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A review

Can the synchrony of nitrogen supply and crop demand be improved in legume and fertilizer-based agroecosystems? A review

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Abstract

Asynchrony between nitrogen (N) supply and crop demand is the source of many environmental hazards associated with excess N in the biosphere. In this review, we explore some of the complexity of the synchrony issue in agroecosystems that obtain N via legume rotations or synthetic fertilizers. Studies that have simultaneously compared the fate of both sources of N suggest that in rainfed agricultures, crops recover more N from fertilizer, but a higher proportion of the legume N is retained in the soil and N losses tend not to differ greatly from either source. However, investigations from irrigated cropping systems indicate that legume N is generally less susceptible to loss processes than fertilizers. Such general conclusions need to be qualified by acknowledging that not all comparative studies have used 'best management practices' when applying the fertilizer or legume residues. When information-intensive management approaches are used, fertilizer-based systems can potentially out-perform the synchrony achieved by legume-based rotations. We suggest that the inclusion of perennials in cropping systems may hold the greatest promise for decreasing the risk of N losses in future farming systems.

Introduction

Humans have approximately doubled the rate at which nitrogen (N) is entering the earth's ecosystems compared to pre-industrial times (Vitousek et al. 1997; Smil 2001). The most important sources of anthropogenic N are synthetic fertilizers and biological N_2 fixation by legumes (Vitousek et al. 1997; Boyer et al. 2004). The relative importance of these two N sources varies greatly by region, and is related to a range of socio-economic factors including population density and patterns of land use. However, when considering N inputs to agricultural lands, applications of fertilizer N

dominate legume sources in Asia, Europe, and North America, but biological N_2 fixation exceeds synthetic fertilizer inputs in Latin America, Africa and Oceania (Table 1). These inputs of N are crucial in supplementing the capacity of soils to provide sufficient N to satisfy the 40–190 kg N ha^{-1} harvested annually in the major food crops (Table 2, Smil 2001).

Unfortunately, only a fraction of the fertilizer of legume N applied to crops is recovered by plants under current farming practices (Fillery 2001; Balasubramanian et al. 2004). Some of the inefficiencies in uptake can be attributed to the volatile and mobile nature of N. It is easily

Table 1. Regional differences in the annual inputs of N into agroecosytems via biological N_2 fixation by legumes or from fertilizer N[a].

Region	Biological N_2 fixation (Tg N year^1)[b]	Fertilizer N (Tg N year^1)
Asia	23	44
Europe	6	14
North America	10	13
Latin America	8	5
Africa	3	2
Oceania	5	1
Global total	55	79

[a]Adapted from data presented by Boyer et al. (2004).
[b]Data have been adjusted to include estimates of inputs of fixed N associated with legume nodules and roots (Rochester et al. 1998). Includes detailed national estimates for Australia in the Oceania region (Crews and Peoples 2004).

Table 2. The amounts of N typically harvested each year in important food crops.

Crop	N removed in produce (kg N t^1)[a]	Yield per crop (t ha^1)[b]	Annual N removed (kg N ha^1)
Wheat (*Triticum aestivum*)	20	2–8	40–160
Corn (*Zea mays*)	15	3–8	45–120
Rice (*Oryza sativa*)	12	3–8	70–190[c]
Potato (*Solanum tuberosum*)	4	12–36	50–145

[a]Calculated from data presented by Peoples et al. (1995b) and Lægreid et al. (1999).
[b]Range of average yields for different regions of the world reported in Lægreid et al. (1999).
[c]Commonly two crops of rice are grown each year.

transformed among various reduced and oxidized forms and is readily distributed by hydrologic and atmospheric transport processes. Nitrogen can be lost from the site of application in farmers' fields through soil erosion, runoff, leaching of nitrate (NO_3^-) or dissolved forms of organic N, or via gaseous emissions to the atmosphere in the form of ammonia (NH_3), nitrogen oxides (NO and NO_2), nitrous oxide (N_2O), or dinitrogen (N_2) (Goulding 2004). All these avenues of loss, with the important exception of N_2, can potentially impact one or more environmental hazards, and/or have important implications for human health (Crews and Peoples 2004; Peoples et al. 2004).

The environmental hazards associated with N in agroecosystems stem from various specific microbial N transformations in soils as well as the behavior of mineral N in relation to soil physio-chemical properties (Peoples et al. 1995a). However, the central concept that defines the relationship between the N that feeds us and the N that harms the environment is 'synchrony'. That is, the extent to which the rates of N supply to crops match rates of crop demand for N (Campbell et al. 1995; Robertson 1997). It is when crop demand for N and N supply (via fertilizer applications or organic matter mineralization) do not synchronize, that N has the potential to accumulate in soils and is then susceptible to various loss pathways (Goulding 2004; Peoples et al. 2004).

We have argued elsewhere (Crews and Peoples 2004) that it is not only desirable, but possible in some countries to reduce the reliance on synthetic N fertilizers and move towards greater use of legumes to supply N for food production. Our review suggested that, on balance, legume-based farming systems were likely to be more sustainable than fertilizer-based systems. In the current paper, we explore some of the key factors influencing the synchrony of N supply and demand in fertilized and legume-based farming systems, and examine possible strategies that may result in greater efficiencies in N management and use in agroecosystems, and reduce N-related environmental problems.

Synchrony defined

Swift (1984) originally proposed the concept of synchrony to describe the linking of nutrient demand with nutrient release from mineralization of organic matter. However, we will use the broader definition described by Myers et al. (1994, 1997) which includes nutrient inputs from other sources such as commercial fertilizers. With the concept of synchrony defined as a close balance between nutrient supply and demand, there is the potential for two types of asynchrony. One occurs when nutrient availability exceed, plant requirements, often because release occurs at a time when plant demand is restricted or non-existent, as in winter or early spring in temperate annual cropping systems. The second occurs when nutrient supply is insufficient to meet plant needs at certain times (Myers et al. 1994). We will refer to these as 'excess-asynchrony' and 'insufficient-asynchrony', respectively.

Essentially all of the environmental hazards associated with N in cropping systems are the result of excess-asynchrony. When inorganic/mineral N (ammonium and nitrate) is allowed to accumulate in a soil – which by definition implies that supply > crop or microbial demand – the N is vulnerable to loss particularly in the presence of surplus soil water (Peoples et al. 2004). When water inputs into the soil system exceed even short-term evapotranspiration demands, the surplus water can result in losses of nitrate through leaching and/or denitrification (Craswell and Godwin 1984; Peoples et al. 1995a). This is true whether the N originates from fertilizer or organic sources.

Temporal patterns of soil N availability and crop N use can differ substantially from tropical to temperate regions and across climatic zones, but potential for asynchrony (i.e. when the accumulation of soil mineral N *and* precipitation > crop demand) appears to exist in most ecosystems, as we will explore below. Implicit in the desire for greater synchrony between crop demand and N supply is the recognition for the need to enhance the efficiency of use of both the inputs of applied N and indigenous N derived from soil (Dobermann and Cassman 2004).

Synchrony in legume-based systems

A high level of synchrony between N release from legume residues and crop N uptake might seem probable given that the same general environmental factors – temperature and moisture – regulate processes of decomposition as well as net primary productivity and thus nutrient demand (Rosenwig 1968; Myers et al. 1994). However, in practice, the pathways by which plant-available forms of N are released from legume organic residues and taken up by a subsequent crop can be complex.

