Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture

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ABSTRACT Wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), and maize (*Zea mays* L.) provide about two-thirds of all energy in human diets, and four major cropping systems in which these cereals are grown represent the foundation of human food supply. Yield per unit time and land has increased markedly during the past 30 years in these systems, a result of intensified crop management involving improved germplasm, greater inputs of fertilizer, production of two or more crops per year on the same piece of land, and irrigation. Meeting future food demand while minimizing expansion of cultivated area primarily will depend on continued intensification of these same four systems. The manner in which further intensification is achieved, however, will differ markedly from the past because the exploitable gap between average farm yields and genetic yield potential is closing. At present, the rate of increase in yield potential is much less than the expected increase in demand. Hence, average farm yields must reach 70–80% of the yield potential ceiling within 30 years in each of these major cereal systems. Achieving consistent production at these high levels without causing environmental damage requires improvements in soil quality and precise management of all production factors in time and space. The scope of the scientific challenge related to these objectives is discussed. It is concluded that major scientific breakthroughs must occur in basic plant physiology, ecophysiology, agroecology, and soil science to achieve the ecological intensification that is needed to meet the expected increase in food demand.

This paper explores biophysical constraints to global food security in the next century. Emphasis is placed on wheat, rice, and maize, because these three plant species account for the majority of calories in human diets (http://apps.fao.org/, agricultural production, November 1998), and they are likely to remain the mainstay of human nutrition in the foreseeable future. Intensification of wheat, rice, and maize cropping systems was largely responsible for averting a shortfall in food supply during the past three decades—a 30-year period marking the advent of the so-called "green revolution." The most salient feature of these intensified systems was greater yield per unit land and time.

Although appropriate government policies and social conditions also were required to promote intensification, three production factors were largely responsible for the increased production achieved by farmers. These factors were: (*i*) new "miracle" varieties of wheat and rice released in the mid to late 1960s, which had a higher harvest index (HI; the ratio of grain to total crop biomass), shorter stature, and increased stalk strength that reduced susceptibility to lodging, as well as steady improvement in maize hybrids; (*ii*) increased application of N fertilizer, which allowed greater net primary production without fear of lodging; and (*iii*) massive investments in irrigation infrastructure, which were justified by the greater yield potential, fertilizer responsiveness, and increased cropping intensity made possible with new varieties and hybrids. In addition, the reduction in time, from planting to maturity of the new varieties, also permitted an increase in cropping intensity. While only one crop harvest per year was possible with landrace genotypes, earlier maturity allowed two and sometimes three cereal crop harvests per year on the same piece of land. Annual double-crop systems with rice, wheat, and maize are now the dominant cropping system where soil, climate, and water allow intensified cropping. Hence, the scope for a further increase in cropping intensity is limited. Continued expansion of irrigated area has slowed markedly in recent years, and future prospects for increasing irrigated land are limited by both water supplies and environmental concerns (1).

The foundation of global food security now is built on four major cereal production systems in which modern farming practices are used. These systems include: (*i*) irrigated annual double- and triple-crop continuous rice systems in the tropical and subtropical lowlands of Asia, which account for about 25% of global rice production, (*ii*) irrigated annual rice-wheat double-crop system, which is the primary cereal production system in northern India, Pakistan, Nepal, and southern China, (*iii*) temperate maize-based, rain-fed cropping systems of the North American plains, which contribute more than 40% of global maize supply, and (*iv*) the favorable rain-fed wheat systems of northwest and central Europe, which account for more than 20% of global wheat supply. Cropping systems of smaller extent comparable to each of the major systems listed above also are found in other regions of the world that have similar natural resource endowments.

The Need for Ecological Intensification

Increased yield from intensification of wheat, rice, and maize systems contributed 79–96% of the total increase in the global supply of wheat, rice, and maize since 1967 (Table 1). Although wheat area has remained relatively constant, total maize area increased by 30 million hectares (ha), which is 12% greater than the total USA maize area in 1997 (http://apps.fao.org/). An additional 446 million ha of land would be required to achieve 1997 levels of wheat, rice, and maize production at 1967 yield levels, which represents 3-fold greater more area than the present total area of wheat, rice, and maize in the USA and China combined. Hence, intensification of cereal production systems has spared expansion of agriculture into natural ecosystems and marginal land prone to degradation from intensive cropping (2).

Although intensification has spared natural ecosystems from conversion to agricultural uses, greater use of applied inputs and inefficient farming practices have contributed to

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Abbreviations: HI, harvest index; ha, hectare.

