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Nitrogen Use Efficiency in Row-Crop Agriculture: Crop Nitrogen Use and Soil Nitrogen Loss

G. Philip Robertson

I. Introduction

Nitrogen loss from cropping systems has interested agronomists since the early recognition by Liebig and others that most crops are nitrogen limited. The widespread early adoption of crop rotations that include legumes (Oakley, 1925; Francis and Clegg, 1990) provides historical acknowledgment of the importance of nitrogen gains and losses to cropping system success. It is now recognized that even in semiarid regions (Breman and deWit, 1983) nitrogen is usually the principal resource limiting crop production (Fig. 1).

It was not until the post-World War II era, when munitions plants were converted to fertilizer factories and synthetic nitrogen became cheap and readily available, that nitrogen use efficiency became a moot point for most producers in the United States and other economically developed regions. Even today it is easier and usually more cost-effective at the farm scale to apply another 50 kg N ha^{-1} to an already fertilized field than to devise a means to prevent an equivalent 50 kg^{-1} N ha^{-1} loss. In fact, the price of nitrogen fertilizer in constant dollars has declined over past decades to its current average global price of about \$0.10 kg^{-1} N for urea and anhydrous ammonia (Bumb, 1995; Fee, 1995), providing an even further disincentive for nitrogen conservation. This has resulted in an exponential increase in nitrogen fertilizer use over the past 50 years—first in developed countries and now, with about a 20-year lag, in developing regions (Fig. 2). Globally,

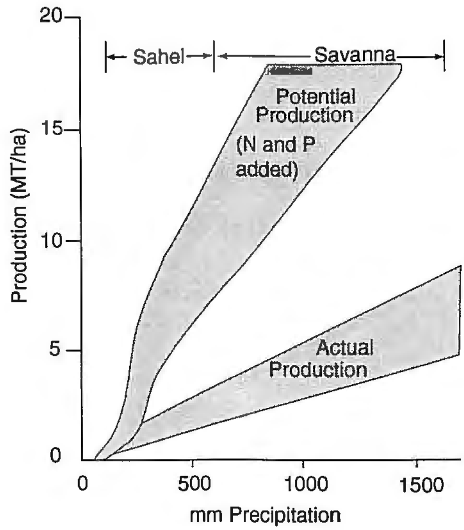

Figure 1 Ranges of actual and potential production in West African pastures at different rates of rainfall. Redrawn from Breman and deWit (1983).

today almost as much fertilizer is fixed from industrial sources as appears to be fixed biologically (Soderland and Svensson, 1976; Vitousek and Matson, 1993).

There is also an off-farm, environmental cost to fertilizer use, however, and the emerging recognition of this cost has renewed interest in finding ways to minimize nitrogen loss from fertilized cropping systems. Moreover, in some developing regions where fertilizer remains unavailable because

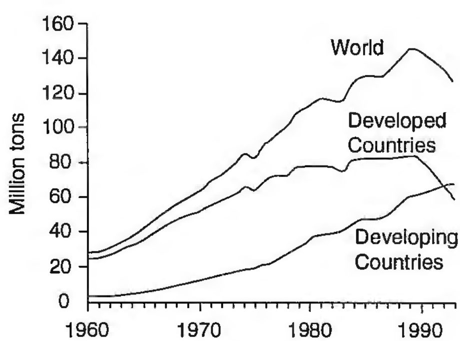

Figure 2 World nitrogen fertilizer consumption since 1960. From FAO (1960–1992) and Bumb (1995).

of economic constraints, and elsewhere where there is interest in reducing farm chemical use (NRC, 1989; Harwood, 1990), the conservation of endogenous nitrogen remains an important management goal. Regardless of the magnitude of fertilizer use, the effective containment of cropping system nitrogen requires a greater nitrogen use efficiency at the ecosystem scale. This is a difficult management goal despite decades of research that have provided substantial insights into process-level details of the nitrogen cycle in many different types of ecosystems.

A. An Overview of the Nitrogen Cycle

The nitrogen cycle is distinguished from many other nutrient cycles by its complexity: Nitrogen in the biosphere exists in a number of different oxidation states, each of which is differentially available to plants, microbes, and other organisms and each of which is differentially reactive with the chemical and physical environment. Moreover, most transformations among nitrogen's different oxidation states are biologically mediated, including changes among ionic (NH_4^+, NO_2^-, and NO_3^-), organic (both particulate and dissolved), and gaseous (N_2, N_2O, NO_x, and NH_3) forms.

