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Crop Yield Gaps: Their Importance, Magnitudes, and Causes

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Abstract

Future trajectories of food prices, food security, and cropland expansion are closely linked to future average crop yields in the major agricultural regions of the world. Because the maximum possible yields achieved in farmers' fields might level off or even decline in many regions over the next few decades, reducing the gap between average and potential yields is critical. In most major irrigated wheat, rice, and maize systems, yields appear to be at or near 80% of yield potential, with no evidence for yields having exceeded this threshold to date. A fundamental constraint in these systems appears to be uncertainty in growing season weather, thus tools to address this uncertainty would likely reduce gaps. Otherwise, short-term prospects for yield gains in irrigated agriculture appear grim without increased yield potential. Average yields in rain-fed systems are commonly 50% or less of yield potential, suggesting ample room for improvement, though estimation of yield gaps for rain-fed regions is subject to more errors than for irrigated regions. Several priorities for future research are identified.

Keywords: agriculture, climate uncertainty, food production, yield constraints yield potential

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1. Introduction

Demand for both food and energy is quickly rising and will continue to rise with increases in global population and average income. By 2030, global cereal demand for food and animal feed alone is expected to total 2.8 billion (B) tons per year, or 50% higher than in 2000 (1). The additional demand from future biofuel consumption is less clear but could be considerable; the United State's renewable fuel mandate for starch-based biofuel in the 2007 Energy Independence and Security Act alone will require 0.2 B tons of grain. Because grain supply is the product of crop area and crop yields (production per hectare), meeting this higher demand will require an increase in one or both of these factors.

There is considerable scope for cropland expansion because many natural ecosystems possess conditions suitable for crops, and indeed, many projections of global food supply indicate a sizable amount of land conversion in Latin America and Africa (1, 2). Yet, the goal of many scientists and policy makers is to improve yields at a rate sufficient to keep food prices low and avoid significant expansion of croplands. The reasons for this goal are many and include improvement in food security, preservation of natural habitats and biodiversity, and protection of the climate system (3, 4).

Yield potential: the yield of an adapted crop variety or hybrid when grown under favorable conditions without growth limitations from water, nutrients, pests, or diseases

In this context, the Green Revolution in the latter half of the twentieth century was a remarkable success, as it led to rapid increases in food supply without major increases in crop area or food prices, made possible by rapid increases in yields of the major food crops. The real price of food gradually declined throughout this period as supply growth outpaced demand. Of course, many of the technologies central to the Green Revolution, namely higher fertilizer, pesticide, and irrigation use, can negatively impact environmental quality and ecosystem services if not utilized properly (5, 6). These negative outcomes can potentially outweigh the positive environmental effects of higher yields that accrue from less cropland expansion into natural ecosystems. High yields are thus not sufficient for environmental protection, but they will remain a critical and necessary component of a global strategy to achieve food security while also protecting natural resources and environmental quality for future generations.

Although the need for higher yields is clear, the prospects for achieving them are less so. There is increasing evidence of stagnation in crop yield potential as measured under the best possible growing conditions (7, 8), and even some indications that average crop yields in major cereal-producing countries have plateaued (4). As Evans (9) points out, it is important to recall that history is littered with many examples of yield projections based on short-term trends that quickly proved far too pessimistic. Yet, the lack of progress in yield potential, coupled with absence of recent yield growth for some of the major cereal crops in several countries, is certainly cause for concern and raises the critical issue of how much average yields can continue to increase in the face of potentially stagnant yield potential. Put differently, what causes the difference between average and potential yields, and what are the prospects for narrowing this yield gap?

Average farm yields in a region or country are inevitably smaller than yield potential, sometimes significantly so, because achieving yield potential requires near perfect management of crop and soil factors that influence plant growth and development throughout the crop growth cycle. Although a few superior farmers may come close to this state, it is neither profitable nor feasible for a large population of farmers to do so. Moreover, the existence of a sizeable gap between average and potential yields is believed necessary to maintain growth in average yields, because yields begin to plateau once they near the yield potential ceiling (3, 10). Therefore, as the average farm yields appear to fall off from historical yield trends, it is important to determine if this stagnation is caused by the diminishing size of the exploitable yield gap or by other factors such as soil degradation, pollution, or climate change.

This article addresses these issues by reviewing evidence on the magnitude and causes of yield gaps for the major cereals—rice, wheat, and maize—in their major growing regions. We view an understanding of yield gaps as important for at least two reasons. First, as mentioned above, it helps to inform projections of future crop yields for different regions and crops because close proximity of yields to their upper limits may indicate that growth rates are likely to slow in the future (10, 11). Second, knowledge of factors that contribute to the yield gap is useful for efficiently targeting efforts to increase production. Critical questions, for instance, are whether the smallest observed yield gaps in the world reflect a fundamental limit to yields, or whether it is possible with new technologies to achieve average yields even closer to potential. To answer these questions requires knowledge of which specific factors represent the largest constraints to productivity in the world's major cropping systems.

The following section provides an overview of various definitions and methods for estimating yield gaps. Section 3 reviews current evidence on the magnitude of gaps for different crops and regions, and the causes of yield gaps are examined in Section 4. The main conclusions and prospects for global food security through closure of existing yield gaps are presented in Section 5.

2. Definitions of Yield Gap

The term yield gap has been widely used in the literature for at least the past few decades (12). Yield gaps are estimated by the difference between yield potential and average farmers' yields over some specified spatial and temporal scale of interest. Yield potential, in turn, can be defined and measured in a variety of ways, which has resulted in lack of consistency in yield gap analysis in the literature. Here, we attempt to clarify the definition of yield gap and the various methods used to estimate it.

Yield gap: the difference between average and potential yields, often expressed as Mg ha^{-1}

2.1. Definition

The yield gap is a concept that rests on the definition and measurement of yield potential. Here, we define yield potential as the yield of an adapted crop variety or hybrid when grown under favorable conditions without growth limitations from water, nutrients, pests, or diseases (9). For any given site and growing season, yield potential is determined by three factors: (*a*) solar radiation, (*b*) temperature, and (*c*) water supply.

We use the term yield potential for irrigated systems because it is assumed that an irrigated crop can be provided with adequate water supply throughout growth. In contrast, we refer to maximum possible yields under rain-fed conditions as "water-limited yield potential" because most rain-fed crops suffer at least short-term water deficits at some point during the growing season.

Water-limited yield potential: the yield of an adapted crop variety or hybrid when grown under rain-fed, favorable conditions without growth limitations from nutrients, pests, or diseases

All three environmental factors vary throughout the year, and therefore yield potential will depend not only on location but also on the crop-sowing date and maturity rating. The latter is a genetic trait that determines the length of the growing season when a crop is sown on a given date, with longer maturity cultivars or hybrids requiring more growing-degree days to reach maturity than shorter maturity varieties. In fact, crop yield potential at a given location can vary considerably owing to different planting dates and maturity ratings. For example, wheat trial yields in Ludhiana, India, were roughly 1 Mg hectare $(ha)^{-1}$ lower when the crop was planted on December 15 than on November 15 (13). Likewise, simulated maize yield potential at Lincoln, Nebraska, in the United States increased by 2 Mg ha^{-1} with a seven-day increase in hybrid maturity (14). Yield potential must therefore be defined in relation to a specific planting date and cultivar or hybrid maturity, with the maximum value considered to be the optimum combination of planting date and maturity for a given location. Alternatively, a sowing date that represents the average date of sowing by farmers in a given region and the most common varietal maturity used by these farmers can be set a priori, and the yield potential can be thereby defined for that planting date and maturity combination, whether or not this combination gives the maximum yield potential, or water-limited yield potential, at the site(s) and year(s) in question.

Plant population, the term typically used in agronomy for plant density and measured as the number of plants per m^2, also affects the yield potential at a given location, because maximum dry matter accumulation rates occur when the spatial density of plants allows rapid leaf canopy development to intercept all incoming solar radiation as early as possible in the growing season. Under irrigated conditions, optimal plant density for grain yield is somewhat smaller than for maximum dry matter accumulation because too much vegetative growth makes the crop more susceptible to late-season diseases and instability, which causes the plants to fall over (called lodging). For rain-fed systems where rainfall amounts decrease in the second half of the growing season (typical for most monsoonal climates), optimal plant density for grain yield can be considerably smaller than for maximum dry matter accumulation. In this case, rapid growth during the vegetative phase can use up too much of the stored soil moisture such that the crop runs out of water during the grain filling period. Thus, plant population must be specified to estimate both yield potential and water-limited yield potential at a given site.