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Table 1. Worldwide harvested area of the major cereals in 1967 and 1997, average growth rates in yield and production since 1967, and the projected growth rate in cereal demand from 1993 to 2020

| Crop | Harvest area, ha $\times 10^6$ | | Annual growth rate, % | | |
| | | | 1967–1997 | | Grain demand, 1993–2020 |
	1967	1997	Yield	Production	
Wheat	219	229	2.3	2.5	1.22
Rice	128	150	1.9	2.5	1.19
Maize	112	142	1.8	2.6	1.49

Sources: http://apps.fao.org/ and ref. 5.

non-point-source pollution problems, such as ground and surface water pollution, and a reduction in biodiversity in agroecosystems as well as other ecosystems that are affected by outputs from food production systems (3). In addition, both intensification and expansion of agricultural area contribute to anthropogenic effects on the Earth's biogeochemical cycles (4). At issue, then, is whether further intensification of cereal production systems can be achieved that satisfy the anticipated increase in food demand while meeting acceptable standards of environmental quality. This goal can be described as an ecological intensification of agriculture. Success will depend on sustaining yield increases in the existing major irrigated and favorable rain-fed cereal systems because of limited opportunities for greater cropping intensity and expansion of irrigated area.

An important question is how much additional cereal production will be required. The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) is one of several econometric models used to estimate future food demand based on population and economic growth rates as well as other factors that influence supply and demand. A recent update of this model predicts a rate of increase in demand for the major cereals between 1993 and 2020 of about 1.2% per annum for wheat and rice, and 1.5% for maize (Table 1) (5). Extrapolating these rates of increase from 1997 to 2027 gives estimates for wheat, rice, and maize demand of 882, 827, and 916 million metric tons, respectively. Hence, cereal production increases during the next 30 years of 44% for wheat, 43% for rice, and 56% for maize provide reasonable targets for researchers concerned with the factors governing global food supply capacity. The goal of achieving this increase without a net expansion of cultivated area also seems appropriate to avoid further losses of the Earth's remnant natural ecosystems.

Intensification in Favorable and Unfavorable Environments

Rice yield trends since 1967 in three Asian countries illustrate the relationship between intensification, natural resource endowments, and the potential impact on global food supply (Fig. 1). In South Korea, all rice is produced with irrigation. Yields increased rapidly until 1980 because of adoption of modern farming practices. Thereafter, yields have stagnated because the average yield of about 6.3 tons (t)·ha^{-1} is approaching the existing yield potential that can be achieved with the best available technology. South Korea has a summer monsoon climate with low solar radiation during the rice growing season that is similar to Kyoto, Japan where rice yield potential averages about 7.8 t·ha^{-1} (6). Assuming a similar yield potential in South Korea, average rice yields achieved by South Korean farmers are about 80% of the yield potential ceiling.

Indonesian rice yields have increased steadily because of expansion of irrigated area, adoption of improved varieties, and use of fertilizers. At present, about 70% of rice area is irrigated (Fig. 1). The yield trajectory suggests that further increases in Indonesian rice yields are possible. In contrast, rice yields in Thailand have barely increased because 75% of rice area is produced without irrigation (i.e., rain-fed systems) on
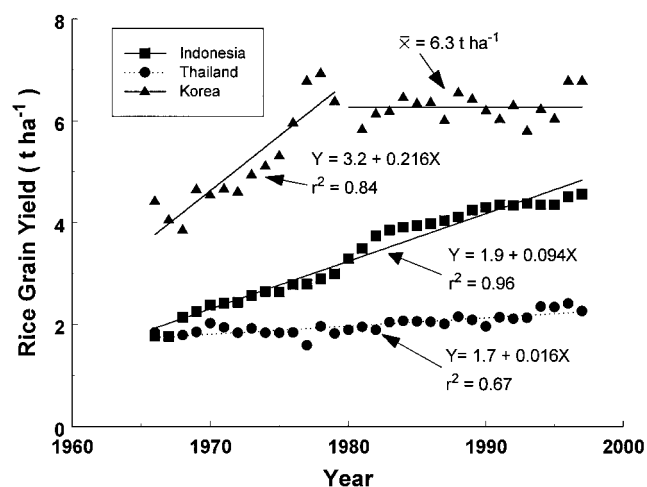

FIG. 1. National average rice yields from 1967 to 1997 in three Asian countries (http://apps.fao.org).

poor quality soils. Drought, flooding, and infertile soils impose severe limits on the ability to increase yield even though farmers have access to improved varieties and fertilizer inputs. Despite these constraints, it is noteworthy that Thailand is presently the world's largest exporter of rice, which reflects an extensive rice production area rather than high productivity, and the scope for increased rice production is very limited.

Similar tendencies in relation to natural resource endowments are seen in the yield trends of wheat and maize. Modern crop management practices have had the greatest impact on yields in irrigated systems, such as the high-production rice and wheat systems in Asia, and in rain-fed environments where both climate and soil quality are favorable for crop growth, such as the wheat systems of northwest and central Europe and maize-based systems in North America. In unfavorable rain-fed environments with poor soils and harsh climate, wheat and maize yields have risen slowly during the past 30 years.

