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Biological nitrogen fixation: An efficient source of nitrogen for sustainable agricultural production?

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Abstract

A fundamental shift has taken place in agricultural research and world food production. In the past, the principal driving force was to increase the yield potential of food crops and to maximize productivity. Today, the drive for productivity is increasingly combined with a desire for sustainability. For farming systems to remain productive, and to be sustainable in the long-term, it will be necessary to replenish the reserves of nutrients which are removed or lost from the soil. In the case of nitrogen (N), inputs into agricultural systems may be in the form of N-fertilizer, or be derived from atmospheric N_2 via biological N_2 fixation (BNF).

Although BNF has long been a component of many farming systems throughout the world, its importance as a primary source of N for agriculture has diminished in recent decades as increasing amounts of fertilizer-N are used for the production of food and cash crops. However, international emphasis on environmentally sustainable development with the use of renewable resources is likely to focus attention on the potential role of BNF in supplying N for agriculture. This paper documents inputs of N via symbiotic N_2 fixation measured in experimental plots and in farmers' fields in tropical and temperate regions. It considers contributions of fixed N from legumes (crop, pasture, green manures and trees), *Casuarina*, and *Azolla*, and compares the relative utilization of N derived from these sources with fertilizer N.

Introduction

Globally, cereal cropping dominates cultivated land use (around 50% of total area, Table 1). The remaining arable land is used for production of oilseed, fibre, or food and cash crops. In addition, vast areas are maintained under temporary or permanent pasture for forage production (2–3 fold greater than the total area under cultivation and permanent crop; Table 1, Fig. 1). All cultivated crops, except for legumes (pulses and legume oilseeds) require the soil to provide relatively large amounts of nitrogen (N). It is necessary for the three most important cereals, wheat (*Triticum aestivum*), rice (*Oryza sativa*) and maize (*Zea mays*), to take up 20 to 40 kg soil N ha^{-1} over a period of 3 to 5 months to satisfy the N requirements of the seed and supporting vegetative structure for each tonne of grain produced (e.g. Fig. 2; Myers, 1988). Productive pastures on the other hand may assimilate > 100 kg N ha^{-1} each annum, of which 50 to 90% will be consumed by livestock in intensively grazed systems (Ledgardy, 1991; Thomas, 1995). Even though 75 to 95% of the N ingested is returned as excreta, large amounts of N can be leached or lost as gaseous emissions (Peoples et al., 1994e; Steele and Vallis, 1988), so that the annual demand for N can be continuing and substantial.

The problem facing farmers everywhere is that the capacity of their soils to supply N declines rapidly once agricultural activities commence and N derived from the breakdown of soil organic matter must be supplemented from other sources (Herridge et al., 1994a). During the 1990s, around 1 billion additional people will be added to the 1990 population of 5.3 billion. Over 90% of the increase will occur in the developing countries of Asia, Africa and Latin America, where, already, nearly 1 billion people endure some degree of malnutrition. For productivity to be simply sustained at current levels, let alone improved in the future, the N removed in agricultural produce or lost from the system, must be replaced by N derived either from nitrogenous fertilizers, or biological N_2 fixation (BNF). It is difficult to judge whether farmers are mindful of this concept and manage their N resource accordingly. Evidence suggests that inputs of fertilizer N might well exceed N removal in intensively managed arable soils of the USA and Europe (Sánchez, 1994); however, amounts of N removed from farms in grain or hay and lost through runoff, erosion, leaching and denitrification have been calculated to exceed inputs by fertilizer and BNF in the agricultural systems of the Canadian prairies (on average by 24 kg N ha^{-1} yr^{-1}, Doyle and Cowell, 1993) and Kenya (by 112 kg N ha^{-1} yr^{-1}, Sánchez, 1994). Clearly where agricultural activities are currently "mining", soil reserves, external nutrient inputs in the form of fertilizer and BNF must be increased if farmers are to have any prospect of meeting the food and fibre requirements of a growing world population.

Table 1. Global allocation of arable land between different commodities

Commodities[a]	Proportion of land area (%)
Cereals	
Wheat	16
Rice	10
Maize	9
All other cereals	13
Total	48
Legumes	
Legume pulses	5
Legume oilseeds	6
Total	11
Other crops	
Other oilseeds	6
Beverages / Tobacco	7
Roots and tubers	4
Sugars	2
Vegetables and fruits	2
Fibres / Rubber / Oil palm	1
Total	22
Temporary pastures / Fodder crops	14
Other	6

[a] Distribution of 1442 million ha estimated to be arable land and under permanent crop in 1991–1992 (FAO, 1992b, 1993).

