Ecological Intensification of Agriculture and Implications for Improved Water and Nutrient Management

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Abstract

Econometric models predict that global cereal demand will increase by 1.3% annually through 2025; cereal yields must increase by 1% annually to meet this demand. This scenario assumes a 50-Mha increase in cereal production area. However, recent trends suggest that the cereal production area will stay constant, at best, or may decrease slightly because of land conversion for other uses. Likewise, rising costs of fossil fuels are driving the diversion of grain for production of biofuels and bio-based industrial feedstocks. It is, therefore, plausible that current econometric models underestimate cereal demand and the rate of yield increase that will be needed to meet it. The rate of increase in cereal yields is decidedly linear; it is falling below the rate of increase in demand, and would do so more rapidly under a scenario in which cereal demand is greater and the cereal production area smaller than forecast by current econometric projections. There is a need for accelerated yield gain – combined with protection of natural resources and environmental quality for future generations. Ecological intensification of cereal production systems provides the framework for achieving these dual goals. It involves concomitant improvements in nutrient use efficiency, especially of nitrogen (N), water use efficiency, and energy efficiency. Fertigation holds tremendous promise for contributing to ecological intensification in irrigated systems, because it facilitates improved congruence, in time and space, between crop nutrient demand and the available nutrient supply. With advanced irrigation technology, such as low-pressure sprinkler systems or drip irrigation, fertigation can help sustain the required rate of yield gain while also achieving a substantial decrease in nutrient and water requirements per unit of grain production.

Keywords: food security, crop yield potential, nutrient use efficiency, environmental quality, irrigated agriculture.

Introduction

The rapid economic development that has occurred in Asia during the past 30 years was supported by low commodity prices for the major food crops. Reasonable food prices were especially important for the development turnaround since 1990 in countries like China, India, Thailand, and Vietnam. Indeed, reasonable food prices will be required to sustain rapid economic development in these countries and worldwide.

Economic development is accompanied by increased demand for land and water for: expansion of industry, improvement of living conditions, expansion of the range of recreational activities, and the conservation of natural resources. Thus, the per capita consumption of land and water increases with economic development, which results in intensified competition between agriculture and other economic sectors, for land and water resources. At issue is whether there is enough good arable land to sustain the increases in crop production that are required to meet the demands of a much larger and wealthier human population without causing shortages that would drive up food prices substantially, and without causing environmental degradation.

To examine this issue requires accurate prediction of future trends in crop production, and of the land area and water available for crop production. Because much of the negative impact of agriculture on environmental quality results from nutrient losses associated with intensive cropping systems, the trends in nutrient use efficiency and the technologies to increase it must also be considered. This paper will, therefore, investigate production trends of the major cereal crops – maize, rice, and wheat – to gauge whether current trajectories are sufficient to meet human food needs in the coming decades. Underpinning issues are the rate of gain in yield, the land area available for crop production – especially the trends in irrigated area, the technologies needed to improve nutrient use efficiency, and the role of fertigation. Emphasis is placed on the three major cereals because they contribute more than 50% of all human energy intake, eaten either directly or indirectly as livestock products, and because they receive about 57% of all commercial fertilizer used in agricultural production (Cassman *et al*., 2003).

Projected Food Demand and Supply

Future global food demand can be estimated from the rates of population growth and of economic development, summed globally on a country by country basis. The economic development rate is an important parameter because human diets include a greater diversity of food sources and increased consumption of meat and livestock products as income levels rise. These trends follow the same general pattern, regardless of culture, religion, or geographical location (Delgado *et al.*, 2002). Because 2-4 kg of grain are required to produce 1 kg of meat or fish, grain demand will rise faster than the rate of population increase.

Food supply can be predicted from trends in crop yields and in the arable land area available for crop production, and econometric models have been developed to predict global food demand and supply. One of the most influential and comprehensive food supply-demand models is the IMPACT model developed by Mark Rosegrant *et al*. (2002) at the International Food Policy Research Institute in Washington, DC. According to the IMPACT model, demand for the three major cereals is projected to increase at a compound annual rate of 1.29% from 1995 to 2025 (Table 1). This increase is predicted to come from increases in cereal yields (0.98%/yr) and an expansion of the crop growing area by 50 Mha.

