounds on sustainable production and indicate whether local needs can be satisfied with local resources.

Many of the resource availability and environmental impact issues raised in the previous sections can be illustrated with site-specific examples from China. China is a large agricultural producer that has experienced rapid population growth, a changing diet, and stress on water and land resources, including groundwater overdraft, nutrient enrichment, soil degradation, loss of biodiversity, and desertification.

The North China Plain is one of the most serious cases of large-scale aquifer overexploitation. In the past 60 years, water tables have dropped continuously at a rate of 0.5–2 m yr^{-1}. The natural groundwater flow system is recharged at the piedmont of the Taihang mountains on its western boundary as well as in the plain. While in the past it had its discharge in the Bohai Sea, the flow direction has been reversed in both the lower and the shallow aquifer layers due to the formation of deep cones of depression in heavily exploited areas [*Cao et al*., 2013; *Wu*, 2013; *Pei et al*., 2015].

The North China Plain overexploitation is a consequence of the intensification of agriculture since the 1960s. While the natural annual precipitation of 500–600 mm is sufficient to support one grain crop per year under average rainfall conditions, the double cropping of mainly winter wheat and summer maize (with a combined evapotranspiration of 900–1000 mm) can only be sustained by the depletion of groundwater resources. The situation has been aggravated by the fact that annual precipitation has decreased by 14% over the last 5 decades.

The North China Plain contributes 40% of China's grain production, including two-thirds of total wheat output [*Lu and Fan*, 2013]. The conflict between China's self-sufficiency in grain and sustainable agricultural production is difficult to solve unless the nation changes its food security policy. The South-North Water Transfer will provide additional water but, due to its high price, this will be exclusively for household and industrial use, replacing their portion of groundwater pumping. This transfer is not sufficient to bring the aquifer back to a balance between recharge and pumping. The only other viable option is to change the cropping system. Since rainfall is concentrated in summer, winter wheat is responsible for most of the groundwater overpumping. Reduction of this crop seems to be the most efficient solution to the overdraft problem, especially considering the low profit made with wheat.

Some of the issues become more concrete when looking at a smaller subunit, Guantao county in Handan prefecture. This area is frequently used as an example, typical of many of the counties in North China Plain, to illustrate what is necessary to reach a balanced groundwater budget [*Foster and Garduño*, 2004]. The aquifer system is composed of a shallow phreatic aquifer and a deeper confined aquifer. The deeper aquifer is used by households and industry, but also by agriculture in parts of the county where the salinity of the phreatic aquifer is too high. As there is zero recharge to the lower aquifer, all pumping of the deep aquifer has to stop by 2017, with household and industry water being supplied by the South-North Water transfer scheme. Agricultural use of the lower aquifer will be forbidden, creating a gap in irrigation water supply of 6.3 million $\text{m}^3\ \text{yr}^{-1}$. The shallow aquifer is an important resource for agriculture since surface water supply from reservoirs and rivers is very limited. The gap between pumping and recharge in the shallow aquifer is 34.5 million $\text{m}^3\ \text{yr}^{-1}$, giving a total of 40.8 million $\text{m}^3\ \text{yr}^{-1}$ obtained by unsustainable drawdown of the groundwater.

The options for the future include better irrigation efficiency, waste water recycling after treatment, buying up to 10 million $\text{m}^3\ \text{yr}^{-1}$ off-season water from the Yellow River Basin, using South-North transfer water,

Table 1. Water Supply and Cost for Sustainable Food Production Options, Guantao County, China