Ecological intensification of cropping systems in unfavorable rain-fed environments mostly depends on reducing the reliance on subsistence cereal production, integration with livestock enterprises, greater crop diversification, and agroforestry systems that provide higher economic value and also foster soil conservation (7). The magnitude of increase in the food supply from such advances will be relatively small, however, because present yields are very low and the primary constraint is lack of water. All crop yields are directly related to the amount of water transpired (8). Hence, the potential to increase the amount of transpiration in water-limited environments by genetic improvement is relatively small. Instead, increasing the amount of plant-available water per unit of rainfall by improvements in soil and residue management that increase infiltration and reduce runoff will have much greater impact on yield and yield stability than can be expected from genetic improvement. No-till and reduced tillage systems developed in the USA are examples of such practices (9). In tandem with research on integrated nutrient management, applied research to adapt conservation tillage technologies for use in unfavorable rain-fed systems in developing countries would have a large positive impact on local food security and increased standards of living, but they will have little impact on the global food-supply balance.

At the other extreme are high-production systems in which average farm yields are presently above 70% of yield potential. Rice production in Korea, Japan, and parts of the USA and China, and wheat production in some areas of northwestern Europe have reached this level. Further increases in yield will be difficult to achieve without an increase in the genetic yield potential of crop varieties and hybrids.

The greatest opportunities for sustained yield increases from further intensification are found in irrigated and favorable rain-fed systems where present average farm yields are less than 70% of yield potential. Rice systems in Indonesia are an example of such systems (Fig. 1), and most irrigated rice and wheat systems in the developing countries of Asia fall into this category. For example, the mean climate-adjusted rice yield potential in this region is estimated to be about 8.5 t·ha^{-1} (10) while average irrigated rice yields are presently 5.0 t·ha^{-1} (7), or about 60% of the climate-adjusted yield potential. Other major food production systems in this category are the favorable rain-fed maize-based systems in North America, the irrigated rice-wheat systems of Pakistan, northern India, Nepal, and China, rain-fed wheat in central Europe, and the cereal production areas in favorable rain-fed regions of Argentina and Brazil.

Yield Potential

The gap between average yields presently achieved by farmers and yield potential is determined by the yielding ability of available crop varieties or hybrids and the degree to which crop and soil management practices allow expression of this genetic potential. Maintaining a sizable yield gap is crucial for sustaining steady increases in average crop yields as can be seen in the example of rice production in South Korea (Fig. 1). Knowing the rate of gain in yield potential and the physiological basis for these gains in the past 30 years provides insight about future prospects.

Evans (11) defines crop yield potential as the yield of a cultivar when grown in environments to which it is adapted, with nutrients and water nonlimiting and with pests, diseases, weeds, lodging, and other stresses effectively controlled. Although this definition seems straightforward, it is difficult to measure yield potential under actual field conditions because it is impossible to eliminate all abiotic and biotic stresses. Hence, a more functional definition of yield potential is the yield obtained when an adapted cultivar is grown with the minimal possible stress that can be achieved with best management practices. Although there is some imprecision in the specification of minimal possible stress and best management practices, crop simulation models can provide reasonable estimates of functional yield potential in a given environment based on the physiological relationships that govern plant growth and development (6, 12). In irrigated systems, yield potential primarily is determined by solar radiation and thermal regime during crop growth. A water-limited yield potential also can be simulated for rain-fed systems by accounting for the water balance of the system.

The largest contribution to the increased yield potential of modern wheat and rice varieties came from the increase in HI. In both crops, there was a quantum leap in HI from introduction of dwarfing genes into the new varieties developed the 1960s. There has been little further increase in HI of rice, which is about 0.50–0.55 in recently released varieties (13), and the scope for continued increases is limited by the need to maintain sufficient leaf area and stem biomass for interception of solar radiation, physical support, and storage of assimilates and N used in grain filling. Recent wheat cultivars appear to have a relatively low HI of 0.41–0.47 when grown with irrigation in California and Mexico (14, 15), and a further increase in HI might be feasible. In maize, increased HI has contributed little to the genetic yield gains of modern hybrids (16).

With relatively little possibility for increases in HI, greater yield potential must come from increases in net primary productivity. Heterotic vigor has been heavily exploited during the past 50 years of maize breeding. Hybrid rice provides about a 7–10% yield advantage compared with the best inbred varieties when grown at yield potential levels (17). Although it

has been widely adopted in China, hybrid rice technology is in the early stages of testing and commercialization in other Asian countries. Development of hybrid wheats also may deliver an increase in yield potential, but it remains in the experimental phase because of high seed production costs.

Switching from inbreds to hybrids provides a one-time boost to yield potential on the order of 10%. Thereafter, further increases in yield potential depend on an increase in canopy photosynthesis per unit of intercepted light or a decrease in the metabolic costs of synthesis and maintenance of carbohydrates, proteins, and lipids. There is little compelling evidence, however, that plant physiologists or breeders have been successful at increasing the assimilatory or metabolic efficiencies of the major cereal crops (11). Some argue that the processes governing radiation use efficiency, a parameter that integrates both photosynthetic capacity and metabolic costs, are conservative and therefore offer little opportunity for improvement through genetic manipulation (12).