Table 1. Prediction of global aggregate demand, supply, and yield of the three major cereals (maize, rice, and wheat) from 1995 to 2025, by the IFPRI-IMPACT model‡, and a modified prediction based on updated trends in land use.

	1995	2025	Annual rate of change	Modified 2025 prediction	Modified annual rate change
			%		%
Population (10^9)	5.66	7.90	1.12	Same	1.12
Demand (million mt)	1,657	2,436	1.29	2,558	1.46
Production area (million ha)	506	556	0.31	491	-0.10
Mean grain yield† (kg/ha)	3.27	4.38	0.98	5.21	1.56

‡Rosegrant *et al*., 2002, International Food Policy Research Institute.

While the IFPRI-IMPACT prediction accounts for grain demand for human food and livestock feed, it does not consider grain used for biofuel or bio-based industrial feedstock production; the modified prediction assumes that 5% of global grain supply in 2025 is used for production of biofuel and bio-based industrial feedstocks.

†Weighted average for the three major cereals.

However, small changes in the assumptions that go into such econometric models can have large impacts on the resulting prognosis for meeting future food demand. In contrast to the IMPACT model's projection of increased land area for cereal crop production, actual land-use trends indicate that there has been no increase in area devoted to the three major cereal crops since 1980, while the area devoted to all cereal crops (including maize, rice, wheat, sorghum, millet, oats, and other minor grain crops) has been decreasing by 2.1 Mha per year since 1981 (Fig. 1). Given the rapid increase in economic development, it is plausible that the land area available for the major cereals will decline somewhat in the coming decades, in response to demands for better housing, roads, recreation, and expansion of industrial facilities.

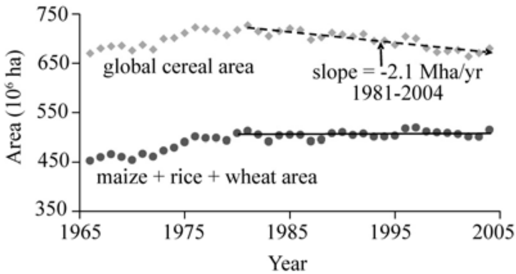

Fig. 1. Global trends in production area of all cereal crops (data at top) and to the three major cereal crops maize, rice, and wheat (data at bottom). *Source*: http://faostat.fao.org.

Most of this development will occur in the peri-urban areas surrounding cities – areas that are typically located in regions with highly productive agricultural soils. In contrast, there are few remaining uncultivated areas with good-quality soils, so that replacement of cereal-growing areas lost to development will be with land characterized by ever more marginal soils, in harsher climates not suited to intensive cropping systems.

In addition, the IMPACT model primarily considers grain use for human food and livestock feed, and does not take into account the increasing use of grain as an industrial raw material for biofuels such as ethanol, or as a source of industrial feedstocks such as starches or plastic precursors. In the USA, in 2004, about 11% of the maize crop was used for ethanol production, and this will double over the next 7 years, under the new Energy Bill recently passed by the US Congress. Concern about high energy prices has motivated a number of other countries to increase production of ethanol and industrial feedstocks from grain. Therefore, it is likely that at least 5% of global grain production could be used for biofuel and bio-based industrial feedstock production by 2025.

If we take into account the increased use of grain for biofuels and bio-based products, and a small annual decrease of 0.1% in the area dedicated to growing the major cereals, we obtain a very different scenario for the food demand-supply balance. Under this scenario, global demand for maize, rice, and wheat will increase by 1.46% annually, compared with the required rate of yield increase of 1.56% per annum (Table 1).