Figure 3 shows a generalized nitrogen cycle for a typical row-crop ecosystem. Nitrogen enters the plant in inorganic form: primarily as nitrate (NO_3^-), and perhaps ammonium (NH_4^+; see Chapter 5, this volume) from the soil solution. Leguminous crops can also acquire significant nitrogen

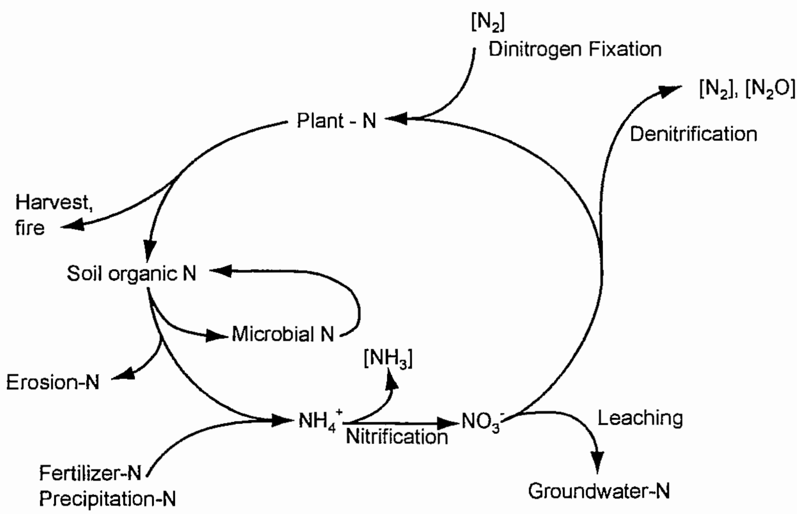

Figure 3 A simplified nitrogen cycle for a typical row-crop ecosystem; only major pathways are shown. Gas-phase nitrogen appears in brackets. For nonleguminous crops, N_2 fixation will be nil.

from the atmosphere when soil solution nitrogen pools are low. At harvest, some proportion of the aboveground plant nitrogen is removed from the system with the crop yield; the remainder, as well as nitrogen contained in roots, joins the crop residue pool as soil organic nitrogen unless a portion is burned.

In erosive environments a portion of soil organic nitrogen can be lost to surface water or to another portion of the field. Most of the residue nitrogen, however, will be oxidized and released to the soil solution as ammonium, although a portion may temporarily remain as microbial biomass nitrogen or in a more recalcitrant organic form. In agricultural soils ammonium is usually quickly nitrified to nitrate, which will be subject to leaching, denitrification, and also available again for plant uptake. All three of these soil nitrogen pools can be supplemented with exogenous inputs: Manure and, more commonly, urea-N can be added to the organic N pool, and inorganic fertilizers (in particular, anhydrous ammonia) can supplement the ammonium and nitrate pools. In most soils urea-N quickly hydrolyzes to the ammonium pool (Ladd and Jackson, 1982), and for both urea and anhydrous ammonia a significant portion of the added nitrogen can be volatilized as NH_3 within a few days of application.

Nitrogen availability represents the net rate at which the pools of inorganic nitrogen are replenished. For most row-crop systems the relevant pool is nitrate (cf. Chapter 5, this volume). Often, the size of the nitrate pool can be used to assess its availability, as is used, for example, in the widely prescribed presidedress nitrogen test. Recognize, however, that nitrogen availability can be high even when the nitrate pool is small if nitrate consumption is high (and vice versa if nitrate consumption is low). Thus, nitrogen mineralization assays (e.g., Hart *et al.*, 1994) are usually the better measure of endogenous nitrogen availability.

B. Nitrogen-Efficient Cropping Systems

Nitrogen-efficient cropping systems are those in which nitrogen availability is high and from which losses occur principally via nitrogen removed from the field in crop yield. Nitrogen efficiency thus requires

1. knowledge of crop nitrogen demands vs systemwide nitrogen inputs and outputs; whether inputs are synthetic or biological, they must be sufficient to replace the nitrogen lost in yield plus that lost via other pathways, principally leaching, denitrification, and, especially in tropical systems, fire;
2. synchrony between soil nitrogen availability and crop nitrogen demand, such that availability—inputs to soil inorganic nitrogen pools—is low except during periods of grand crop growth when available nitrogen must be well matched to crop needs;
3. the placement of available nitrogen in soil such that it coincides with locations of high sink strength, i.e., placement that is coincident with crop

root distributions both at the local row–interrow scale and at a broader field scale that includes underlying patterns of soil heterogeneity; and

4. knowledge of important nitrogen loss pathways—especially leaching and denitrification—sufficient to suggest strategies to minimize their impact.