The theoretical upper limit to crop yields is dictated by the amount of energy absorbed by a crop canopy and the light-use efficiency of photosynthesis (energy fixed in carbohydrate per unit of light energy intercepted). Integrated over a growing season, the maximum values of light-use efficiency for C_3 crops are about 0.024, whereas those for C_4 crops are about 0.032 (15). Although these numbers seem quite low, they are constrained by a number of important limits. These include the facts that about half of the light energy is in wavelengths too long to be used in photosynthesis and that all plants need to consume some of the photosynthate they fix in the mitochondrial respiration that powers construction and maintenance of plant tissues (16). After accounting for unavoidable losses, the overall efficiency of light utilization is high enough that it leaves limited room for improvement. The photon yield of photosynthesis (mol CO_2 fixed per mol light absorbed) is very consistent across C_4 species (17). It varies with CO_2 concentration and temperature in C_3 plants, but it is very consistent across species (17). Maximum rates of photosynthesis have not generally increased as a result of crop breeding (18), although yield is generally associated with photosynthesis in experiments with elevated atmospheric CO_2 (19). Detailed analyses of the biochemistry of photosynthesis suggest that, with targeted efforts potentially involving genetically modified organisms, improvements in light-use efficiency could be substantial. Long and colleagues (15) estimate that the improvements could be as large as 50%, if one includes changes in the efficiency of light interception as well as light utilization. The fact that the intrinsic photon yield is so uniform across species suggests that, at least with traditional breeding, progress in improving the intrinsic efficiency of photosynthesis will be slow. Moreover, others argue that complex traits, such as photosynthetic efficiency, that give competitive advantage to individual plants have likely been optimized by natural selection such that the potential for improving such traits by genetic engineering is very small (20).

2.2. Traditional Measures of Yield Potential

Yield potential is a concept, rather than a quantity, which makes estimation both challenging and complicated (3). By definition, yield potential is an idealized state in which a crop grows without any biophysical limitations other than uncontrollable factors, such as solar radiation, air temperature, and rainfall in rain-fed systems. Therefore, to achieve yield potential requires perfection in the management of all other yield-determining production factors (such as plant population; the supply and balance of 17 essential nutrients; and protection against losses from insects, weeds, and diseases) from sowing to maturity. Such perfection is impossible under field conditions, even in relatively small test plots let alone in large production fields. Thus, yield potential is sometimes estimated by crop models that assume perfect management and lack of all yield-reducing factors. The validity of such models relies on validation under field conditions, which can never achieve perfect management. We are left with a circuitous loop in which simulations are based on mathematical relationships that capture our current understanding of plant physiological processes that determine maximum possible net primary productivity (NPP) and the portion of NPP converted to grain yield, and these simulations are validated against field studies that attempt to establish perfect growth conditions but can never achieve it.

The uncertainty as to whether highest possible yields were achieved in the validation field studies justifies conjunctive use of other methods to estimate yield potential. Other approaches include surveys of highest recorded historical yields at agricultural research stations, highest yields achieved in long-term experiments that included treatments thought to provide optimal management, and the yields achieved by contest-winning farmers who participate in sanctioned yield contests (7). At broader scales of relevance to food production capacity and regional to global food security, measurement of yield potential is even more difficult because of spatial variations in the climatic and soil conditions across the thousands of fields in a given production domain. Here, we consider three main techniques for assessing yield potential and yield gaps over relevant spatial scales, each with its own strengths and weaknesses.

NPP: net primary productivity

2.2.1. Model simulations. Crop models have been used to estimate crop yield potential at scales ranging from a specific field (21) to a region or country (22–24). Most crop models simulate phenological development in relation to photothermal time, net assimilation, resource allocation to different organs, transpiration, and soil water dynamics on a daily or hourly time step. Less sophisticated models simplify simulation of net assimilation by using a standard value for radiation-use efficiency that accounts for both photosynthesis and respiration (25); more sophisticated models simulate both photosynthesis and respiration directly (26). Although most models can simulate yield potential under both irrigated and rain-fed conditions, only a few are robust in simulating the impact of other stresses, such as a deficient supply of nitrogen and other nutrients and yield losses from insects, disease, and weed pressure. Despite these differences in sophistication, there are a number of robust crop models of that give reasonable estimates of yield potential as estimated by the highest measured yields in research studies and farmers' fields.

To simulate yield potential for a given field requires a minimum set of input data that vary by model but typically include: daily maximum and minimum air temperature at canopy height, solar radiation, rainfall, relative humidity, sowing date and depth of seed placement or the date of emergence, the genotype-specific photothermal phenological development coefficients for the cultivar or hybrid to be simulated, and plant density. For water-limited yield potential under rain-fed conditions, soil texture, initial moisture levels, and effective rooting depth must also be provided as inputs to the model. Information about nutrient supply and pest pressure is not required because it is assumed that these factors do not limit yield.

One weakness of most models is the lack of sensitivity to short-term severe abiotic stresses of one to two days, related to unusually cold or warm temperatures that can affect yield-determining steps, such as pollination or spikelet viability during the initial phase of seed development. This lack of sensitivity leads to higher estimates of yield potential than will actually occur in the field. Despite this and other shortcomings, simulation models are likely to provide the most accurate estimate of the yield potential ceiling for specific fields and for regions when information on spatial variation of model inputs is available. They are also helpful for the initial evaluation of a single management factor, such as planting date, across multiple environments (27) and for more complex interactions among several management factors, such as planting date, plant population, or cultivar maturity (14).

2.2.2. Field experiments and yield contests. Direct measures of yield potential can be made in field experiments that utilize crop management practices designed to eliminate all yield-reducing factors, such as nutrient deficiencies or toxicities, damage from insect pests and diseases, and competition from weeds. Achieving perfect growth conditions throughout the cropping period is quite difficult, and the degree of difficulty rises as test plot size increases from small quadrants of <10 m^2, which can be intensively managed by hand, to test plots of several hundred m^2, which allow use of production-scale field equipment but have relatively uniform soil properties, to production-scale fields of >4 ha that require use of full-size equipment and typically contain some heterogeneity in soil properties that determine optimal practices for management of inputs, such as nutrients and water. To obtain robust estimates of yield potential for a given location requires conducting such experiments over many years to ensure that the mean estimate reflects a typical range of climatic variation. In fact, year-to-year climate variation is so large at most locations that the best estimates of site yield potential would employ a crop simulation model that has been validated for the site or in the surrounding region based on an adequate number of site years. The combination of simulation and field validations provides a more robust approach for estimating yield potential for a region than using either method alone.

Researchers conducting the field experiments for direct measurement of yield potential must make a number of decisions regarding optimal crop management. Recommended best management practices, however, were not developed to achieve full yield potential because it is not profitable to do so. It therefore generally requires several years of testing to identify the optimal suite of management practices that give maximum yields at a given location. Moreover, optimal management practices can vary substantially year to year in response to normal variation in climate. For example, optimal plant population or nitrogen rate in a rain-fed environment will depend heavily on the amount of rainfall (28). Optimal planting date also varies considerably year to year at the same location. Here again, it is beneficial to combine direct measurement of yield potential with crop simulation to identify the combination of management practices that has the greatest probability of giving highest possible yield.

Sanctioned yield contests provide another direct estimate of yield potential for a given region because farmers are motivated to win for the recognition and rewards that come to the winner (7). Rewards include use of new tractors and other machinery from equipment dealers, free seed from seed companies, and paid speaking engagements sponsored by agricultural input suppliers. Contests such as the annual yield contest sponsored by the National Corn Growers Association include hundreds of such motivated farmers. To avoid cheating, this contest requires independent verification, although there have been disqualifications owing to irregularities. Contest rules also require a minimum field size of about 4 ha to ensure that the results are based on large-scale commercial farming practices that can be replicated elsewhere. When properly conducted, such yield contests provide a robust estimate of the attainable yield potential under production-scale conditions with the expertise of a large number of motivated farmers, each trying to maximize yields. Simulation of contest-winning yields using the actual planting date, plant population, and hybrid used by the winner would help ensure the integrity of such contests, although this additional form of verification is not currently performed.

2.2.3. Maximum farmer yields. An alternative but less common approach to estimating yield potential is to observe the maximum yield achieved among a sizable sample of farmers in a region of interest (29, 30). Typically, estimates must rely on farmer-reported values rather than direct measurements to achieve large sample sizes, and therefore much care is needed to identify farmers with reliable records for individual fields and to convert all yields to standard moisture content. As an additional step to ensure data quality, one should also obtain independent estimates of yields in a subset of fields, such as by harvesting several small plots within farmers' fields.

The use of maximum farmer yields as a proxy for yield potential is only appropriate in intensively managed cropping systems, where farmers apply levels of fertilizer and pest and disease controls that make it possible to approach yield potential. Although it is still improbable for a farmer to reach yield potential even with high inputs, for the reasons discussed above, in a landscape of many farmers, it is likely that at least one will come quite close. For example, if a single field has only a 1% chance of achieving yield potential, then in a group of 100 independent fields there will be a 63% chance ($1–0.99^{100}$) that at least one reached yield potential. Of course, the key here is whether the yield constraints in different fields are in fact independent or, more specifically, whether they are independent enough that maximum yields provide a good approximation for yield potential. This is an empirical question that is addressed in the following section for a single region, but it is yet to be asked in most cropping systems.

