The Browning of the Green Revolution

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World population has doubled in half a century since the onset of the Green Revolution that tripled global cereal production with high-yielding varieties and escalating inputs of synthetic nitrogen. Under this strategy, annual sales have increased from 13 to more than 110 million tons of nitrogen, applied largely in ammoniacal fertilizers produced by the energy-expensive Haber-Bosch process.

Today's intensive use of nitrogen fertilizers, besides supplying the most important plant nutrient for achieving high yields, is generally believed to build soil organic matter by increasing the input of residue carbon as well as supplying nitrogen, itself a key constituent. After several decades of high-input agriculture, the benefits should be readily apparent from long-term cropping experiments specifically directed toward documenting changes over time in crop yield and soil properties for sites with detailed management records.

One such site with historic significance is the Morrow Plots, America's oldest experiment field that represents the prairie soils of the Corn Belt and today's intensified production practices. Here corn is grown continuously and following soybeans or two years of oats and alfalfa hay, with and without synthetic nitrogen fertilization that was introduced in 1955. Five decades later, soil sampling was being repeated (to 18 inches) by three soil scientists at the University of Illinois, in an effort to understand how modern grain production has affected soil properties as well as productivity. Their findings have global implications that are documented by Richard Mulvaney, Saeed Khan, and Tim Ellsworth in the November-December 2009 issue of the *Journal of Environmental Quality* at http://jeq.scijournals.org/cgi/reprint/38/6/2295.

Logically, the soil should gain nitrogen if fertilizer inputs exceed grain removal. In the case of the Morrow Plots, these inputs, ranging from 1.8 to 5.6 tons per acre in 51 years, provided at least 60% more nitrogen than the cumulative amount removed in corn grain, yet there was a net decline of 624 to 1606 pounds per acre in total soil nitrogen. The decline occurred even when annual fertilization for continuous corn exceeded grain nitrogen removal by 86 to 102%, the result being much lower fertilizer efficacy for increasing corn yield as compared to either rotation. Despite five decades with approximately double the input of synthetic nitrogen, corn yields are still lower with monoculture cropping than with the two rotations. This disparity is consistent with differences in potentially available soil nitrogen, a key factor in sustaining soil productivity.

The same logical fallacy was substantiated by 120 data sets that document nitrogen changes over time for fertilized soils, encompassing a global range of climates, soils, cropping systems, and management practices. This database reveals that synthetic fertilization has often been ineffective for preventing soil nitrogen depletion, even in cases involving an ample input of nitrogen and the incorporation of crop residues. The problem is that mineral nitrogen, particularly in the form of ammoniacal fertilizers, stimulates microbial carbon decomposition, promoting the loss of crop residues and also indigenous organic matter that serves as the major reservoir of soil nitrogen.

Even with intensive fertilization, soil reserves usually supply the bulk of nitrogen uptake by nonleguminous crops. As a consequence, a decrease in soil nitrogen supply is inherently detrimental to productivity, although cereal yields may for a time be sustained or even increase because of improved varieties or a change in agronomic practices, such as a higher fertilizer rate

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despite the lower incremental return per unit of nitrogen applied. Eventually, however, soil degradation must contribute to yield stagnation or decline, an emerging concern for input-intensive agriculture in Southeast Asia where population is growing rapidly and land area is a major agricultural constraint. Higher nitrogen rates may offer temporary relief, but the long-term consequences will be a further decline in soil productivity that increases the need for synthetic nitrogen fertilization, intensifies food insecurity, and exacerbates environmental degradation.

To mitigate ongoing soil degradation by modern cereal production, every effort should be made to increase fertilizer efficiency by reducing unnecessary fertilizer inputs. Unfortunately, these inputs have been intensified for decades by fertilizer recommendations currently advocated as best management practices, which continue to follow a prescriptive approach utilizing generic models of economic response, and often involving direct or indirect subsidies at public expense. The resulting recommendations are apt to exceed crop nitrogen requirement because soil nitrogen availability is not adequately accounted for, nor do current input-intensive practices emphasize the need to synchronize fertilizer form, placement, or timing with soil and crop nitrogen dynamics. The combined effect is bad news for producers: low efficiency for crop uptake of fertilizer nitrogen, averaging one-third of the nitrogen applied in long-term static fertility trials and often even less for on-farm sites under cereal production.

The low uptake efficiency has adverse economic and ecological ramifications that can be easily identified but not fully quantified. The most obvious of these is the global economic penalty producers pay for unutilized nitrogen, which may exceed $90 billion per year. A nitrogen loss of this magnitude inevitably has an ecological cost, documented by four decades of rising aquatic nitrate concentrations and the growing occurrence of hypoxic dead zones in the world’s coastal waters, the most extensive area in recent years being 466,000 square miles of the Indian continental shelf. The modern era of intensive nitrogen fertilization has also increased greenhouse gas emissions to the atmosphere, mainly in the form of carbon dioxide and nitrous oxide.

Half a century after the onset of input-intensive agriculture, many of the world’s most productive soils have been degraded and cereal production is increasingly exceeded by grain demand for a burgeoning human population. This dilemma warns of the critical need to reevaluate nitrogen fertilizer management and usage, and may ultimately require a transition toward agricultural diversification utilizing legume rotations, instead of further intensifying inputs under the auspices of another Green Revolution. An inexorable conclusion can be drawn: the prevailing system of agriculture does not provide the means to intensify food and fiber production without degrading the soil resource. Sustainability was no less a concern 3500 years ago for the civilization of northern India: ‘Upon this handful of soil our survival depends. Husband it and it will grow our food, our fuel and our shelter and surround us with beauty. Abuse it and the soil will collapse and die taking man with it.’