Yield trends

Yields of the major cereals have been increasing steadily, but unlike the projected demand, which is predicted to increase at an exponential rate of increase of 1.29% annually, according to the baseline scenario of the IMPACT model (Table 1), the rates of increase in yields are decidedly linear (Fig. 2). Thus, the rate of yield increase is declining relative to the average yields. For example, the relative rates of increase of the average maize, rice, and wheat yields ranged from 2.62-2.93% in 1966, and had fallen to 1.24-1.42% of the average yields in 2004 (Table 2). Moreover, the proportional rate of gain will continue to decline as long as average grain yields maintain their linear rates of increase. In fact, the relative rate of gain in cereal yields will fall below the baseline IMPACT scenario rate of increase in cereal demand within the decade.

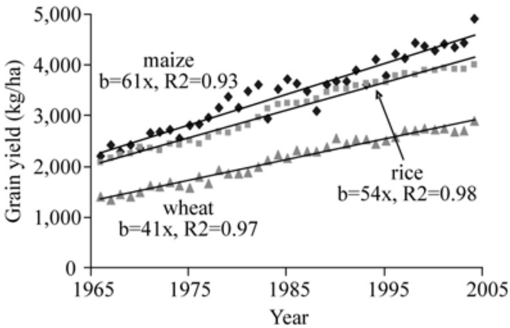

Fig. 2. Global trends in yield of maize, rice, and wheat from 1966-2004. Linear regression slopes (b) represent the annual rate of yield gain in kg/ha/yr. *Source*: http://faostat.fao.org.

In light of the more realistic scenario of declining land area devoted to cereal crop production and increasing global use of grain as a raw material for biofuel and industrial feedstocks (Table 1), the linear trends in grain yield are currently well below the rates of increase in demand for the major cereals. Unless the improvements in cereal yields accelerate, this scenario presents a prospect of rapidly increasing grain prices and even the specter of grain shortages.

Table 2. Global rate of increase in yield of maize, rice, and wheat, 1966-2004.

Crop	Mean yield		Rate of gain	Proportional rate of gain	
	1966	2004		1966	2004
	-------- *kg/ha* --------		*kg/ha/yr*	----------- % -----------	
Maize	2,210	4,907	61.0	2.76	1.24
Rice	2,076	4,004	54.5	2.62	1.36
Wheat	1,408	2,907	41.2	2.93	1.42

The need for ecological intensification

While it could be argued that increased grain prices would stimulate the expansion of cropped areas, there are two factors that make this option unlikely, or at least undesirable. First, as mentioned earlier, there is little remaining uncultivated land with adequate soil quality in regions with climates that are favorable to intensive cereal crop production. In fact, most of the remaining land is of poorer quality than the existing cereal land that is being diverted to other uses. Second, a large proportion of the uncultivated land that is capable of supporting crop production supports natural ecosystems, such as rainforests, grassland savannah, and wetlands, all of which provide critical habitats for conservation of plant and animal species. Expanding cultivated systems at the expense of these natural ecosystems would threaten the biodiversity they contain and the ecosystem services they provide.

A more desirable outcome would involve the ecological intensification of major cropping systems – especially those that produce the major cereal crops (Cassman, 1999). Ecological intensification implies the achievement of substantially higher yields relative to both land area and time, by means of crop and soil management practices that protect soil and water quality. Such ecologically intensified systems would be a departure from the intensification associated with the initial phases of the green revolution, which led to considerable negative impacts on ecosystems, because of the effects of inefficient and sometimes ineffective use of pesticides and fertilizers (Matson *et al.*, 1997; Tilman *et al.*, 2002). Since then, the use of integrated pest management and improved fertilizer management has demonstrated the potential for a more ecological intensive agriculture.

Growing importance of irrigated agriculture

Irrigated agriculture has expanded rapidly during the past 40 years, from 153 Mha in 1966 to 277 Mha in 2002 (Fig. 3). Moreover, global food security is more dependent on irrigated agriculture today than in the past, because the irrigated area now forms 18% of all cultivated land, compared with 11% in 1966, and it currently accounts for about 40% of our global food supply.