A growing body of evidence suggests that much of the observed genetic gain in yield during the past 30 years can be attributed to greater stress resistance rather than an increase in yield potential. In large part, this change in perspective results from greater recognition of factors that confound interpretation of side-by-side comparisons of old and new cultivars or hybrids. Such studies have provided most of the estimates of genetic gain in yield potential. Table 2 summarizes recent reports in which rates of gain in both yield potential and resistance to stress were evaluated (13, 15, 17, 18). For tropical rice and temperate maize, these reports suggest that there has been no detectable increase in yield potential although steady progress has been made toward improving stress tolerance. Tollenaar (16) also concluded that resistance to multiple stresses has contributed most to genetic yield gain of temperate maize hybrids used in southern Canada. Only wheat has shown a genetic gain in both yield potential and stress resistance. It also should be noted that the rate of genetic gain in yields has been mostly linear for each of these cereals, regardless of whether it results from an increase in yield potential or stress resistance. Hence, the relative rate of increase has decreased with time.

In summary, breeders have greatly improved stress resistance in each of the major cereals but have been less successful in pushing out the yield frontier. For tropical rice and temperate maize, the exploitable yield gap appears to be closing. During the past 30 years, breeders have relied on empirical selection for yield as their primary selection criteria by using a brute-force numbers approach. While the use of molecular markers should improve breeding efficiency for increased

Table 2. Annual rate of genetic gain in yield of wheat and rice varieties and maize hybrids in relation to year of release when grown without full control of biotic and abiotic stresses (with stress) or at yield potential levels (minimal stress)

| | | Rate of genetic yield gain, annual percentage rate | | | |
| | | With stress | | Minimal stress | |
Crop and region	Period	Oldest	Newest	Oldest	Newest
Bread wheat, NW Mexico	1962–88	2.6	1.6	1.0	0.8
Tropical rice, Philippines	1966–95	1.0	0.8	0	0
Temperate maize					
Iowa, USA	1967–91	1.2	0.9		
Nebraska, USA	1983–97			0	0

Rates of gain are linear in relation to year of release and therefore are computed separately in relation to the yield levels of the oldest and most recent (newest) releases. Yield potential with minimal stress has not changed in rice and maize during the period of study (13, 15, 17, 18).

resistance against diseases and insect pests and for improving the fit of genotype to the environment, it is not clear whether marker-assisted breeding can contribute to raising the yield potential ceiling in nonstress environments. Seed yield is under complex genetic control involving thousands of genes. The notion that "yield genes" can be concentrated by marker selection to achieve greater yield potential remains to be proven. In contrast, breakthroughs in molecular biology now allow new approaches for manipulating and investigating the genetic controls on key assimilatory and metabolic processes that govern radiation use efficiency. While these possibilities are exciting, such work is in the early stages of experimentation. Therefore, the most likely scenario for yield potential of the major cereal crops is one of small, incremental increases during the next three decades, and these modest improvements will require considerable research investment. Nonetheless, even small increases in yield potential represent important contributions to global food security.

Soil Quality

Soil quality, like yield potential, is an elusive concept that is difficult to define and measure. Definitions of soil quality in recent literature stress the capacity to support biological productivity, maintain environmental quality, and promote plant and animal health (19). Despite this broad definition, it can be argued that the specific soil properties that support crop productivity, such as nutrient reserves, water holding capacity, and favorable structure for root growth, are the same properties that contribute to the environmental services that soils furnish. These soil properties include: physical attributes such as the size and continuity of pores, aggregate stability, impedance, and texture, which together determine soil structure; chemical properties such as organic matter content and composition, nutrient stocks and availability, mineralogy, and the amount of elements and compounds that are deleterious to plant growth; biological attributes such as the quantity, activity, and diversity of microbial biomass and soil fauna.

A reduction in soil quality as a result of human activities can be defined as soil degradation. Water erosion, wind erosion, chemical degradation (including nutrient depletion and loss of organic matter, salinization, acidification, and chemical pollution), and deterioration of physical properties are the four major types of soil degradation. One recent study, which involved 250 scientists from 21 regions, estimated the global extent, severity, and causes of soil degradation (20). Total area with some form of soil degradation was estimated to be about 2,000 million ha. Inappropriate farming methods, deforestation, and overgrazing were identified as the primary causes. Water or wind erosion was estimated to have affected 84% of the total degraded area. More than 80% of all degraded land was located in Africa, Asia, and South and Central America. About 60% was found in dry-land regions poorly suited for intensive agriculture. Because the production practices and physical processes that cause erosion are well understood, technical solutions to prevent this kind of degradation are available. Barriers to adoption often involve issues of land tenure, access to credit and inputs, and other socio-economic factors. Efforts to encourage adoption of erosion control practices are crucial to improve the local food security and welfare of people who live in erosion-effected areas. Likewise, prevention of erosion in upland watersheds that feed major irrigation systems can have an impact on food production capacity in highly productive lowland areas as a result of reduced sedimentation in reservoirs and irrigation systems. This sediment load increases maintenance costs of irrigation infrastructure and reduces reservoir storage capacity, which can result in water shortages in highly productive irrigated areas.

