AGRICULTURE

Nutrient Imbalances in Agricultural Development

Nutrient additions to intensive agricultural systems range from inadequate to excessive—and both extremes have substantial human and environmental costs.

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Nutrient cycles link agricultural systems to their societies and surroundings; inputs of nitrogen and phosphorus in particular are essential for high crop yields, but downstream and downwind losses of these same nutrients diminish environmental quality and human well-being. Agricultural nutrient balances differ substantially with economic development, from inputs that are inadequate to maintain soil fertility in parts of many developing countries, particularly those of sub-Saharan Africa, to excessive and environmentally damaging surpluses in many developed and rapidly growing economies. National and/or regional policies contribute to patterns of nutrient use and their environmental consequences in all of these situations (*1*). Solutions to the nutrient challenges that face global agriculture can be informed by analyses of trajectories of change within, as well as across, agricultural systems.

Harvested crops remove nitrogen, phosphorus, and other nutrients from agricultural soils—and sustaining agricultural production requires replacing those nutrients, whether through biological processes like nitrogen fixation or through the addition of animal wastes or mineral fertilizer to fields. Globally, fertilizer is the major pathway of nutrient addition; it has more than doubled the quantities of new nitrogen and phosphorus entering the terrestrial biosphere (*2*, *3*). These inputs have helped to keep world crop productivity ahead of human population growth and can enhance rural economic development. However, environmental costs of nutrient pollution from agriculture have been substantial, including the degradation of downstream water quality and eutrophication of coastal marine ecosystems, the development of photochemical smog, and rising global concentrations of the powerful greenhouse gas nitrous oxide (*4*).

Here, we evaluate nutrient balances (*5*) of three corn-based agricultural systems—low-input corn in Western Kenya, high-input wheat and corn double-cropping systems in Northeast China (see figure, page 1520), and corn-soybean rotations in the upper midwestern United States. Unlike most regions of the world, crop yields have not increased substantially in sub-Saharan Africa, and 250 million people remain chronically malnourished there (*6*). Nutrient additions to most fields do not replenish soil nutrients extracted in crop harvest (*7*). For example, on the 90 smallholder farms sampled in the Siaya District of Kenya, nitrogen inputs from fertilizer were less than the amount taken out as grain and stover (see table, above) (*8*). This system persists by drawing down the nutrient capital of what were once high-fertility soils.

In contrast, agricultural production in China has increased dramatically since ~1975, with per-hectare yields of grain doubling in many areas. Policy-driven increases in fertilizer use contributed to rising crop yields as China strived for food security. Nutrient additions to many fields far exceed those in the United States and Northern Europe (*9*–*11*) (see table, above)—and much of the excess fertilizer is lost to the environment, degrading both air and water quality (*11*).

Finally, increased N and P fertilization in the Mississippi Basin has contributed to increased yields since the 1940s (*12*). From ~1970 to 1995, nutrient additions were well in excess of crop nutrient removals, and hydrologic losses caused eutrophication of freshwaters and the coastal Gulf of Mexico. More recently, nutrient imbalances have been reduced (*13*) (see table, above) (*14*). In Western Europe, post–World War II national

Inputs and outputs	Nutrient balances by region (kg ha $^{-1}$ year $^{-1}$)					
	Western Kenya		North China		Midwest U.S.A	
	N	P	N	P	N	P
Fertilizer	7	8	588	92	93	14
Biological N fixation					62	
Total agronomic inputs	7	8	588	92	155	14
Removal in grain and/or beans	23	4	361	39	145	23
Removal in other harvested products	36	3				
Total agronomic outputs	59	7	361	39	145	23
Agronomic inputs minus harvest removals	-52	+1	+227	+53	+10	−9

Inputs and outputs of nitrogen and phosphorus by managed pathways in a low-input corn-based system in Western Kenya in 2004–2005 (*8*), a highly fertilized wheat-corn double-cropping system in North China (2003–2005) (*9*–*11*), and a tile-drained corn-soybean rotation in Illinois, USA (1997–2006) (*14*). Potential crop yields are similar in these systems, but realized yields of corn were 2000, 8500, and 8200 kg ha^{-1} year^{-1} per crop in the Kenya, China, and U.S. systems, respectively. Wheat yielded another 5750 kg ha^{-1} year^{-1} in China, and soybeans yielded 2700 kg ha^{-1} year^{-1} every other year in Illinois. (Because the Illinois system represents a 2-year rotation, all nutrient inputs and removals were adjusted to place them on an annual basis.)