In the following pages is an overview of the nitrogen use efficiency of modern row-crop ecosystems, the significant features of these systems that either promote or hinder conservative nitrogen use, and emerging management strategies that use this knowledge to improve efficiency. Although most of this discussion is focused on annual row crops typical of the U.S. Midwest, the principles should be applicable in row-crop systems everywhere, temperate and tropical, perennial and annual.

II. Crop Nitrogen Demand

Crop nitrogen needs vary widely, largely as a function of crop species and growing conditions. For most crops nitrogen needs are well known and easily determined from yield data so long as the crop is not overfertilized. Typical rates of nitrogen extraction for fertilized row crops appear in Table I. Amounts of nitrogen removed with crop yields vary widely, largely as a function of crop and yield; in general 100–200 kg N ha^{-1} is removed during harvest, although when the whole aboveground plant is removed—such as for alfalfa and silage corn—extraction values may be 50% higher.

Extraction values represent the minimum levels of nitrogen that must be added back to a cropping system after each harvest if the system is to remain sustainable. Additionally, of course, nitrogen must also be added to cover other nitrogen losses as described later. Failure to completely resupply nitrogen from exogenous sources means that the following equivalent crop will be nitrogen deficient to the extent that it cannot be provided nitrogen that is newly mineralized from native soil organic matter (SOM). In many arable soils nitrogen in native SOM sums to only 3–15 MT N ha^{-1} prior to the onset of cultivation (assuming an A horizon depth of 25 cm with a bulk density of 1.2 g/cm^3 and a nitrogen content of 0.1–0.5 %N). At crop nitrogen extraction rates of >0.1 MT N ha^{-1} $year^{-1}$ (Table I), it is easy to see why continuous cropping—even in the absence of other losses that can be of a similar magnitude—requires exogenous nitrogen and why soil nitrogen pools are typically depleted substantially following only 30–40 years of crop production (Haas *et al.*, 1957; Bauer and Black, 1981; Paustian *et al.*, 1995). Moreover, only a portion of the 3–15 MT N ha^{-1} present prior to cultivation is actually mineralizable—much of it will be in passive or

Table I Typical Nitrogen Extraction Rates for Major Row Crops under High Yield Conditions[a]

Crop	Tissue	Yield (MT/ha)	% N	Total N (kg/ha)
Alfalfa	Above ground	9.0	2.8	252
Maize	Grain	10.0	2.6	260
	Residue	9.0	0.7	63
Soybeans	Grain	2.8	6.3	176
	Residue	5.4	0.9	49
Wheat	Grain	5.4	2.0	108
	Residue	6.0	0.8	48
Rice	Grain	7.9	1.8	142
	Residue	10.0	0.5	50
Cotton	Lint and seed	4.2	2.9	122
	Residue	5.0	1.3	65
Potatoes	Tubers	56.0	0.3	168
	Residue	5.0	1.8	90
Sorghum	Grain	9.0	3.0	270
	Residue	5.0	0.7	35
Sugar beets	Roots	68.0	0.2	136
	Residue	36.0	0.4	144
Sugarcane	Stalks	112.0	0.1	112
	Residue	50.0	0.2	100

[a] From Olson and Kurtz (1982) and Robertson and Rosswall (1986).

resistant soil organic matter fractions that turn over on the order of centuries or millennia (Juma and Paul, 1984; Paustian *et al.*, 1992).

Typically, exogenous nitrogen is supplied as anhydrous ammonia, urea, or some other form of synthetically fixed nitrogen (Jones, 1982; Neeteson, 1995), as organic nitrogen in the form of manure or waste sludge (e.g., Baldock and Musgrave, 1980), and/or as nitrogen biologically fixed either by the crop itself (in the case of a grain or forage legume) or by a preceding cover crop such as the winter annual *Vigna villosa* (e.g., Ebelhar *et al.*, 1984; Harris *et al.*, 1994). Some exogenous nitrogen also arrives in precipitation, though typically values are small (ca. 10 kg N ha^{-1} $year^{-1}$) relative to crop needs, as are amounts of N_2 fixed by associative and free-living N_2 fixers.