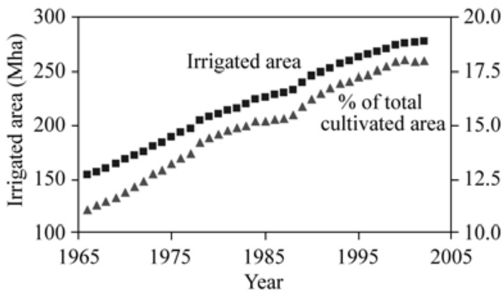

Fig. 3. Trends in total global irrigated crop area and % total cultivated area. *Source*: http://faostat.fao.org.

Irrigated agriculture currently uses about 70% of the fresh water estimated to be available globally for use each year (Postel, 1998). However, increasing competition for water between agriculture and other users will require producers of irrigated crops to be increasingly more efficient, so that the yield per unit of applied water must increase substantially. At the same time, because of the importance of irrigated agriculture to the global food supply, the farmers who use irrigation must sustain or even accelerate the rates of increase of crop yields. Fortunately there are a number of existing technologies that can greatly improve water use efficiency, compared with the traditional flood or furrow irrigation. Low-pressure pivot irrigation and sub-surface drip irrigation systems are good examples of such technologies, although such systems require substantial capital investment. However, when these systems are coupled with improved methods for scheduling irrigation and controlling the amount applied, it is possible to achieve significant increases in both crop yields and water use efficiency (WUE).

Environmentally sound nutrient management in high-yield systems

Higher grain yields require greater uptake of crop nutrients, because the relationship between crop biomass yield and nutrient uptake is tightly conserved. This tight conservation is especially true for N (Greenwood *et al.*, 1990), which is the plant nutrient of greatest concern because of the negative impacts of N losses on water quality and greenhouse gas emissions (Galloway and Cowling, 2002; Matson *et al.*, 2002). Losses of phosphorus, and the associated effects on water quality, are also a matter for concern in heavily manured cropping systems.

The challenge, similarly to that with water, is to produce higher grain yields while at the same time achieving greater N fertilizer efficiency. The focus here is on commercial N fertilizers. Although organic N sources are an important source of the nutrients used in crop production, their relative contribution continues to decline because there is simply not enough manure to meet crop N requirements, worldwide (Sheldrick *et al.*, 2003). The same is true for the other macro-nutrients.

However, achieving higher N-fertilizer use efficiency (NUE) in high-yield crop production systems is difficult, because the response to N follows a diminishing-return function (Cassman *et al.*, 2002, 2003). Hence, the marginal responses to increased N applications decrease for all components of N efficiency as yields approach the potential ceiling (Fig. 4). In fact, the average NUE achieved by farmers is quite low in high-yield cereal production systems: 31% for irrigated rice in Asia, 18-49% for irrigated wheat in rice-wheat systems of India, and 37% for rainfed maize in the USA Corn Belt (Cassman *et al.*, 2002).