Fertilizer N is a convenient and (currently) cheap source of N for crop growth which provides opportunities for strategic and rapid applications of plant nutrients. However, the use of fertilizer-N in different agricultural systems is ultimately regulated by economic considerations (e.g. per capita income, credit facilities, the current commodity value and expected return for investment at a farmer level, and availability of for-

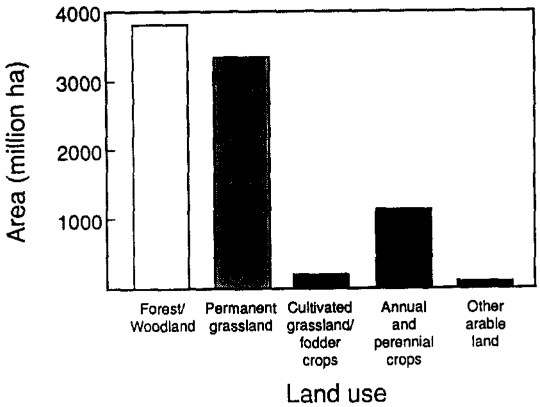

Fig. 1. Global patterns of land use indicating the relative areas under cropping and temporary or permanent pasture (used for forage production for 5 years or more), or containing forests and woodlands (data from FAO, 1993).

eign exchange at a national level), and the presence of effective infrastructures for fertilizer production and distribution. This taken in conjunction with the poor efficiency of utilization of fertilizer N by crops (seldom exceeding 50%) and increasing awareness of the environmental costs of N lost from fertilizers (Bohlool et al., 1992; Craswell and Godwin, 1984; Peoples et al., 1994e), suggests that there is likely to be a limit to the amounts of fertilizer N that farmers' might be willing to apply to improve agricultural production in the long-term. The contribution of BNF to the N-cycle on the other hand can be controlled by manipulating various physical, environmental, nutritional or biological factors (Hansen, 1994) and may therefore be more open to management than fertilizer N.

There is growing international concern about issues of global warming, environmental degradation and loss of natural resources. This concern is summarized in the sentiments expressed by Suzuki (1990) : "We no longer inherit the Earth from our parents, we borrow it from our children". With the current emphasis on the use of renewable resources for environmentally sustainable development, it is timely to assess the potential for BNF to complement or replace fertilizer inputs, and to consider its contribution to the N fertility of agricultural land. Yet we need to achieve more than simply ensuring that inputs balance outputs. Among other things, we should evaluate the capacity of BNF-based farming systems to maintain or enhance agricultural production in the long term in a way that is economically viable and socially acceptable in the short-term. We should also be aware that in some socio-economic frameworks food security can be more important than productivity, and consider the role that BNF can play in reducing the level of production risk and managing agriculture's resource base (Giller and Cadisch, 1995).

If BNF is to represent a reliable renewable resource for sustainable agriculture, its rate of use will be limited by its rate of regeneration and use by non-N_2-fixing crops and grasses. Therefore, it is necessary to know:

(a) The amounts of N fixed by different N_2-fixing systems in a range of environments,
(b) The contribution of BNF to the soil N pool,
(c) The recovery and losses of N derived from BNF sources, and
(d) Options that are available to enhance BNF inputs.

Examples of N_2 fixation inputs observed by researchers at experimental sites and in farmers' fields will be described, and the ultimate fate of that N will be discussed and compared with N from fertilizer in the following sections. Various approaches that are available to increase BNF are described in following papers in this volume.

Most attention will be directed towards N_2 fixation inputs by legumes because of their proven ability to fix N_2 and contribute to integrated agricultural production systems in both tropical and temperate environments. Crop legumes alone occupy 11% of land under cultivation or permanent crop (Table 1). However, legumes are also present in some of the 3541 million ha estimated to be temporary and permanent pastures (Fig. 1), and may provide valuable inputs of N in natural plant communities, forest ecosystems, tree plantations, and intensive cropping systems (Becker et al., 1995; Giller and Cadisch, 1995; Hansen, 1994). Discussion concerning BNF by non-legumes will be restricted to symbiotic systems involving either:

(a) *Anabaena* and the aquatic fern *Azolla*, or
(b) Actinorhizal associations: There are far fewer plant species nodulated by N_2-fixing actinomycetes (*Frankia* spp.) than *Rhizobium*-legume associations, but their numeric inferiority is offset by their capacity to occupy ecological niches where legumes do not thrive. In this particular discussion we specifically consider N_2-fixation by the actinorhizal association with the tree *Casuarina*.

