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Integrated soil–crop system management for food security

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Integrated soil–crop system management for food security

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China and other rapidly developing economies face the dual challenge of substantially increasing yields of cereal grains while at the same time reducing the very substantial environmental impacts of intensive agriculture. We used a model-driven integrated soil–crop system management approach to develop a maize production system that achieved mean maize yields of 13.0 t ha^{-1} on 66 on-farm experimental plots—nearly twice the yield of current farmers' practices—with no increase in N fertilizer use. Such integrated soil–crop system management systems represent a priority for agricultural research and implementation, especially in rapidly growing economies.

environmental integrity | nutrient use efficiency | crop yield | nitrogen fertilization | smallholder farm

Recently the challenges of ensuring global food security have received increasing attention from the scientific community, including high-profile features in *Science* (1, 2) and *Nature* (3, 4). However, except for some discussion of the slowly developing agricultural systems of sub-Saharan Africa and their requirements (5), much of the attention in those and other features has focused on biotechnology and on precision management of the large-scale agricultural systems typical of developed countries (6–9).

Are biotechnology and high-technology precision agriculture in fact the most important priorities for agricultural research to ensure food security in the near term? If we focus attention on the rapidly growing economies where the demand for food is growing most rapidly, where achieving food security requires reaching yields close to their biological potentials, and where the environmental consequences of intensive agriculture are most severe, we believe other research investments have higher priorities.

National-scale food security is not now a major concern in the developed economies of Europe, North America, and Oceania; rather, research on intensive grain-production systems in these countries has focused on adding new products (for example biofuels) to agricultural systems, and on technologies that make farming less costly (by creating pest- and disease-resistant crop varieties) or less damaging to the environment (through precision agricultural approaches that match resource inputs to crop demands, thereby reducing both waste and losses to the environment).

The countries where hunger and malnutrition are most widespread (notably in sub-Saharan Africa) face a very different set of challenges. To reduce the price and increase the availability of food there, it will be necessary to increase yields substantially and to distribute those yields more effectively. However, current average yields are so low that large relative increases—sufficient to achieve food security for at least the next decade—can be achieved through existing technologies (10, 11). For example, Malawi more than doubled its maize yields on the national scale in a very short time (2 to 3 y) through the use of currently available improved seed and fertilizer, supported by an input subsidy program provided by the national government and international organizations (12). There are many challenges inherent in extending this success, but now and for some time to come, success will not require achieving yield levels close to their biological potential.

We suggest that the greatest challenges for agricultural science and technology today occur in rapidly developing countries such as China, India, Brazil, Mexico, Indonesia, Vietnam, Pakistan, and Sri Lanka. Although fertility rates have dropped substantially in these countries, populations are continuing to grow rapidly in most of them as a consequence of demographic momentum. Moreover, all are experiencing increasing per-capita demands for food, as some seek to overcome substantial regional malnutrition, and as all experience increasing demand for meat and other animal products.

These rapidly developing countries achieved substantial yield increases from green-revolution technologies during the 1960s to 1980s, but rates of gain in cereal yields have slowed markedly in the past 10–20 y (13), even though agricultural inputs such as nitrogen (N) and phosphorus (P) have continued to increase. For example, Chinese cereal grain yields increased by 10% from 1996 to 2005, whereas the use of chemical fertilizers increased by 51% (14). That large increase in inputs without a correspondingly large increase in yields further decreased the already-low ratio of grain harvested to fertilizer applied in China. Often twice as much fertilizer N and P is applied than is recovered in crops, and this nutrient imbalance in turn drives environmental pollution problems, such as eutrophication (15), greenhouse gas emissions (16), and soil acidification (17). These problems have become increasingly severe in rapidly developing countries, and their consequences are meaningful on a global scale. For example, 80% of the global increase of N fertilizer consumption in the last 10 y (2000–2009) came from China and India (18).

A further challenge derives from the fact that across many rapidly developing economies, crops are produced by hundreds of millions of farmers on small parcels of land (Fig. 1). The scale of these individual farms makes the use of many advanced agricultural technologies that are being developed for the larger (often industrial) farms of the developed economies much more difficult.