The amount of nitrogen removed in harvested biomass is also a function of the crop's nitrogen use efficiency (NUE). NUE is the efficiency with which carbon is fixed relative to available nitrogen. Operationally it is defined as plant tissue C:N ratio or plant nitrogen concentration: Plants with a higher C:N ratio (or lower N concentration) are more nitrogen efficient (cf. Chapter 2, this volume). In natural populations NUE appears to be a well-characterized response to a limited nitrogen supply. Evidence for this comes mainly from studies of noncultivated ecosystems in which it appears that nitrogen is used more efficiently—i.e., NUE is higher—where it is less available. Inferential evidence includes changes in litterfall C:N ratios along nitrogen availability gradients (e.g., Boerner, 1984; Birk and Vitousek, 1986). Experimental evidence dates from Turner's (1977) work showing increased C:N ratios in the litterfall of Douglas fir fertilized with sugar to immobilize available soil nitrogen and from Shaver and Melillo's (1984) work showing lower C:N ratios in marsh grasses following nitrogen fertilization.

In annual crops NUE shows similar trends: Nitrogen fertilization generally leads to lower whole plant C:N ratios as crop yield begins to fail to respond to added N above some near-saturating level. In Fig. 4, for example, the response of maize to added nitrogen was greatest between 0 and 112 kg ha $^{-1}$ N addition, falling to little or no additional response beyond 224 kg N ha^{-1} (Broadbent and Carlton, 1978). This means that for most crops nitrogen demands increase disproportionately with yield—in this case (Fig. 3) the final 20% yield increase required 50% more fertilizer N.

III. Matching Nitrogen Availability to Demand

A. Synchrony between Nitrogen Supply and Demand

Synchrony between nitrogen release from either SOM or fertilizer and the demand for nitrogen by plants is a critical component that controls

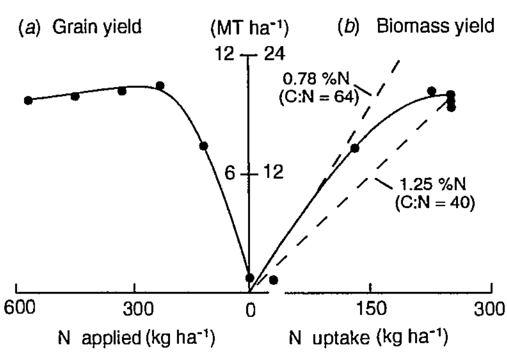

Figure 4 The response of corn (maize) to nitrogen fertilizer. (a) Grain yield response to fertilization rate; (b) total plant biomass as a function of nitrogen uptake. Dashed lines represent the minimum and maximum nitrogen use efficiencies, i.e., the amounts of biomass produced per kilogram N taken up at low and high fertilization rates. Data from Broadbent and Carlton (1978), after Loomis and Conner (1992).

systemwide nitrogen use efficiency and thus can strongly affect nutrient retention. In mixed-species native communities and in many cropped perennial systems there will be few times during the year when soil microbial activity does not coincide with periods of at least some plant uptake. In systems cropped to annual monocultures, on the other hand, this synchrony may be largely absent. Most grain crops, for example, are part of the ecosystem for only 12–16 weeks, and for only a few weeks of this period will biomass be accumulating at a significant rate. During the grand phase of vegetative growth of corn, for example, nitrogen can be taken up at the astonishing rate of 4 kg N ha^{-1} day^{-1}, but uptake is only sustained at this rate for 3 or 4 weeks and falls to nil within the following 2 or 3 weeks (Olson and Kurtz, 1982). This matches rather poorly the much longer periods during which soil temperature and moisture will be sufficient to support microbial activity. During these periods microbes continue to mineralize nitrogen from crop residue and other SOM pools, and this asynchrony can contribute to a large potential for nitrogen loss and a correspondingly low systemwide NUE (Fig. 5).

Asynchrony between nutrient supply and plant demand can in some cases be ameliorated by other attributes of the system. If, for example, soil water flux is low prior to plant growth, then not much nitrogen will be lost by leaching, and if denitrification is equally low then soil nitrate may remain available for crop uptake later. Likewise, if soil carbon remains available prior to plant growth, microbes may reduce nitrogen loss by immobilizing

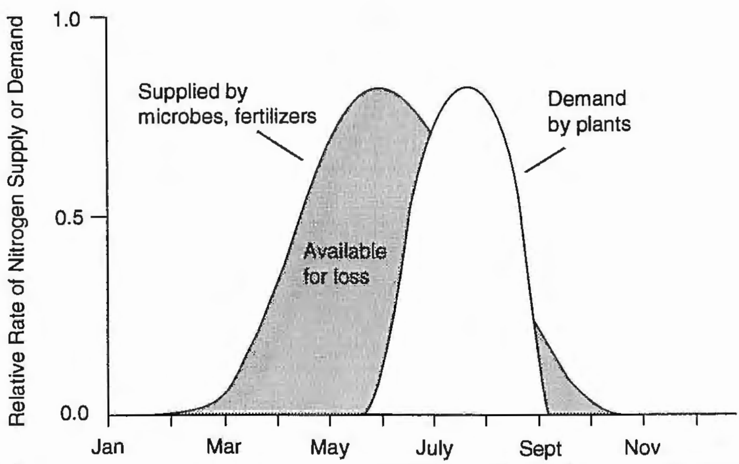

Figure 5 Asynchrony between nitrogen supply (from mineralized soil organic matter and fertilizers) and the demand for nitrogen by plants in a hypothetical north temperate annual cropping system. The shaded area represents the period during which the system is especially vulnerable to nitrogen loss via leaching and denitrification.

springtime nitrogen in microbial biomass, prior to releasing it later in the season as labile carbon stores are depleted.

