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*).

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.)

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

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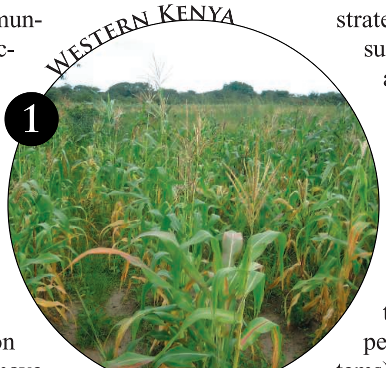
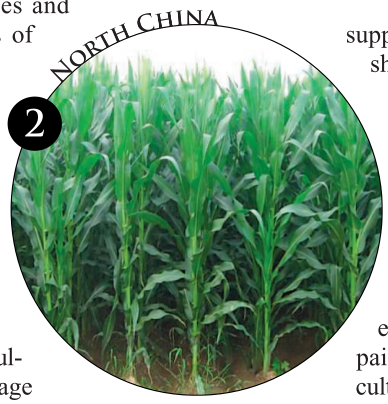
and, later, European Community policies to boost food security (*1*) caused many areas to reach nitrogen surpluses within integrated crop and animal production systems as large and damaging as those now observed in China. Since the 1980s, increasingly stringent national and European Union regulations 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.





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.

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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LETTERS

edited by Jennifer Sills

Too Sanitary for Vultures

THE CURRENT CRISIS OF BIODIVERSITY HAS HIT OLD-WORLD VULTURES ESPECIALLY HARD; populations that flourished in the mid-20th century over much of Asia and Africa are in some cases close to extinction (*1*). In Europe, however, vultures have been spared, and today the Mediterranean basin is home to the largest populations of the Western Palearctic (*2*). The availability of carcasses around stock farms became a decisive factor in the survival and expansion of vulture populations in southern Europe (*3*).

The outbreak of bovine spongiform encephalopathy (BSE) in 2001 led to the passing of sanitary legislation (Regulation CE 1774/2002) that greatly restricted the use of animal byproducts not intended for human consumption. All carcasses of domestic animals had to be collected from farms and transformed or destroyed in authorized plants, contradicting member states' obligations and efforts to conserve scavenger species (*4*). The effects of this policy include a halt in population growth, a decrease in breeding success, and an apparent increase in mortality of young age classes (*2*).

Bearded vulture

Griffon vulture

Conservation concerns determined the appearance of a number of European dispositions (2003/322/CE 2005/830/CE) regulating the use of animal byproducts as food for necrophagous birds. Although the aim of these dispositions is to guarantee food supplies, in practice the spatial distribution of feeding stations has become almost totally predictable and habitat quality has been modified artificially as a result. The repercussions of these changes on individuals, populations, and communities of avian scavengers are undoubtedly significant (*2*, *5*–*7*).

Partial solutions to this problem are being found, albeit slowly. In 2009, the European Union began discussing a Spanish proposal for a revised regulation of the use of animal byproducts not intended for human consumption. In April 2009, amendments were approved by the European Parliament obliging the European Commission to regulate exceptions that will guarantee the supply of carcasses and thus satisfy the requirements of avian scavenger populations. It is hoped that the definitive legislation will be in place by 2010 to 2011. The philosophy of this new policy should allow member states a greater flexibility in carrion provisioning. Taking into account sanitary guarantees, it seems clear that encouraging fallen stock to be left in situ is the most ecologically harmonious, inexpensive, and efficient management method for the conservation of scavengers. Fortunately, current knowledge of scavenger ecology is increasing rapidly and so, more than ever, collaboration between ecologists, veterinarians, farmers, and legislators is both possible and desirable.

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Underestimating Energy

IN THE NEWS FOCUS STORY "LEAPING THE efficiency gap" (D. Charles, 14 August, p. 804), Stephen Selkowitz states that "[n]o one measures building performance," which is true of most building designers and owners.

Even when someone does take these measurements, they reveal a systematic bias—much lower energy use is predicted than is actually found. For example, the Swedish city of Malmö opened a small community in 2001 as a model of sustainability (*1*). The design objective for the project was 105 kWh/m^2 per year. Estimates of energy use for 20 buildings were in the range from 32 to 107 kWh/m^2 per year. Although seven buildings had measured performance that met the design objective, each of the buildings used more energy than estimated, with a range for the group of 74 to 356 kWh/m^2 per year. Careful investigation showed a lower electrical load than expected, but actual heat use significantly higher than expected. Another example is the highly publicized Lewis Center at Oberlin College (*2*), which similarly measured energy use in the range of 120 to 200 kWh/year after a design team estimated that it would be only about 64 kWh/year. Furthermore, in its first year, the Energy and Environment building at Stanford was pre-

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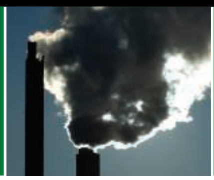

Pollution and climate change

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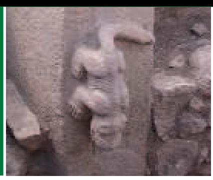

Inheritability of wealth

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dicted to use 198 kWh/m^2 per year, but actual energy use is 380 kWh/m^2 per year (*3*). More and better performance data, improved analytical methods to predict performance, and improved construction methods will all be required to improve estimation accuracy.