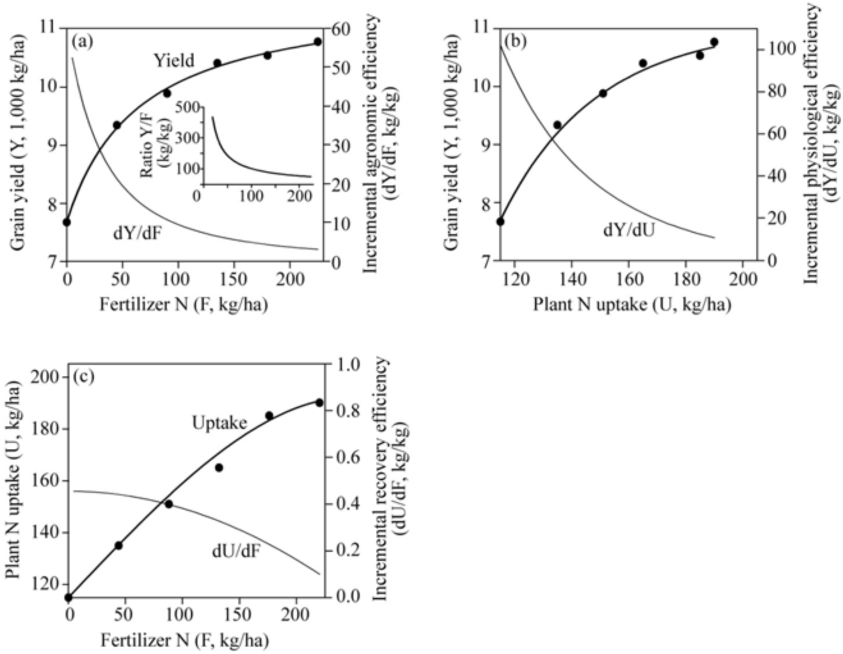

Fig. 4. Relationships among grain yield, plant N accumulation, and the amount of N applied to irrigated maize, and their effects on different components of N-use efficiency. Measured values (symbols) and fitted curves are based on a field experiment conducted in eastern Nebraska. The experiment represents a favorable environment, with fertile soils, use of a well adapted hybrid, and good pest control. (Cassman *et al.*, 2003).

Greater NUE can be achieved, however, by improving the congruence between the immediate N demand of the crop and the N supply from both indigenous soil N resources and applied N fertilizer (Cassman *et al.*, 2002; Dobermann and Cassman, 2002). Such tactics reduce N losses by decreasing the amount of inorganic N in the soil system that is in excess of the short-term crop demand, and which can be lost through leaching, denitrification, volatilization, or runoff. Both yield and NUE under on-farm conditions can be greatly improved by means of technologies such as: multiple split applications; real-time sensing of plant N status with a chlorophyll meter, to guide N application timing; and site-specific or field-specific N management, in large or small fields, respectively (Olk *et al.*, 1996; Peng *et al.*, 1996; Dobermann and Cassman, 2001; Dobermann *et al.*, 2002; Wuest and Cassman, 1992). Controlled-release fertilizers also show promise for improving NUE, by increasing the congruence between N supply and crop N demand (Shoji and Kanno, 1994).

Fertigation and ecological intensification

Fertigation enables the application of N and other nutrients in multiple small doses that can be timed to achieve congruence with crop demand. Like other methods of N application, however, fertigation requires the real-time estimation of the crop N status and N demand, to ensure that N is applied at the proper times and in the correct amounts. When coupled with an efficient irrigation system, such as a low-pressure pivot or lateral-moving sprinkler systems, or drip irrigation, it is possible to achieve very high levels of both NUE and WUE. Fertigation is particularly useful on crops that have a large N requirement, because it is relatively easy to apply a large number of N doses, in order to avoid excess N supply, which would increase the risk of N losses and luxuriant vegetative growth. In contrast, fertigation may not improve NUE when used with a furrow irrigation system, unless the irrigation can be applied in uniform amounts across the field (Vories *et al.*, 1991; Alva and Paramasivam, 1998). In the case of small flood-irrigated rice fields in China, however, irrigation uniformity is not a problem, and there appears to be a significant increase in NUE as a result of using fertigation (Chen *et al.*, 1989).

Fertigation via drip irrigation can help to improve the use efficiencies of P and K, also, especially in soils that contain minerals that fix these nutrients in unavailable forms. Examples are highly weathered P-fixing tropical soils and K-fixing vermiculitic soils. Under these conditions, fertigation with a drip system allows fertilization to be applied to a smaller soil volume, which in turn ensures greater nutrient availability in the fertilized zone than would be obtained with a broadcast-incorporated application. The result can be greater nutrient uptake from the applied fertilizer (Barber, 1984; Ouyang *et al.*, 1999).

In conclusion, the ultimate challenge is to sustain increases in crop yields that are sufficient to meet a substantial increase in food demand, while protecting water resources from nutrient contamination and reducing the release of greenhouse gases, especially nitrous oxide. An added challenge is to achieve this increase in food production while using less irrigation water, because of the increasing diversion of water supplies to uses other than crop production. Fertigation holds tremendous promise to assist in the ecological intensification of major food crop systems, because it facilitates the optimization of both nutrient- and water-use efficiency.

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