

The greening of the green revolution

David Tilman

In comparison with conventional, high-intensity agricultural methods, 'organic' alternatives can improve soil fertility and have fewer detrimental effects on the environment. These alternatives can also produce equivalent crop yields to conventional methods.

It is not clear which are greater — the successes of modern high-intensity agriculture, or its shortcomings. The successes are immense. Because of the green revolution, agriculture has met the food needs of most of the world's population even as the population doubled during the past four decades. But there has been a price to pay, and it includes contamination of groundwaters, release of greenhouse gases, loss of crop genetic diversity and eutrophication of rivers, streams, lakes and coastal marine ecosystems (contamination by organic and inorganic nutrients that cause oxygen depletion, spread of toxic species and changes in the structure of aquatic food webs)^{1,2}. It is unclear whether high-intensity agriculture can be sustained, because of the loss of soil fertility, the erosion of soil, the increased incidence of crop and livestock diseases, and the high energy and chemical inputs associated with it^{1,3}. The search is on for practices that can provide sustainable yields, preferably comparable to those of high-intensity agriculture but with fewer environmental costs¹.

For millennia, farmers countered the loss of soil fertility caused by agriculture (Fig. 1) by manuring fields, by alternating crops that increase soil fertility (such as legumes, which 'fix' atmospheric nitrogen into organic compounds and so add nitrogen-containing compounds to the soil) with other crops, and by abandoning fields and allowing them to be taken over gradually by natural vegetation (succession). This changed with the advent of the green revolution.

A hallmark of high-intensity agriculture is its dependence on pesticides and chemical fertilizers, especially those containing nitrogen. Since 1960 the worldwide rate of application of nitrogen fertilizers has increased by seven times², and now exceeds 7×10^7 tonnes of nitrogen per year. Inputs from humans now equal all natural inputs to the nitrogen cycle and are seriously affecting terrestrial, freshwater and marine ecosystems², because half to two-thirds of nitrogen fertilizers enter these non-agricultural ecosystems.

On page 262 of this issue⁴, Drinkwater, Wagoner and Sarrantonio report two alternative practices for growing maize that maintain yields while increasing soil fertility

and decreasing losses of nitrogen by leaching. This advance is not based on a miracle of technology but is a lesson from agriculture's past that may presage its future.

In Drinkwater and colleagues' conventional, high-intensity system, pesticides and mineral nitrogen fertilizer were applied to a maize/soybean crop rotation just as on typical farms. Two 'organic' alternatives represented partial returns to traditional agriculture, and neither synthetic fertilizers nor pesticides were used. One of these alternatives was a manure-based system in which grasses and legumes, grown as part of a high-diversity crop rotation, were fed to cattle. The resulting manure provided nitrogen for periodic maize production. The other system did not include livestock; instead,

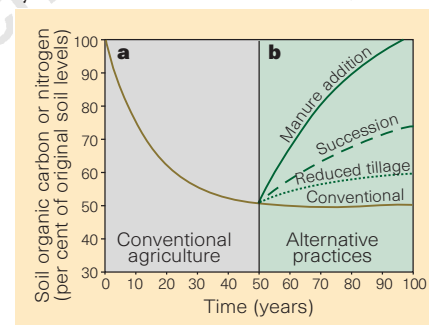


Figure 1 Typical effects of different agricultural practices on the total organic carbon or nitrogen content of soil. a, Over about 50 years, conventional agricultural fields that are tilled and then fertilized with mineral nitrogen, phosphorus and potassium (NPK) fertilizer lose 50–65% of pre-agricultural amounts of soil carbon and nitrogen¹. b, The effects of different practices on recovery of soil fertility after 50 years of tilling. Practices that reduce the amount of tillage of soils can lead to accumulation of about 20% of the lost carbon or nitrogen¹. Succession here refers to the process by which abandoned fields are gradually invaded by successive populations of native vegetation and animals, eventually reaching a stable 'climax' community structure. We have found that it takes about 200 years of natural succession for fields to recover pre-agricultural carbon and nitrogen levels (J. Knops and D. Tilman, manuscript in preparation). The addition of manure can double soil carbon or nitrogen levels in about 40 years^{7,9}.

nitrogen fixed by a variety of legumes was incorporated into soil as the source of nitrogen for maize.

Amazingly, ten-year-average maize yields differed by less than 1% among the three cropping systems, which Drinkwater *et al.* say were nearly equally profitable. The manure system, though, had significant advantages. Soil organic matter and nitrogen content — measures of soil fertility — increased markedly in the manure system (and, to a lesser degree, in the legume system), but were unchanged or declined in the conventional system. Moreover, the conventional system had greater environmental impacts — 60% more nitrate was leached into groundwater over a five-year period than in the manure or legume systems.

Why were the organic methods superior to conventional, high-intensity agriculture? The answer is not yet known, but two possibilities stand out. First, when fertilizing, timing is crucial⁵. The nitrogen pulse from a single application of mineral fertilizer can cause soil nitrate concentrations to greatly exceed plant needs. The unconsumed nutrients are susceptible to loss by leaching and denitrification. In contrast, the organic methods supply nitrogen in organic forms that gradually release mineral nitrogen, perhaps better synchronizing nutrient availability with plant needs.