Inputs of N by free-living diazotrophs in soil and plant residues, and non-symbiotic N_2-fixing associations with cereals and C4 grasses will not be discussed here; however, readers are referred to several recent publications (e.g. Chalk, 1991; Peoples and Craswell, 1992; Roger and Ladha, 1992) and papers presented

Table 2. Global changes in consumption of nitrogenous fertilizers between 1960 and 1990[a]

Region	1960	1970	1980	1990	Change 1960–1990
	(million t N)				(%)
Developed economies					
North America	2.6	7.1	11.7	11.3	335
Europe	3.3	9.1	14.3	13.6	312
former USSR	0.7	3.8	8.3	8.7	1,143
Oceania	<0.05	0.1	0.3	0.5	900
Other	0.7	1.0	1.1	1.0	43
Total developed	7.2	21.1	35.7	35.1	388
Developing economies					
Africa	0.1	0.3	0.6	0.8	700
Latin America	0.3	1.2	2.9	3.5	1,067
Asia	1.9	6.2	21.5	37.5	1,874
Other	<0.1	<0.1	0.1	0.2	233
Total developing	2.4	7.7	25.1	42.0	1,650
Total global	9.6	28.8	60.8	77.1	703

[a] Source: FAO (1992a) and Bumb (1994).

Table 3. Trends in domestic price of fertilizer-N in various geographical regions[a]

Region and country	Currency	Price (local currency t N^{-1}) 1980	1990	Change 1980–1990 (%)
Asia				
Bangladesh	Taka	5,127	10,826	111
Tukey	Lira	21,739	552,174	2,440
Africa				
Ghana	Cedi	762	223,819	29,273
Zambia	Kwacha	506	16,696	3,200
Latin America				
Mexico	Peso	7,679	434,783	5,562
Venezuela	Bolivar	952	3,333	235

[a] Bumb (1994).

elsewhere in the volume (Boddey et al., 1995; Roper and Ladha, 1995) which review these topics.

Fertilizer-N inputs into agriculture

There has been a substantial increase in the use of nitrogenous fertilizer in the past 30 years (Table 2). A near doubling of global cereal production between the early 1960s and 1990 has been attributed in part to a seven-fold increase in fertilizer-N use over the same period (Table 2). Globally the consumption of fertilizer-N increased from 8 to 17 kg N ha^{-1} of agricultural land in the 15 year period from 1973 to 1988 (FAO, 1990). Significant growth in fertilizer-N usage was experienced in both developed and developing countries (Table 2). But while fertilizer usage in Asia and the developing world continued to expand at around 6 to 7% per annum during the, 1980s, fertilizer consumption either remained static or declined in the developed economies of North America and Europe, as a result of grain surpluses and declining, crop prices.

Urea is the major form of N-fertilizer used so trends in urea prices reflect trends in N prices. International urea prices decreased steadily in real terms throughout much of the 1980s from around US$ 310 t^{-1} (adjusted to 1990 US$) in 1980 to US$155 t^{-1} in 1990 (Bumb, 1994). The economic and political reforms in Eastern Europe and West Asia have led to a fall in domestic fertilizer use in these parts and requirements for foreign exchange have resulted in the diversion of domestic supplies to international markets leading to further decreases in price from 1990 levels to around US$ 100 t^{-1} by mid 1993. Despite the decrease in urea prices in international markets, farmers in many developing countries were not able to benefit from such low prices because domestic prices increased astronomically (Table 3). Devaluation of domestic currencies, removal of fertilizer subsidies, and domestic inflation have contributed to the rapid increase in prices. In the 1980's, prices in Ghana, for example, increased by over 29,000% and by between 100 and 5,000% in other countries (Table 3).