While annual legume rotations often have a flush of N mineralization from residues, the rate of accumulation of inorganic N in soils does not normally match that caused by conventional fertilizer applications (Groffman et al. 1987; Campbell et al. 1995; Robertson et al. 2000). The decomposition and mineralization of legume proteins in organic residues into inorganic forms is a microbial-mediated process with the breakdown of

organic compounds being used to provide the soil microbes with a carbon (C) source for respiration and growth (Fillery 2001). Much of the simple organic N released is rapidly assimilated (immobilized) by the soil microbial population. Inorganic N only accumulates in soil if the amounts of N released from the organic residues exceed the C-limited microbial requirement for N for growth. Since legume residues tend to have a relatively high N content and a low C:N ratio they are usually expected to result in net mineralization (Kumar and Goh 2000). However, a range of other constituents (e.g. lignin, polyphenols, soluble C and N compounds) also influence microbial activity and mineralization, and predictions based simply on the basis of the %N or C:N ratio of legume tissues can be misleading (e.g. Thomas and Asakawa 1993; Palm et al. 2001a; Bolger et al. 2003).

Estimates of N release from legume residues for crop uptake are typically made in one of three ways: (1) measuring (usually by subtraction) N released from decomposing substrates (e.g. Frankenberger and Abdelmagid 1985; Ibewiro et al. 2000), (2) N-difference method where available N in soils or N uptake by crops following legume incorporation is compared with control plots that received no legume residues (e.g. Sarrantonio and Scott 1988; Baggs et al. 2000), and (3) measuring the fate of ^{15}N in crops and soils that originated from labeled legume materials (Jensen 1994; Glasener et al. 2002; references cited in Table 3). Method (1) is useful for understanding and manipulating cover crop tissue quality to achieve greater synchrony. It cannot be used to estimate N synchrony itself, however, because only N release, not N uptake, is measured. Method (2) is the most useful for evaluating the agronomic utility of a particular cover crop rotation, and can be used to interpret N synchrony in a legume-based system when the rotation has been followed long enough to reach an equilibrium in soil organic matter dynamics (e.g. Cassman et al. 1996).

The third method involving the application of ^{15}N labeled legume residues offers the most detailed short-term assessment of N behavior in the soil/crop continuum. Such studies indicate that between 10 and 30% of the legume N is commonly taken up by the subsequent crop (Table 3, Giller and Cadisch 1995; Peoples et al. 1995b; Fillery 2001). The relatively low recovery of legume

Table 3. Examples of the fate of ^{15}N-labeled fertilizers or legume residues applied to field experiments in different regions of the world.

Crop and system	N source	Region	N added (kg ha^1)	Time from N application to sowing	Time from N application to harvest	%N in crop	%N in soil	%N lost[a]	References
Rainfed									
Upland rice	Urea	Indonesia	30 + 30	0	115d	19	–	–	Sisworo et al. (1990)
	Cowpea		33	0	115d	28	–	–	
Corn/barley	(NH$_4$)$_2$SO$_4$	USA	124	5.5 months	14.5 months	51	19	30	Harris et al. (1994)
	Red clover		165	5.5 months	14.5 months	17	57	25	
Corn	Urea	Nigeria	–	–	–	27	15[b]	58	Vanlauwe et al. (2001)
	Leucaena		–	–	–	9	56[b]	35	Vanlauwe et al. (1998)
Corn (alley crop)	Urea	Indonesia	60	1 month	70 days	22 (11)[c]	33	34	Rowe et al. (2004a, b)
	Gliricidia		178	1 month	70 days	6 (9)[c]	58	27	
Wheat	(NH$_4$)$_2$SO$_4$	Canada (3 sites/2 years)	50	0	~5 months	29–44	28–30	28–41	Janzen et al. (1990)
	(NH$_4$)$_2$SO$_4$		50	~9 months	13–14 months	16–33	33–38	29–51	
	Lathyrus		76	~9 months	13–14 months	9–26	37–48	26–54	
	Lentil		85	~9 months	13–14 months	12–27	48–59	14–40	
Wheat	Urea/KNO$_3$/ (NH$_4$)$_2$SO$_4$	Australia	50	0	~8 months	46–50	31–34	16–21	Ladd and Amato (1986)
	Medic		39	7 months	~15 months	19	66	15	
Barley	NH$_4$NO$_3$	Sweden	80	0	3 months	36	–	–[d]	Bergström and Kirchmann (2004)
	Red clover		160	0	3 months	15	–	–[d]	
Mean	Fertilizer					36	31	33	
	Legume					18	58	24	
Irrigated									
Lowland rice	Urea	Phillipines	60 + 30	1 day	95 days	42	19	39	Diekmann et al. (1993)
	Sesbania rostrata		90	1 day	95 days	49	44	7	
	Aeschynomene afraspera		90	1 day	95 days	47	40	13	
Lowland rice	Urea	Phillipines	30 + 30	1 day/?	–	27	38	35	Becker et al. (1994)
	Sesbania rostrata		60	1 day	–	31	59	10	
Cotton	Urea	Australia	100	9 months	14 months	17[e]		83	Rochester et al. (2001a)
	Faba bean		100	9 months	14 months	62[e]		38	
	Field pea		100	9 months	14 months	80[e]		20	
Cotton	Urea	Australia	100	5–6 months	10–11 months	4[e]		96	Rochester et al. 2001a
	Soybean		100	5–6 months	10–11 months	66[e]		36	
	Lablab		100	5–6 months	l0–11 months	82[e]		38	
Mean	Fertilizer					37[e]		63	
	Legume					80[e]		20	

[a]Calculated by difference: % applied N assumed lost = 100–(% ^{15}N applied recovered in crop + % ^{15}N applied recovered in soil).
[b]Recovery of ^{15}N refers only to the top 10 cm of soil so is likely to be an underestimate of the total amount of fertilizer of legume N remaining.
[c]Values in parentheses indicate uptake of applied N by the Gliricidia hedgerows growing either side of the corn alley crop.
[d]N leached below the root zone represented 2% of the fertilizer N applied and 5% of the red clover green manure N.
[e]Value includes both plant uptake and labeled N remaining in soil.

Table 4. Comparison of measured agronomic N benefits from including a legume in a rotation with wheat with ^{15}N-based estimates of wheat uptake of legume-N[a].