Option	Maximum New Supply (million m^3 yr^{-1})	Percentage Closure of Supply Gap (%)	Cost (million CNY yr^{-1})	Cost/Percentage Closure (million CNY yr^{-1} $percent^{-1}$)
Water efficiency (subsidy)	16	39	4.4	0.11
Wastewater reclamation	10	24	10	0.42
Yellow River transfer	7.5	18	0.5	0.03
S-N water transfer	7	17	35	2.06
No winter wheat (subsidy)	83	203	156	0.77

and/or a change of the cropping system. Estimates of the supply and costs for these options are summarized in Table 1. Overall, water efficiency has improved considerably over the last 50 years in North China Plain [*Jia et al*., 2011]. In Guantao, a World Bank project described in *Foster and Garduño* [2004] introduced subsurface pipe irrigation, which saves water by reducing unproductive evaporation and allowing more water to go either to productive evapotranspiration or to groundwater recharge. Ideally, this innovation could reduce irrigation diversions by 25%. Up to now 20% of fields in Guantao have been equipped with water saving subsurface irrigation. The remaining 80% could save up to 16 million m^3 yr^{-1} by 2030, assuming that subsidies are provided for installation. Water saving irrigation requires a relatively small subsidy since higher yield and savings in fertilizer compensate for some of the cost.

Wastewater could theoretically provide 10 million m^3 yr^{-1} of irrigation water in the future. Presently, however, it is not treated to a sufficient level and its use in irrigation is not advisable as it may lead to soil pollution. The soil report of the *Chinese Ministry of Environmental Protection and Chinese Ministry of Land Resources* [2014] states that 19% of China's agricultural soils have been polluted, mainly by heavy metals but also by persistent organic pollutants to concentrations above the permitted levels for food crop use. In many cases, this was caused by irrigation with wastewater.

Since the 10 million m^3 yr^{-1} diversion from the Yellow River will only be available outside of the irrigation season, it can only be used for aquifer recharge. The recharge would be carried out through unlined canals, which would result in up to 25% being lost to evaporation. It is clear from the table that Yellow River transfer is the cheapest way to reduce the gap between supply and demand.

The only measure that can entirely eliminate the gap is abandonment of the winter wheat crop. A farmer has to be paid a compensation of 7500 CNY ha^{-1} yr^{-1} to abandon this crop, to save about 5000 m^3 ha^{-1} of water. Covering the gap could start with the cheapest method before going to the next more expensive method to provide the remaining water. *McKinsey Resources Group* [2009] suggested this net marginal cost curve method as a strategy for closing China's national water gap. The large benefit obtained by of abandoning winter wheat makes it possible to eliminate the supply-demand gap with this measure alone. Alternatively, the winter wheat option can be viewed as a backup to be used when less expensive measures are insufficient. In Guantao, only about 10% of the winter wheat has to be eliminated if all the cheaper measures are taken first. This reduction, which would likely be covered by subsidies, is relatively small compared to the 640 million CNY yr^{-1} of total revenue from Guantao grain. The subsidy could even be reduced considering that abandonment of winter wheat will allow three more months for maize cultivation, with an associated net grain yield increase of about 30% [*Pei et al*., 2015].

The Yellow River is an example where upstream consumptive use has contributed considerably to flow depletion in the downstream, to an extent that the traditionally perennial river went dry in 7 of the 10 years from 1990 to 2000. In the most severe case, this occurred for up to 226 days over the 700 km reach upstream of the river's mouth [*Zhang et al*., 2009]. Strict management and slightly better rains improved the situation considerably [*Ringler et al*., 2010]. No more serious flow interruption has occurred in the past decade, although the low flows are still below minimum ecological demands.

The conflict between irrigation agriculture and ecology is clearly revealed in the inland basins of China such as the Hei and Tarim River Basins. In both cases, upstream consumptive use led to drying up of the lower river stretches and terminal lakes. In 2000, the State Council decreed that, of the total annual flow of 3.1 billion m^3 yr^{-1} from the Hei River, an amount of 0.9 billion m^3 yr^{-1} has to be reserved for downstream uses in an average year [*Cheng et al*., 2014]. This new regulation made the farmers turn to groundwater for irrigation, which resulted in overdraft and the decline of groundwater tables in some areas. In the long run, groundwater is more useful for buffering drought years than for compliance with the downstream requirement. A long-term balance that honors the ecological constraint of delivering 0.9 billion m^3 yr^{-1} downstream can only be achieved with a reduction of irrigated agriculture.

