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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