Parameter	Cropping sequence	
	Faba bean–Wheat	Barley–Wheat
Residue N remaining from faba bean (kg N ha^{-1})	96	–
Wheat N at maturity (kg N ha^{-1})	97	59
Wheat N benefit from legume (kg N ha^{-1})	38[b]	
Non-isotopic estimate of recovery of legume N (%)	40[c]	
[15]N-based estimate of recovery of legume N (%)	10[d]	

[a]Adapted from data of Khan (2000).
[b]Calculated as: (wheat N after faba bean)−(wheat N after barley) = 97−59.
[c]Calculated as: 100 × (wheat N benefit)/(faba bean residue N) = 100 × (38/96).
[d]Calculated from recovery of the legume derived ^{15}N present in the wheat crop.

residue N by subsequent crops, particularly in temperate regions, has led some to suggest that legumes are an inefficient source of N (Hesterman et al. 1987; Harris et al. 1994). However, in studies that compared yields of crops grown on legume vs. fertilizer sources of N, the yields achieved were often similar (Ladd and Amato 1986; Janzen et al. 1990; Harris et al. 1994). Thus, studies that estimate uptake efficiencies of labeled N from recently applied legume residues have a tendency to underestimate the overall N-supplying capacity of a legume-based system. This is a result of N 'pool substitution' whereby the newly applied ^{15}N-labeled legume N is immobilized in the microbial biomass and unlabeled N is mineralized. Microbial immobilization and pool substitution are generally more pronounced where N inputs are supplied via organic sources such as in legume-based systems than from fertilizers because the N in the legume residues is accompanied by large amounts of C substrates (Varco et al. 1993). The importance of pool substitution was illustrated by Murphy et al. (1998) in a ^{15}N isotope dilution experiment in Western Australia. In the second year of a lupin (*Lupinus angustifolius*)–wheat rotation, they found gross N mineralization in the top 10 cm of soil to be 120 kg N ha^{-1}, and net N mineralization (i.e. gross mineralization–immobilization) to be 59 kg N ha^{-1}; 69% of which (41 N kg) originated the soil microbial pool. These data suggest that most of N initially released from lupin residues was immobilized and thus not immediately accessible to the wheat crop, but mineralization of older (unlabeled) microbial-N occurred, which subsequently became available for crop uptake. As a result, calculations based on crop recovery of ^{15}N-labeled leguminous material can be somewhat lower than 'agronomic' determinations of net N benefits from including a legume in a rotation (e.g. Table 4).

In addition to pool substitution, interpretation of data such as those presented in Table 4 may be further confounded by possibly a greater degree of immobilization of mineral N by the high C:N cereal or grass residues (such as the remaining barley stubble in the barley (*Hordeum vulgare*) – wheat sequence (Table 4), than by legume residues with lower C:N ratios (Green and Blackmer 1995; Peoples and Baldock 2001).

Synchrony in fertilizer-based systems

As the adoption of synthetic fertilizers in the second half of the 20th century became widespread, so to did the occurrence of excess-asynchrony in agriculture. Interestingly, this asynchrony has been the inadvertent result of farmers trying to avoid periods of insufficient-asynchrony. Almost universally, pre-industrial and modern-day traditional farmers have struggled to avoid or reduce periods of N deficiency that can reduce crop yields. These farmers have been challenged in their management practices largely because of their limited abilities to control the complex abiotic and biotic conditions that govern mineralization and thus nutrient supply from legume residues, manures and other organic materials (Giller et al. 2002).

The advent and mass production of synthetic fertilizers gave farmers unprecedented control over the supply of N to crops (Smil 2001). For the first time, it was consistently possible to assure that

potential crop yields would not be constrained by an insufficient supply of N. Widespread use of N fertilizers was only possible because they were affordable. Nitrogenous fertilizers have been relatively inexpensive in parts of Asia, Europe and North America. In part their affordability was tied to the low costs of the fossil fuels (especially natural gas) that are used in their production. Indeed, the price of urea fell from \$310 to \$155 t^{-1} in real US dollars during the 1980s (Smil 2001). Whether low prices will continue in light of the recent volatility and record high prices for fossil fuels and what impact increased fertilizer prices might have on future trends in fertilizer availability and use is open to speculation.

Patterns of fertilizer use have already begun to change in various countries around the world where government policy and legislation either restricts the amounts that can be applied to agricultural lands, or encourages more environmentally friendly farming practices (Palm et al. 2004). However, nutrient uptake efficiency has generally been only a minor consideration in the past (Mosier et al. 2001). The low cost of N fertilizers generally led farmers to apply them at rates calculated to maximize productivity. This commonly included additional 'insurance N' in excess of the required amount to guarantee no loss of yield or income (Dobermann and Cassman 2004). Indeed, in the case of valuable cash crops, farmers have often used excessive amounts of fertilizer because of the high economic returns, and standard farming practices have resulted in substantial N losses (e.g. Tripathi et al. 1997). In such situations many farmers could increase N use efficiencies and reduce environmental problems simply by applying less N (Dobermann and Cassman 2004).

Estimates of N synchrony, N use efficiencies and N losses involving fertilizer applications are commonly made by either: (1) following the fate of ^{15}N-labeled fertilizer (Table 3, Strong 1995), (2) using N-balance calculations (e.g. Tripathi et al. 1997), or (3) N-difference methodologies (Cassman et al. 2002). While a smaller percentage of ^{15}N-labeled fertilizer tends to be immobilized and remain in soil compared to legume residue-N (Table 3), microbial pool substitution does confound short-term assessments of synchrony using ^{15}N (Reddy and Reddy 1993; Strong 1995). Estimates of apparent N use efficiencies and N losses using N-balance calculations are usually derived

from comparisons of the amount of fertilizer N applied with the amounts of N either removed in the harvested products or remaining in crop residues and measurements of any net changes between pre-sowing and post-harvest concentrations of soil mineral N. Unfortunately, such simple calculations appear to ignore the contributions of N mineralized from soil organic matter during crop growth (Angus et al. 1998) They are also incapable of differentiating between soil- and fertilizer-derived N or between the immobilization and loss of inorganic N. The N-difference method is preferred for undertaking synchrony estimates over a multiple year time-frame, provided that soil organic matter dynamics in the study plots are near steady state (i.e. N mineralization and immobilization are in equilibrium).

The N-difference method has been used to calculate N fertilizer uptake efficiencies from data collected from farmer fields and suggest fertilizer recoveries of between 18–49% for wheat in India, 30–40% for rice in Asia, and 37% for corn in North-Central US (Cassman et al. 2002; Dobermann et al. 2002). These on-farm determinations are generally comparable to estimates of grain fertilizer N recoveries derived from either N-difference or ^{15}N-based approaches averaged across many research studies conducted across all regions of the world (wheat: 37–39%, rice: 32–36%, corn: 37–38%, Krupnik et al. 2004). However, it should be acknowledged that such average values disguise a wide range of fertilizer recoveries (5–96%) for individual studies and locations (Balasubramanian et al. 2004; Krupnik et al. 2004).

Comparing fertilizer and legume-based systems

Various investigations have indicated general similarities between fertilizer and legume N in so much as the efficiency of N uptake generally decreases for both sources of N as the amounts of N applied increases (Cassman et al. 2002). The question of whether a fertilizer- or a legume-based approach has a higher potential of achieving synchrony between crop N demands and nutrient supply and/or is less susceptible to losses is not straightforward. Unfortunately there are only a limited number of studies where legume and fertilizer sources of N have been directly com-

pared. These investigations have generally used [15]N- labeled inputs which allows direct measurement of plant uptake and soil retention of the applied N, and provides indirect information about losses based on the amount of the applied ^{15}N not recovered in either the plant or soil. Collectively these studies suggest that in the first year following application, rainfed (dry land) crops tend to recover more applied N from fertilizer than from legume residues, but a higher proportion of the applied legume N generally remains in the soil at harvest (Table 3). As a consequence, estimates of losses from legume N in rainfed agriculture are usually either slightly lower than, or similar to, fertilizers (Table 3, Peoples et al. 2004). The limited data available for lowland rice and irrigated systems, on the other hand, indicate that crop recoveries of N from high quality, green manure residues can be similar to fertilizers (Table 3), but losses from fertilizer N are usually substantially higher than from legume sources (see also Becker and Ladha 1995, who calculated mean losses of N for 10 studies in lowland rice systems to be 14% of the legume green manure N applied compared to 35% for urea). These general conclusions about the relative use and losses of legume and fertilizer N should be qualified by acknowledging that: (1) it is not clear how many of the comparative studies summarized in Table 3 have used 'best management practices' when applying the fertilizer or legume residues, and (2) often the ^{15}N-labeled legume inputs represented only shoot material, which ignores the potentially large contributions of below-ground N in legume-based rotations associated with, or derived from, roots and nodules (Rochester et al. 1998; Fillery 2001).