2.3. Comparison of Yield Potential Measures

The relationships between true (model simulated) yield potential, experimental yields, maximum farmer yields, and average farmer yields are illustrated in Figure 1. To aid comparison of different studies, we find it useful to denote the method used to measure yield potential in each estimate of yield gap: model-based yield gap (YG_M), experiment-based yield gap (YG_E), and farmer-based yield gap (YG_F). As illustrated in Figure 1, one would expect the

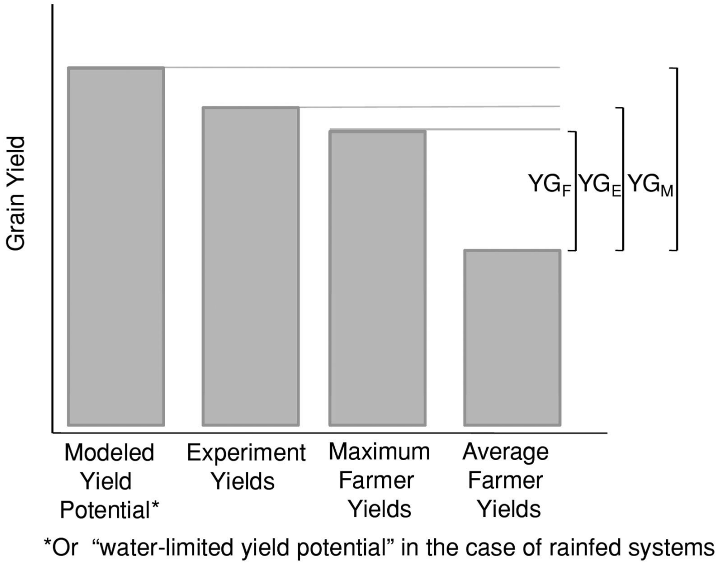

Figure 1 A conceptual framework depicting the relative rankings of average farmer yields and three measures of yield potential. Different measures of the yield gap (YG) are indicated at the right side of the figure and are as follows: YG_M, model-based yield gap (yield potential is simulated with a model); YG_E, experiment-based yield gap (yield potential is estimated with a field experiment); and YG_P farmer-based yield gap (yield potential is estimated with maximum of farmers' yields).

Table 1. Average yield gap in India for four crops, computed using three different methods for estimating yield potential[a]

Crop	Simulated potential	Experimental potential	On-farm potential	Average
Cotton	1117	635	549	767
Mustard	856	149	376	460
Rice	2556	1478	973	1669
Wheat	14	0	196	70

[a] Yield gap is the difference between yield potential and average farm yields expressed in kg ha^{-1} (31). Note that the average farmer yields used to compute yield gaps included irrigated areas, whereas yield potential was for rain-fed crops. Because all of these crops are commonly irrigated, the true yield gap is therefore likely much larger.

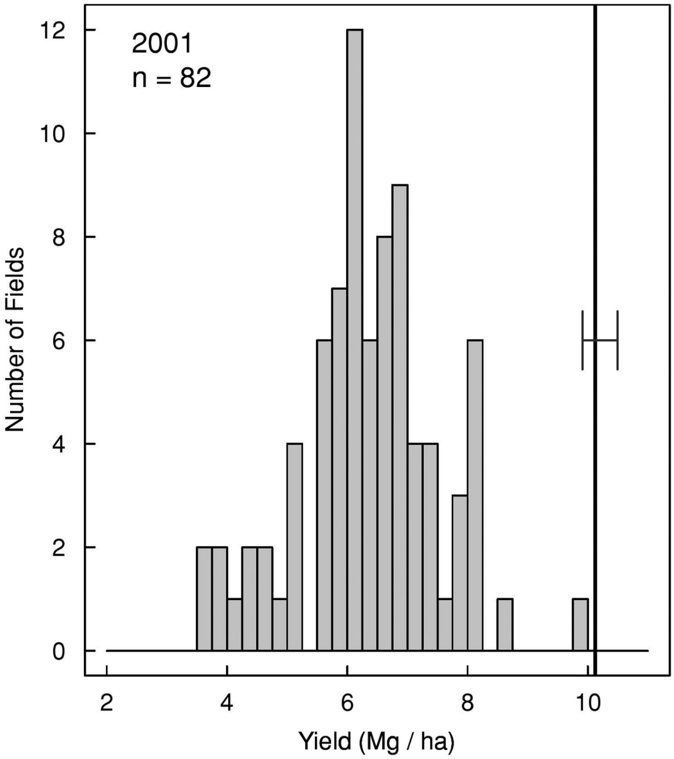

Figure 2. Histograms of irrigated wheat yields reported by farmers in field surveys for three separate years in the Yaqui Valley, Sonora, Mexico. The vertical lines indicate average yields for the most common Yaqui Valley wheat variety achieved in field experiments at a local research station, where the goal of the trial was to use crop and soil management practices to achieve yield potential [courtesy of Ken Sayre, International Center for Maize and Wheat Improvement (CIMMYT)]. Error bars indicate the range of yields within the trials over three replicates. The maximum reported yield, which provides a farmer-based estimate of yield potential, varied from nearly 10 Mg ha^{-1} in 2001 to less than 8 Mg ha^{-1} in 2003. Superimposed on these distributions is a vertical line indicating the yields obtained in local yield potential trials for the most common wheat variety in each year (Ken Sayre, personal communication). The proximity of the two estimates suggest that maximum farmer yields are indeed a reasonable measure of yield potential in this system, although in some years (e.g., 2001) only a single farmer was within the range of yields achieved in the trials.

following relationship between these different measures:

$$YG_F \le YG_E \le YG_M \tag{1}$$

In very intensively managed systems where farmers attempt to avoid all nutrient, pest, and disease stresses, the three values would likely be close to each other. In contrast, in low-input systems, YG_F will be considerably lower than YG_E and YG_M.

Unfortunately, most yield gap studies use only a single definition of yield potential, which prevents a direct comparison of different methods for the same location and crop. An exception is provided by Aggarwal et al. (31), who compared yields from crop simulation models, experimental trials, and on-farm demonstration trials for rice, wheat, cotton, and mustard in various Indian states. Simulated water-limited yield potential was significantly higher than the other two methods in nearly all states for all crops, whereas the difference between experimental and on-farm yield potential varied from negative to positive. Except in the case of wheat, yield gaps computed using simulated potential were larger than the corresponding values for the other methods, sometimes by a factor of two (Table 1).

Another comparison of experiment-based and farmer-based yield potential is provided in Figure 2, which illustrates the distribution of wheat yields reported by farmers in three surveys conducted in the Yaqui Valley of Mexico.

2.4. Other Approaches to Yield Potential

Given the importance of yield potential and the limitations associated with the three most common methods discussed above, there is a need for continued innovation and evaluation of alternate techniques. In particular, techniques that rely on readily available information may prove useful even if they are not perfectly correlated with true yield potential. Two approaches that appear deserving of more study are the use of crop yields across analogous climates and the use of productivity in the preexisting or neighboring natural ecosystems.

2.4.1. Climate analogs. Global datasets on crop area and yields are available at increasingly fine levels of disaggregation, such as for 5′ × 5′ grid cells—an area of roughly 25 km^2 at the equator (32, 33). These datasets have recently been used to assess yield gaps by comparing yields in each cell with all other cells with similar climatic characteristics (Rachel Licker, personal communication). The key assumption in this approach is that the maximum yield observed among cells with similar climates is equivalent to yield potential and thus that the proximity of observed yield in each cell to this maximum represents a reliable measure of yield gap. This assumption is yet to be tested, and at best, one would expect maximum yields over 25 km^2 to be only ~70% to 80% of yield potential at present (see Section 3). The approach is consequently likely to underestimate yield potential and yield gaps by a large margin, but it may prove useful for mapping rough estimates of relative yield gaps for different regions.

2.4.2. Natural ecosystem net primary productivity. As a general rule, the plants native to a habitat are well adapted to it (34). In contrast, crop plants often have characteristics that tend to limit their ability to capture resources. These include shallow roots and, in annual crops, brief duration of a closed canopy. As a consequence, the total plant growth or NPP of crop plants grown without irrigation is often less than the yield of the native vegetation in the same location. Globally, the NPP of the world's croplands is estimated to average 397 g carbon m^{-2} years^{-1}, approximately 65% of the average value