Erosion also can be a problem in favorable rain-fed regions with good soils and adequate rainfall for crop production. Much of the crop land in the north-central USA falls into this category but soil conservation methods have been developed to prevent erosion. No-till and reduced tillage systems maintain crop residues on the soil surface and protect against the direct impact of raindrops and increase infiltration rates. As a result, a greater proportion of incident rainfall is stored in the soil profile while both runoff and erosion are reduced. Long-term experiments also indicate that these soil conservation practices help maintain soil quality by stabilizing soil organic matter content at higher levels than with conventional plowing (21).

In addition to erosion, the Oldeman study (20) estimates 555 million ha have undergone various forms of chemical and physical degradation not directly associated with erosion. For most forms of chemical degradation, the governing processes and methods of prevention and restoration are well understood. Salinization (22) and acidification (23) fall into this category, as do human-induced soil toxicities which are side effects of salinization, acidification, or pollution. Although these kinds of degradation can be remedied, the cost can be prohibitive as degradation becomes severe. Prevention is the key. Nutrient depletion and loss of soil organic matter in cropping systems that receive little or no nutrient inputs as fertilizers or manure are also straightforward to diagnose and correct given access to nutrient sources, purchasing power, or credit. For example, soil degradation by nutrient depletion occurs in traditional slash and burn systems practiced by subsistence farmers in the forests and savannas of the humid and subhumid tropics where the fallow period is decreasing because of population pressure (24). Here again, technical solutions are available and the major constraints to adoption are mostly social, political, and economic in nature.

Although blatant forms of degradation occur largely in areas with poor soils or unfavorable climate and there are technical solutions to prevent these problems, it would be a mistake to conclude that soil degradation is not a major threat to food security. Instead, subtle and complex forms of soil degradation can occur in some of the world's most productive agricultural systems, and it is argued here that these less obvious forms of degradation may become an increasingly important constraint to food production capacity in the next century. Moreover, it is unlikely that the previous estimates of soil degradation (20) account for subtle forms of degradation in high-production systems because the extent and causes of such degradation have only recently been recognized.

The yield decline phenomenon that occurs in a number of long-term experiments with annual double- and triple-crop irrigated rice systems is an example of faint changes in soil properties that can have a large impact on productivity (25). It appears to result from a cascade of effects associated with a subtle change in soil organic matter chemistry. These effects have been studied in several long-term experiments in the Philippines that were initiated in the 1960s concurrent with the release of IR8, the first widely grown modern indica rice variety in Asia. In one study, for example, six rice varieties were grown each season in replicated treatment plots with different amounts of applied N. All other nutrients are supplied as required. Weeds and insects were controlled by using recommended practices. From 1968 to 1991, IR8 was one of the six varieties grown while the other five entries were continually changed to represent the best available International Rice Research Institute germplasm at each point in time. A yield decline occurred in all three cropping seasons of the year and at all levels of N addition (26). In the dry season when solar radiation and temperature provide conditions for greatest yield potential, yield of the highest-yielding varietal entries decreased by 130 kg·ha^{-1}·yr^{-1} in the treatment receiving the

greatest amount of N fertilizer, which was also the highest yielding N treatment (Fig. 2).

The yield of IR8 decreased more rapidly and displayed considerably more variability than the highest-yielding varieties. Greater yield stability of the newer varieties resulted from greater resistance to fungal and bacterial diseases and to insect vectors that transmit viral diseases. Eventually IR8 could not be adequately protected from viral infection despite the use of recommended insecticide control measures for the insect vectors. In contrast, this same level of pest control was adequate to protect the newer varieties from viral infection. Hence, the difference in yield and the greater yield stability of the highest-yielding varieties compared with IR8 provides an estimate of the genetic gain breeders have made in resistance to pests as discussed in the previous section.

Even with greater disease and insect resistance, however, yield of the newest varieties also declined with time although yield potential of the more recent varieties was no different from IR8 (ref. 13; Table 2). Subsequent studies demonstrated that yields could be restored to yield-potential levels when additional N fertilizer was added and the crop was protected against sheath blight (*Rhizoctonia solani*) (26, 27). Both the incidence and severity of this disease increase when plants are supplied with sufficient N to achieve yield-potential levels in the humid tropics (28). These results indicated that soil N supply capacity had decreased because yields could be restored by application of additional N in combination with fungicide, but not with fungicide alone. This reduction in soil N supply was not associated with a decrease in soil organic matter or soil N content, both of which increased in the treatments that received the greatest amount of applied N (26). In fact, the conservation or increase in soil organic matter appears to be a common feature of continuous, irrigated double- and triple-crop rice systems although the chemical structure of the most labile soil organic matter fractions become enriched with phenol subunits (29, 30). It is hypothesized that the decrease in soil N supply was caused by the accumulation of phenol C in these youngest humic fractions, and that phenol enrichment

results in a reduced rate of N mineralization from these organic matter pools (27, 29).