The Tarim River had no flow beyond Daxihaizi reservoir for 30 years from 1970 to 2000. This left 320 km of river, between the reservoir and the terminal Taitema lake wetland, without water, destroying riparian ecosystems. In 2000, the basin managers began a large experiment by reducing irrigation diversions and reserving a portion of the reservoir releases as ecological water for the downstream area [*Hou et al*., 2010]. This experiment has subsequently become standard practice. On average, ecological releases were 350 million m^3 yr^{-1} between 2000 and 2013. Groundwater tables along the river were monitored and showed the positive impact of the releases. Initially, infiltrating water had to lift the low groundwater table into the region of 10 m below ground, the suitable depth for the phreatophyte *Populus euphratica* trees growing along the river course. Only then could the tree transpiration start. The corridor that is watered in this way is much narrower than the original Populus belt [*Schilling et al*., 2014].

The amount of water released from Daxihaizi for ecological flows is worth 17.5 million CNY or 2.8 million US$ yr^{-1} at a usual irrigation water price of 0.05 CNY per m^3. The associated reduction in irrigation diversions corresponds to a much higher loss in agricultural revenue of 330 million US$ yr^{-1}, assuming 4200 m^3 ha^{-1} of water demand for vegetables, an irrigation efficiency of 60%, and a revenue of 7000 US$ ha^{-1}. This loss is about the same as the value of the agricultural production of the neighboring Yanqi Basin, which provides a large part of the ecological water flow from its Lake Bosten. However, it is still relatively small when compared to the agricultural production value of 9.8 billion US$ for the province.

These examples suggest that reduction of agricultural water consumption to achieve sustainable water use is feasible. However, it results in production losses that have to be covered by increased imports. In a sense, this means that the water shortage problem is “exported” and sustainability is “imported,” by transferring water use and production to another region. This process works only so long as there are water surpluses and production potential elsewhere. As more areas become resource limited, sustainability becomes more difficult to achieve, especially with regard to conservation of natural ecosystems and biodiversity.

5. Sustainable Approaches for Achieving Food Security

Food security involves at least three different requirements. First, global production needs to meet global demand or there will be shortages. This is, of course, a necessary rather than a sufficient condition for security. In addition, local populations need enough water, land, and nutrient resources to feed themselves or they need an income sufficient to purchase the food they cannot grow. Finally, food production must be conducted in a way that sustains the environment it depends upon. This implies that the methods used to achieve food security should preserve the quality of water, land, and ecological resources.

It is useful to consider the connection between the global perspective of the first requirement and the local perspective of the second. Many water security analyses focus on regional or local scales. Examples include studies of China’s groundwater overdraft problems and of droughts in Australia and the western U.S. There is extensive evidence for water scarcity on these scales, although less for water scarcity at the global scale. Similar comments apply to land shortages, which are more important at regional scales than globally. A large fraction of the global population now lives in environments that simply do not have the local resources needed to reliably support a growing population. This includes most residents of large urban areas.

Food security in such areas is maintained by trade and the associated movement of virtual water and land resources. But trade can only insure food security where local income is sufficient to cover shortages with imports. If individual or regional income is inadequate, imports cannot come to the rescue (except for food aid) and local resources are essential for survival. This situation applies to somewhere between 1 and 2 billion people, depending on how income and food security are measured. Global food production is important because it establishes the upper bound for the supply to international markets. But local production is important because it determines the portion of demand that needs to be satisfied through imports and it sustains poor populations left out of the global trading system.