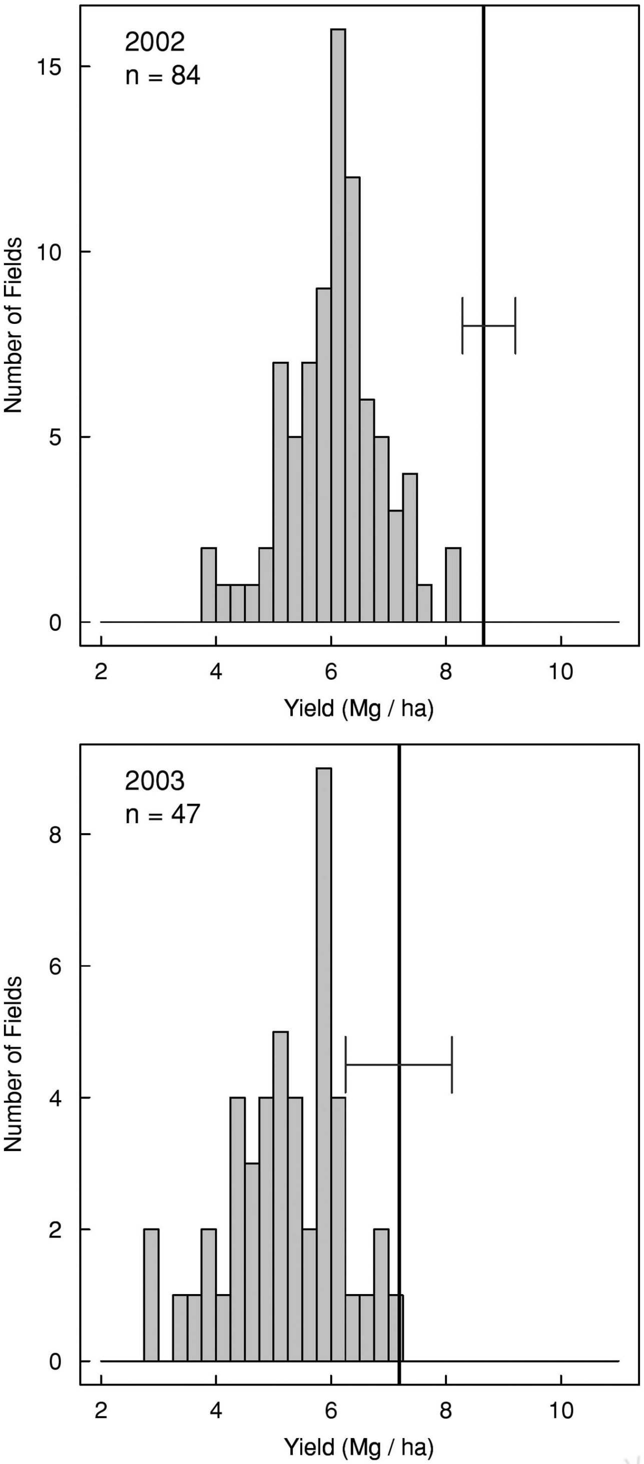

Figure 2 (*continued*).

Relative yield: the average yield as a percent of yield potential; inversely related to the size of the yield gap

of the native ecosystems the crops replaced (35). In parts of Africa and Asia, land-use change has decreased NPP to less than 10% that of the original vegetation (36). These two factors, the generally well-adapted status of the native vegetation and the consistently higher NPP in native vegetation than in croplands, suggest that the NPP of native vegetation can be used to set an upper limit on yield potential, especially for areas not currently in agriculture (37). While this approach lacks sensitivity to a number of factors that can influence yield potential, including the identity of the crop, the status of breeding, and the intensity of management, it may provide a useful starting point, especially for identifying locations where realized yields are far below yield potential.

2.5. Measurement Errors for Yield Potential

As discussed above, the challenges of measuring yield potential in nonwater-limiting conditions are considerable and relate to spatial and temporal variations in solar radiation and temperature. In water-limited conditions, the challenge is even greater owing to variations in soil moisture that reflect differences in rainfall and soil physical properties that determine water retention characteristics. One can therefore expect estimates of yield potential to be least accurate for rain-fed crops grown in environments with high spatial variability in rainfall or soil properties because spatially and temporally continuous measurements of soil moisture are not available for any scale beyond relatively small experimental plots. This is an important point to remember as we begin to consider the magnitude of yield gaps for different crops, some of which (e.g., rice) are predominantly irrigated and others (e.g., maize) that are mostly rain-fed.

3. How Big Are Yield Gaps?

A survey of the literature on wheat, rice, and maize cropping systems revealed a wide range of estimated yield gaps throughout the world (Table 2). For tropical maize in Africa, where biophysical and management conditions result in frequent nutrient, water, pest, and disease stresses, average yields are commonly less than 20% of yield potential. In contrast, average yields in irrigated wheat systems in northwest India can reach 80% of potential. The full range of values in Table 2 extends from 16% to 95%, although the true range is likely narrower owing to measurement errors that result in spuriously high or low values. We consider a range of 20% to 80% to include nearly all of the major cropping systems of the world.

To examine the dependence of reported yield gaps on the technique used to measure yield potential, a task made difficult by the failure of most studies to use more than one approach, we have sorted values in Table 2 according to the method used in each study. For maize, only experiment-based methods were found, and therefore no comparisons were possible. For rice and wheat, yield gaps followed the expected trend with the smallest yield gaps (highest relative yields) found in studies using farmer-based estimates of yield potential, and the biggest gaps found for model-based estimates of yield potential. However, the differences were often quite small. The average yield gap for studies of rice in India, for instance, averaged 52% when using a model-based estimate of yield potential (n = 11), and 53% for an experiment-based approach (n = 11).

Even comparisons of the same crop in the same region can be misleading, however, because aspects of the studies other than yield potential method can differ. In the case of Indian rice mentioned above, the model-based study considered yield potential as a weighted average of yield potential in irrigated and rain-fed conditions, with weights proportional to the percent of irrigated rice area within each state. The experiment-based study compared the state's average yields with yield potential from irrigated trials, even though several states have a significant area of rain-fed rice. Had the latter study considered water-limited yield potential for the fraction of area that is rain-fed, the inferred yield gap would have been significantly smaller. Thus, the method of estimating yield potential for an

Table 2. Comparison of average yields and yield potentials in various studies

Method[a]	Crop	Location (season or crop)	Average yield[b]	Yield potential	Yield gap	Average:potential (%)	Reference[c]
M	Wheat	Northern India	3	7.5	4.5	40	(24)
		Uttar Pradesh, India	2.5	5	2.5	50	(1)
		Punjab, India	4.1	5.5	1.4	75	(1)
		Haryana, India	3.8	4	0.2	95	(1)
		Madhya Pradesh, India	1.7	3	1.3	57	(1)
		Rajasthan, India	2.5	4.2	1.7	60	(1)
		Bihar, India	2.2	3.8	1.6	58	(1)
		Gujarat, India	2.4	2.7	0.3	89	(1)
		Maharashtra, India	1.1	2.5	1.4	44	(1)
	Rice	Philippines (wet season)	3.7	7.8	4.1	47	(67)
		Philippines (dry season)	3.9	9	5.1	43	(67)
		West Bengal, India	3.4	5.1	1.7	67	(1)
		Uttar Pradesh, India	3.1	6.1	3	51	(1)
		Andra Pradesh, India	3.9	7.9	4	49	(1)
		Tamil Nadu, India	4.9	7.7	2.8	64	(1)
		Punjab, India	5	8.8	3.8	57	(1)
		Bihar, India	2	5.5	3.5	36	(1)
		Orissa, India	1.9	4.1	2.2	46	(1)
		Madhya Pradesh, India	1.4	3	1.6	47	(1)
		Karnataka, India	3.7	6.1	2.4	61	(1)
		Assam, India	2	6.7	4.7	30	(1)
		Maharashtra, India	2.5	3.2	0.7	78	(1)
E	Rice	Bangladesh	4.6	5.4	0.8	85	(68)
		China	5.9	7.6	1.7	78	(68)
		India	3.6	5.9	2.3	61	(68)
		Indonesia	5.3	6.4	1.1	83	(68)
		Nepal	4.2	5 0.8		84	(68)
		Myanmar	4.2	5.1	0.9	82	(68)
		Philippines	3.4	6.3	2.9	54	(68)
		Thailand	4	5.3	1.3	75	(68)
		Vietnam	4.3	6.1	1.8	70	(68)
		China (early rice)	5.6	9.8	4.2	57	(69)
		China (single rice)	7.2	11.5	4.3	63	(69)
		China (late rice)	5.6	9.5	3.9	59	(69)
		West Bengal, India	3.1	5	1.9	62	(70)
		Uttar Pradesh, India	2.9	6.6	3.7	44	(70)
		Andra Pradesh, India	3.8	5.9	2.1	64	(70)
		Tamil Nadu, India	4.5	5.3	0.8	85	(70)
		Punjab, India	5	6.5	1.5	77	(70)
		Bihar, India	1.8	6.1	4.3	30	(70)
		Orissa, India	2	5.6	3.6	36	(70)
		Madhya Pradesh, India	1.6	4.7	3.1	34	(70)

(*continued*)

Table 2 (*continued*).

Method[a]	Crop	Location (season or crop)	Average yield[b]	Yield potential	Yield gap	Average:potential (%)	Reference[c]
		Karnataka, India	3.5	5.3	1.8	66	(70)
		Assam, India	2	6.4	4.4	31	(70)
		Maharashtra, India	2.4	4.5	2.1	53	(70)
		Philippines (wet season)	3.7	5.7	2	65	(70)
		Philippines (dry season)	3.9	7.5	3.6	52	(70)
	Maize	Nebraska, United States[d]	10	18	8	56	(7)[e]
		Nebraska, United States[f]	6	15	9	40	(7)
		Midlatitude/subtropical, East and Southeast Asia	3	8	5	38	(71)[g]
		Tropical lowland, East and Southeast Asia	2.2	5.5	3.3	40	(71)
		Tropical lowland, South Asia	1.4	4.5	3.1	31	(71)
		Midlatitude/subtropical, sub-Saharan Africa	2.5	7	4.5	36	(71)
		Tropical lowland, sub-Saharan Africa	0.7	4.5	3.8	16	(71)
		Midlatitude/subtropical, Latin America	1.1	6	4.9	18	(71)
		Highland/transitional, Latin America	4	10	6	40	(71)
		Tropical lowland, Latin America	1.5	5	3.5	30	(71)
		Western Kenya	1.7	3.7	2	46	(72)
F	Wheat	Bangladesh	2.9	4.2	1.3	69	(73)
		Yaqui Valley, Mexico	5.8	8.2	2.4	71	(45)
		San Luis Rio Colorado Valley, Mexico	6.4	9	2.6	71	(45)
	Rice	China (early rice)	5.6	7	1.4	80	(69)
		China (single rice)	7.2	8.7	1.5	83	(69)
		China (late rice)	5.6	7.6	2	74	(69)

[a] The data are organized by method of yield potential estimation (M, model simulation; E, experimental trial; F, maximum farmer yields).