A wide range of studies in both the tropics and temperate environments suggest that crops commonly recover 30–50% of the fertilizer N applied (Strong 1995; Cassman et al. 2002; Balasubramanian et al. 2004; Krupnik et al. 2004) and < 25–30% of the N present in leguminous material unless it is applied as high quality green manured residues (Table 3, Giller and Cadisch 1995; Peoples et al. 1995b; Fillery 2001). If it is assumed that similar efficiencies prevail in crop recovery of native soil inorganic N to those observed for fertilizer N then that implies that total pools of plant-available N equivalent to at least 100–450 kg N ha^{-1} must be derived each year from the mineralization of soil organic matter and legume residues, or supplied by fertilizer to achieve the current amounts of N typically harvested in crop produce (Table 2).

It seems that there may be an inherent conflict in trying to avoid both excess and insufficient asynchronies. There is evidence from both legume-based (Becker and Ladha 1997; Rochester et al. 2001a) as well as fertilizer-based systems (Sylvester-Bradley 1993; Cassman et al. 1996; Dobermann and Cassman 2004) that crop yields respond to increases in N in a curvilinear fashion. In other words, a proportionately greater amount of N is required per kg product as the yield maximum is approached. Sylvester-Bradley (1993) reported that an 8-tonne ha^{-1} winter wheat grain yield required 50% more N fertilizer than a 7.5-tonne ha^{-1} yield, demonstrating a strong diminishing return in fertilizer uptake efficiency as the maximum yield was approached. Becker and Ladha (1997) reported that when they attempted to manage N supply to closely synchronize rice N demands using urea or green manuring the legume sesbania (Sesbania rostrata), grain yields fell short of their potential. Elevated levels of soil N may initiate a priming effect, or simply reduce the root:shoot ratio of the crop, but regardless of the mechanism, the large pools of available soil mineral N that appear to be required to attain current annual crop yields are vulnerable since N losses increase in proportion to the amount of available N present in the soil profile (Dobermann and Cassman 2004).

If the strategy to increase nutrient synchrony shifts from one of reducing periods of nutrient deficiency to reducing periods of excess nutrient availability, then there is some reason to believe that conventionally-managed legume-based systems could achieve greater N synchrony than conventionally-managed fertilizer-based systems – at least in areas with a high potential of leaching or denitrification. Sisworo et al. (1990) undertook a two-year experiment where uptake of ^{15}N-labeled urea and crop residue-N were measured in successional crops over two cycles of a rice–soybean (Glycine max)–cowpea (Vigna unguiculata) rotation and a rice–corn–cowpea rotation. The first rice crop following applications of labeled urea and cowpea crop residues recovered 19 and 28%, respectively, of the ^{15}N applied (Table 3). Urea ^{15}N was recovered in two subsequent crops – soybean and cowpea – bringing the total urea-N

recovery to 23% of the initial 60 kg N applied. The ^{15}N from cowpea residues was recovered in the five subsequent crops following rice bringing the total cowpea residue–[15]N recovery to 73% of the initial 33 kg N applied. They found similar relative recoveries from fertilizer vs. legume N sources over 2 years in the rice–corn–cowpea rotation (Sisworo et al. 1990). Other studies with lowland rice, or in irrigated cropping systems (Table 3) have also shown greater plant recovery of N and/or lower total N losses from legume-based compared to fertilizer-based systems (Table 3, Becker and Ladha 1995; Peoples et al. 1995b).

The results form these studies contrast with findings from one of the longest-running investigations undertaken in lowland rice to date. Cassman et al. (1996) compared N uptake efficiencies and yields on 19–22 consecutive rice crops, across two urea fertilizer treatments, residue treatments from two N_2-fixing plant species (the aquatic fern azolla (*Azolla* spp.), and sesbania) as well as rice straw and combinations of primary treatments. All fertilizer and plant amendments were calculated to deliver equivalent amounts of N. In contrast to the short-term experiments designed to follow the fate of ^{15}N-labeled fertilizer or residue additions, the experimental plots used by Cassman et al. (1996) most likely reached equilibrium in regards to N; that is, rates of net N mineralization approximated net N immobilization.

In the final year of their experiment Cassman et al. (1996) found yields to be greatest in the super granule urea treatment at the two study sites. Yields in the prilled urea treatments were second greatest at one site and tied for second with azolla green manure at the other. Sesbania treatments were only established at one study site, and yields were statistically equivalent to azolla-plot yields. These results are consistent with greater synchrony in the fertilizer-based systems. However, it is interesting to note that data collected across a wide range of studies indicate that green manure N is used more efficiently by lowland rice than urea at application rates < 80 kg N ha^{-1}, but the % uptake of legume N declines more rapidly than for fertilizer when rates exceed 100 kg N ha^{-1} (Becker and Ladha 1995).

The period of potential greatest asynchrony and therefore periods of greatest risk of N loss in fertilized systems occurs after fertilization early in the
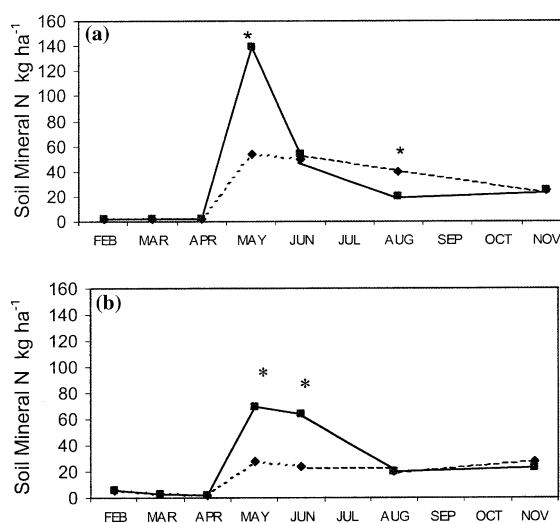

Figure 1. Soil mineral N (NH_4^+-N plus NO_3^--N) over 0–21 cm from fertilizer (square symbols, solid lines) or clover residues (diamond symbols, dashed lines) under (a) conventional and (b) no-tillage systems. The symbol* indicates significance at $p = 0.05$. Adapted from Groffman et al. (1987).

growing season when levels of soil available N far exceed the crop's capacity to utilize it. This window of asynchrony is exemplified by data from Groffman et al. (1987) who compared soil mineral N concentrations in a Georgia US soil following fertilization with either a single application of ammonium nitrate or incorporation of a clover covercrop (Figure 1). Levels of soil available N from legume mineralization also increased early in the growing season, but substantial amounts of N remain either immobilized or in undecomposed residues.