Mean rates of fertilizer consumption range from < 1 to > 200 kg N per ha of agricultural land for individual countries (Table 4). However, such figures can be misleading since there are wide variations in the extent of use of N-fertilizer for individual crops and agricultural commodities. When considered on a regional basis, a high proportion of the major food and cash crops and intensively grazed pastures and forage crops are heavily fertilized to promote growth (Table 5; Peoples et

Table 4. Average rates of application of fertilizer-N to agricultural land[a]

Consumption rate (kg N ha^{-1})	Examples of countries within category
< 1	Australia, Argentina, Bhutan, Bolivia, Ethiopia, Paraguay, Senegal
10 – 25	Canada, Mexico, Papua New Guinea, Syria, Thailand, former USSR, USA, Venezuela, Zimbabwe
40 – 60	Bangladesh, China, Cuba, El Salvador, Greece, India, Indonesia, Ireland, Italy, Malaysia, Pakistan, Philippines, Sri Lanka, Vietnam
75 – 100	France, Hungary, Poland, United Kingdom
100 – 200	Belgium, Denmark, Germany, Japan
> 200	Egypt, Korea, Netherlands

[a] FAO (1990).

al., 1994e). Applications of fertilizer-N to wheat, rice and maize alone accounted for around 53% of the total global consumption in 1991 (Table 5).

Current assessments of fertilizer usage indicate that two conflicting forces are in operation (Bumb, 1994). Fertilizer use is being depressed in Eastern Europe and West Asia as a result of economic restructuring and political reform, and in Western Europe because of environmental concerns and subsidy removal. Population growth and food security considerations in Asia, Latin America and Africa, on the other hand, are stimulating fertilizer consumption. Fertilizer use in North America is expected to remain stable unless prospects for grain exports improve significantly. Projections of future demand for fertilizer suggest that the net effect of these forces will result in a gradual increase in global fertilizer demand to between 80 to 90 million t N by the year 2,000 (Bumb, 1994). Projections of fertilizer production indicate that fertilizer-N supply should exceed demand throughout the 1990s, therefore stabilizing international fertilizer prices at current low levels. It is anticipated however, that on a regional basis, there will fertilizer surpluses in some regions (Eurasia, North America and North Africa.) and deficits in others (Asia, sub-Saharan Africa and Latin America) where the availability of foreign exchange and domestic fertilizer prices will be critical in ultimately determining the levels of fertilizer use. The likely decrease in fertilizer consumption in Europe and Eurasia could also have an adverse impact on global food production, and therefore, may affect the supply of grains available through aid and trade to developing nations (Bumb, 1994).

In the future, potential to redress this projected shortfall in the supply of fertilizer-N, or replace fertilizer inputs with N derived from BNF sources is likely to be greatest in rain-fed systems where, depending upon the timing and intensity of rainfall, the risk of crop failure is high compared with irrigated crops, and fertilizer responses are more unreliable (Craswell and Godwin, 1984; Myers, 1988). Substantial areas of arable land in all regions of the world support rain-fed agriculture (Table 6), and the challenge to researchers and farmers alike is to improve the contributions of BNF in these systems.

Measured inputs of fixed N

Estimates of the total annual terrestrial inputs of N from BNF range from 139 to 170 million t N (Burns and Hardy, 1975; Paul, 1988), with symbiotic associations growing in arable land accounting for 25 to 30% (35–44 million t N) and another 30% (45 million t N) coming from permanent pasture. While the accuracy of these figures may be open to question, they do help illustrate key points:

(1) The relative importance of BNF in cropping and pasture systems,

(2) The magnitude of the task necessary if BNF is to be improved to replace a proportion of the 80 to 90 million t N of fertilizer-N expected to be applied annually to agricultural land by the end of the decade (Bumb, 1994).

Table 5. Patterns of production of major cereal crops indicating the proportion of each crop receiving fertilizer-N, the average rate of application and estimates of total amounts of N applied in various geographical regions[a]