Yield increases in these rapidly developing countries must follow new trajectories if they are to meet the challenge of greatly increasing yields to meet growing demands for food without further compromising environmental integrity. The potential to increase yields well beyond the substantial input-driven increase of the past decades exists. Even though yield ceilings (defined as yields achieved under optimum management in well-controlled experimental systems) for some major crops and cropping regions have themselves either leveled off or increased only slowly (19) in

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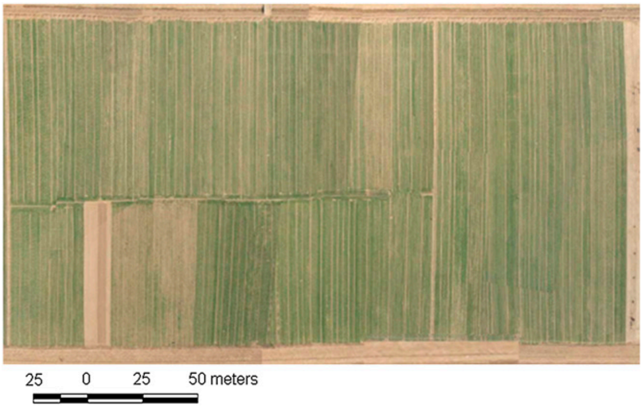


Fig. 1. Aerial photograph of wheat and maize fields at Huimin, Shandong Province, in the North China Plain. The average area per field is only 0.1 ha (160 × 6.8 m).

recent years, substantial yield gaps (defined as the difference between yield ceilings and the yields actually achieved by farmers) persist in most rapidly developing countries (20). Unlike sub-Saharan Africa, however, attempting to increase yields by increasing inputs is not viable on either practical or environmental grounds in most rapidly developing economies; modern crop varieties are already in widespread use, fertilizer applications have reached levels of diminishing returns in many areas, environmental costs of excessive fertilizer applications already are substantial, and competing demands for water constrain irrigation supplies in many nations. Genetic and crop-breeding research leading to the development of more productive/better protected/more efficient varieties will continue to contribute to increasing yields, and possibly to increased yield ceilings. However, the development, application, and adaptation of appropriate cropping systems also can contribute substantially to increasing yields and decreasing environmental degradation—and we believe research in this area is likely to have the largest payoff in rapidly developing economies.

Several conceptual frameworks have been proposed to guide efforts that could increase potential yields and reduce yield gaps, while at the same time reducing environmental consequences of intensive agriculture. These frameworks include "ecological intensification" (21) and "evergreen revolution" (22); they share a view of cropping systems as ecosystems that should be designed to make maximum use of fixed resources (land, light, and favorable growing conditions) and optimum use of agricultural inputs (water, fertilizer, and other chemicals) to produce useful products. Such systems can draw upon features of traditional agricultural knowledge and add new ecological information into the intensification process (23). Although there is agreement on the need for such improvements, there are few examples of how they can be developed and adapted across hundreds of millions of farmers' fields.

Here we draw upon studies from China Agriculture University to illustrate the kinds of research that we believe will be required to reduce yield gaps and bring yields closer to their biological potential while reducing the environmental consequences of intensive agriculture. Earlier research in China and elsewhere developed crop and soil management systems that maintained yields and grain quality, while at the same time greatly reducing inputs of N fertilizer, and to an even greater extent reducing losses of reactive N to the environment (24, 25). Although these practices represent a large step forward, in some sense they meet the needs of agriculture in the most developed economies (described above) more than those in rapidly developing economies. In the latter, increasing rather than merely maintaining grain yields remains a fundamental challenge.

In collaboration with partners in China, the United States, and Germany, China Agriculture University scientists recently completed a study with the dual goals of doubling maize yield and reducing N fertilizer requirements, using technologies that could be adapted to and implemented on hundreds of millions of small farms. We developed an integrated soil–crop system management (ISSM) approach designed to make maximum use of solar radiation and periods with favorable temperatures, and designed for greater synchrony between crop demand for N and its supply from soil, environment, and applied inputs (Fig. 2). From 2006 to 2009, we tested this ISSM approach in a total of 66 experiments in farmer's fields, across nine provinces in the major Chinese maize production regions. For comparison, we collected recently published data from 43 studies across seven provinces where maize yields were maximized, generally by selecting favorable weather and soil condition and using very large inputs of water and nutrients. Finally, we also collected and summarized yields and N fertilizer application rates of 4,548 farmers' fields in the main maize production areas in China.