Asynchrony can also be buffered by serial intercrops that temporarily immobilize nitrogen. In temperate regions winter annuals such as vetch (*Vigna* spp.) or some native weeds may be particularly well suited in this regard because they can begin growth in early fall prior to crop senescence, lay dormant over winter, then accumulate mineralized or newly fixed nitrogen rapidly prior to their killing before crop planting the following spring. If properly managed, the nitrogen accumulated should eventually be available to the crop during its 6- to 8-week growth phase (Harris *et al.*, 1994). Theoretically, as long as moisture conditions are favorable, this cover crop nitrogen could be available to the target crop within the same growing season: Nitrogen mineralization within a 25-cm-deep A horizon (with a bulk density as above) must sum to 1.3 mg g^{-1} day^{-1} N to meet crop nitrogen needs of 4–6 kg ha^{-1} day^{-1} during the target crop's period of grand vegetative growth (Olson and Kurtz, 1982). This rate of N mineralization is well within the range of mineralization rates for most forest and prairie soils of 1–4 mg g^{-1} day^{-1} N under favorable moisture and temperature conditions (e.g., Birch, 1960; Keeney, 1980; Robertson, 1982).

Other mechanisms might also be used to buffer asynchrony in specific systems. For example, many highly weathered tropical soils have a net positive charge (Uehara and Gillman, 1981) and this anion exchange capacity could temporarily retain mineralized nitrogen that might otherwise be lost as leached NO_3^- (Sollins *et al.*, 1988; Matson *et al.*, 1987). Nitrification inhibitors have been developed for a similar purpose—to protect mineralized nitrogen from leaching—and have been used with mixed success (Meisinger *et al.*, 1980). By and large, however, asynchrony in cropping systems has not been addressed in a comprehensive manner, and it deserves serious attention where system wide NUE is an important management goal.

B. Spatial Coincidence

Equal to the importance of ensuring that soil nitrogen availability and uptake are well synchronized is the concept of spatial symmetry—ensuring that N availability and uptake are well matched spatially. Management—particularly the management of row crops—does not necessarily result in a spatial arrangement of plants and resources within a field that are well matched, and a poor match will correspondingly reduce systemwide NUE.

The spatial variability of soil resources occurs at a number of scales, ranging from the sub-mm scale of the rhizosphere to the 10^3 km scale of regional landscapes (Robertson and Gross, 1994). From a local management perspective only two of these scales are relevant—variability associated with row spacing, i.e., row–interrow heterogeneity, and variability associated with field-scale heterogeneity, i.e., historical features of the landscape that can lead to an uneven distribution of soil resources across individual fields.

Row–interrow effects on nutrient availability have been recognized for decades (e.g., Linn and Doran, 1984; Klemedtsson *et al.,* 1987), and a number of management strategies take these differences into consideration to increase both water and nutrient use efficiencies of row crop systems. Such strategies range from drip irrigation in vegetable, citrus, and sugarcane to banding fertilizer and/or herbicides within crop rows. Placing fertilizer within crop rows, rather than broadcasting or injecting it indiscriminately, typically increases fertilizer use efficiency substantially (e.g., Malhi and Nyborg, 1985). Other techniques can also rearrange row–interrow nutrient availability. Ridge tillage, for example, an important soil management technique for many low-input farmers in the U.S. Midwest (NRC, 1989), is a tillage technique whereby spatial asymmetry is minimized by periodically mounding the between-row A_p horizon into semipermanent ridges into which the crop has been planted. This appears to effectively concentrate labile organic matter and soil biotic activity within the rows, achieving the same effect as fertilizer banding.