[b] Yields are expressed in units of Mg ha^{-1}.

[c] This table includes studies from several of the major agricultural research institutions (e.g., FAO, CGIAR) but does not represent an exhaustive survey of the entire published and gray literature.

[d] Irrigated.

[e] Duvick & Cassman (7) used contest-winning maize yields.

[f] Rain-fed.

[g] Pingali & Pardey (71) do not report exact method of yield potential estimation but describe it as yields "achievable on farmers fields with use of improved seed, appropriate levels of nutrients, water, and weed control."

individual location can be secondary to the method used to extrapolate this value to the scales over which estimates of farmer average yields are available.

A comparison between crops reveals that average yields exceed 70% of potential in several wheat and rice systems but in none of the major maize regions. There are several possible explanations for this. First and foremost, irrigation is less common in maize compared to wheat and rice. As such, maize farmers must contend with the tremendous uncertainty associated with water supply from year-to-year variation in rainfall and in doing so often use risk management tactics, such as low plant density, to reduce yield variability in dry years and limited investments in technologies, such as fertilizer or insect control, that may be unprofitable in dry years with lower water-limited yield potential.

Secondly, maize is most commonly found in North and South America and Africa, regions that have relatively large amounts of arable land and relatively low population density, whereas the rice and wheat systems that dominate much of Asia have the reverse situation. The scarcity of land and abundance of labor in Asia favors land-saving technologies that work to maximize the amount of yield achieved per hectare and thus minimize the yield gap (38). In regions with low population density, the emphasis of farmers may be equally or more so on labor-saving technologies, such as mechanized planting, cultivation, and harvesting. Variations in land and labor productivity across both space and time correspond strongly to the relative availability of land and labor, supporting the notion that the development and implementation of technologies that would reduce yield gaps are most likely to be found in the land-scarce areas more common to rice and wheat than maize (38). Increased demand for livestock products in Asia, however, and the associated rise in demand for feed grains, such as maize, may result in increased production of maize in regions with high population density, which may increase the pressure to close the maize yield gap in these areas.

Despite these two economic explanations of why maize farmers are likely to be further below yield potential than for the other major cereals, namely the constraints placed by rainfall variability and the scarcity of labor relative to land, one cannot discount a possibly large role for methodological issues. The added difficulties of estimating yield potential in rain-fed environments (see Section 2.5) suggest that yield potential may be systematically overestimated in maize systems. This is possible, for instance, if the experiments on which maize yield potentials are based tend to be conducted in locations with better soils or more rainfall than in the locations used by the average farmer. Moreover, extrapolation of yield potential to the scale of districts or states will invariably be more difficult in rain-fed systems than irrigated ones because of the need to account for high spatial heterogeneity in soils and rainfall.

3.1. Case Studies

To further explore maize yield gaps, we present two examples of yield gap analysis that compares simulated yield potential from crop models with average reported farmer yields.

3.1.1. U.S. maize yields. Here we draw upon recent simulations of rain-fed and irrigated maize yield potential at 18 sites in the United States over three years using the Hybrid-Maize model (21). Yields at each site were compared to the corresponding average yield for surrounding county (Figure 3), which is reported by the U.S. Department of Agriculture both for rain-fed and irrigated systems (39). The average ratio of county yields to yield potential was 65% across all sites and years for rain-fed maize, and 75% for irrigated maize. Here again this difference most likely reflects the greater use of risk management tactics by farmers in rain-fed agriculture as discussed previously.

Although more detailed analysis is needed, the values of 65% and 75% for relative yields suggest that maize yields in this important system have a relatively little room to grow before reaching the practical limit of observed yield gaps, which is about 80% of yield potential. Irrigated maize already appears close to this threshold. Given the apparent lack of growth in irrigated maize yield potential since 1980, as indicated by contest-winning yields (7), and the likely negative effect of climate change on U.S. maize yield potentials over the coming decades (40, 41), these small yield gaps imply that average farmer yields may begin to decline in these systems without significant genetic gains in yield potential, although much higher grain prices that would moti-

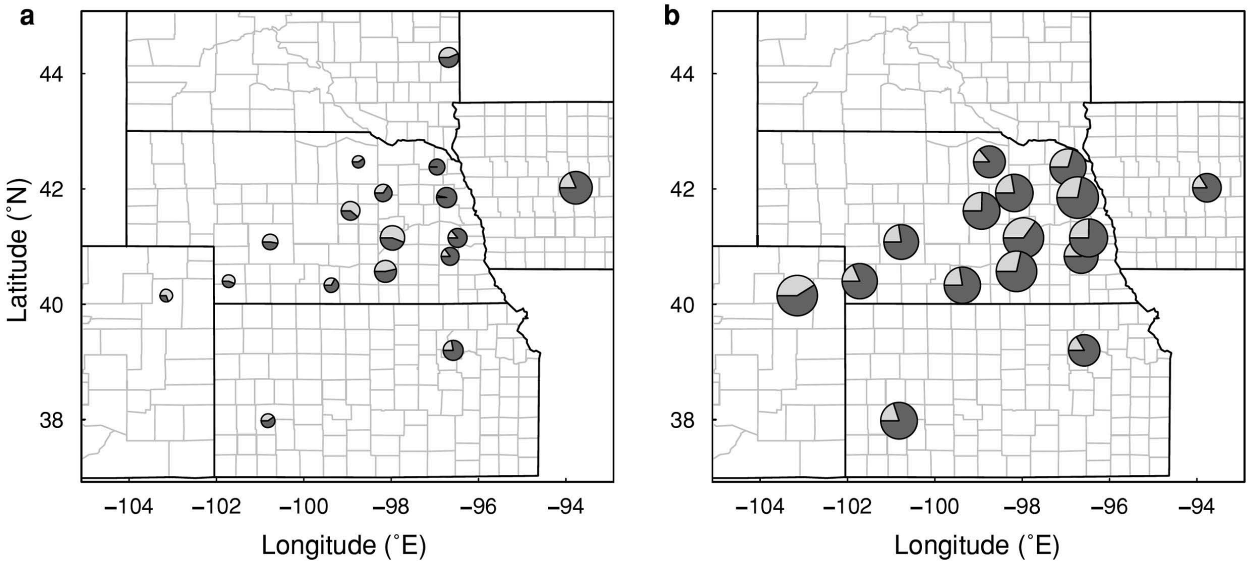

Figure 3. Estimated yield gaps for rain-fed (*a*) and irrigated (*b*) maize in the western Corn Belt of the United States, which were based on simulated yield potential by the Hybrid-Maize model and reported county level yields from the U.S. Department of Agriculture (39) for 2004–2005. The location of each pie chart represents a weather station where yield potential was simulated. The size of the pie is proportional to the average simulated yield potential over the three years, and the dark shading indicates the average yield, as a fraction of yield potential, for the county containing each station. Rain-fed and irrigated yield potentials ranged from 6.6 to 11.1 and from 12.2 to 17.6 Mg ha^{-1}, respectively.

vate farmers to invest in technologies that would allow average farm yields to consistently achieve yields in excess of 75% of yield potential (see Section 4.2).

3.1.2. Asian rice yields. As another example of yield gap analysis to supplement the existing literature, we compared a recent gridded dataset of average rice yields circa 2000 (33) with model simulations of irrigated rice yield potential in Asia (Figure 4*a*) (42). Importantly, the yield potential simulations used planting dates and densities that are representative of current farmers' practices. However, the comparison is confounded by the fact that average yields are aggregated over both rain-fed and irrigated systems, whereas yield potential has only been simulated for irrigated conditions. This mismatch is illustrative of a common impediment to yield gap analysis: The ideal datasets— in this case disaggregated production data by irrigated and rain-fed systems and/or simulated yield potential for both conditions—are often not available. Despite these shortcomings, Figure 4 reveals clearly that in most environments in which nearly all rice is produced with irrigation, namely Japan, Korea, and southern China, average yields are frequently 75% or more of estimated yield potential. Northwest India appears an exception to this pattern, but it is based on a single location and contrasts with other studies indicating average yields above 70% of yield potential in this region (Table 2). Although yield gaps appear more sizable in countries with significant rain-fed areas, this mostly results from overestimating yield potential because the simulation-based estimates were based on irrigated production. Disaggregated data is needed to correct this bias.