Results and Discussion

First, we used the Hybrid-Maize simulation model (26, 27) to identify the most appropriate combination of planting date, crop density, and plant variety to use at a given site. We based this analysis on long-term weather data and sought cropping systems that would be robust to year-to-year environmental variation. Fig. 3 provides an illustration of this process in a spring maize production system. We simulated the yield potential of the current set of practices in a site near Beijing, using the Hybrid-Maize simulation model and 15-y weather data (Fig. 3*A*) to be 8.9 t ha^{-1}, with a range from 8.0 to 9.8 t ha^{-1} (Fig. 3*E*). Through a scenario analysis in the model, we found that delaying the planting date would increase maize yield potential because of longer growth periods for grain filling under relatively lower-temperature conditions (Fig. 3*B*); that increasing plant density would increase yield potential significantly by capturing more resources early in the growing season (Fig. 3*C*); and that changing to varieties with longer growth periods [increasing growing degree days (GDD) to harvest] would increase maize yield potential by capturing more solar radiation and making use of favorable temperatures for growth (Fig. 3*D*). Integrating these measures, we developed a

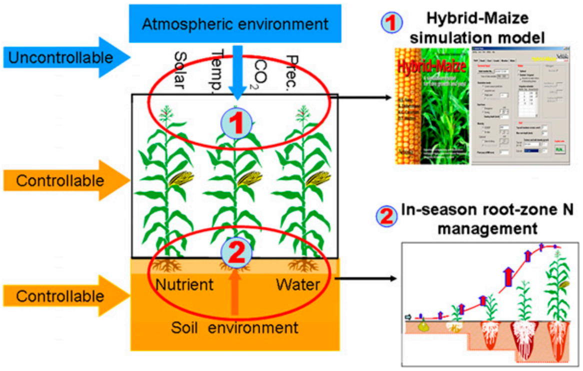


Fig. 2. Conceptual framework for the ISSM approach. Blue arrow represents the atmospheric environment, including solar radiation, temperature, precipitation, and CO_2 concentration—all factors that agricultural practices cannot control but must adapt to. Orange arrows represent crop canopy and soil nutrient or water supply, which can be altered by agricultural practices. Using the Hybrid-Maize model (29) (*Upper Right*), we selected the most appropriate combination of planting date, crop maturity, and crop variety to optimize capture of radiation and favorable growing conditions at a given site. Using an IRNM strategy (32, 33) (*Lower Right*), we managed total N supply to match high-yielding crop N requirements in time, space, and quantity.

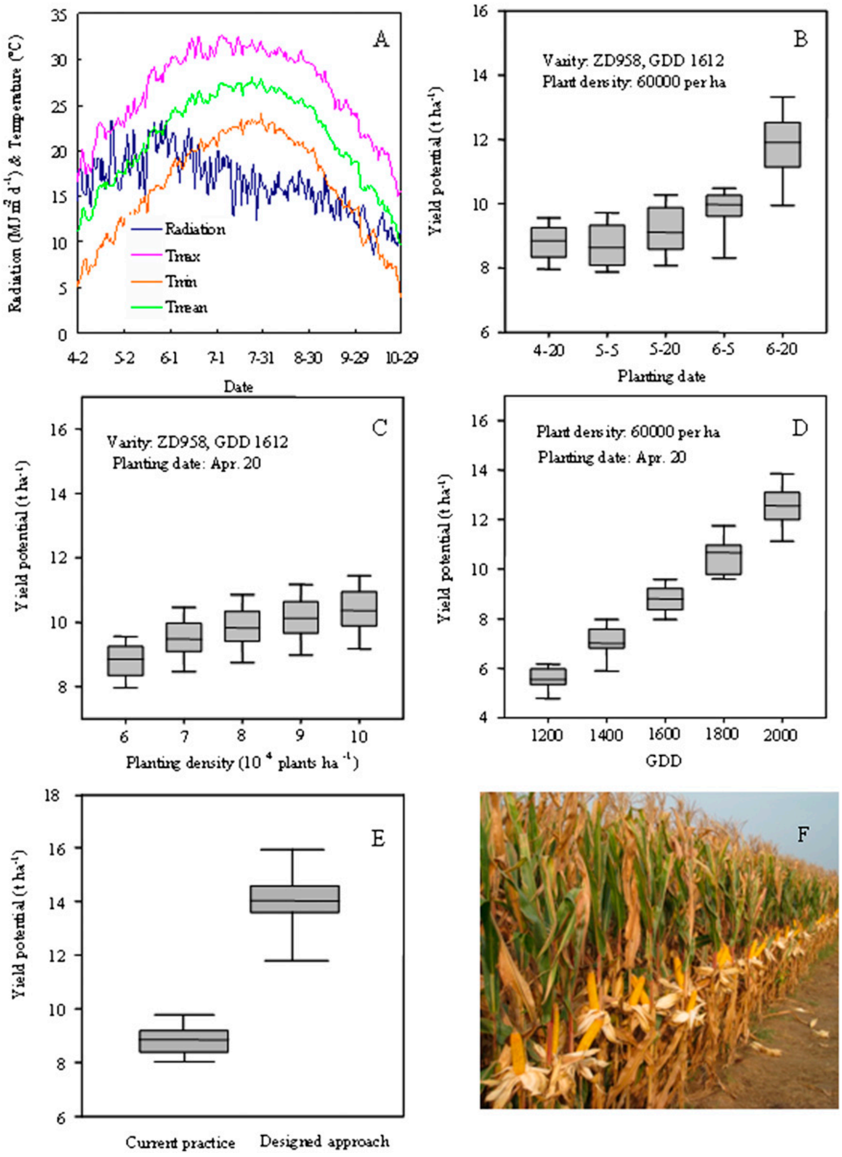
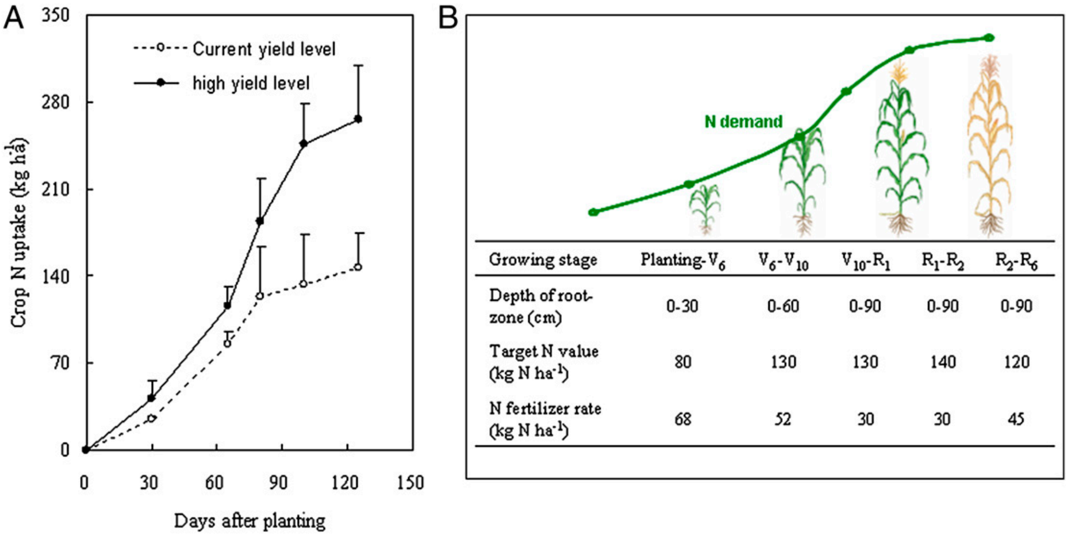