Companion studies have found that phenol accumulation in young humus appears to be a characteristic feature of irrigated rice systems in the tropics, and it appears to reduce the N use efficiency of the system. A recent field study demonstrated that incorporation of rice stubble during the fallow period when soil is aerated, instead of the standard practice of incorporation in flooded soil, can increase the soil N supply to a following rice crop (31). This finding is consistent with the phenol accumulation hypothesis and suggests that tillage and residue management practices can be modified to increase soil N supply by allowing phenol oxidation and thereby reducing requirements for applied N.

Further work is required to fully elucidate the factors responsible for the yield decline in long-term experiments on intensive rice systems. More important, however, is to determine the extent of this phenomenon in farmers' fields. Making this assessment is difficult because soil N supply could decrease in a farmer's field, just as it does in the long-term experiments, but it would be not be detected if farmers applied increasing amounts of N to maintain yields (32). Although this situation would mean a decrease in yield per unit of applied N, many other production practices and environmental conditions also affect N fertilizer efficiency and farmers are not likely to notice the reduction in N fertilizer efficiency. Macronutrients other than N and perhaps micronutrients also may become limiting at high yield levels once the N constraint is alleviated (33). These non-N nutrients may not be limiting at the reduced yield levels achieved when the crop was N deficient, but they become limiting at higher yield levels made possible by improved plant N nutrition. Nutrient balance studies clearly indicate that soil potassium is being depleted in most irrigated rice systems in Asia at present levels of K inputs and outputs.

There is also evidence of subtle forms of soil degradation occurring in other major high-production cereal production systems, including rice yield declines in long-term experiments on rice-wheat systems in India (34, 35) and in a no-till continuous corn system in the USA (36). In both systems, declining yield trends also were associated with an increase in soil organic matter although present understanding asserts that soil organic matter content is positively correlated with soil quality. It is also noteworthy that there is no evidence of a positive maize yield trend during the past 25 years in long-term experiments conducted in the north-central USA despite regular replacement of hybrids. Each of these experiments include both irrigated and rain-fed maize systems, with and without crop rotation, and at least one treatment receives recommended nutrient inputs and crop management practices. In all of these experiments, however, mean yield is well below yield potential levels, which indicates the crop is exposed to stress of some kind during the growing season. This notable lack of a positive yield trend is inconsistent with the steady genetic improvement in stress tolerance of maize hybrids (refs. 16 and 17; Table 2). Subtle forms of soil degradation could account for the lack of a positive yield trend in these long-term experiments, although, to date, there is no direct evidence to support this hypothesis and there has been little effort to investigate it. In contrast to rice and maize, positive yield trends in wheat yields during the past 25–30 years can be found in a long-term experiment conducted in India and another in northwest USA (37). These trends are consistent with the steady increase in wheat yield potential (Table 2).

Subtle changes in soil properties and subsequent effects on yield and input requirements illustrate the complexity of the relationships between soil quality and cropping system performance. It is postulated that subtle forms of soil degradation are occurring in some of the most important cereal production systems in the world. It is further argued that an increase in soil quality will be required to achieve sustained yield increases of
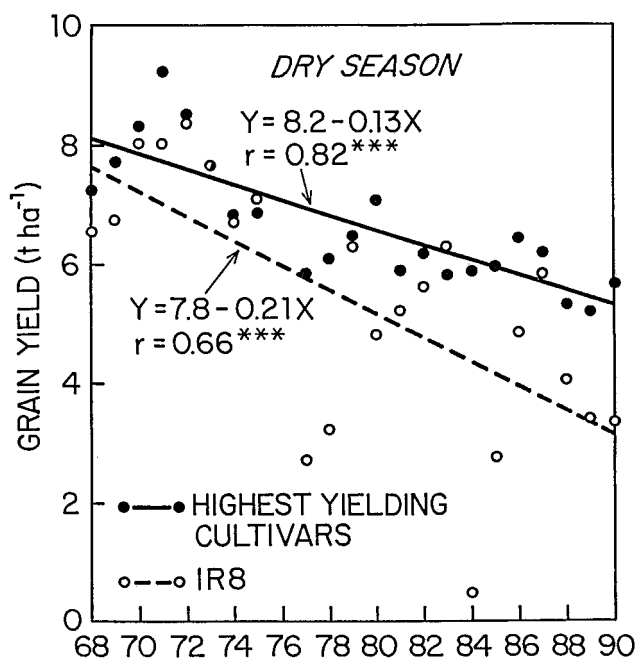

FIG. 2.   Yield trends from 1968 to 1990 of the highest yielding rice cultivars and IR8 in a long-term continuous cropping experiment at the International Rice Research Institute in the Philippines. Reproduced from ref. 25 with permission of John Wiley & Sons, Ltd., London.

