IMPROVING WATER AND NUTRIENT-USE EFFICIENCY IN FOOD PRODUCTION SYSTEMS

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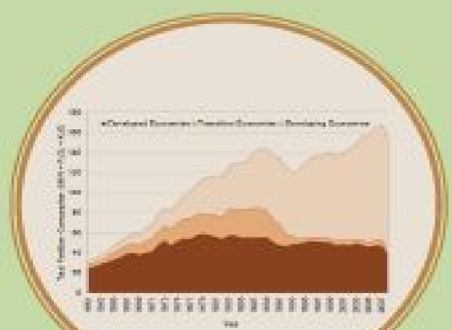
Zed Rengel



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Preface

With a world population having reached 7 billion in 2012, and with projections of a 50% increase in the next four decades, coupled with expected increases in the living standards and increased demand for milk and dairy products by a greater proportion of the world population,-agriculture is faced with a huge challenge to double the food production in the next 40 years, but on a shrinking area of farmland. Providing food, feed, and fiber for the increasing population on this planet will also need to be achieved using declining water and nutrient resources. In many parts of the world, there is a severe shortage of good quality water that is to be used for irrigation, which is at least partly caused by increased frequency and severity of droughts in the rain-fed, food-producing areas as a result of climate change and variability. On the other side of the issue, raw materials used in producing some fertilizers (e.g., phosphorus [P] and potassium [K]) are becoming scarce and expensive, and the price of energy is also high (production of nitrogen [N] fertilizers is particularly energy demanding), pushing fertilizer prices up. As a result, agriculture must produce more food with lower water and nutrient input; therefore, increased water- and nutrient-use efficiency is of utmost importance.

Increasing efficiency of water and nutrient use (i.e., increasing food production per unit of water and nutrient input) will be crucial in (a) maintaining food security and food quality for increased global population as well as (b) decreasing potentially negative environmental impacts of growing food. In covering both water- and nutrient-use efficiency, this book takes a broad approach that includes social, economic, political, and agronomic aspects of maximizing water- and nutrient-use efficiency in food production, while maintaining healthy natural ecosystems.

The first five chapters provide a global context in which increased efficiencies of water and nutrient use need to be achieved. Historical perspectives are coupled with the regional case studies as well as future projections in terms of changing and variable climate and the population growth effects as they bear not just on increasing food production, but also on doing it sustainably. The food production and consumption patterns are also assessed. The past, present, and the future of fertilizer production and demand are analyzed. A particular emphasis is placed on the water and-phosphorus cycling in agricultural and natural landscapes.

Chapters 6 to 11 deal with various agronomic means of improving water- and nutrient-use efficiency in food and feed production, with a strong emphasis on genetics and breeding. The basics of soil nutrient supply and crop nutrient demand (and how to match the two) are covered first, followed by physiology and genetics of nitrogen-use efficiency, and then breeding for water- and nutrient-use efficiency. Given the importance of roots in accessing water and nutrients, an attempt to aid breeding for important root traits by using three-dimensional computer models of root-structure and function is particularly interesting.

The remaining five chapters (12 to 16) cover a range of issues relevant to increasing water- and nutrient-use efficiency in a variety of food-producing systems, from arid Mediterranean regions in Europe, Africa, and Australia to two most populous countries in the world, China and India, and to the country with the largest fresh-water resources in the world, Brazil.

This book is intended to provide professionals, students, and administrators with in-depth view of various aspects of water- and nutrient-use in production of food, feed, and fiber. The book takes a multidisciplinary approach in covering issues ranging from political, economic, and social to agronomic. Hence, professionals and scholars working in food policy, environmental regulation, and land conservation as well as agronomists, horticulturalists, plant and soil scientists, geneticists, breeders, soil microbiologists, and others may find an interest in the book.

All chapters have been reviewed according to the standards of international scientific journals. I would like to thank the authors for patiently revising the chapters, sometimes repeatedly, to meet the high standards.

Zed Rengel

Improving Water and Nutrient-Use Efficiency in Food Production Systems

1 Current State and Future Potential of Global Food Production and Consumption

Christine Heumesser, Simon Thaler, Martin Schönhart, and Erwin Schmid

Introduction

The Food and Agriculture Organization (FAO) estimated the number of undernourished people in the world to be 925 million in 2010, which was 98 million below 2009 levels (FAO 2010c). Hence, more than 1 in 7 people live on a caloric intake below the minimum dietary energy requirement needed for light physical activity. However, the share of hungry people in the world has been declining since the mid-1990s and is at present below the 1970 level (FAO 2009c).