Fig. 3. Design of a highly productive cropping system for spring maize in a site near Beijing, China, using the Hybrid-Maize model. (*A*) Average solar radiation and air temperature, 1990–2005. The model used weather data from individual years to calculate the range and variability of yields. (*B*) Influence of planting date on yield potential. (*C*) Influence of planting density on yield potential. (*D*) Influence of crop varieties that differ in GDD requirements on yield potential. (*E*) Integrated effects of the optimal combination of factors, as determined using the Hybrid-Maize model, in comparison with current farmers' practice. Current practice represents widespread maize varieties (ZD958, GDD 1,612), an early planting date (April 20), and a relatively low plant density (60,000 ha^{-1}); the designed approach included selected new varieties (DH3719, GDD 1,952), later planting (April 28) and higher density (100,000 ha^{-1}). (*F*) Field photo from high-yielding maize in Beijing, 2007. In *B*–*E*, the lines and squares within the box represent the median values of all model simulations (with the variation derived from year-to-year variation in climate); the bottom and top edges of the box represent 25th and 75th percentiles of all data, respectively; and the bottom and top bars represent 5th and 95th percentiles, respectively.

high-yielding maize production system with an increased simulated yield potential of 14.1 t ha^{-1} (range, 11.6–16.9 t ha^{-1}, depending on weather conditions in different years) (Fig. 3*E*), vs. 8.9 t ha^{-1} in current practice.

The second step involved identifying the most effective N fertilizer management tactics to ensure nonlimiting N supply with minimum losses to the environment. We based this approach on an in-season root-zone N management strategy (IRNM) (28, 29), in which we managed the total N supply in the root zone, including residual soil nitrate-N and applied fertilizer, to match the total quantity required for the model-designed maize system in dose, space, and time. We observed that the ISSM maize required more N during the late growing period, especially after anthesis, compared with current practices—31% of total N uptake occurred after anthesis in the ISSM maize, vs. only 16% for current yield level (Fig. 4*A*). On the basis of these observations, our IRNM strategy divided the growth season of ISSM maize into five periods. By measuring soil nitrate-N content in the root zone at the beginning of each of these intervals, we calculated an optimal rate of N application for each maize growth period to be 68, 52, 30, 30, and 45 kg N ha^{-1} (in a particular field experiment in a Beijing suburb) (Fig. 4*B*). After validating this soil-testing-based IRNM approach in three of our 66 experiments, we developed a "simplified IRNM" approach without soil testing to make the system practical for hundreds of millions of smallholder farmers on small parcels of land and applied it in the other 63 experiments. This system was based on (*i*) limiting the total N fertilizer rate to bring N inputs and outputs into balance, and (*ii*) applying N in split doses,