4. Why Do Yield Gaps Exist?

As challenging and important as estimates of yield gap magnitudes may be, they are of limited use without an understanding of the likely, as well as potential, rates at which these gaps will narrow or widen. This task is only possible if one can identify the underlying causes of yield losses in farmers' fields. The list of factors that commonly affect crop growth and yields in farmers' fields is long and varied (Table 3). These factors include stresses that are biotic in nature and others that are mainly abiotic, factors that are easy to measure and some that are difficult to detect, factors that relate mainly to management and others to soil properties, as well as interactions among these various factors. The challenges we face to understand yield gaps for any given farming system are to identify among the many possible explanations for yield losses the few that have the greatest influence and, if possible, to quantify the gains that could be realized if these constraints were removed. Several approaches can be used to study causes of yield gaps, each with their own advantages and shortcomings.

4.1. Approaches

4.1.1. On-farm experiments. The most conceptually straightforward (but expensive) way to research on-farm constraints to yields is to conduct controlled experiments that compare alternative management treatments in a series of farmers' fields. A seminal study using this approach was conducted as part of the International Rice Agroeconomic Network (IRAEN) in the 1970s (43). In six Asian countries, farmers were enlisted to run experiments side by side with their usual practices. The management aspects that varied in the experiments were chosen on a site-by-site basis by researchers, who selected a few factors they felt most likely to improve yields—typically higher fertilizer rates or more intensive insect and weed control measures. Economic surveys were simultaneously conducted to understand the underlying socioeconomic reasons that dictated farmers' management choices.

The results, summarized in Figure 5, demonstrate three important lessons. First, yields with more intensive management exhibited tremendous variation across study

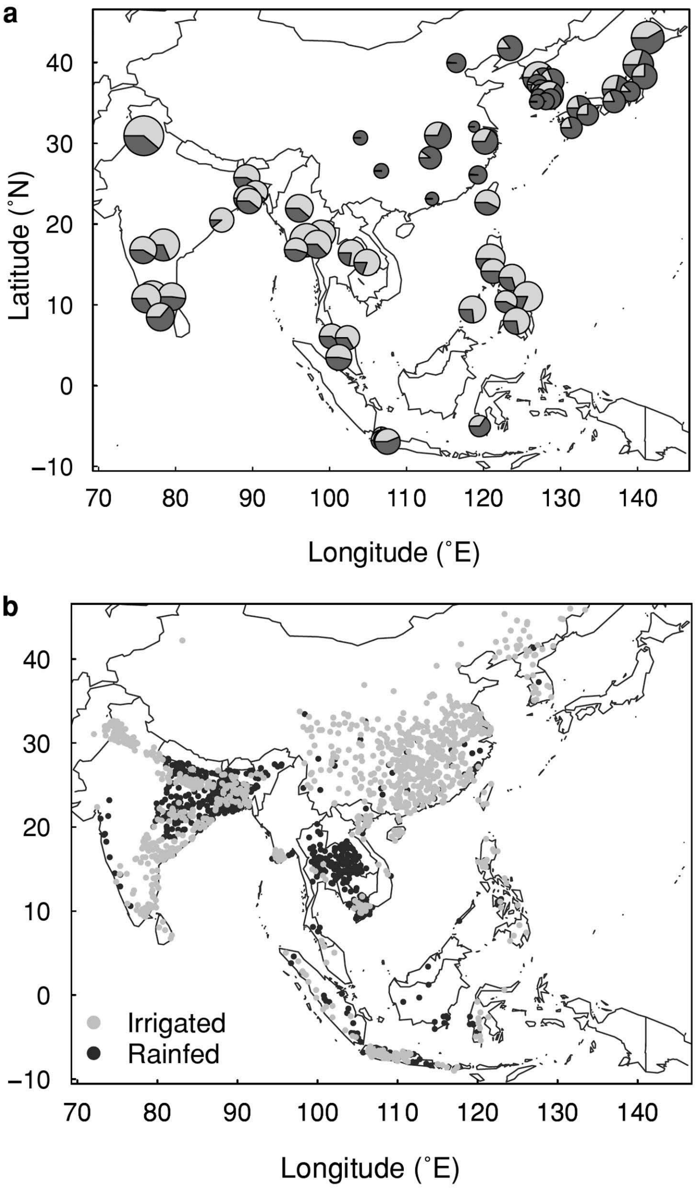

Figure 4. (*a*) Estimated yield gaps for rice in Asia on the basis of average yields from Reference 26 and the potential irrigated rice yields simulated by the Oyza model in Reference 31. The location of each pie chart represents a weather station where yield potential was simulated. The size of the pie is proportional to the simulated yield potential, and the dark shading indicates the average yield, as a fraction of yield potential, for the 5' × 5' grid cell containing the location. Results are similar when using yield potential from the SIMRIW model (not shown). The large yield gaps suggested for much of South and Southeast Asia are misleading because a large proportion of rice production in these regions is not irrigated and thus likely has lower yield potential. (*b*) The distribution of rice area dominated by irrigated or rain-fed rice production in Asia on the basis of Reference 66 and information provided by R. Hijmans, International Rice Research Institute.

Table 3. Common factors that contribute to yield losses in farmers' fields[a]

Biophysical factors	Socioeconomic factors
Nutrient deficiencies and imbalances (nitrogen, phosphorus, potassium, zinc, and other essential nutrients)	Profit maximization
Water stress	Risk aversion
Flooding	Inability to secure credit
Suboptimal planting (timing or density)	Limited time devoted to activities
Soil problems (salinity, alkalinity, acidity, iron, aluminum, or boron toxicities, compaction, and others)	Lack of knowledge on best practices
Weed pressures	
Insect damage	
Diseases (head, stem, foliar, root)	
Lodging (from wind, rain, snow, or hail)[b]	
Inferior seed quality	

[a] A goal of yield gap analysis is to quantify the percent of total losses attributable to each factor.

[b] Lodging means that the crop fell over because the stems broke or because it became too top heavy.

IRAEN: International Rice Agroeconomic Network

locations, as well as across fields within individual sites (not shown). Put differently, the correlation between farmer yields and the yield gain under high inputs was very low. Thus, much of the apparent gap between yields on experiment stations and in farmers yields could be attributed to differences in factors governing field-specific yield potential or to biophysical factors, such as soil quality in those fields. Such field-specific factors are those related to management practices not included in these studies and other factors affecting yield losses as listed in Table 3.

Second, high inputs improved yields over average farmers' practices in all situations, by an average of 0.9 Mg per ha (or 25%) in 410 wet-season on-farm trials and 1.3 Mg per ha (30%) in 366 dry-season trials. Factorial combinations revealed that much

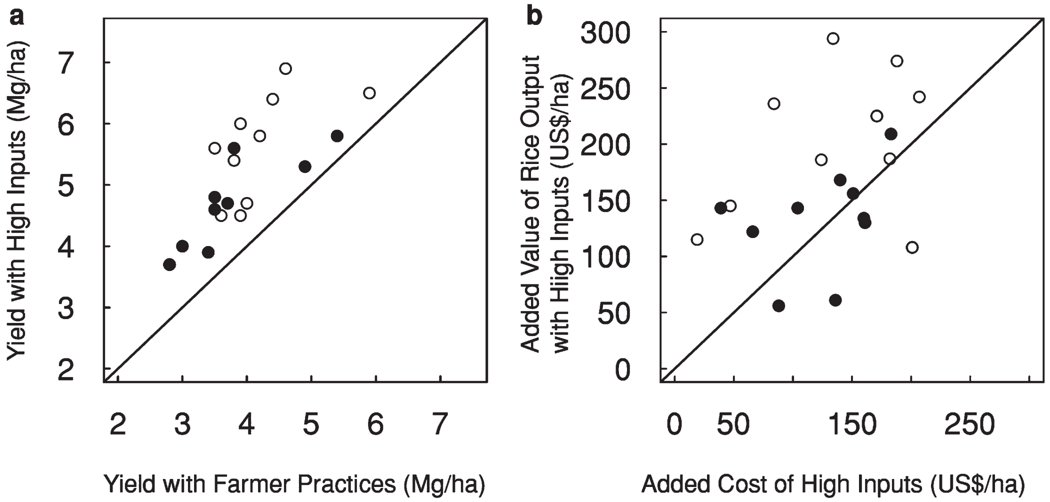

Figure 5. A comparison of yields (*a*) and economics of the yield gap (*b*) in wet- and dry-season rice. Each point represents an average value from on-farm trials conducted at each of 10 locations in six Asian countries, 1974–1977. Solid circles represent values for the wet season and open circles for the dry season (33).

of the gap was attributed to improved fertilizer and insect pest management. Third, the costs and benefits of greater fertilizer rates or insect control were such that yield gains were rarely justified on economic grounds at the prevailing prices for grain and inputs in the 1970s. Only fertilizer in the dry season appeared to be a cost-effective addition. Thus, the main conclusion of this effort was that new technologies or institutional reforms that reduce the costs of fertilizers or insect control would be needed to reduce the existing yield gaps. As Herdt (44) succinctly summarized, "the overall weight of the evidence examined suggests that it is relatively easy to account for the dramatic gap between what is technically possible and what has been achieved: what is technically possible is more modest than most observers admit; the economics of substantially higher yields is not attractive."