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1.2–1.5% annually for the next 30 years because increased inputs of energy, nutrients, water, and pest control measures are required to offset a decrease in soil quality (Fig. 3). In addition, more sophisticated management practices are needed to apply the additional inputs properly because soil degradation reduces the resource buffer provided by good soil quality and decreases the margin of error for nearly all crop management practices, especially in high-yield systems. Consequently, identifying the critical thresholds for specific soil properties that have the greatest influence on productivity is an important, but neglected, scientific quest. Although there is considerable research interest in the assessment of soil quality (38), most of this work is descriptive and does not attempt to quantify relationships between specific properties and crop productivity. A thorough understanding of the rate and causes of change in soil quality and subsequent effects on yields and input requirements will be required to sustain yield increases in the major high-production cereal systems.

Precision Agriculture

The gap between average farm yields and the yield potential ceiling must shrink during the next 30 years because the yield potential of tropical rice and maize appears to be stagnant and wheat yield potential is increasing more slowly than the expected increase in demand (Tables 1 and 2). Hence, achieving consistent cereal yields that exceed 70% of the yield potential barrier depends on sophisticated management of soil and water resources and applied inputs. A precision agriculture approach is required to insure that the requisite resources for crop growth are available and crop protection needs are met without deficiency or excess at each point in time during the growing season. Precision management can be applied uniformly to an entire field by exact timing and placement of a particular field operation, or it can involve site-specific management within a field to account for variation in soil properties, crop resource requirements, pests, and disease.

Site-specific management that relies on variable application of an input or management operation is most relevant to large-scale agriculture in which field size and within-field variation are great enough to justify the cost of needed equipment. In most developed countries, this technology is presently available and allows application of seed, nutrients, water, and pest control measures to meet the specific require-
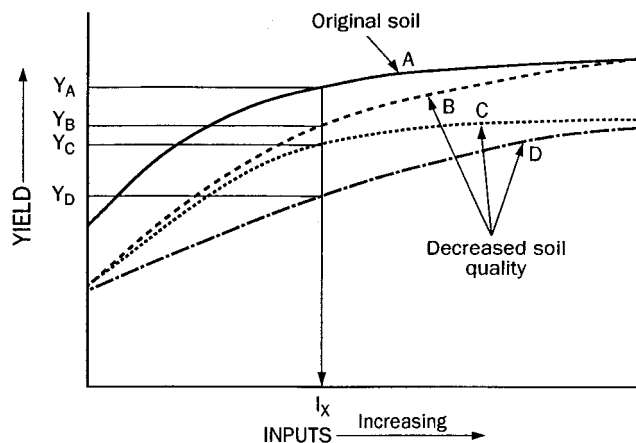

FIG. 3. Conceptual model illustrating the relationship between crop yields and input requirements as influenced by soil quality. A decrease in soil quality from an initial state (curve A) can result in the need for greater inputs of energy, nutrients, water, seed, and pest control measures to achieve the same yield. The slope and asymptote of the shifted response (shown by curves B, C, and D) depend on the type of soil degradation and can result in a reduction in input use efficiency, yield potential, or both.

ments at each location within a field. Theory predicts increasing fertilizer use efficiency from site-specific versus uniform nutrient application as the magnitude and negative skewness of variation in native soil nutrient supply increases and as yield levels approach the yield potential ceiling (39). Simulations also predict a reduction in nitrate leaching from improved N fertilizer efficiency with site-specific management (40).

In practice, validation of theory has been difficult to achieve. One study, which compared uniform versus site-specific N application to irrigated maize, found a significant yield increase from site-specific application in one of 12 site-year comparisons and a negative yield response in another (41). No yield difference was observed in the other 10 comparisons, and the amount of N applied was similar using both methods. Despite detailed soil sampling to develop the site-specific N application guidelines, the authors attributed the lack of response to the inaccuracy in prediction of N fertilizer requirements by present methods of soil testing that do not account for the dynamic controls on soil and fertilizer N availability or crop N requirements.

Although theoretical estimates of economic and environmental benefits from site-specific deployment of variety or hybrid, plant density, nutrients, pest control measures, and irrigation are large, successful implementation by farmers will require accurate data about the spatial variability in soil properties, pest and disease incidence, and crop physiological status, as well as exact knowledge of crop response to this variability. Remote sensing capabilities are under development that may improve the accuracy and reduce the cost of real-time measurements of spatial variability in crop physiological status and pest pressure. In contrast, detailed knowledge of the ecophysiological processes governing crop response to interacting environmental factors is not sufficiently robust to make accurate predictions of site-specific input requirements or the expected outcome from their application. This knowledge gap is the key limiting factor to adoption of site-specific management in large-scale agricultural systems in developed countries.