The generally favored approach for achieving sustainable food security at both global and local scales combines moderation in demand with “sustainable intensification” [*Cassman*, 1999; *Tilman et al*., 2002, 2011; *Godfray et al*., 2010; *Foley et al*., 2011; *West et al*., 2014]. This includes reduction of food loss at the producer end and food waste at the consumer end [*Gustavsson et al*., 2011]; moderation of increases in per capita caloric intake, especially from animals fed from crops [*Keyzer et al*., 2005]; limited expansion of agricultural land area [*Foley et al*., 2011]; limited use of crop land for nonfood production, including biofuels [*Tilman et al*., 2009; *Searchinger and Heimlich*, 2015]; increases in nutrient use efficiency through better monitoring and control of fertilizer application [*Cassman*, 1999; *Tilman et al*., 2011]; irrigation improvements that reduce water use while avoiding salinization [*Hillel*, 2000; *Oster and Wichelns*, 2003]; modification of tillage practices to improve soil quality and sequester carbon [*Hobbs et al*., 2008]; and development of new, possibly transgenic, crop varieties with higher yields, lower water use, and/or better pest resistance [*Ronald*, 2011; *Von Caemmerer et al*., 2012]. Ideally, a judicious combination of these measures will provide sustainable growth.

Critics of sustainable intensification suggest that it may be a contradiction or at least that it is often oversimplified [*Garnett et al*., 2013]. Many articles that advocate sustainable intensification set forth the general principle that yield gaps should be closed in a sustainable manner without indicating exactly how this might be done. It seems quite possible that future yield improvements based on expanded nitrogen application, pesticide use, and irrigation could cause environmental problems similar to those encountered in the past. Efforts to monitor and control these problems may be costly and/or actually reduce yield. A global study by *Seufert et al*. [2012] concludes that low-input organic agriculture generally gives lower yields than high-input conventional agriculture. However, the authors stress that their results are highly context dependent and may not fully capture regional differences or possible consequences for human health. *West et al*. [2014] have made an effort to identify “leverage points” where yields could be increased without adverse environmental consequences, primarily by adopting practices that have proven effective in other settings. Their analysis suggests that sustainable intensification may be able to increase global production while minimizing adverse environmental impacts. However, the cost of requiring that intensification must be sustainable remains uncertain.

It is difficult to make precise estimates of the demand and production changes that could be achieved with sustainable intensification, especially in the presence of climate change. However, it is possible to compile a set of hypothetical changes to get a feeling for the feasibility of achieving projected food requirements. Some typical figures are listed in Table 2, which gives fractional changes in global consumption and production estimated for the period from 2011 to 2050. These changes depend on several postulated demand and supply actions. Associated changes in agricultural water and land are included to show the impact on natural resources. The table is based on data from FAO’s Food Balance Sheets (FBS), available at http://faostat3.fao.org/home/, accessed 31 January 2015, and from *de Haan et al*. [2002]. Nominal crop demand is derived from the UN median population growth projection shown in Figure 1 and from a 3500 kcal yr^{-1} average per capita diet, giving a 68% nominal increase in food consumption. This nominal value assumes no change in the proportions of the various crops grown to support the human diet (vegetal foods and food crops fed to animals).

For our sample analysis, the nominal demand can be modified in two ways. The first is an additional increase (or decrease) in the fraction of dietary calories obtained from meat and dairy products. The crop demand for meat and dairy is based on an aggregate feed conversion ratio of 4.7 (kg feed) (kg animal $\mathrm{product})^{-1}$ calculated from FAO totals over all crops, meat, and dairy products. This aggregate conversion ratio is on the high side since it ignores some animal products (fat and offal) but includes all feed. Meat production is measured in terms of carcass weight (as reported by FAO) and dairy (milk and cheese) production is measured in terms of milk solids weight. Total meat and dairy production weight is decreased by the fraction obtained from grazing (noncrop fed) ruminants [*de Haan et al*., 2002]. The second adjustment to nominal demand is an assumed reduction in food waste, which depends on consumer behavior that may be not be easy to influence, except indirectly through rising food prices.