Region	Wheat				Rice				Maize			
	Global prod^n (%)	Crop fertilized (%)	Rate of applic^n (kg N ha^{-1})	Fertilizer consumed (10^3 N)	Global prod^n (%)	Crop fertilized (%)	Rate of applic^n (kg N ha^{-1})	Fertilizer consumed (10^3 t N)	Global prod^n (%)	Crop fertilized (%)	Rate of applic^n (kg N ha^{-1})	Fertilizer consumer (10^3 t N)
East Asia	18	100	146	4569	41	100	127	4690	19	100	100	2241
Southeast Asia	< 1	-[b]	-	-	22	72	40	1077	3	63	59	316
South Asia	13	96	83	2613	28	80	67	3047	2	72	62	347
Middle East	7	62	83	115	< 1	-	-	-	1	85	97	84
Africa	2	99	52	476	3	23	74	116	5	61	81	1012
Eastern Europe and former USSR	21	88	50	2516	< 1	-	-	-	7	89	136	1169
Western Europe	15	100	134	2250	< 1	-	-	-	3	100	173	4016
North America	17	80	56	2003	2	97	117	124	47	97	157	5062
Latin America	4	96	47	390	3	95	37	222	12	65	88	1523
Oceania	3	66	23	150	< 1	-	-	-	< 1	-	-	-
Total global				16082				9276				15770

[a] Data for 1989–1992 (FAO, 1992b, 1993). Total N applied = 41.1 million t N, or 53% of total global consumption of fertilizer-N in 1991.
[b] No data presented if regional contribution to total global grain production < 1%.

Table 6. Relative areas of irrigated and rainfed agricultural land in the various geographical regions[a]

Region	Proportion of arable land	
	(Irrigated %)	(Rainfed %)
East Asia	52	48
Southeast Asia	19	81
South Asia	34	66
Middle East	56	44
Africa	7	93
Eastern Europe and former USSR	10	90
Western Europe	14	86
North America	8	92
Latin America	12	88
Oceania	4	96
Total global	18 (242)[b]	82 (1105)[b]

[a] Data for 1991 (FAO, 1993).
[b] Values in parenthesis represent millions of ha of arable land either irrigated or rainfed.

Food legumes

Experimental estimates of the proportion of plant N derived from N_2 fixation (P_{fix}) and the amounts of N_2 fixed by important tropical and cool season crop legumes are presented in Table 7. Although experimental treatments and environmental or nutritional variables have generated a large range of P_{fix} values (0–98%) and inputs of fixed N, it appears that potential BNF for most species is in the range of 200 to 300 kg N ha^{-1} crop^{-1} (Table 7). However, since crop N is partitioned either into seed, or vegetative parts at crop maturity, not all of the N_2 fixed will be available for return to the soil. The final contribution of fixed N to the soil following harvest will depend upon the N-balance at harvest, which is determined by the difference between the amounts of N_2 fixed and seed N removed:

$$\text{N} - \text{balance} = (\text{N}_2\text{fixed}) - (\text{seed N}) \qquad (1)$$

With protein levels of 20 to 40%, legume seeds have a high demand for N and up to 60 kg N ha^{-1} can be removed with every tonne of seed harvested. Global

Table 7. Range of experimental estimates of the proportion (P_{fix}) and amount of N_2 fixed by important pulses and legume oilseeds[a]

Species	P_{fix} (%)	Amount N_2 fixed (kg N ha^{-1})
Cool-season legumes		
Chickpea (*Cicer arietinum*)	8 - 82	3 - 141
Lentil (*Lens culinaris*)	39 - 87	10 - 192
Pea (*Pisum sativum*)	23 - 73	17 -244
Faba bean (*Vicia faba*)	64 - 92	53 - 330
Lupin (*Lupinus angustifolius*)	29 - 97	32 - 288
Warm-season legumes		
Soybean (*Glycine max*)	0 - 95	0 - 450
Groundnut (*Arachis hypogaea*)	22 - 92	37 - 206
Common bean (*Phaseolus vulgaris*)	0 - 73	0 - 125
Pigeon pea (*Cajanus cajan*)	10 - 81	7 - 235
Green gram (*Vigna radiata*)	15 - 63	9 - 112
Black gram (*V. mungo*)	37 - 98	21 - 140
Cowpea (*V. unguiculata*)	32 - 89	9 - 201

[a] Collated from Peoples and Craswell (1992), Herridge et al. (1993), and Peoples et al. (1994a). Additional data were derived from Jensen (1987) - pea, Evans et al. (1989) - lupin and faba bean, Hardarson et al. (1993) - common bean, and Ladha et al. (1995) - pigeon pea.

average yields of around 2 t ha^{-1} for crops such as soybean (Table 8) mean that at least 120 kg N ha^{-1} must be fixed before the soil can receive any net benefit from BNF (Peoples et al., 1994c).