The window of time when asynchrony appears to be greatest in legume-based systems is when a fallow period follows a legume plow-down or crop harvest (Campbell et al. 1994; Jensen 1994). This pattern was apparent in data presented by Harris et al. (1994) where losses of N (^{15}N-labeled) from legume residues were 43–51% lower than losses of labeled fertilizer-N at the end of a corn-growing season. However, following a winter fallow and a subsequent barley crop, losses of legume N had increased to 82–84% of the N losses measure from the fertilizer plots.

While off-season fallows may represent the window of greatest asynchrony in annual legume-based systems, in some cases, N losses during fallows of fertilized systems may even be higher. Rochester et al. (2001a) studied the fate of

^{15}N-labeled urea and ^{15}N-labeled residues of soybean and faba bean (*Vicia faba*) harvested for grain, or green-manured lablab (*Lablab purpureus*) or field pea (*Pisum sativum*) through 5–9 month fallow periods before the sowing of cotton (*Gossypium hirsutum*) and at cotton harvest. They found much smaller losses of legume-N than fertilizer-N in the fallow period between legume cropping and cotton sowing, with relatively little further losses of legume–derived N during growth of the subsequent cotton crop (Table 3).

Strategies to improve the efficiency of N use

The fact that efficiencies of N use on-farm using current farming practices (20–40%, Cassman et al. 2002; Dobermann et al. 2002) tend to be well below maximum values reported with intensive management in research trials (typically 60–95%, Balasubramanian et al. 2004; Krupnik et al. 2004) suggests that there is potential to both enhance N recovery and reduce N losses. However, the challenge is how farm-scale technologies can be improved to enable farmers to achieve N recoveries similar to the highest efficiencies measured in small-scale research plots (Dobermann and Cassman 2004).

Regardless of whether N inputs originate from synthetic fertilizer or biological N$_2$ fixation, a number of key basic principles hold true. Synchrony should be improved and/or the risk of N losses and environmental degradation reduced by strategies aimed at either:
(1) Increasing plant N demand,
(2) Manipulating N supply, or
(3) Capturing the excess inorganic N before it is lost.

Increasing plant N demand

Although the careful choice of crop species or variety most adapted to a specific environment or soil type will undoubtedly influence plant N demand, there is probably little scope for anything more than marginal gains in genetic enhancement of efficiencies of N uptake by conventional breeding or molecular techniques (Cassman et al. 2002). The main approach to create a stronger plant sink for N in both fertilizer and legume-

Table 5. Example of the relative impact of improved water availability on above-ground dry matter (DM) and N accumulation, and the recovery of ^{15}N-labeled fertilizer by wheat[a].

Parameter	Rainfed	Irrigated
Above-ground DM (t ha^{-1})	4.89	9.57
Above-ground N (kg N ha^{-1})	75	144
Recovery of applied fertilizer N (%)[b]		
Grain and straw	49	71
Soil and roots (to 105 cm)	37	19
Unaccounted for/lost[c]	13	10

[a]Adapted from data presented by Campbell et al. (1977) and Campbell and Paul (1978).
[b]Averaged across six fertilizer rates.
[c]Note that not all of the ^{15}N fertilizer that was unaccounted for at maturity was necessarily lost. A proportion of the 'unaccounted' determination may reflect experimental error. In this particular field trial measurement error was estimated to represent 6% of the amount of N applied.

based systems is to follow good agronomic practices to address factors that may reduce crop growth and thus limit the capacity to take up N when it is available (Smil 2001; Giller et al. 2002). This includes effective rotations to control disease and pests, timely sowing, good crop establishment, low weed competition, and a balanced nutrient supply (Lægreid et al. 1999; Cassman et al. 2002). In many areas, soil water availability during the growing season is a key factor affecting both the recovery of N and rate of N uptake by crops (Craswell and Godwin 1984). Improving water supply via irrigation can enhance crop dry matter production and the demand for, and uptake of, N, but it may not necessarily always influence the magnitude of N loss (Table 5), since the additional water could also increase the risk of leaching or denitrification (Peoples et al. 2004). Other factors likely to restrict root growth and/or the ability of roots to access water and nutrients include soil acidity, alkalinity, salinity, or sodicity, subsurface compaction, poor soil structure and a range of other physical and chemical subsoil constraints (Passioura 1992).

Management practices that have the potential to improve recovery of N in fertilizer and legume-based cropping systems by effectively increasing crop demand also include growing multiple crop species together within the one field (intercropping) that have different temporal and spatial nutrient demands (Shepherd et al. 1993).

Table 6. Examples of potential strategies to improve the management of N to manipulate N supply to either better match crop N demand or to avoid applications of excess N.

Strategy	References
Simple management adjustments	
Change timing of N application, form of fertilizer used	1,2,3
Adjusting the timing of green manuring or residue incorporation	4,5
Apply N in split applications/top-dressing	1,2,3,6,7
Placement of fertilizer deep, in bands or nests rather than broadcast	1,7
Eliminate N applications before pre-plant irrigation	8
Target yields slightly below the maximum potential for the region	9
Information-intensive management adjustments	
Pre-sowing testing of soil mineral N status	10,11
Base timing and quantity of fertilizer split application based on:	
post-sowing monitoring of crop N (tissue nitrate or chlorophyll) status	2,7,8,10,11,12
soil-availability indices using tools such as NIR spectroscopy	13
Carry out pre-sidedress (soil) nitrate test early in the growing season to calibrate application rates	6
Credit endogenous N mineralization in soil test N recommendations	2,3,14
Technological innovations	
Remote sensing of soil and/or crops	11,12
Variable rate/zonal management using global geographic information coupled with	2,11,12
global positioning systems on tractors	
Application of alternative forms/slow-release fertilizers	7,12,15
Use of nitrification or urease inhibitors	1,2,7,5,12
Computer-based or 'decision tree' decision support systems	12,16,17
Policy adjustments	
Reduce or eliminate fertilizer subsidies	18,19
Incorporate externality costs into the price of fertilizer.	

Sources: 1. Peoples et al. (1995a), 2. Dinnes et al. (2002), 3. Cassman et al. (2002), 4. Shepherd et al. (1993), 5. Francis et al. (1995), 6. Magdoff (199l), 7. Strong (1995), 8. Cassman et al. (1998), 9. Sylvester-Bradley (1993), 10. Rochester et al. (200lb), 11. Blackmer and White (1998), 12. Giller et al. (2004), 13. Russell et al. (2002) 14. Angus et al. (1998), 15. Shaviv and Mikkelsen (1993), 16. Angus (1995), 17. Palm et al. (2001b), 18. Matson et al. (1998), 19. Palm et al. (2004).

Manipulating N supply

A whole range of existing and prospective strategies have the potential to influence N availability to crops during a growing season (summarized in Table 6). The various approaches have been divided into simple cultural adjustments, information-intensive cultural adjustments, and technological innovations. Improved management of N supply could start with pre-sowing soil testing to assess the concentrations of mineral N already in soil profile. This soil information is particularly useful if it is combined with a suitable decision support tool to aid farmers or consultants to make key decisions about the amount and form of N applied before planting or during the growing season. These tools may be:

(a) Computer-based systems using sophisticated soil–crop simulation models which take into account the likely N release from the previous crop in combination with actual weather data to predict N requirements at the beginning of the growing season and during crop growth (Angus 1995; Giller et al. 2004),

(b) Based on N-budget sheets or empirical relationships (Angus et al. 1998; Rochester et al. 2001b),

(c) Simple 'decision trees' to provide information about organic matter quality and relative N supplying capacity for different legume residues and practical guidelines to more appropriately manage combinations of legume and fertilizer N (Palm et al. 2001a, b; Giller et al. 2002).