The revised demand figures given in the table assume a 25% increase in meat and dairy consumption (balanced by a calorically equivalent reduction in vegetal consumption, to keep the total caloric intake constant at 3500 kcal $\mathrm{person}^{-1}\ \mathrm{d}^{-1}$) and a 10% reduction in food waste. Both figures are reasonable and give a final 2050 crop production increase of 62% over 2011 values. If total meat and dairy consumption is assumed to decrease rather than to increase this number falls significantly. In the limit of no meat or dairy consumption

Table 2. Possible Water and Land Impacts of Increasing Global Food Production Over 2011–2050

	Units	Crop Increase	Green Water	Blue Water	Rain fed Cropland	Irrigated Cropland	Grazing Land
Recent water use [*Postel et al.*, 1996; *Rost et al.*, 2008]	$km^3\ yr^{-1}$		18,000	2,000			
Recent land use [*Siebert and Döll*, 2010; *Ramankutty et al.*, 2008]	$10^3\ km^2$				12,000	3,000	28,000
Nominal demand increase 2011–2050[a]	Fraction	0.68					
Demand Actions							
25% increase in fraction of total calories from meat and dairy[b,c,d,e,f,g,h,i,j]	Fraction	0.12					
10% food loss reduction on all crop production[k]	Fraction	−0.18					
Revised demand increase 2050		0.62					
Supply Actions							
25% yield increase on all cropland[l]	Fraction	0.25	0.25	0.25			
30% expanded cropland, yield increases on existing, and new land	Fraction	0.38	0.38	0.38	0.30	0.30	
10% water savings on all irrigated land	Fraction			−0.16			
25% increase in grazing land[m]	Fraction						0.25
Net supply increase 2011–2050	Fraction	0.63	0.63	0.46			
Water	$km^3\ yr^{-1}$		11,250	925			
Land	$10^3\ km^2$				15,600	3,900	35,000

[a] The 2011 global population = 6.9 billion, assumed 2050 global population = 9.5 billion; 2011 FBS per capita global diet: Vegetal = 2360, Animal = 510, Total = 2870 $kcal^{-1}\ d^{-1}\ person^{-1}$; Nominal 2050 global diet: Vegetal = 2880, Animal = 620, Total = 3500 $kcal^{-1}\ d^{-1}\ person^{-1}$.

[b] Based on FBS annual kg and kcal per capita human food consumption and annual kg animal feed consumption for selected crops (cereals, oils fruits, vegetables, sugar, roots, pulses).

[c] Fraction crop increase with additional meat and dairy = (revised normalized production) ÷ (nominal normalized production).

[d] Nominal normalized crop production = (nominal meat calorie fraction) × (meat production ratio) × (feed conversion ratio) + (nominal vegetal calorie fraction) × (vegetal production ratio).

[e] Revised normalized production = (revised meat calorie fraction) × (meat production ratio) × (feed conversion ratio) + (revised vegetal calorie fraction) × (vegetal production ratio).

[f] Production ratios: vegetal = 5.9×10^{-4}, animal = 3.6×10^{-4} $kg\ kcal^{-1}$.

[g] Nominal calorie fractions: animal = 620/3500 = 0.18, vegetal = 1 − animal = 0.82.

[h] Revised calorie fractions: animal = 1.25 × (nominal meat calorie fraction), vegetal = 1 − animal.

[i] Feed conversion ratio for all crop-fed animals (crop-fed ruminants, pork, poultry) = (Total FBS feed) ÷ (Total FBS crop-fed meat and dairy) = 4.7 $kg\ kg^{-1}$.

[j] Fraction of crop-fed ruminant production = 0.37 [*de Haan et al.*, 2002].

[k] Food loss reduction = −(1 + nominal demand increase + demand increase from additional meat and dairy) × 0.25.

[l] Crop water requirements increase in proportion to yield. All rain fed cropland water use is green.