Spatial heterogeneity at larger scales is also emerging as a management issue. Evidence is accumulating to suggest that soil nitrogen availability is highly variable in natural communities, with variable patches of fertility—e.g., higher soil organic matter levels or higher rates of potential nitrogen mineralization—occurring within fields at scales that can affect individual plants (e.g., Robertson *et al.,* 1988; Hook *et al.,* 1991). One might expect conversion to agriculture to remove this patchiness where it is not related to landscape-level geomorphological features such as slope position, but this does not appear to be the case. Rather, long-term cultivation appears to simply attenuate and enlarge precultivation fertility patches (Robertson *et al.,* 1993), thus underscoring the persistence of biological legacies in even agricultural ecosystems (Franklin and Forman, 1987; Magnuson, 1990).

Whether the result of biological or geomorphologic processes, or—more likely—some combination of the two, field-scale soil variability (e.g., Fig. 6) appears to be a major feature of most cropping systems (Webster, 1985; Trangmar *et al.,* 1985; Aiken *et al.,* 1991; Dessaint *et al.,* 1991; Robertson *et al.,* 1997). This knowledge has led to the development of soil-specific crop management techniques (e.g., Mulla, 1993) that allow crop inputs to be applied at variable rates across individual fields. This approach holds great promise for better matching crop inputs to actual needs, and thus great promise for improving systemwide NUE. Consider, as a simple example, differences in plant productivity across a 100-ha corn field. It is likely—based on what we now know about spatial variability—that across perhaps 25% of the field maximum yields will be achieved with N inputs of 100 kg ha^{-1} N, across another 50% yields will respond to as much as 140 kg ha^{-1}

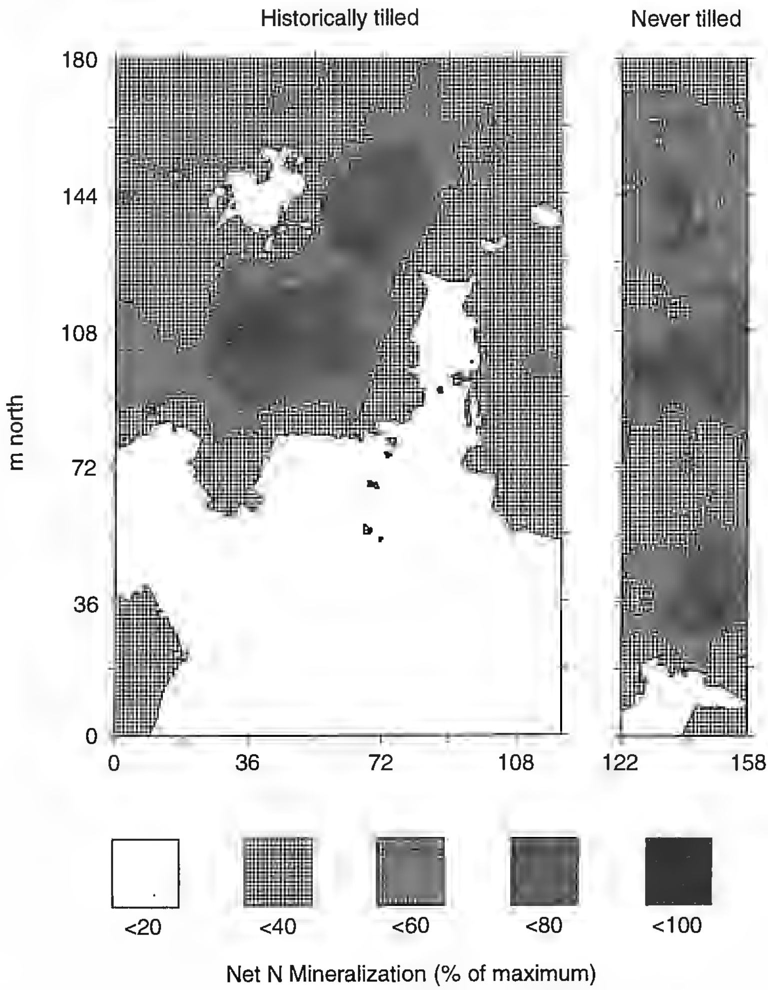

Figure 6 The variability of soil nitrogen availability (nitrogen mineralization potentials) across a 0.5-ha field cropped for decades in southwest Michigan. From Robertson *et al.* (1993).

N, and across the remaining patches of low fertility yields will respond to 180 kg ha^{-1} N. Standard management practices designed to maximize yield would proscribe fertilization for the lowest common denominator, i.e., as much as 180 kg ha^{-1} N across the entire field—despite the fact that only 25% of the field will respond to this level of fertilization. Over the remaining 75% of the field some 40–80 kg ha^{-1} N will be ignored by the crop and thus is highly likely to be lost. An agronomic approach that allows rates of fertilizer application across this field to vary by geographic position from 100 to 180 kg ha^{-1} N will substantially decrease the nitrogen available for total field loss. The direct economic benefit will likely be minor at least for the next decade or two—fertilizer is currently inexpensive and the cost of the technology required to implement site-specific farming practices is still prohibitive for most producers—but the environmental benefit could be substantial.