Many of the strategies listed in Table 6 have been shown to increase N synchrony substantially, at least in research plots. For example, in the Yaqui Valley of Mexico, wheat growers conventionally apply fertilizer before a pre-plant irrigation application. Matson et al. (1998) demonstrated that by reducing overall N inputs,

and changing the timing of N applications, including elimination of the pre-plant fertilization, the fraction of applied N taken up by wheat plants increased from 46 to 57% with no effect on yields. Similar improvements have been reported using visual or spectral measurements of leaf color or chlorophyll, sap nitrate concentrations, or near infrared spectrometry (NIR) to monitor crop N staus in order to tailor in-season fertilizer applications at critical growth stages (e.g. Blackmer and White 1998; Rochester et al. 2001b; Giller et al. 2004). Using a cholophyll/leaf color-based system in rice as a surrogate for crop N status and supplying the crop with 3–4 split fertilizer applications, Cassman et al. (1998) found that the uptake efficiency of applied N could be increased from 34% (representing farmer average), to 62%. However, it may be difficult to translate these achievements to working farms. For example, in a study involving 179 on-farm sites in six Asian countries, Dobermann et al. (2002) report that field-specific N management approaches using intensive in-season N monitoring protocols and involving up to four split applications to rice increased average fertilizer uptake efficiencies from 30 to 40% with only 20% of farmers achieving recoveries of 50% or more. Thus, even when best management practices were being used on farms, the crop uptake was still considerably less than the maximum 70–95% recoveries reported for rice in research trials (Krupnik et al. 2004).

Strategies in legume-based systems to potentially reduce the rate of N supply around periods of potential asynchrony include changing the timing and placement of legume residues (Palm et al. 2001b) manipulating residue quality through choice of legume tissue or species (Frankenberger and Abdelmagid 1985; Palm et al. 2001a; Rowe et al. 2004a, b) or mixing ratios of legume to other residues with different tissue qualities to influence microbial activity and thus rates of decomposition and net mineralization (Myers et al. 1994; Handayanto et al. 1997). A combination of experimental and modeling approaches were used by Becker and Ladha (1997) to demonstrate how adjustments in residue tissue quality (in this case lignin: N ratios), could help achieve greater N synchrony in a flooded rice system (Figure 2). However, non-additive nutrient availability patterns from mixes of low quality (high lignin or polyphenol) and high quality (high N, low lignin,

low polyphenol) materials have been observed – these are difficult to predict in advance and may not necessarily result in improvements in the synchrony between N availability and patterns of crop demand (Palm et al. 2001b).

Insufficient-nutrient asynchronies can be problematic in some legume-based systems of less developed countries, particularly in the tropics. Giller et al. (2002) describe how farmers with few resources can improve synchrony significantly by observing crop development during the growing season and broadcasting modest levels of N on fields at times of high nutrient demand. In this way, legume residues may supply the majority of N requirements by a crop, while fertilizers can be used to optimize yields, taking advantage of favorable growing conditions when they occur. This same principle can also be applied to more intensive, high production systems. For example, Rochester et al. (2001a) found consistent and substantial savings in the amounts of fertilizer N required to achieve optimum yields of irrigated cotton grown following either green manured legumes (80–180 kg N ha^{-1} less fertilizer than rotations without legumes), or legume crops harvested for grain (50–140 k N ha^{-1} less fertilizer).

We know of almost no studies that have compared N synchrony with fertilizer-based and legume-based systems when best possible management practices are employed to manage both treatments. While most direct comparisons of conventional (as opposed to best management) legume-based and fertilizer-based systems suggest that legume-based systems demonstrate higher N retention in soil (Table 3), we also recognize that use of precision crop and fertilizer techniques such as split applications, time-release fertilizers, nitrification inhibitors, reduced tillage, and other management strategies can potentially boost synchrony in fertilizer-based systems up to or beyond that which is achievable in legume systems (Giller et al. 2004). Indeed, Cassman et al. (2002) argue that research into precision management in time and space of all production factors associated with input-intensive agriculture holds the greatest promise of increasing N synchrony and therefore alleviating environmental stresses caused by excess leaching and gaseous N losses. Yet, the work they present suggests that even if best management practices are adopted by fanners, including the use of complex simulation models in making man-
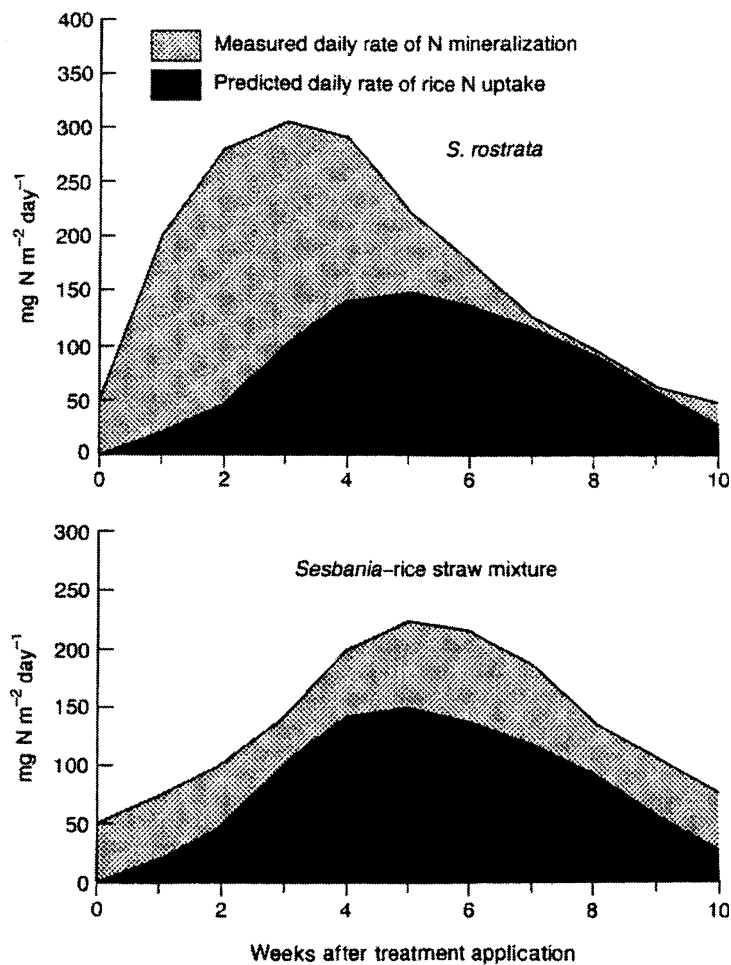
112

Figure 2. Daily rate of soil exchangeable NH_4^+-N mineralization (measured in unplanted plots in the field) and daily rate of rice N uptake (simulated for a target yield of 6 t ha^{-1}, using ORYZA1 model) with application of two materials with different lignin-to-N ratios (2 and 6 for *Sesbania rostrata, S. rostrata*-rice straw mixture, respectively). Adapted from Becker and Ladha (1997).

agement decisions, they will be fortunate to achieve the levels of N synchrony necessary to consistently obtain recoveries substantially greater than 50% of the N applied in most cropping systems. It appears that a stage of diminishing returns may have been reached where intensive management of annual cropping systems might yield only marginal gains in N synchrony on farms.