Growing stage	Planting-V_6	V_6-V_{10}	V_{10}-R_1	R_1-R_2	R_2-R_6
Depth of root-zone (cm)	0-30	0-60	0-90	0-90	0-90
Target N value (kg N ha^{-1})	80	130	130	140	120
N fertilizer rate (kg N ha^{-1})	68	52	30	30	45

Fig. 4. (*A*) Timing of N uptake by maize grown with current farmers' practice (average yield, 6.4 t ha^{-1}, n = 22) and with the cropping system designed using the hybrid maize model (Fig. 3) (with an average yield of 13.1 t ha^{-1}, n = 27). (*B*) Target N value in the root zone, and the actual N fertilizer application required to meet the target values calculated using the IRNM system for maize with a high yield level of 13 t ha^{-1}. Through IRNM, the growth season of maize was divided into five periods (34). The target N value was the sum of N uptake by shoot and root scaled by target yield and the needed minimum residual of soil available N at the end of each growth period (32, 33). The optimal rate of N fertilizer application in each maize growth period was determined by deducting measured soil nitrate-N content in root zone from the target N value.

with the largest amount applied during rapid growth stages to synchronize supply with in-season N demand by the ISSM maize.

Results of field experiments comparing the ISSM approach with typical farmers' practices and with high-input systems designed to maximize yield are summarized in Table 1. We found that most of the improvement in yield and efficiency identified by the model could be realized in practice, with average yields of 13 t ha^{-1} in 66 on-farm trials across northern China (86% of the simulated yield potential calculated from the Hybrid-Maize model) (Table 1). In contrast, yields under typical farmers' practices averaged 6.8 t ha^{-1}. For comparison, the mean maize grain yield in high-input, high-yielding studies carried out in the most favorable sites was 15.2 t ha^{-1}, 91% of the simulated yield potential.

Equally importantly, N fertilizer application averaged 257 kg ha^{-1} in the farmers' fields, with a low overall ratio of 26 kg of grain per kilogram of N applied, and an average of 127 kg of fertilizer N per hectare unaccounted for and potentially lost to the environment from each crop (Table 1). The ISSM approach used no more N (an average of 237 kg ha^{-1}) to produce nearly twice as much grain, with 57 kg of grain per kg of N and little or no N from fertilizer inputs unaccounted for in harvest removals. The high-yielding studies achieved their yields in part by increasing fertilizer N inputs from 257 kg N ha^{-1} in the farmers' practice to 774 kg N ha^{-1}, producing only 21 kg of grain per kilogram of applied N and leaving an astonishing 457 kg of N per hectare unaccounted for in the mass balance of N (Table 1). Although the high-yielding results are consistent with the suggestion by Tilman et al. (30) that a doubling of agricultural food production would require a 2.4-fold increase in N use, the ISSM approach nearly doubled maize yield but used no more N fertilizer than did farmers' practice.

Many steps remain to be taken between doubling maize yields in on-farm trials and achieving those gains on hundreds of millions of farm fields in China—even without considering the extension of this approach to other crops and cropping systems in China and many other rapidly developing economies. Some of the questions that need to be addressed are primarily biophysical: How close to the yield potential can average farm yields rise while maintaining efficient use of applied inputs? What are tolerable thresholds for losses of nitrogen to ground- and surface water and to the atmosphere? Is it possible to sequester carbon in high-yield, high-efficiency production systems? Other questions are primarily policy oriented: How can farmers obtain the information necessary to apply the ISSM system? What are the barriers to implementation by individual farmers, and how can they be alleviated? How can knowledge about these approaches

Table 1. Mean maize grain yield and modeled yield potential, N balance (fertilizer inputs − harvest outputs), and N applied per unit of grain produced for different management systems: ISSM approach (*n* = 66), farmers' practice (FP, *n* = 4,548), and high-input, high-yielding studies (HY, *n* = 43)