IV. Major Pathways of Nitrogen Loss from Cropping Systems

Nitrogen not removed in harvest is lost through three major pathways in most row-crop ecosystems: fire, leaching, and denitrification. Other pathways of loss can be important in specific systems or climates but are less important in general because of improved crop management practices. Nitrogen losses from erosion and runoff, for example, can still be high in some cropping systems but have been minimized elsewhere by the adoption of conservation tillage and sound residue management techniques. Protection from fire, leaching, and denitrification, however, appears to be more difficult to implement, though probably more often because of economic or management trade-offs than because of a lack of agronomic knowledge.

A. Fire

Fire has historically contributed to nitrogen losses in traditional bush-fallow rotation systems, and fire remains an important loss vector in many parts of the tropics. Robertson and Rosswall (1986), for example, estimated that in 1978 in West Africa, 5.5×10^9 kg N was lost annually from mainly mid-successional forests cleared for the crop phase of shifting cultivation. Annual residue burning during this phase and from continuous cultivation systems can also remove substantive amounts of nitrogen from the local system. In West Africa, ca. 253×10^6 kg N $year^{-1}$ was volatilized by fire from all annual crops in 1978, a value that is not far from the 870×10^6 kg N estimated to have been removed from these cropping systems in primary yield.

Burning losses from individual crops range widely owing to crop-specific management practices and residue nitrogen contents. Losses from West African sorghum summed to 43×10^6 kg N with 152×10^6 kg N removed in yield, whereas burning losses from cassava were less than 0.1×10^6 vs. 43×10^6 kg N removed in yield. Even in developed economies with fully mechanized agriculture, residue burning remains a conventional agronomic practice in specific situations, usually for pathogen control. For example, in South Australia and Kansas burning is used to control take-all disease in continuous wheat rotations, and in Texas and California it has been common to burn lowland rice residue.

B. Leaching

Nitrogen losses to leaching are important in all cropping systems in which precipitation exceeds actual evapotranspiration (AET), i.e., in all systems with water flow through the solum. In semiarid cropping systems leaching may thus occur only rarely, and this may also be the case in more humid regions during the growing season—in the northern United States, for example, growing season AET is often sufficient to keep most rainwater from percolating through the soil profile and thus sufficient to keep leachable nitrogen within the rooting zone (e.g., Allison, 1973). Outside of the growing season, however, when AET is low relative to precipitation and when precipitation remains moderately high (ca. 75 mm $month^{-1}$), leaching losses can be high (e.g., Chichester, 1977). This can be especially true in the fall and spring when soil nitrate pools are also moderately high (ca. 5–10 μg N g $soil^{-1}$) from a combination of low plant uptake and the ongoing mineralization of soil organic matter nitrogen while soil temperatures and moisture are sufficient to support microbial activity.

Actual amounts of nitrogen leached from the pool of available nitrate (NO_3^-) are a complex function of the amount of water that moves through the profile and its path and residence time—controlled largely by the soil's pore geometry and aggregate structure. Water that moves quickly through a profile may do so primarily through macropores and may thus pick up very little of the nitrate in smaller pores and inside soil aggregates (e.g., Thomas and Phillips, 1979; Helling and Gish, 1991; Smucker *et al.,* 1995). Slower moving wetting fronts may, on the other hand, spend sufficient time in the profile to equilibrate with micropore and intraaggregate spaces that may contain high concentrations of nitrate from high rates of microbial activity and prior protection from the fast-moving wetting fronts. These slower-moving fronts may thus leach proportionately more nitrogen from the system.

There is a large body of literature regarding nitrogen leaching at the plot, field, and landscape scales, mostly dating from the 1970s when health concerns caught up with widespread fertilizer use (see reviews in Singh and Sekhon, 1979; Burden, 1982; Keeney, 1982; Legg and Meisinger, 1982; Magee, 1982; Hallberg, 1989). In general, reported studies have delineated many of the important interrelationships among the matrix of factors that regulate leaching—climate, soil, crop, agronomic management practices, and landscape position—and have fueled the development of quantitative models for predicting leaching losses from cropped ecosystems in general (e.g., Godwin and Jones, 1992; Tanji and Nour el Din, 1992; Paustian *et al.,* 1992). Many of these models do an excellent job of predicting leaching losses under specific conditions, but it is clear from their performance under other conditions and in other systems that our understanding of leaching losses at the ecosystem level is still incomplete.