Capturing excess inorganic N before it is lost

The single greatest challenge to achieving synchrony in legume-based or fertilizer-based agroecosystems is inherent in annual agriculture itself. The release of inorganic N from organic matter or

fertilizers in soils does not begin with the planting of seeds, or end with the harvest. Mineral N continues to accumulate after the crop is finished, or before it has gained in stature. Moreover, high N demand by annual crops is often concentrated in a brief window of 1–2 months, and considerable excess N has to be applied to even approach meeting this peak demand (Figure 3).

Both legume-based and fertilizer-based systems tend to experience a period of excess asynchrony following crop harvests or legume incorporation (Figure 3). Unutilized mineral N that remains after cropping as well as ongoing net microbial mineralization can result in substantial accumulations of nitrate in the soil profile during a period when there is essentially no plant demand (Groffman et al.
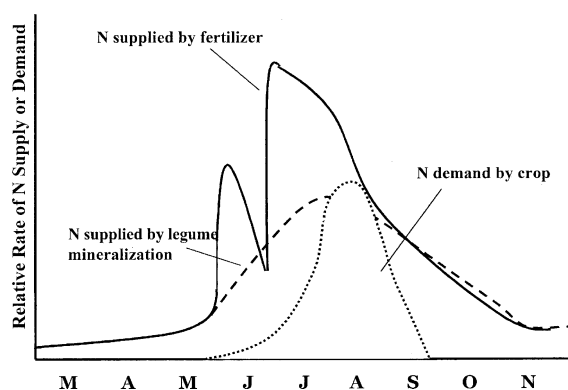
Figure 3. Asynchrony of crop N demand (...) and N supply via either a split application of fertilizer (—) or N mineralization from legume residue (- - - - -) in a hypothetical northern temperate annual cropping system (modified from Robertson 1997).

1987; Campbell et al. 1994). Whether this residual mineral N remains available to be assimilated by following crops, is immobilized by the soil microbial biomass to be remineralized at a later time, or is lost from the root zone will largely depend upon its distribution in the soil profile and the incidence of rainfall, water logging or leaching events before the next cropping cycle. A number of ^{15}N-based studies suggest that the uptake of residual ^{15}N by second or successive crops tends to be relatively small (commonly < 15–20% of the ^{15}N remaining after the first crop), regardless of whether it was carried over as inorganic N or was associated with organic material (Giller and Cadisch 1995; Fillery 2001; Macdonald et al. 2002; Krupnik et al. 2004). Both the crop species used in a cropping sequence and soil type may influence the extent of subsequent N recovery by crops.

Strategies to reduce the risk of N losses during periods of fallow include planting legume (George et al. 1994; McCracken et al. 1994), or non-legume cover crops to immobilize and conserve available N in an organic form (Shipley et al. 1992; McLenaghen et al. 1996). An alternative approach that could substantially decrease the risk of N loss both during the crop-growing season and in periods of fallow between crops, is the integration of perennial plant species into cropping systems. Compared to annuals, perennials have longer growing seasons, maintain deeper, more extensive root systems that occupy the soil volume year-round,

and hence have a greater ability to uptake soil N in both time and space.

While there are a few exceptions in the international literature (e.g. Campbell et al. 1994), the deep-rooted, perennial legume alfalfa (lucerne, *Medicago sativa*) is generally considered to have an impressive ability to scavenge mineral N (Mathers et al. 1975; Owens et al. 1994; Rasse et al. 1999). For example, Randall et al. (1997) compared nitrate losses through subsurface tile drainages in continuous corn, a corn–soybean rotation and an alfalfa stand. They found nitrate leaching in the corn systems to be almost 40-fold greater than in the alfalfa systems. Moreover, alfalfa cropping reduced soil nitrate to a depth of 3 m.

Similar results have also been reported in dryland farming systems of Australia where the integration of alfalfa and other perennial pasture species has been shown to be very effective in preventing nitrate accumulation and potential leaching events (Dear et al. 1999; Fillery 2001; Ridley et al. 2001). When annual clovers or medics are grown in pastures with little to no alfalfa in the mix, seasonally induced growth–death cycles induce flushes of nitrate accumulations in the soil. However, when alfalfa occurs at higher densities in pastures, the N mineralized from the clover and medics is assimilated by the alfalfa, so concentrations of soil mineral N remain low (Dear et al. 1999; Peoples and Baldock 2001).

Given that most studies have found deep-rooted species such as alfalfa to dramatically reduce soil nitrate, how can perennials be integrated into food and fiber producing agroecosystems other than pastures? One well-studied approach is the planting of 'alley farming systems'. Alley cropping is a form of agroforestry in which arable crops are grown in the interspace (which may be 5–30 m) between rows of planted shrubs or trees. These woody perennials can either be N_2-fixing or non-N_2-fixing species. The N_2-fixing trees most commonly investigated include leucaena (*Leucaena leuccephala*) and gliricidia (*Gliricidia sepium*) in the tropics (Ladha et al. 1993; Sanginga et al. 1995), tagasaste (also known as tree lucerne, *Chamaecytisus profliferus*) in temperate environments (Lefroy and Stirzaker 1999), or actinorhizal species such as alders (*Alnus* spp.) (Crews and Gliessman 1991). Often the foliage is periodically trimmed to maintain the trees as hedgerows, and the prunings added to the soil as a green manure

or mulch prior to cropping (Haggar et al. 1993; Ladha et al. 1993).

Alley cropping systems involving legumes have the potential of substantially increasing N inputs via N_2 fixation (Ladha et al. 1993; Unkovich et al. 2000), and the N mineralization potential under an alley system, total biomass and N content of crops can be higher in an alley crop than a sole crop Haggar et al. 1993). The lateral network of tree roots that develop beneath the cropped areas can help prevent excess water and leached nitrate or other nutrients escaping the crops or being lost during the fallow period between crops (Lefroy et al. 2001; Rowe et al. 2001). However, managing the nutrient and water capturing functions of the trees while trying to avoid direct competition with annual crops can be challenging (Lefroy and Stirzaker 1999), and in some instances the desired outcome is not always achieved. For example, Rowe et al. (2004a, b) found lower rates of nutrient capture in alley-cropped corn compared to monocropped plots in Sumatera, Indonesia. The alley-cropped corn in this particular study experienced lower productivity and lower N uptake due to competition with the hedgerow. The hedgerow species did not fully compensate for the reduced N recovery by crops. Rowe et al. suggested that N_2 fixation by the hedgerow legume Gliricidia limited its capacity to recover leached soil-N. The non-legume hedgerow plant Peltophorum (*Peltophorum dasyrrhachis*) was found to be more effective at capturing leached N than *Gliricidia* both because it was not an N_2-fixer and because it maintained a deeper fine root system.

Livesley et al. (2002) demonstrated how selecting woody species with relatively greater reliance on internal N cycling and lower N uptake requirements can reduce competition for N between crops and trees. Other challenges that have been reported in alley cropping systems are that the direct contribution of N in the mulched tree prunings to crop growth seems to be low (commonly 5–20% of applied N, Peoples et al. 1995b; Sanginga et al. 1995), losses of N can still be unacceptably high (Table 3, Haggar et al. 1993; Rowe et al. 2004a, b).