When the quantities of N involved in plant growth, in N_2 fixation, and in the seed are calculated for crop legumes, it appears that levels of fixation achieved by many crops might not always be sufficient to offset the N removed with seed (Peoples and Craswell, 1992; Peoples et al., 1995). Comparisons of N_2 fixation and amounts of seed N harvested have been undertaken for many crops and examples of final N-balances range from as little as −132 kg N ha^{-1} to as much as +80 kg N ha^{-1} in soybean (Bergersen et al., 1989; Hughes and Herridge, 1989), −34 to +64 in groundnut (Bell et al., 1994; McDonagh et al., 1993), −42 to +34 in chickpea (Doughton et al., 1993), −11 to +25 in lentil (Bardarneh and Ghawi, 1994), −32 to +96 in pea and −41 to +135 kg N ha^{-1} in lupin (Evans et al., 1989), depending upon the amounts of N_2 fixed, the harvest index for N (the proportion of total crop N removed in seed), and whether the vegetative residues are removed from the field (Bell et al., 1994; Ying et al., 1992).

Forage legumes, green manures and N_2-fixing trees

Far fewer measures of N_2 fixation are available for the forage legumes, cover crops, and N_2-fixing trees than for crop and green manure legumes (Giller and Wilson, 1991; Becker et al., 1995). However, the available data indicate that levels of N_2 fixation can be similar to crop legumes (Tables 8 and 9). Levels of P_{fix} have often been reported to be >60%, and inputs of fixed N can be considerable (eg 120–290 kg N ha^{-1} in 45–55 days by shrub legumes; >350 kg N ha^{-1} per year by lucerne). However, in the case of forage legumes, small amounts of fixed N have been measured in some instances (<20 kg N ha^{-1}, Table 8), despite high levels of P_{fix}. This reflects a low legume component in a pasture sward (Peoples et al., 1994d, 1995; Thomas, 1995).

One of the advantages of using BNF of trees, forages, or green manures as a N source is that a larger proportion of the N accumulated is generally available for return to the soil because much less N is removed from the system in agricultural produce compared to the amounts of N harvested in the seed of crop legumes. In these systems, the potential for the return of BNF to soil either through leaf fall, mulch, or via a gazing animal and undetermined turnover of roots and nodules may be considerable.

BNF in farmers' fields

Food legumes

By comparison with the gains made in yields of cereals between 1981 and 1991, global yield increases of major crop legumes were relatively small (Table 10). That a large yield gap (1–3 t ha^{-1}) exists between crop legume yields in experimental plots and those in farmers' fields (particularly in, Asia; e.g. Bhatnagar and Tiwari, 1989) suggests that N_2 fixation of the food legumes could be increased through management practices that remove growth constraints.

The limited surveys of N_2 fixation in farmers' crops indicate that values for P_{fix} (6–91%) and amounts of N_2 fixed (15–267 kg N ha^{-1}, Table 11) are similar to experimental observations (Table 7). The range of N-balance determinations calculated following seed harvest for lupin and soybean (Table 11), are almost identical to those described above for experimental crops.

However, experimental studies are generally designed to generate ranges of N_2 fixation as a means of

Table 8. Range of experimental estimates of the proportion (P_{fix}) and amount of N_2 fixed by important forage legumes[a]

Species	P_{fix} (%)	Amount N_2 fixed (kg N ha^{-1})	Period of measurement
Temperate forages			
Lucerne / alfalfa (*Medicago sativa*)	46 - 92	90 - 386	Annual
Strand medic (*M. littoralis*)	51 - 82	52 - 102	144d
M. truncatula	70	90	na
Birdsfoot trefoil (*Lotus cornicuatus*)	30 - 85	49 - 109	Annual
White clover (*Trifolium repens*)	62 - 93	54 - 291	Annual
Red clover (*T. pratense*)	35 - 87	69 - 373	Annual
Subterranean clover (*T. subterraneum*)	50 - 93	2 - 206	Annual
Crimson clover (*T. incarnatum*)	75 - 81	124 - 185	Annual
Vetch (*Vicia sativa*)	75	106	na
Tropical forages			
Arachis pintoi	72 - 87	1 - 7	84d
Calopogonium spp.	na[b]	64 - 182	Annual
Centrosema spp.	82 - 83	41 - 43	119d
	na	67 - 280	Annual
Clitoria ternatea	77 - 81	197 - 249	190 - 195d
Desmodium spp.	80 - 100	24 - 380	Annual
Desmanthus virgatus	77 - 80	193 - 228	190 - 195d
Siratro (*Macroptilium atropurpureum*)	78 - 92	15 - 167	Annual
Pueraria spp.	75 - 88	9 - 115	72 - 199d
Stylosanthes spp.	60 - 95	2 - 75	63 -77d
	na	20 - 263	Annual
Zornia glabra	88	61	119d