C. Denitrification

Denitrification is the conversion of soil nitrate to the nitrogen gases N_2O and N_2 by a diverse array of bacteria that use nitrate as a terminal electron acceptor in the absence of oxygen. The importance of this process as a pathway of N loss in upland cropping systems is evident primarily from mass balance studies, in which denitrification is assumed to equal the difference between known inputs and harvest plus leaching outputs (e.g., Allison, 1953; Frissel, 1977; Legg and Meisinger, 1982; Paustian *et al.*, 1990). Not until the development of a technique for studying *in situ* denitrification directly—using acetylene to block N_2O reductase (Yoshinari *et al.*, 1977)—was the importance of this pathway fully appreciated. Various studies have since proceeded to confirm the magnitude of losses estimated from mass balance approaches and to identify the mechanisms whereby denitrification can be active even in well-drained soils.

It is now well accepted that denitrification can occur wherever available carbon, nitrate, and low oxygen concentrations co-occur—in aggregates (e.g., Sexstone *et al.*, 1985a), soil organic matter particles (e.g., Parkin, 1987), and in bulk soil following precipitation events. Cultivation can further favor denitrification via its effects on soil bulk density, infiltration rates, and soluble C levels. Field estimates of denitrification rates range from nil to >100 kg N ha^{-1} $year^{-1}$ in different upland cropping systems (von Rheinbaben, 1990; Aulakh *et al.*, 1992; Peoples *et al.*, 1995), a range similar to that of leaching losses. In general, annual rates appear to be on the order of 20–50 kg N ha^{-1} $year^{-1}$. As a proportion of total N loss, the importance of denitrification relative to leaching losses appears to range from no leaching with moderate denitrification, denitrification and leaching about equal, to moderate leaching with no denitrification (e.g., Jones *et al.*, 1977; Winteringham, 1980).

Part of the difficulty of measuring—and therefore of understanding—denitrification sufficiently well to accurately model the process at a field scale is related to denitrification's high spatial (e.g., Folorunso and Rolston, 1984; Robertson *et al.*, 1988) and temporal (e.g., Sexstone *et al.*, 1985b; Parsons *et al.*, 1991) variability in most ecosystems. Perhaps because of this variability, minimizing denitrification losses has not been a specific target of management techniques to date except in lowland rice production, where denitrification is known to represent a very high proportion of nitrogen loss.

V. Management to Maximize Nitrogen Use in Row-Crop Ecosystems

Strategies to maximize nitrogen use in row-crop ecosystems must necessarily concentrate on nitrogen retention. For some cropping systems—in particular for low-yield or low-fertility systems—our understanding of the processes involved and their major field-level controls is probably sufficient to allow the design of nitrogen-efficient rotations. This is not the case for most high-yield systems, however, in which an enormous amount of nitrogen is made available to the crop over a very short-term period of rapid growth. In these systems, making 100–200 kg N ha^{-1} available over a 6- to 8-week period without saturating the system with excess nitrogen remains a substantial challenge.

The principle barriers to efficient nitrogen use in high-yield cropping systems are both economic and scientific. From a scientific standpoint, we lack basic knowledge of the ecological interactions in soil that regulate the seasonal timing of nitrogen release from organic matter. We also lack knowledge about the field-level controls on important pathways of loss—notably about controls on denitrification and leaching, and in particular on ways in which they interact.

From an agronomic standpoint, in some cases minimizing nitrogen loss will be easy and relatively inexpensive. Devising for tropical regions a means for residue control other than burning can save as much as a third of the nitrogen typically removed in grain yields for many crops. The emerging adoption of new technology that allows crop inputs to be applied differentially across individual fields can help to better match crop demands for nitrogen with the supply of fertilizer N, thereby reducing excess application. On the other hand, devising a cover crop or residue management strategy that can help to synchronize soil nitrogen availability with nitrogen release from soil organic matter may first require the basic ecological knowledge noted previously.

In many regions, however, the implementation of nitrogen-efficient cropping practices may ultimately depend on economic factors. Until the cost of nitrogen fertilizer increases, or until the environmental costs that are now externalized are made more direct, there may be little incentive for growers to adopt nitrogen conservation strategies that require additional expense or the management of additional information.

To summarize, agronomists today have many strategies at their disposal for designing nitrogen-efficient cropping systems, and, with the development of new knowledge about ecological interactions in cropping systems, will have additional strategies in the coming years. The implementation of these strategies will not be cost-free, however, and may require marketplace and societal pressures in order to be enacted.

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