An alternative approach, which avoids the use of woody perennials, is to oversow a field of perennial, herbaceous legumes, such as alfalfa, with cereals. Such intercropping (also known as companion cropping) systems have been evaluated experimentally in a range of environments (Abdel Magid et al. 1991; Jordan et al. 1993; Angus et al. 2000; McCallum et al. 2001), and have been adopted locally by a number of farmers in the higher rainfall regions of southern Australia (Harris et al. 2003).

Potentially, the deep-rooted alfalfa could capture leached nitrate and other nutrients to be returned to the active rooting zone of the companion crop (Campbell et al. 1994). However, ^{15}N studies suggest that the crops may recover only modest amounts of N directly from the neighboring alfalfa (4–12% Jordan et al. 1993, 1–8 kg N ha^{-1} Crews and Peoples, unpublished data). While crop yields in rainfed systems may be similar in average or above-average rainfall years (Angus et al. 2000), interspecies competition for soil water can lead to yield reductions by the intercropped cereal in dry years (McCallum et al. 2001). Agronomic strategies aimed at avoiding direct competition during key times in the growing season include growing alfalfa varieties with differing growth habits, and the selective suppression of alfalfa growth with herbicides, cutting or tillage (Jordan et al. 1993; Davies and Peoples 2003).

By capturing leached nitrate, deep-rooted perennials in alley cropping or intercropping systems have the potential to compensate for excess-asynchrony in the accompanying annual crops. Another potential approach to improving the efficiency of N use may be the development of perennial crops. Given their deeper and more permanent roots perennial crops generally recover more applied N than annual crops (Balasubramanian et al. 2004). The idea of increasing reliance on nut or seed producing woody perennial trees in place of annual grain production is not new (Smith 1953). However, tree roots tend to have lower uptake efficiencies compared to fibrous rooted herbaceous plants such as grasses or cereals. This may limit the N synchrony potential in tree cropping systems of wet regions, particularly when N is supplied as soluble fertilizers in one application. For example, Dinkelmeyer et al. (2003) applied ^{15}N-labeled ammonium sulfate to a polyculture of four tree crops in a region of Brazil that receives ~2100 mm precipitation year^{-1}. After ten months they recovered only 24% of the applied fertilizer from crops or soils. While total N capture was low,

the results by Dinkelmeyer et al. (2003) did suggest, that improvements in synchrony could be obtained by planting multiple tree species with different rooting morphologies together in polyculture.

In regions where deciduous tree crops are widespread, asynchronies may still occur during periods of dry-season or winter dormancy. In these situations, improvements in N recovery would depend upon capture of N leached during the dormant season by roots deep in the soil profile during the subsequent growing season. Alternatively, an herbaceous perennial groundcover such as a cool season grass may serve to capture some leached N during episodes of tree dormancy.

A perennial alternative to annual grain production across the prairie regions of the US has been proposed and investigated at the Land Institute in Salina, Kansas (Jackson 1980; Cox et al. 2002). As defined over the last 25 years, the perennial polyculture includes four main functional groups that are typically found in the US tallgrass prairie – a warm season grass, a cool season grass, a sunflower (*Helianthus* spp.) and a legume (Soule and Piper 1992). By diversifying the cropping system into these functional groups, researchers hope to capture some of the mechanisms that appear to promote high levels of N synchrony in the native prairie. For example, native perennial grasses have been shown to have very different tissue qualities, root:shoot ratios, and in turn, N mineralization rates (Wedin and Tilman 1990). Variation in these and other species-specific attributes can lead to spatial and/or temporal partitioning of N resources (McKane et al. 1990; Van Der Krift and Berendse 2001). Through diversification of plant tissue quality, rooting depths, and crop phenologies, the synchrony of N supply and demand in a perennial polyculture has the potential to increase beyond what is possible in annual monocultures (Piper 1993; Myers et al. 1994; Randall and Mulla 2001).

Conclusions

The issue of synchrony in cropping systems is at the root of most environmental hazards associated with excess N in the atmosphere, terrestrial and marine ecosystems (Peoples et al. 2004). Current levels of synchrony and the extent of N losses vary dramatically depending on the prevailing farming practices, crop, climate and soil characteristics. While relatively few studies have carefully compared synchrony over a range of cropping systems, our review of the literature has revealed a number of key points. A higher proportion of the applied N is usually recovered by plants from fertilizer than from legume residues in the first cropping cycle. However, more legume N is typically retained in the soil and the impacts of N derived from leguminous organic materials on microbial 'pool substitution' and subsequent soil N dynamics is such that total N availability for crop uptake is often much greater than would appear solely from measurements of the direct crop recovery of applied legume N. Nitrogen losses from legume or fertilizer sources of N may be comparable in rainfed agriculture, but higher losses of fertilizer are more prevalent in lowland rice and irrigated annual cropping systems, EN particularly where single applications of fertilizer N result in periods of pronounced excess asynchrony early in the growing season. A lesser, but still important period of asynchrony can also occur during fallow periods after crop harvest regardless of whether fertilizer or legume residues were used.

Various management practices have been proposed that might improve the synchrony between N supply and demand, or lower the risk of N losses in both fertilizer and legume-based systems. Most focus on either maximizing plant growth potential, or controlling N availability during the growing season. However, it is recognized that some periods of asynchrony are probably unavoidable in annual cropping systems, and other strategies have also been developed that specifically aim to capture the excess inorganic N before it is lost. Much of the knowledge and technology for many of these options is already available and they could be applied immediately, but other approaches will require more research before they become viable farming alternatives (Crews and Peoples 2004). While there is some evidence that on-farm N use efficiency has been improving in some areas (e.g. rising trends in US national corn grain yields with stable rates of N application, or constant cereal yields in Japan with declining fertilizer N use, Dobermann and Cassman 2004), for the most part, innovations to increase the recovery of applied N have not been widely

adopted by farmers. There are a number of possible reasons for this:

(1) Producers are either unaware of the options, or do not perceive that these management practices deliver tangible benefits. Large investments have been made in research, but relatively less has been invested in the communication and dissemination of the research outcomes, or in farmer education (Dobermann and Cassman 2004).

(2) Important prerequisites for the adoption of N management technologies are that they should be simple, provide consistent large gains in N recovery, involve little extra time or effort, and be cost-effective. Many of the technologies described in this review do not fill these criteria and will require some initial support to encourage adoption (Giller et al. 2004).

(3) For technologies to be attractive to farmers in the absence of external incentives from society or government (e.g. see Palm et al. 2004), the risk of profit loss must be small and/or the potential for profit gain need to be high (Cassman et al. 2002; Giller et al. 2004). Such economic considerations have not always been demonstrated or effectively communicated.

(4) Relative costs of fertilizers are currently too low for producers to be overly concerned about inefficiencies and, because there is a disconnection between the sources of N loss and the subsequent environmental consequences, farmers are unaware of the implications of their actions.

These issues will need to be addressed in the short term before any real progress can be made towards improving the efficiency of N recovery from applied N and enhancing the environmental sustainability of crop production. In the long term, significant investment in research and development of perennial crops may hold the greatest promise for improving on N synchrony in high-yielding agroecosystems.

Acknowledgements

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