Variable	ISSM	HY	FP
Maize grain yield (t ha^{-1})	13.0 ± 1.6	15.2 ± 2.6	6.8 ± 1.6
Yield potential (t ha^{-1})	15.1 ± 1.9	16.8 ± 2.0	—
Yield potential (%)	86	91	—
N input from fertilizer and manure (kg ha^{-1})	237 ± 70	747 ± 179	257 ± 121
N removal in harvest (kg ha^{-1})	250 ± 31	292 ± 50	132 ± 31
Inputs minus harvest removals (kg ha^{-1})	−12 ± 56	457 ± 155	127 ± 42
Yield per unit fertilizer N applied (kg kg^{-1})	57 ± 13	21 ± 5	26 ± 20

most effectively be shared and integrated into the knowledge base of farmers? For this approach to be useful—and used—each of these questions must be investigated in systems that achieve yield levels substantially greater than today's average yields. This effort will require greater understanding of interactions among soil, crop, and environment, including processes governing the relationships among agricultural inputs, soil quality, climate, and crop productivity. It will also require greater understanding of the knowledge system through which information is produced, shared, and used by decision makers, and the economic, social, and biophysical impediments to implementation at the scale of farmers' fields (31, 32).

Nevertheless, the gains in yield and environmental quality that can be achieved through an integrated agronomic approach—one based on the use of current varieties and locally relevant technology—is striking (Table 1). Moreover, we believe that most of these gains can be realized in practice, in many crops and countries—if we invest in agronomic research that incorporates an ecosystem perspective and if the effort to modify and adapt intensive agricultural systems is pursued across disciplinary boundaries. Without multidisciplinary cooperation among (at least) soil science, agronomy, ecology, genetics, economics, and social sciences, and without engagement of farmers in the effort, it is unlikely that we will be able to double crop yield while also protecting environmental quality and conserving natural resources.

Despite these challenges, the demonstration that it is possible to increase grain yield dramatically, both in absolute terms and per unit of N fertilizer applied, in sites across the Chinese maize belt suggests that we should reevaluate priority areas for agricultural research to ensure food security and environmental quality over the next several decades. Since the mid-1980s in the United States and the 1990s in rapid developing countries, increasing attention has been given to research approaches that use molecular genetics and biotechnology to produce higher-yielding or better-protected crop varieties (7, 8, 33). These genetic approaches can contribute significantly to increasing crop resistances to various biotic and abiotic stresses and can thereby contribute to increasing both potential and actual yields. However, without concurrent research and outreach on management of the plant–soil system, the influence of genetic approaches will be limited. A recent illustration in China involved several new maize hybrids that were released with strong financial and policy support from the government and gained widespread adoption. Although these hybrids provided a significant yield increase of ≈2 t/ha in selected experimental fields under highly favorable growth conditions (34), improvements of average yield levels in farmers' fields at regional and national scales were not detectable (14).

Moreover, investment in increasing agricultural yields is not enough: the pathways by which yields are increased are crucial to the environment and well-being of people in rapidly developing economies, and indeed to the global system. If yields increase because inputs are increased with little regard to their off-site consequences—the path of the recent past in rapidly developing economies—then the environmental consequences of those increases will be devastating locally, regionally, and globally. However, if yields increase as a consequence of ISSM that match inputs to agricultural systems to crop requirements in amount, time, and space (Table 1), the yield increases can be accompanied by environmental improvements. Matching inputs and requirements will be challenging in rapidly developing countries with hundreds of millions of smallholder farmers; it will require a different approach than the high-technology version of precision agriculture practiced in large farms in developed economies (6). We believe that with the involvement of agricultural economists and other policy specialists, agricultural extension, and (most crucially) farmers themselves, systems can be developed and adapted that allow simplified "rules of thumb" to implement greater precision of management, including field-specific nutrient management (35) and root-zone in-season N management (29, 36).

Overall, we suggest that society needs to balance investments across genetic, agronomic, and policy-oriented research, to accelerate the growth of yields and to reduce negative environmental consequences of crop production. Investments in genetics and the breeding of some crops are strongly supported by the private sector because of the opportunities for property rights and profits, but there are fewer opportunities for private profit from agronomic research designed to improve crop and soil management. Such research, however, provides public goods in the forms of greater yields and of cleaner water, better soil quality, reduced greenhouse gas emissions, and enhanced biological diversity. Such research should be supported by governments and nongovernmental organizations in the rapidly developing countries and elsewhere; it is likely to provide substantial benefits to slowly developing and highly developed economies, as well as to its most important and immediate target, intensive agricultural systems in the rapidly developing economies.

Materials and Methods

Study Areas. Three different representative maize planting regions in China were selected: Northeast China (45–55 °N, 110–125 °E), the North China Plain in central-eastern China (32–41 °N, 113–120 °E), and Northwest China (34–40 °N, 105–115 °E). These three areas provide ≈80% of Chinese maize production.