[m] Grazing land changed to accommodate change in fraction of total calories from meat (grazing portion).

(a reduction of 100%), 2050 crop production rises only 10% above 2011 values (calculations not displayed here). This analysis does not consider protein requirements, which need to be maintained with vegetal substitutes when meat and dairy consumption are reduced.

A more realistic scenario than a purely vegan diet would be a modest decrease over current global levels and/or a reduction in the fraction of crop-fed meat and dairy products. Even these measures would require significant behavioral change in both developed and developing countries, reversing current consumption trends [*Bouwman et al.*, 2005]. It is important to emphasize that global estimates of the food crops consumed and land required for meat and dairy production are highly uncertain due to limited information on the role of mixed farming systems (which combine production of crops for human and animal consumption), overlaps between estimates of land area suitable for food crop production and grazing, and variations in reporting criteria [*de Haan et al.*, 2002].

The food supply side is likely to be more responsive to market incentives than the demand side and is also more influenced by new technology. In Table 2, we assume an across-the-board yield increase of 25%. This would most likely be achieved through focused increases in nutrient application and genetic improvements. We also assume that irrigated and rain fed cropland areas will both increase by 30%. This increase is large enough to have significant environmental impact, especially in currently forested regions. In reality, expansion to this level will require an even larger amount of new land to be converted to agriculture since some existing cropland will need to be taken out of production due to chronic water shortages and/or soil degradation. In our analysis, grazing land area increases only to the extent needed to increase the noncrop fed portion of meat consumption above nominal values (25%). An assumed 10% increase in water use efficiency reduces diversions for irrigation but does not directly affect production [*Howell*, 2001].

The illustrative assumptions used here balance 2050 supply and demand at about 63% above 2011 levels. Of course, there is no guarantee that these values can actually be achieved. The exercise summarized in Table 2 does suggest that it may be possible to satisfy the global food security requirement listed above with a combination of reasonable measures. The feasibility of achieving local food security while sustaining a satisfactory environment for agriculture must be assessed with more focused regional and local analyses.

A sustainable path to food security will most likely combine improvements in technology, some of them possibly dramatic, with improvements in agricultural management and public policy. These improvements will evolve in a world with a changing climate, changing consumer preferences, a changing energy landscape, and continuing migration from rural to urban environments. It seems likely that the need to produce more food while also protecting natural resources will require significantly more investment in agriculture, including improved infrastructure, farmer education and assistance programs, and research. This could raise food prices compared to current levels but could also generate benefits ranging from improved health and security to new economic opportunities. It is not easy to predict what will happen but it is apparent that our natural and human resources are substantial. This gives us reason to be cautiously optimistic.

There is ample opportunity for water resource professionals to contribute to the broader study of food security. Some important topics include better characterization of the water resources available for agriculture and of the carrying capacity of agricultural systems; improved understanding of the water requirements of plants and of the processes that affect evapotranspiration; investigation of two-way interactions between agriculture and climate; better understanding of the connections between water resources and natural ecosystems; improvements in the technology and policy considerations that affect water use efficiency; and development of new data sources that can reduce uncertainty about natural processes relevant to food security. The contributions of water specialists in these areas will generally be most effective when they connect with other disciplines so that the many different aspects of food security can be kept in perspective.

6. Conclusions

We can conclude by returning to the question "Do we have enough land and water resources to feed the Earth's population?" The short answer is "It depends on how we manage these resources." If we demand higher calorie meat-based diets, allow fertile land to degrade, release excessive amounts of nutrients and pesticides into the environment, overdraft groundwater, waste valuable food, and promote unsustainable irrigation projects, we are likely to hit critical resource limits, especially in the world's poorest regions. But there is no reason to do this. It is quite possible that market forces and technological innovation will enable mankind to increase food production to meet reasonable needs in a sustainable way. Ultimately, the issue of food security is as much about people as about finite resources.

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