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Nutrient Imbalances: Follow the Waste

IN THEIR POLICY FORUM ("NUTRIENT IMBALances in agricultural development," 19 June, p. 1519), P. M. Vitousek and colleagues appropriately addressed the consequences of both overextraction and excess application of nutrients in low-input, rotation, and high-input corn production systems in Kenya, the United States, and China, respectively. The authors provided several on-farm mitigating approaches to these imbalances and called for a more sustainable approach to nutrient management in both developed and developing nations. Unfortunately, the human waste stream and the resulting nutrient redistribution went unmentioned.

Over the past 200 years, global populations have become increasingly urban, shifting from 97% rural in 1800 to about 50% in 2007 (75% in developed countries) (*1*). Nutrients in plant and animal products collected broadly across rural landscapes are increasingly concentrated in urban environs where waste removal efforts result in transformation of nutrients into gases, dilution into rivers and marine bodies, and deposition in pits and landfills. Only a fraction of these assets (nutrients and carbon) are ever returned to rural lands. As a result, soils are slowly being drained of trace elements, soil carbon reserves are being depleted, and it is necessary to mine nutrients and chemically produce N fertilizer to satisfy crop demands. Global N fertilizer use (*2*) currently outpaces global human N demand (*1*, *3*) by a factor of 7 at an annual energy expense equivalent to 1.1 billion barrels of oil. Conversely, N in human excreta in urban centers is nearly equivalent to the total global anhydrous NH_3-N production and represents sufficient N to fertilize 100 million hectares of cropland at 150 kg N ha^{-1} year^{-1}. Sustainable agriculture cannot be achieved until we learn to efficiently and safely redistribute the nutrients in agricultural byproducts and human excreta to the soils of rural landscapes.

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Nutrient Imbalances: Pollution Remains

IN THEIR POLICY FORUM ("NUTRIENT IMBALances in agricultural development," 19 June, p. 1519), P. M. Vitousek *et al*. propose a promising idea: Compare solutions to nutrient challenges among countries and regions. However, policies to control nonpoint pollution are not so easy to design. The United States and the European Union are mentioned as examples of places that have reduced nutrient imbalances, yet pollution remains very high in their water.

European regulations include the 1991 Urban Wastewater Directive, with investments above 100 billion euros. The huge investments of the Wastewater Directive should have reduced pollution, but the European data (*1*) for the past 15 years on nitrate concentration indicate only a slight reduction in rivers and a 50% increase in pollutant levels in aquifers. The data from the Organisation for Economic Cooperation and Development (*2*) also found that most major European rivers show no abatement of nitrates and some have even grown worse.

The Nitrates Directive of 1991 also sought to reduce pollution. The Nitrates Directive only applies to cultivation over aquifers declared officially polluted, not to cultivation over whole basins or very polluting crops that do not receive subsidies (such as greenhouses). The achievements of this Directive are questionable (*3*).

Nonpoint pollution is a common pool "resource" (or public bad) where economic instruments such as taxes and subsidies fail (*3*). Policy-makers must recognize that pollution abatement is impossible without farmers' voluntary cooperation and active support. This is also the message of this year's Nobel prize in economics.

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Response

AS DELUCA SUGGESTS, APPLICATIONS OF N fertilizer worldwide exceed human consumption of that N in the form of protein by several-fold. Our Policy Forum focused in part on the more than 80% of fertilizer N (and P) that does not make it into our diet—the fertilizer that could in some sense be considered "wasted." DeLuca is correct in pointing out that closing nutrient cycles by returning agriculturally derived nutrients to crops would make an additional contribution to the sustainability of intensive agriculture. A parallel problem exists for nutrients in animal waste, due to the adop-

Letters to the Editor

Letters (~300 words) discuss material published in *Science* in the previous 3 months or issues of general interest. They can be submitted through the Web (www.submit2science.org) or by regular mail (1200 New York Ave., NW, Washington, DC 20005, USA). Letters are not acknowledged upon receipt, nor are authors generally consulted before publication. Whether published in full or in part, letters are subject to editing for clarity and space.

tion of confined animal feeding operations (CAFO), which use feed derived from fertilized crops in distant areas (*1*, *2*). In either case, the result is too much N and P in waste near the city or CAFO, and not enough where food or feed is grown.

Albiac points out, and our Policy Forum noted, that the reduction in excess nutrient applications in the midwestern United States and Northern Europe has not ended serious nutrient pollution of surface or groundwater (or the atmosphere) in those regions. Part of the problem may be the decades-long residence time (from application to appearance in surface water) of added nutrients in many systems (*3*); part no doubt reflects inadequacies of the policy instruments designed to reduce water (and air) pollution by excess agricultural nutrients. The European Union in particular has put substantial resources into efforts to reduce this pollution, as Albiac describes, and the relatively small successes to date are disappointing. Albiac points to restricted spatial coverage and inadequate engagement of stakeholders as reasons for failed nutrient policies. Equally important, efforts to date have not been sufficiently systematic; they have not considered the full mass balance of excess nutrients and their multiple possible fates. Excess nutrients cannot be controlled piecemeal (for example, by considering only nitrate rather than total N or by considering effects on aquatic systems in isolation from effects on the atmosphere). Successful policies must address the problem of excessive nutrient applications at their source. Maintaining the high levels of production that we require to meet aggregate cereal and meat demand while reducing losses of nutrients to the environment represents a very difficult challenge. Meeting that challenge will require careful, well-monitored, long-term experiments with policy instruments as well as with agricultural nutrients themselves.

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