Integrated Soil–Crop System Management. A total 66 experiments were conducted in three main maize production areas, including 16 in the North China Plain in central-eastern China, 11 in Northeast China, and 39 in Northwest China. At a given site, the most appropriate crop system combination of planting date, crop maturity, and plant population was designed according to long-term weather data and the Hybrid-Maize simulation model. In the Northeast and Northwest China, maize is planted in the spring, with a single crop each year; thus planting date, varieties, and density all could be modified by the ISSM approach. In the North China Plain, maize is double-cropped each year with winter wheat, and therefore the maize planting date cannot be changed. However, plant density can be increased, and varieties with longer growth period can be selected within the double-cropping system.

Nitrogen fertilizer application was based on the IRNM approach (with soil mineral N testing) in three initial experiments (28, 29, 36) and on the "simplified IRNM" approach (without soil testing) in another 63 experiments. For the IRNM approach, the maize growth period was divided into five periods: from planting to six-leaf stage (V_6), V_6 to 10-leaf stage (V_{10}), V_{10} to anthesis (R_1), R_1 to blister stage (R_2), and R_2 to physiological maturity (R_6). We sought to have 80, 130, 130, 140, and 120 kg ha^{-1} of N, respectively, available to the crop in each of these periods. For the "simplified IRNM" approach, the total N fertilizer rate for the whole maize growing season was calculated according to expected yields and the N input–output balance. The proportion of N applied during each period was calculated according to a maize crop N demand curve, with the largest amount N fertilizer applied during rapid growth stages.

All experimental fields received appropriate amounts of phosphorus and potassium fertilizer according to soil testing, weeds were well controlled, and no obvious water or pest stress was observed during the maize growing season. Soil tillage and pest management were optimized according to local ecological conditions in this ISSM approach. Maize was planted in the spring and rain-fed in all experiments in Northeast China and most in Northwest China; maize was planted in summer and irrigated in all experiments in the North China Plain and some in Northwest China. Irrigation was optimized according to local ecological conditions in the ISSM approach.

Farmers' Practice. In this study, 4,548 farmers from 64 counties in five provinces were surveyed. A multistage sampling technique was used to select representative farmers for inquiry. In each county, 4–14 townships were randomly selected, then four to six villages were randomly selected in each township, and then 8–10 farmers were randomly surveyed to determine the form of fertilizer they used, application rate, timing, technique, and grain yield in past year.

High-Yielding Studies. We summarized published information from 43 sites in which high-yielding studies had been carried out. Of these data, 29 sites were published in journals (37–39), and 14 sites came from a project workshop (40). These sites were distributed in the main maize production areas in China; all sites sought to maximize yields regardless of the cost of agricultural inputs, and all made use of favorable combinations of soil, climate, and crop management in selected fields.

Statistical Analysis. We used the Hybrid-Maize model (29) to simulate maize yield potentials. The yield potential is defined here as the modeled maximum yield that could be achieved under the management, soil, and weather conditions specified; it is not the same parameter as the yield ceiling. Hybrid-Maize requires daily weather variables: total solar radiation, minimum air temperature, and maximum air temperature. Other input settings include crop variety, water regime, and soil properties. In this study, we simulated maize yield potential in all 66 experiments in our ISSM studies and in all 43 sites where high-input, high-yielding studies had been reported.