Unfortunately, follow-on experimental studies of yield gaps with the depth and breadth of the IRAEN experience have been lacking, undoubtedly because of the expenses required. Although nothing can replace the ability of controlled experiments to uncover causes and effects, researchers have resorted to other indirect but less costly approaches to understand the causes of yield gaps.

4.1.2. Empirical studies of yield heterogeneity. The remarkable heterogeneity of agricultural systems is often overlooked in discussions of crop yields. Studies that document yields for 50+ fields within a small region most often report ranges spanning at least a factor of two (30, 45–48). As mentioned in Section 2, one manifestation of this heterogeneity is that maximum farmer yields often provide a reasonable estimate of yield potential. This heterogeneity also provides an attractive setting in which to study causes of yield variation. The most straightforward analysis can proceed when, in addition to yield measurements, one has detailed information on the specific soil and management factors likely to affect yields.

For example, Calvino & Sadras (46) studied the statistical relationships between wheat yield, climate, and management data from 103 commercial farms in the Pampas region of Argentina and concluded that management to reduce late-season water deficits would be the most effective strategy to reducing the yield gap. Lobell et al. (29) used remote sensing estimates of yields and management surveys on 80+ farms in two years to identify fertilizer rates and irrigation timing as two important factors in the Yaqui Valley of Mexico. Cassman et al. (49) evaluated the impact of N fertilizer practices, soil N supply, and plant N status on the yield of irrigated rice on 64 farms in the Philippines.

In the absence of management and soil measurements, it is still possible to learn something about causes by analyzing the pattern of yields in space and time and by comparing these patterns to those expected for different factors. For example, a spatial correlogram of yields reveals the amount of yield variability for different spatial scales. Factors such as soil properties tend to vary gradually across a landscape, whereas management variations follow strict field boundaries (50). The relative amount of variability seen over short distances therefore provides a useful indicator of the importance of one set of factors (management) relative to another (soil), even if it cannot pinpoint specific factors causing the variation. Similarly, analysis of yields through time can indicate the relative importance of location-dependent factors, such as farmer skill or soil quality (see Section 4.3) (45, 47).

4.1.3. Models. The same crop growth simulation models used to measure yield potential (see Section 2.2.1) can also be used to evaluate the yield gains possible with specific management changes. In this approach, controlled simulation experiments are conducted wherein all factors are fixed except for one or two factors on which the analysis focuses. Ideally, the models have been validated for the specific aspect being investigated, although this is not always the case. Often the most limiting step in this analysis is knowledge of the existing management practices, which can be assessed with farmer surveys.

Aggarwal & Kalra (24) present an early example of this approach in Indian wheat systems. The WTGROWS crop model was used to simulate yield potentials for the optimal sowing date (typically early to mid-November) and for the common sowing date of December 15. The difference between the two ranged from 0.5 to 2.5 Mg per ha^{-1} throughout India and, in many locations, was as much as half the value of the total yield gap. Their conclusion that Indian wheat yields are reduced by late sowing is supported by a remote sensing study in the eastern Gangetic plains that estimated 60% of wheat area is sown after the optimum window (51). Late sowing in these systems, a product of both late harvest of summer rice and the time needed to prepare the fields for sowing under conventional tillage, therefore appears a substantial cause of yield gaps, and it is a factor that can be overcome with adoption of existing technologies (52).

4.1.4. Econometrics. A related but separate body of literature concerns the responsiveness of crop yields to price increases. In economics nomenclature, this is known as the own-price elasticity of yields and is often a critical parameter in models of international agriculture. For example, Keeney & Hertel (53) discuss the strong role that yield elasticities play in determining predictions of indirect land-use responses to biofuel mandates. The relationship between yield elasticities and causes of the yield gap is clear: If yields are highly responsive to prices, then much of the gap must be attributable to input levels and management practices that are readily adjusted, such as fertilizer rates or weed and insect control. Alternatively, low yield elasticities imply that average yields are not constrained by factors amenable to such rapid changes.

Unfortunately, econometric studies that attempt to estimate yield elasticities result in a very wide range of values (54, 55). The disparities can be attributed in part to the fact that most studies rely on time series with high multicollinearity between prices, technology, and weather and in part because of differences between short-run (one-year) and longer-run (five-year) responses that are often confounded (55). Another factor is level of spatial aggregation. For example, individual farmers may show no management response to higher prices, but regional yields could still respond to price in the long run if, for instance, farmers with higher fertilizer rates become more profitable and expand their operations at the expense less-competitive farmers with lower crop yields (56).

Yield elasticities are also likely to vary in relation to the level of current average farm yields. One would expect elasticities to be lower in regions where average farm yields approached 80% of the yield potential of current cultivars and hybrids compared to other areas where average yields were less than 50% of the yield potential ceiling. Such yield-level differences in elasticities are consistent with observations that national average rice yields have stagnated where average farm yields approach 70% to 80% of the genetic yield potential (3).

Expert opinions of short-run elasticities, as judged by parameter value prescriptions in widely used trade models, tend to favor lower values between 0.1–0.2, which indicates that a 10% increase in price results in a 1% to 2% increase in yields (Table 4) (2, 57).

Table 4. Crop yield elasticity with respect to own-crop price, average by region, from the IMPACT model (2)

Crop	South Asia	East Asia	Southeast Asia	West Asia/ North Africa	Sub-Saharan Africa	Latin America	Developed countries
Wheat	0.18	0.16	0.13	0.14	0.19	0.15	0.12
Rice	0.12	0.13	0.10	0.13	0.18	0.15	0.11
Maize	0.15	0.14	0.11	0.13	0.17	0.13	0.14

Thus, even a doubling of price in grain relative to input costs would result in only a 10% to 20% increase of yields. The unprecedented recent increases in crop prices could provide an opportunity to re- fine estimates of these elasticities, although in most cases input costs have risen as fast as or faster than output prices, which will complicate farmer responses.

We therefore do not consider the economics literature to currently be of much assistance for understanding causes of yield gaps. Indeed, the econometric perspective on price-responsive yields may instead have something to gain from the approaches discussed above. In the long run, however, both agronomists and economists would likely benefit from comparisons and potentially integration of the disparate approaches.

4.2. Will Average Yields Ever Exceed ~80% of Yield Potential?

As discussed above, several major rice and wheat systems of the world have yields that currently approach 70% to 80% of yield potential, but none have passed beyond this point. A relevant question in light of the importance of these systems to global food supply is whether this represents a fundamental limit to yield gap reduction. Some have argued that this is the case. For example, Pingali & Rajaram (58) point out that in many wheat-growing environments, such as the Indian Punjab, "the cost of marginal increments in yield, given existing technologies and policies, could exceed the incremental gain. The cost is high not only in terms of increased use of inputs such as fertilizer, fuel, and water, but also in terms of increased management and supervision time for achieving more efficient input use."

In short, farmers seek to maximize profits, not yields. Yields of 80% of yield potential may therefore approximate the economic optimum level of production in a number of major cropping systems. However, the economically optimum decision for a farmer is subject to change as prices and technologies evolve. A particularly important factor in farmer decision making is uncertainty related to environmental conditions, such as weather and soil (59, 60). Can information technologies that reduce this uncertainty, or crop monitoring technologies that reduce the sensitivity to soil and weather variations, provide a pathway toward further reducing yield gaps in a cost-effective manner?

For example, consider a farmer who is deciding whether to add an additional unit of an input at a cost of $100 per ha. Because of weather uncertainties, there is a 50% chance that this investment will raise yields by an amount that will return $200, and a 50% chance that it will return nothing. In theory, the farmer will be completely indifferent between the two strategies because the expected return is equal to the cost, and some will choose to add the input while others will not. If the growing season turns out to be one in which the yield gains from the input are realized, only some of the farmers will have realized this gain. But with an improved technology that can forecast weather with sufficient accuracy to change the probabilities at the beginning of the season from 50/50 to 80/20, so that farmers perceive an 80% chance that the investment will return $200, then in theory farmers will invest in the additional input, leading to an increase in average farm yields. A similar example exists for decisions that have little or no cost, such as when to sow a crop. There may be a 50% chance that a particular sowing date yields more than a date three weeks later, making the farmer ambivalent to either day. But a change in perceived probabilities will change the economically optimum decision from one of indifference to one that favors yield improvements.