Second, although equivalent amounts of nitrogen and organic carbon were added to the soil in all three systems, the manure system included a higher proportion and greater diversity of recalcitrant (that is, slowly biodegradable) organic compounds than the conventional system. This may have caused carbon and nitrogen to accumulate in the manure system, minimizing leaching losses. Indeed, models of soil carbon and nitrogen dynamics predict such accumulation when fields are manured^{6,7} (Fig. 1).

Drinkwater and colleagues' results may seem astounding, or even suspect, given the widespread use of chemical fertilizers. They are not. In the Broadbalk experiment (Fig. 2, overleaf), at the Rothamsted Experimental Station in the United Kingdom, which has been running for more than 150 years, wheat yields have averaged 3.45 tonnes per hectare on manured plots compared with 3.40 tonnes per hectare on plots receiving complete nitrogen, phosphorus and potassium (NPK) fertilizer⁸. Moreover, soil organic matter and soil total nitrogen levels increased by about 120% over 150 years in the manured plots (Fig. 1), but by only about 20% in the NPK plots^{7,9}. Such carbon stores might represent an underappreciated sink for global carbon.

The intensification of agriculture has broken what was once the tight, local recycling of nutrients on individual farms. Indeed, the green revolution and the large-scale livestock operations that have come with it are remi-



Figure 2 Field work: experiments on fertilizer regimes have run at Rothamsted since 1843.

niscient of the early stages of the industrial revolution, when inefficient factories polluted without restriction. The US Environmental Protection Agency estimates that, in the United States alone, livestock operations generate about 10^9 tonnes of manure per year, much of it in large-scale operations in which up to a million or more animals are housed in close quarters. These concentrated sources of manure are often too far from farms to be economically transported to them, or are applied at inappropriately high rates or at incorrect times, or are released into waterways without removing nitrogen and phosphorus. This has created an open nitrogen cycle that is rapidly degrading many other ecosystems². Sustainable and productive ecosystems have tight internal cycling of nutrients, a lesson that agriculture must relearn.

The results of Drinkwater and colleagues⁴ are a step in the right direction. What may lead to further progress? The green revolution turned developments in crop genetics, inexpensive pesticides and fertilizers, and mechanization into greater yields. Further advances, such as precision agriculture, in which fertilizer application rates and timing are adjusted differentially across a field to meet crop needs, will increase agricultural efficiency and decrease adverse effects on the environment. However, a greener revolution is also needed — a revolution that incorporates accumulated knowledge of ecological processes and feedbacks, disease dynamics, soil processes and microbial ecology. Experiments such as those of Drinkwater *et al.* need to be combined with studies of both the mechanisms controlling soil organic matter and nitrogen dynamics^{6,7,9}, and the dynamics of crop nutritional needs.

The principles of ecology, epidemiology, evolution, microbiology and soil science operate in agroecosystems as well as in natural ecosystems. Although the owners of the businesses were probably shocked, I doubt if epidemiologists were surprised that Hong Kong chicken operations, housing up to a million genetically similar chickens, were susceptible to a rapid and devastating out-

break of disease last year. When those running massive livestock operations realize that chronic disease and catastrophic epidemics are the expected result of high densities and low diversity, and when society restricts the release of pollutants from such operations, it may again be profitable for individual farms, or neighbourhood consortia, to have mixed cropping and livestock operations tied together in a system that gives an efficient, sustainable, locally closed nitrogen cycle.

Earth science

Prospecting for hotspot roots

Cecily J. Wolfe

Oceanic islands commonly form linear chains with progressively increasing age away from the active region, reflecting nearly stationary ‘hotspots’ beneath the moving lithospheric plate. These hotspots are believed to be produced by upwelling mantle plumes formed from instabilities at a hot thermal boundary layer in the Earth’s mantle, but the depth of origin of mantle plumes has long been debated.

On pages 251 and 255 of this issue, the seismologists Helmberger *et al.*¹ and Russell *et al.*² propose that they have identified the roots of the Iceland and Hawaiian hotspots at the core–mantle boundary, some 2,900 km beneath the Earth’s surface. Their results are notable because although some hotspots may reflect shallow melting anomalies rather than a deeply rooted mantle plume, Iceland and Hawaii are the two classic hotspots that could plausibly represent continuing upwelling from the core–mantle boundary. These hotspots are long-lived, erupt large volumes of magma, and have distinctive geochemical signatures (in particular a high ratio of ³He to ⁴He, which is interpreted as ³He from an undegassed region of the mantle).

For several years, seismologists brought little insight into resolving plume character-

No other activity has transformed humanity, and the Earth, as much as agriculture¹⁰, but the environmental effects of high-intensity farming increasingly haunt us. In a small world awash with the waste products of humanity, there is a great need to find new approaches to agriculture. □

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