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1. Godfray HCJ, et al. (2010) Food security: The challenge of feeding 9 billion people. *Science* 327:812–818.
2. Barrett CB (2010) Measuring food insecurity. *Science* 327:825–828.
3. How to feed a hungry world (2010) *Nature* 466:531–532.
4. Food: The growing problem. (2010) *Nature* 466:546–547.
5. Ejeta G (2010) African green revolution needn't be a mirage. *Science* 327:831–832.
6. Gebbers R, Adamchuk VI (2010) Precision agriculture and food security. *Science* 327: 828–831.
7. Tester M, Langridge P (2010) Breeding technologies to increase crop production in a changing world. *Science* 327:818–822.
8. Fedoroff NV, et al. (2010) Radically rethinking agriculture for the 21st century. *Science* 327:833–834.
9. Fears over Europe's GM crop plan. (2010) *Nature* 466:542–543.
10. Sanchez P, et al. (2007) The African millennium villages. *Proc Natl Acad Sci USA* 104: 16775–16780.
11. Sanchez P (2010) Tripling crop yields in tropical Africa. *Nat Geosci* 3:299–300.
12. Denning G, et al. (2009) Input subsidies to improve smallholder maize productivity in Malawi: Toward an African green revolution. *PLoS Biol* 7:e23.
13. Cassman KG, Grassini P, Wart J (2010) in *The Handbook of Climate Change and Agroecosystems: Impacts, Adaption and Mitigation*, eds Hillel D, Rosenzweig C (World Scientific, Hackensack, NJ), pp 37–52.
14. National Bureau of Statistics of China (1997–2008) *China Agriculture Yearbook* (China Agricultural Press, Beijing).
15. Le C, et al. (2010) Eutrophication of lake waters in China: Cost, causes, and control. *Environ Manage* 45:662–668.
16. Zheng XH, Han SH, Huang Y, Wang YS, Wang MX (2004) Re-quantifying the emission factors based on field measurements and estimating the direct N_2O emission from Chinese croplands. *Global Biogeochem Cycles*, 18:GB2018, 10.1029/2003GB002167.
17. Guo JH, et al. (2010) Significant acidification in major Chinese croplands. *Science* 327: 1008–1010.
18. International Fertilizer Association. IFA database. Available at: http://www.ifa.com/ Accessed March 5, 2010.
19. Cassman KG, Dobermann A, Walters DT, Yang HS (2003) Meeting cereal demand while protecting natural resources and improving environmental quality. *Annu Rev Environ Resour* 28:315–358.
20. Lobell DB, Cassman KG, Field CB (2009) Crop yield gaps: Their importance, magnitudes, and causes. *Annu Rev Environ Resour* 34:179–204.
21. Cassman KG (1999) Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. *Proc Natl Acad Sci USA* 96:5952–5959.
22. Swaminathan MS (2000) An evergreen revolution. *Biologist (London)* 47:85–89.
23. Matson PA, Parton WJ, Power AG, Swift MJ (1997) Agricultural intensification and ecosystem properties. *Science* 277:504–509.
24. Matson PA, Naylor R, Ortiz-Monasterio I (1998) Integration of environmental, agronomic, and economic aspects of fertilizer management. *Science* 280:112–115.
25. Ju XT, et al. (2009) Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proc Natl Acad Sci USA* 106:3041–3046.
26. Yang HS, et al. (2004) Hybrid Maize-A maize simulation model that combines two crop modeling approaches. *Field Crops Res* 87:131–154.
27. Yang HS, et al. (2006) Features, applications, and limitations of the Hybrid-Maize simulation model. *Agron J* 98:737–748.
28. Chen XP, et al. (2006) Synchronizing N supply from soil and fertilizer and N demand of winter wheat by an improved N_{min} method. *Nutr Cycl Agroecosyst* 74:91–98.
29. Chen XP, et al. (2010) Optimizing soil nitrogen supply in the root zone to improve maize nitrogen management in China. *Soil Sci Soc Am J* 74:1367–1373.
30. Tilman D, et al. (2001) Forecasting agriculturally driven global environmental change. *Science* 292:281–284.
31. Cash DW, et al. (2003) Knowledge systems for sustainable development. *Proc Natl Acad Sci USA* 100:8086–8091.
32. McCullough E, Matson PA (2011) in *Linking Knowledge with Action for Sustainable Development: A Case Study of Change and Effectiveness*, ed Matson PA (Island Press, Washington, DC).
33. Delmer DP (2005) Agriculture in the developing world: Connecting innovations in plant research to downstream applications. *Proc Natl Acad Sci USA* 102:15739–15746.
34. Dai JR (1998) The prospects and countermeasures for maize production in China (in Chinese). *Crops* 5:6–11.
35. Dobermann A, et al. (2002) Site-specific nutrient management for intensive rice cropping systems in Asia. *Field Crops Res* 74:37–66.
36. Cui ZL, et al. (2010) In-season nitrogen management strategy for winter wheat: Maximizing yields, minimizing environmental impact in an over-fertilization context. *Field Crops Res* 116:140–146.
37. Li CH, et al. (2001) Study on relationship between grain-yield of summer corn and climatic ecological condition under super-high-yield cultivation (in Chinese with English abstract). *Scientia Agricultura Sinica* 34:311–316.
38. Chen GP, et al. (1995) Study on cultivation technology with the highest record of maize production in China. *Maize Sci* 3:26–30.
39. Xie ZR (2000) The theory and techniques of maize super-high yield on the single crop a year in Jilin Province (in Chinese with English abstract). *Rev China Agricul Sci Technol* 2:33–37.
40. Zhang JW, Ma WQ, Li SQ, Xue JQ (2010) Workshop on high-yielding and high nutrient use efficiency, Beijing, China. Available at http://www.cnnm.org.cn/. Accessed April 3, 2010.