By 2050, global population is projected to reach 9 billion people (United Nations 2009). The continued population growth and the increasing per capita real income will further increase a total food demand for the next 40 years, with changing dietary patterns toward higher proportions of meat, dairy, and fish as well as processed food (Godfray et al. 2010). FAO (2009a) estimated that the current global food production needs to increase by 70% to meet the total food demand in 2050. On average, global agricultural production is projected to grow at 1.7% in the current decade, compared with 2.6% in the first decade of the 21st century (Organisation for Economic Co-operation and Development [OECD] and FAO 2011).

Meeting the increasing food demand is an unprecedented challenge. Even if attainable under the prospect of changing climate and decreasing growth rates of crop yields (Bruinsma 2003; Schmidhuber & Tubiello 2007), it will be difficult without severely exploiting and degrading natural resources, such as land, water, mineral nutrients, and fossil fuels. Additionally, the price hike of commodities and basic staples from 2006 onward and the subsequent financial and economic crisis from 2009 have drastically affected the number of people suffering from hunger and undernourishment (FAO 2009c). High commodity prices increased aggregated consumer price inflation, reduced purchasing power of poor populations, and negatively affected economic stability and food security (FAO-OECD 2011). For many developing countries, the global economic crisis led to a reduction in export earnings, remittances, foreign direct investment, and foreign aid, which led to employment and income losses (FAO 2009c). The price developments were driven by the connection between the agricultural and energy markets, increasing demands for cereals and oilseeds for biofuel production, weather-induced shortfalls of some food products, historically low grain stockpiles, a declining US dollar, increasing agricultural costs of production, and growing foreign exchange holdings by major food-importing countries (Trostle 2008).

Food security does not only encompass food availability and supply, but it also includes food access (which is determined by political, social, and economic arrangements), food use, and food stability (FAO 2006). In this chapter, we focus on food availability and supply by investigating the current state of, and the future potential for, global, resource-efficient food production and consumption.

We first identify options and challenges in increasing global food production. This includes the expansion of agricultural land and competing usage paths (i.e., food, feed, biofuel, and nature conservation as well as increasing agricultural production by intensifying crop management). Furthermore, we discuss the impacts of changing climate and weather patterns on food production together with the options to decrease food demands by changes in human consumption behavior (i.e., less meat in the diet and reducing food waste). In addition, we provide an overview of the trends and challenges concerning the efficiency of water and nutrient use that will be a crucial factor in managing competing uses (i.e., food, feed, fiber, and biofuel) as well as negative environmental externalities.

Global Food Production

In this section we contrast frequently raised options and challenges to meet the increasing global food demand. We investigate the supply side of the global food production, focusing on the expansion of agricultural land and the productivity growth, in particular through use of fertilizers, irrigation, and biotechnology. We also account for climate change as an overarching challenge, affecting the future production strategies.

Agricultural Land Expansion

The world's total land area amounts to approximately 13 billion ha, of which approximately 5 billion ha (38.5%) are agricultural land. Of that land only 1.4 billion ha (28.6%) are arable land (FAO 2010a). Historically, the expansion of agricultural land has been a way to meet the rising food demand. From the 1960s onward, however, food production has been decoupled from cropland expansion as a result of considerable productivity increases (Lambin et al. 2003). Between the early 1960s and the late 1990s, arable land

and land under permanent crops expanded by 155 million ha, or 11%, while world population almost doubled. Arable land per person fell by 40% from 0.43 ha to 0.26 ha on average, but land productivity growth through intensification compensated for this reduction in area per person (Bruinsma 2003).

To meet the increasing food demand, a remaining question is whether further expansions in agricultural land are necessary as well ecologically and socioeconomically feasible.