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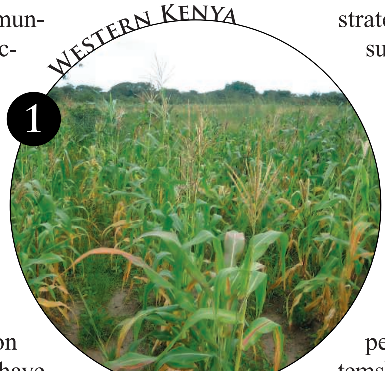

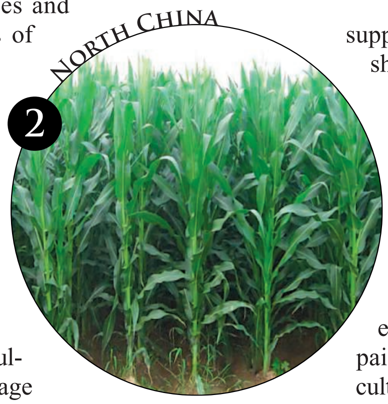

Corn crops in Western Kenya and the North China Plain. Both fields receive sufficient rainfall; they differ primarily in that soil nutrients in the Kenya field have been depleted, whereas the China field receives very large additions of nutrients in fertilizer.

and, later, European Community policies to boost food security (*1*) caused many areas to reach nitrogen surpluses within integrated crop and animal production systems as large and damaging as those now observed in China. Since the 1980s, increasingly stringent national and European Union regulations and policies have reduced nitrogen surpluses and have improved indicators of environmental nutrient excess. Despite these steps toward nutrient balance, nitrogen pollution remains substantial in both the air and water of Northern Europe (*15*, *16*), and coastal eutrophication in the Gulf of Mexico is continuing.

These contrasting agricultural systems (see table, page 1519) require different policies. In sub-Saharan Africa, the initial challenge is to provide more nutrients and to improve cropping practices to build soil organic matter (*17*). Although the reluctance of many policy-makers to accept the economic, environmental, and social costs of subsidized fertilizer use is understandable, inadequate inputs will entrain low productivity, land degradation, and rural poverty until fertilizer for small-holder farmers is subsidized (*18*).

In contrast, the North China Plain wheat-corn systems clearly receive excessive nutrient inputs; Ju *et al*. (*11*) demonstrated experimentally that additions of N fertilizer could be cut in half without loss of yield or grain quality, in the process reducing N losses by >50%. Matson *et al*. (*19*) described a similar overshoot in fertilizer application to intensive wheat systems in Mexico. In these situations, reducing nutrient inputs would be beneficial agronomically, economically, and environmentally. However, this step alone may not suffice to stop environmental damage, as continuing losses of agricultural nutrients and consequent environmental damages in the Mississippi Basin and Northern Europe demonstrate. These systems require further interventions focused on their environmental impacts—and a range of potentially useful strategies and practices have been demonstrated (*20*). Some of these—such as better-targeted timing and placement of nutrient inputs, modifications to livestock diets (*21*), and the preservation or restoration of riparian vegetation strips—can be implemented now. Bolder efforts to redesign agriculture (e.g., by incorporating perennials into cropping systems) also are needed.

More generally, policies supporting nutrient additions should be targeted toward food security objectives early in agricultural development, but those systems should be monitored for changes in soil quality and nutrient losses, as well as for yields. As food security is approached, more attention should be paid to other outputs of agricultural systems—their effects on air and water, on biological diversity, on human health and well-being—and to the ecological and agronomic processes that control them.

One constraint to our ability to diagnose nutrient-driven problems, and to design their solutions, is the scarcity of detailed, on-farm nutrient budgets that quantify multiple pathways of nutrient input and loss over time and under alternative management practices. Both China and the European Union have supported integrated, multiscale biogeochemical research that yields policy-relevant information on nutrient balances and their implications (*11*, *22*). Neither the United States nor most other governments have done as well.

Agricultural systems are not fated to move from deficit to excess. However, most national agricultural agencies lack the means to assess the impacts of changing farm practices at appropriate scales and the incentives to promote the adoption of nutrient-conserving practices and processes. Without these tools, it will be difficult to develop and sustain modern agricultural systems without incurring continuing human and environmental costs.

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