Uncertainties exist not only in weather but in many aspects of the crop environment, including pest and disease pressures, soil nutrients, and water-holding characteristics, and in delivery of water from irrigation networks. In each case, technologies to reduce these uncertainties are likely, but the speed and magnitude with which these technologies will affect average yields depend on various factors, including the relative

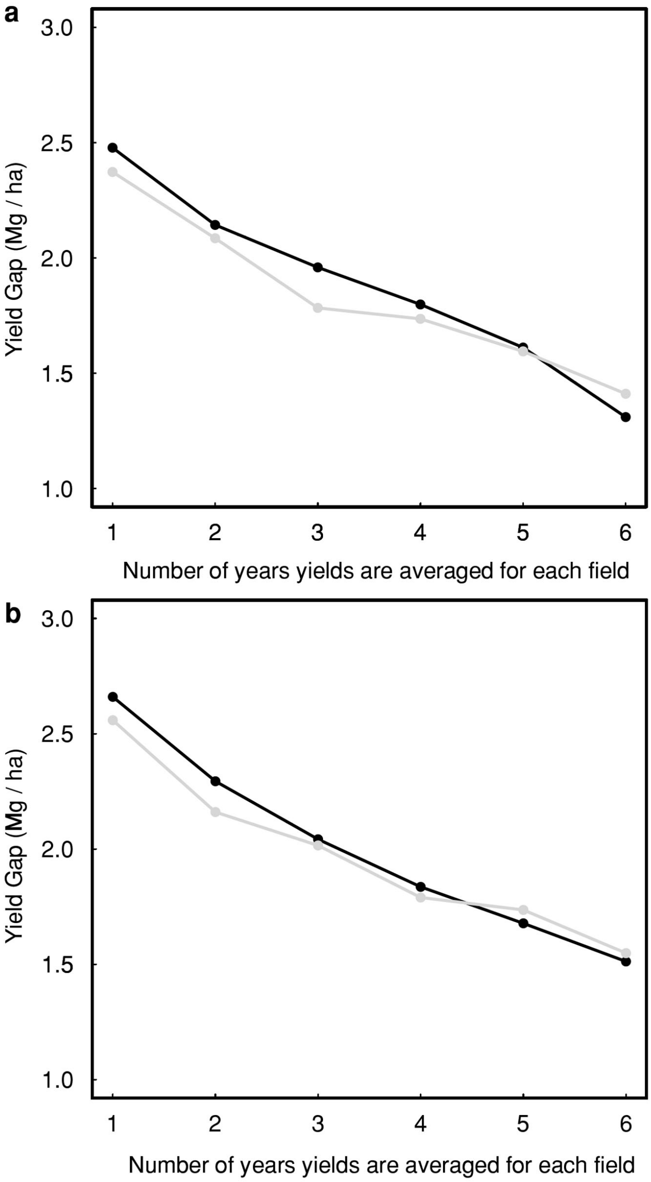

Figure 6. Yield gap curves for fields in Yaqui Valley (*a*) and San Luis Rio Colorado Valley (*b*) of Mexico These curves show the difference between maximum and average yields, where yields in each field are averaged over different lengths of time. A single year corresponds to the typical definition of yield gaps. The gap shrinks as yields are averaged over more years, indicating that factors contributing to maximum yields do not have consistent effects across years. The gray line shows a simulated value of the gap, assuming that yields are entirely random through time at each field (no effect of location). The comparison suggests that nearly all of the yield gap in these regions does not arise from consistent factors such as farmer skill, landscape position, access to credit, or soil conditions, but rather from factors whose effects are hard to predict in advance. Yields were estimated from remote sensing images from 2000–2006. Adapted from Reference 34.

importance of different types of uncertainties in farmer decision making and the ability of technologies to reduce each specific source of uncertainty (61). For example, progress in technologies to measure spatial variability in soil nutrients has been relatively rapid in recent years (62, 63), whereas the ability to forecast growing season weather conditions has arguably progressed more slowly.

Evidence from cropping systems with yields near 70% of potential suggests that yields at these levels are indeed heavily constrained by uncertainties. For example, studies using remote sensing estimates of yields in two major intensive wheat-growing regions in northwest Mexico, the Yaqui and San Luis Rio Colorado Valleys, indicate that yields are not only very heterogeneous across space but also that these patterns change markedly from year to year (45). A simple measure to embody this effect is to plot the gap between highest and average yields in the region for different lengths of averaging periods (Figure 6). In a single year, some farms are able to achieve yields more than 2 Mg per ha^{-1} above average. Yet, these fields are not able to sustain this performance over longer periods, with the gap shrinking to roughly 1.5 Mg per ha^{-1} for a six-year period. If the yield differences between fields in a single year were entirely the result of random (unpredictable) processes, one would expect the gap to shrink at roughly the same rate (indicated by the gray line in Figure 6).

Thus, it appears that much of the success of highest-yielding farmers relative to their peers arises from factors not associated with location, such as farmer skill or soil quality, because in that case the highest-yielding fields would persist through time. Instead, it appears that luck plays a central role, as farmer decisions can result in very different performances depending on the year. Note, this does not imply that farmer skill is not important but rather that skill levels are relatively uniform among the thousands of farmers in the region. Even if tens or hundreds of farmers were in fact especially skillful, there would not be enough variation in skill among the entire population to explain a significant fraction of yield variability. Note, also that many more years would be needed to see whether the long-term average yields in all fields are in fact equal. In both regions, there is a small fraction of area with poor soils and consistently low yields, which suggests that location does matter to a small degree (64). The generality of these findings to other regions remains to be evaluated, although a similar role for luck has been noted for maize in McLean County, Illinois (47).

One problem with evidence from spatial and temporal yield patterns alone is that one implicitly assumes that farmers on a given piece of land are making similar decisions each year. If farmers in fact switch from optimal decisions one year to suboptimal decisions the next, then this assumption would not hold. However, one can also examine the effect of specific decisions for which data exist. A particularly attractive one is sowing date because this can also be estimated reliably with remote sensing techniques. Ortiz- Monasterio & Lobell (65) found that for three years of data, farmers exhibited a range of planting dates that spanned from early November to early January, with the highest yields for sowing dates of December 15, November 28, and December 23 in the three years, respectively. The average difference between average yields and those on the optimal date was 0.5 Mg per ha^{-1}. An inability to predict in advance the optimum of this single decision therefore explains roughly 25% to 30% of the entire difference between average and maximum yields in this region.

In summary, technologies that reduce the myriad uncertainties facing farmers may change economic decisions in a way that motivates farmers to consistently achieve yields beyond 70% to 80% of yield potential. The answer to the question posed by this section heading is therefore probably, but the specific technologies have yet to be developed and the magnitude of potential increase and time frame for achieving it remain unclear.

5. Summary and Conclusions

Future crop yields and global food security may well hinge on the ability of farmers around the world to narrow the gap between current yields and yield potential ceilings, especially as progress in the latter may slow because of climate change and diminishing returns in breeding. Because average crop yields are critical drivers of food prices, food security, and cropland expansion, there is tremendous value in better quantification and understanding of yield gaps. In our analysis of yield gaps, we have distilled some key points and identified several research directions we believe are the most promising over the next decade, see below. With a more comprehensive effort that utilizes new remote sensing, geospatial analysis, simulation models, field experiments, and on-farm validation to assess yield gaps throughout the world, it should be possible to better understand the trajectory of the modern food economy and the key leverage points with which to most effectively improve both food production and environmental quality.

Summary Points

1. Improving crop yields at a pace commensurate with growth in food demand will likely require significant reductions in current yield gaps around the world.
2. Several methods exist to measure crop yield potential and associated yield gaps, each of which has distinct advantages and disadvantages. Estimates of yield potential can often differ by 50% or more, with estimation especially difficult for rain-fed conditions.
3. A wide range of yield gaps are observed around the world, with average yields ranging from roughly 20% to 80% of yield potential.
4. Many irrigated cropping systems, including maize in the United States, wheat in South Asia and Mexico, and rice in Japan and Korea, have yields that have

plateaued at 80% of yield potential. This implies that yield gains in these regions will be small in the near future, and yields may even decline if yield potential is reduced because of climate change. Many rain-fed cropping systems, in contrast, appear to have relatively large yield gaps that could be closed with existing technologies but persist largely for economic reasons.

5. Raising average yields above 80% of yield potential appears possible but only with technologies that either substantially reduce the uncertainties farmers face in assessing soil and climatic conditions or that dynamically respond to changes in these conditions (e.g., sensor-based nutrient and water management). Although these tools are more often discussed because of their ability to reduce costs and environmental impacts, their role in improving future crop yields may be just as important.

Future Issues

1. Several questions that may improve quantification of yield gaps include:
    a. Can historical records of average yields be disaggregated to finer spatial scales and by irrigated versus rain-fed systems in order to aid comparison with simulated yield potentials?
    b. What are the uncertainties surrounding modeled estimates of yield potential, particularly in rain-fed systems with heterogeneous soil properties?
    c. How well can yield potential of one crop (e.g., maize) be used to predict yield potential of another (e.g., switchgrass), and how well can the net primary productivity of native ecosystems predict yield potential of crops?
    d. How well does the difference between maximum and average farmer yields, increasingly available from either remote sensing or ground-based surveys (47), represent the true yield gap in a region?
2. Several questions that may improve understanding of yield gap causes include:
    a. How do yield gaps differ when estimated on the basis of average yields over different timescales (i.e., are the highest yields always achieved on the same fields and with the same farmers)?
    b. What are the most accurate and cost-effective methods to estimate the yield gap of the world's major crops in the major production domains?
    c. Are yield gaps bigger in cropping systems that experience wider ranges of variation in soil and climate? Do the ranges of farmer management decisions, such as input application rates or planting dates, provide a measure of the amount of uncertainty farmers face?
    d. What do model simulations of farmer behavior with different levels of soil and climate uncertainty predict about the response of yield gaps to improved information technologies? How do average yields change as these technologies are increasingly adopted in actual farmer fields, and what impedes the adoption of these technologies?

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