Drivers of Land Use Change

The causes of land use change and agricultural land expansion are manifold and complex, involving situation-specific interactions among a large number of factors at different spatial and temporal scales (Geist & Lambin 2002; Lambin et al. 2003; Smith et al. 2010). Lambin et al. (2003) identified five high-level causes of land use change: (1) resource scarcity and related pressures on natural resources, (2) changing market opportunities, (3) outside policy interventions, (4) loss of adaptive capacity and increased vulnerability of local land users, and (5) changes in social organizations, institutions, and human attitudes. Also, Smith et al. (2010) identified socioeconomic, technological and institutional factors, and social trends, such as population growth and urbanization, as the underlying causes for competition for land. These factors determine the extent of direct pressures on land, which include land transition (e.g., forest clearing to grow crops and pastures), land degradation (e.g., logging, induced fires or overgrazing), and natural causes (e.g., climate change and water availability).

Growing crops for bioenergy has been identified as potential competitor to food production, potentially risking the displacement of forests and grasslands through direct and indirect land use change effects. The International Energy Agency (IEA) estimated that energy crop production took place on 1% of global arable land in 2004 and may increase to between 2% and 3.8% by 2030 because biofuel legislation in several countries supports its expansion. The European Union and North America are predicted to experience the largest growth in the area under biofuel crops, from 1.2% of arable land in 2004 to 11.6% in 2030 (EU), with corresponding numbers for the United States of 1.9% to 5.4%. Comparatively, the land requirements for biofuel production in other parts of the world might increase from 0.1% to 2.7% of arable land in 2030 (IEA 2006). The degree of competition can be reduced by technological progress in biofuel conversion technologies and a switch to second-generation technologies using agricultural and forestry by-products (Fischer et al. 2009).

Land degradation and the subsequent loss of productive capacity could potentially lead to an expansion of agricultural land into remaining natural habitats. Land degradation is increasingly driven by improper agricultural land use, poor soil and water management practices, deforestation, loss of natural vegetation, or excessive use of agro-chemicals, as well as, natural disasters including droughts, floods, and landslides (United Nations Environment Program [UNEP] 2002; Bruinsma 2003). According to various global land degradation assessments (Oldeman et al. 1990; UNEP 1992; Bridges & Oldeman 2010; FAO 2012), approximately 23% of all usable land (excluding mountains and deserts) has been affected by degradation to a degree sufficient to reduce its productivity. In the early 1990s, about 910 million ha of land were classified as “moderately degraded” with greatly reduced agricultural productivity and 305 million ha were classified as “strongly to extremely degraded” (UNEP 2002).

The expansion of agricultural land contributes to the loss of natural ecosystems and corresponding biodiversity losses (Koh & Ghazoul 2008). Nellemann et al. (2009) estimated that 80% of all endangered birds and mammals are threatened by agricultural expansion and unsustainable land use. In a majority of developing economies, the decline in forest and woodland area is mainly the result of land conversion to crop production (FAO 2007).

The Global Forest Resources Assessment 2000 estimated deforestation during the 1990s at 16.1 million ha per year, resulting in a loss of 4.2% of the natural forest that existed in 1990 (FAO 2001). In the period from 1981 to 1990, the area of tropical forests cleared each year in Latin America was 7.4 million ha on average. This is almost as much as the sum of deforested areas in Asia and Africa combined. During 1991 to 2000, deforestation in Latin America declined to 4.3 million ha annually (Barbier 2004). At the same time, there was an increase in the forest area as a result of aforestation, such that the net global decrease in forest area was about 9.4 million ha per year from 1990 to 2000. Overall, the total net forest change was positive for the temperate regions but negative for the tropical ones (FAO 2001).

Deforestation has various adverse effects. In 2004, carbon dioxide-equivalent emissions from deforestation, decay of biomass, and burning of peat land were estimated to be 17.3% of total emissions (International Panel for Climate Change [IPCC] 2007). In addition, tropical forests are rich in floral and faunal diversity, which is threatened by deforestation. Even though a slowdown in deforestation and rangeland clearance for crop production has been observed on a global scale, pressures on forests are likely to continue in some developing countries. Deforestation is driven by a number of site-specific causes (Geist & Lambin 2002), such as a lack of nonagricultural employment opportunities in a large proportion of rural communities (Bruinsma 2003) or unfavorable management options (e.g.. low irrigation and fertilizer rates leading to soil degradation and,- consequently, expansion of agricultural lands) (Barbier 2004).