In developing countries, the need for precision agriculture also will be crucial to achieve cereal yield increases that must approach yield potential levels in the major production systems. Because field size is typically less than 0.5 ha, precision agriculture will involve field-specific management practices. Recent on-farm studies of double-crop rice systems in several Asian countries document tremendous field-to-field variation in native soil N supply within small production domains in which soil properties are similar. For example, grain yields without applied N ranged from 2,400 to 6,000 kg·ha^{-1} in 42 different rice fields surrounding one village in the Philippines, and the variation was attributed to differences in soil N supply (Fig. 4). Similar results have been obtained in other major rice production centers in southern India, Indonesia, Thailand, and Vietnam where double- and triple-crop rice systems are the dominant food production system (42). In all cases, the large variation in soil N supply was not associated with differences in soil organic matter content, total N, or other measures of soil N availability (32), which is consistent with results from the long-term experiments on double- and triple-crop rice systems. Hence, the same processes that account for the subtle changes in soil organic matter composition in the long-term experiments also may influence soil N supply in areas where continuous irrigated rice cropping systems are the dominant cereal production system.

Given the tremendous variation in soil N supply among fields with similar soil types and crop management practices, field-specific N fertilizer requirements will be needed to optimize yield and profit, and to minimize N fertilizer losses. Related studies have identified large field-to-field variability in soil P and K supply. Field-specific management also will be needed for these nutrients. As is the case for soil N supply,
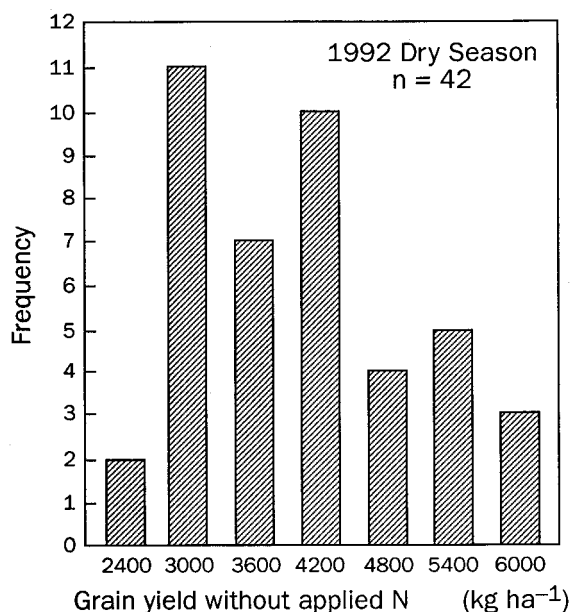
FIG. 4.   Frequency distribution of rice grain yield without nitrogen fertilizer application in 42 different farmer's fields in the Guimba Municipality, Central Luzon, Philippines. Reprinted from ref. 32 with permission from Elsevier Science.

present soil-test methods do not accurately predict soil P or K availability, or the yield response from P or K application (33). One would expect a similar degree of field-to-field variation in soil N, P, and K supply will be found in the irrigated rice-wheat systems of Asia because rice also is grown in flooded soil in these systems.

Most government and regional extension systems in Asia presently provide blanket fertilizer recommendations for large production domains of wheat and rice. Given the magnitude of field-to-field variation within small areas with similar soil type, this approach results in inefficient use of nutrients and will limit efforts to increase average farm yields because of nutrient deficiencies, excesses, and imbalances. On the other hand, the need to achieve field-specific nutrient management in hundreds of millions of small rice and wheat fields in low-income countries is a daunting challenge. Field-specific pest management also will be needed to protect crops from insect pests and diseases while minimizing the use pesticides. In addition, the incidence and severity of a number of major diseases and insect pests increase when cereal crops are provided sufficient N to achieve the lush canopy required for high yield levels. Developing the scientific capacity, technology transfer mechanisms, and farmer education to allow diagnosis of limiting factors, prediction of expected yields and input requirements, and implementation of field-specific management will be a crucial component of food security in these low-income countries that rely on high-production cereal systems.

Conclusions

The projected increase in food demand and the goal of minimizing expansion of cropped area dictates that cereal yields will approach the yield potential ceiling in many of the world's most productive cropping systems within the next three decades. Ecological intensification of these high-production cropping systems is fundamental to achieving food security under this scenario and raises several questions: What is the prognosis for increasing the yield potential of wheat, rice, and maize and by how much? What is the direction of change in soil quality in the major cereal production systems and how will these changes affect crop productivity? Can crop and soil

management practices be improved to achieve consistently high yields while meeting acceptable environmental standards? It is argued that the present state of knowledge is far from sufficient to answer these questions despite the need for answers and widespread application of this knowledge within a relatively short timeline.

It is concluded that global food security 30 years hence will depend on rapid scientific advances in understanding the physiological basis of crop yield potential, the processes governing the relationship between soil quality and crop productivity, and plant ecology related to the many interacting environmental factors that determine crop yields. Achieving these scientific advances is possible, but present levels of investment in these specific research areas, both in the USA and elsewhere, are not adequate to meet the challenge.

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