A major driving factor for deforestation is the expansion of grazing land for livestock, particularly in Latin America. About 70% of deforested land in the Amazon is now managed as pastures. On a global scale, the livestock sector is estimated to account for 78% of agricultural land and as much as 33% of the cropland. Dietary shifts toward more meat will require a much larger share of crop and grazing land for feed production, which will exert pressures on crop production for human uses (Steinfeld et al. 2006).

The literature is ambiguous on whether further agricultural land expansion is feasible or not. For instance, researchers from FAO and the International Institute for Applied Systems Analysis (IIASA) developed an agro-ecological zones model that computes amounts of nonarable and arable land as a function of environmental constraints (Fischer et al. 2002a, b; Fischer et al. 2005). Fischer et al. (2002b) estimated that approximately 2.5 billion ha or 18.6% of land with a potential for rain-fed crop cultivation exist, of which 1.6 billion ha are located in developing countries. This estimate does not account for nonagricultural land uses such as infrastructure, settlements, or legally protected areas. However, even when excluding areas that are forests or legally protected areas, 17.6% of total terrestrial surface has a potential for arable uses (Fischer et al. 2002b). On a regional scale, it is suggested that only 22% of potentially suitable arable land in sub-Saharan Africa, 19% in Latin America, and 52% in East Asia (excluding China) was farmed from 1997 to 1999. In these regions, expansion of arable land continues to contribute to agricultural growth. In contrast, about 87% of suitable area has already been cultivated in the near East and North Africa and about 94% in South Asia (except India) (Bruinsma 2003).

Other studies conclude that much of the land suitable for agricultural production has already been developed (Khan & Hanjira 2008). For instance, Alexandratos (1995) estimated that more than 70% of the potentially available rain-fed cropland in sub-Saharan Africa and Latin America suffers from topographical, soil, and terrain constraints and therefore is not available for agricultural production. Other models predict that under severe climate change, the global amount of land suitable for agriculture will remain the same in 2080 as it was in the early 2000s (Fischer et al. 2002a, b; Parry et al. 2004). Also, Fischer et al. (2002b) concluded that there were severe limitations to their estimates of land with potential for arable uses. An increased use of cultivated land might not be feasible because of competition for land with alternative agricultural uses or severe impacts on biodiversity and the global carbon cycle. Additionally, there might be ecological constraints, low soil fertility, high incidence of crop diseases, or a lack of infrastructure and access to appropriate technologies (including economic incentives to adopt them). Socioeconomic restrictions (e.g., suitability for a particular crop that is not demanded on the domestic or foreign markets) are further limitations to the estimates of potentially available arable lands (Fischer et al. 2002b; Bruinsma 2003).

Overall, some additional land could be used for crop production, but the competition with other land uses, the desire to protect natural habitats, and the required services provided by natural ecosystems (e.g., carbon storage in rainforests and flood control) can make this an unwanted or inefficient solution (Balmford et al. 2005).

Productivity Growth

Intensification can be defined as an increase in production per unit of inputs (e.g., labor, land, time, fertilizer, seed, feed, or cash) (FAO 2004). It has permitted the doubling of the world's food production from 1961 to 1996, with only a 10% increase in the global amount of land under cultivation (Tilman 1999). Driving forces for intensification are releasing capital and knowledge constraints, changes in the price ratios of inputs and outputs, as well as farm technologies as a function of land and water scarcity, growth in population, and investments in crop and livestock breeding that can change the quantity and value of production per ha (Lambin et al. 2001).

Even though yield growth is expected to remain the driving force of crop production, annual yield growth rates for many crops are projected to decline until 2030. The average increase in cereal yield in developing countries has declined from 2.5% per acre in the period from1961 to 1999 to 1.4% between 1991 and 2001 and is projected to decline to 1% in 2030 (Bruinsma 2003). However, there is a wide geographic variation in crop productivity, even across regions with similar natural conditions, for example because of inadequate nutrient and water management (World Bank 2008; Vitousek et al. 2009). There are institutional constraints such as limited access to knowledge and technologies to increase production, lacking finances to undertake investments (e.g., irrigation, fertilizer, soil-conservation measures), and unfavorable prospects for returns on agricultural investment. Closing the yield gap (i.e. the difference between realized productivity and the maximum attainable yield at a site given current genetic material, available technologies, and management) can substantially increase food production levels (Godfray et al. 2010; Foley et al. 2011).

The gains in agricultural productivity are often accompanied by adverse effects on natural resources and the environment, which may risk the future productive potential. Examples are land degradation through soil erosion and salinization; susceptibility to diseases; loss of genetic resources; emissions of greenhouse gases; nitrogen and phosphorus losses causing eutrophication in water aquifers; or losses of habitat and species diversity (Bruinsma 2003).

Increasing land-use intensity such as through higher fertilizer inputs and mowing frequencies as well as homogenization of landscapes reduces biodiversity (Benton et al. 2003). Globally, more than 4,000 plant and animal species are threatened by agricultural intensification (Nellemann et al. 2009). There is an ongoing debate whether the land for nature protection should be separated from the agricultural land use. It may be beneficial under certain circumstances to intensify production in some areas to reduce pressure on the native lands for nature conservation (Balmford et al. 2005; Green et al. 2005). However, one has to acknowledge that leakage and rebound effects may undermine expected land-use effects (Lambin & Meyfroidt 2011). On the other hand, for some parts of the world, such as the European Alps, extensively managed agricultural land-use systems have created semi-natural habitats of high ecological value, within which both intensification as well as land abandonment may lead to biodiversity losses (Tasser & Tappeiner 2002).

Fertilizer Use

One-third of the increase in world cereal production in the 1970s and 1980s has been attributed to increased use of fertilizers (Bruinsma 2003). The other estimates based on the FAO database (FAO 2010a) suggest that between 1961 and 2007, the use of nitrogen fertilizer on a global scale increased 7.5-fold and that of phosphorus 3.3-fold (see Table 1.1).

About 40% of the global human population is dependent on synthetic nitrogen fertilizer (Smil 2002a; Stewart et al. 2005). However, its use varies among regions (Vitousek et al. 2009). In 1997 to 1999, the highest rates of fertilizer use were in East Asia (194 kg/ha of arable land), followed by the industrial countries with 117 kg/ha, whereas farmers in sub-Saharan Africa applied only 5 kg/ha on average (Bruinsma 2003). This resulted in average cereal yields in sub-Saharan Africa of 1.1 t/ha in 2000, whereas average yields in Asia, Latin America, and the Middle East/North Africa amounted to 3.7, 2.8, and 2.7 t/ha, respectively (Kelly 2006).

Table 1.1 Nitrogen and phosphate fertilizer in kg/ha arable land and permanent crops for the years 1961, 1981, 1997, 2002, and 2007.

Source: FAO (2010a).

	Nitrogen fertilizers (total N) in kg/ha					Phosphate fertilizers (total P_2O_5) in kg/ha				
	1961	1981	1997	2002	2007	1961	1981	1997	2002	2007
Sub-Saharan Africa	0.5	3.3	3.7	2.7	2.6	0.3	2.3	2.3	1.5	1.5
Near East/North Africa	3.9	27.9	45.5	50.7	62.8	1.3	14.0	17.7	19.5	20.4
South Asia including India	1.8	26.0	68.8	69.2	89.7	0.4	8.5	22.7	24.7	32.5
South Asia excluding India	3.4	35.0	91.7	105.1	112.0	0.8	11.2	21.1	29.1	32.4
East Asia including China	5.8	77.5	121.8	143.0	150.7	2.5	20.9	47.9	48.6	57.0
East Asia excluding China	6.6	33.1	53.8	54.9	60.9	4.0	11.0	18.5	17.0	21.3
Latin America and the Caribbean	4.2	20.1	29.5	29.8	43.3	3.5	15.3	20.5	24.6	37.1
Industrial countries	16.3	50.8	57.1	61.2	65.2	18.0	28.1	24.3	24.8	24.9
Transition countries	18.7	85.8	18.3	16.0	20.5	10.9	56.4	4.9	5.2	7.5
World	8.5	41.5	53.5	56.4	64.4	8.0	21.3	21.9	22.2	26.3

Note: The country groups correspond to the classification proposed in Bruinsma (2003).

In the past decades, an increase in the consumption of nitrogen and phosphorus fertilizers has been observed globally (see Table 1.1). By 2050, nitrogen fertilization is expected to increase by 2.7 times and phosphorus by 2.4 times on a global scale (Tilman et al. 2001). However, increased fertilizer application rates exhibit diminishing marginal returns such that further increases in fertilizer are unlikely to be as effective in increasing cereal yield as in the past. A declining trend in global nitrogen efficiency of crop