[a]Collated from Giller and Wilson (1991), Ledgard and Steele (1992), Peoples and Craswell (1992) and Thomas (1995). Additional data were derived from Brockwell et al. (1994), and Gault et al. (1995) lucerne / alfalfa, Peoples et al. (1994d) subterranean clover, Heichel et al. (1985) red clover and birdsfoot trefoil, and Ladha et al. (1995) Siratro, *Clitoria*, and *Desmanthus*.
[b]na=information not available.

investigating factors regulating the N_2-fixing process. It is in farmers' fields where issues of sustainability need to be addressed. The presence of low P_{fix} values, poor N yields or negative N-balances in many surveys of commercial crops (Table 11), indicates that farmers do not always fully exploit the potential benefits of BNF.

While there are often large gaps between N_2 fixation measured in farmers' fields and the highest research values, the upper end of the range of N_2 fixation achieved by some farmers approach or exceed those from experimental crops (Tables 7 and 11). The wide range of levels of N_2 fixation found in farmers' fields is encouraging in itself and suggests that management opportunities are available for farmers' to improve BNF inputs (Peoples et al., 1995).

Forage systems

While mean determinations of P_{fix} (69–81%) reported in a survey of BNF of several temperate legume species in annual pastures across southern Western Australia (243 measurements from 81 farms, Sanford et al., 1994) are similar to research results (Table 8); low values (0–65%) were detected at one-third of the sites studied. Low P_{fix} values have also been measured in farmers' fields in the tropics (see data for *Centrosema* in Table 12). This is in stark contrast to the relatively narrow range of values usually reported

Table 9. Range of experimental estimates of the proportion (P_{fix}) and amount of N_2 fixed by important N_2-fixing trees, green manures, and cover crops[a]

Species	P_{fix} (%)	Amount N_2 fixed (kg N ha^{-1})	Period of measurement
Trees			
Acacia holosericea	30	3 - 6	6.5 months
Calliandra (*Calliandra calothyrsus*)			
- hedgerow for forage[b]	14 - 48	11 - 101	3 - 6 months
Casuarina equisetifolia	39 - 65	9 - 440	6 - 12 months
Gliricidia (*Gliricidia sepium*)	52 - 64	86 - 309	Annual
- hedgerow for forage	69 - 75	99 - 185	3 - 6 months
- alley crop hedgerow	43	170	Annual
Leucaena (*Leucaena leucocephala*)	34 - 78	98 - 230	3 - 6 months
Green manures and cover crops			
Aeschynomene afraspera	68 - 76	105 - 145	56d
A. indica	93 - 100	75 - 127	116d
Azolla spp.	52 - 99	22 - 40	30d
Crotalaria (*Crotalaria juncea*)	80 - 96	146 - 221	102 - 190d
Indigo (*Indigofera tinctoria*)	70	79	225d
Calopogonium / Peuraria spp.	50	150	Annual
Sesbania cannabina	70 - 93	126 - 141	Seasonal av
	93	119 - 188	45 - 55d
S. rostrata	68 - 94	70 - 324	45 - 65d
	65 - 78	147 - 281	116d
S. sesban	13 - 18	7 - 18	2 months

[a] Collated from Giller and Wilson (1991), Ladha et al. (1992), Peoples and Craswell (1992), Roger and Ladha (1992), Kumarasinghe and Eskew (1993), and Peoples et al. (1995). Additional data were derived from Ladha et al. (1993) - Gliricidia, Yoneyama et al. (1991) - *Aeschynomene*, *Crotalaria*, *S. rostrata* and Ladha et al. (1995 and unpublished) - *Crotalaria*, indigo.
[b] Trees maintained in hedgerows for forage are usually planted at a 0.5 m spacing, with 1.5 m between rows. In alley-cropping systems, trees may be spaced from 0.25 to 0.5 m apart within hedgerows with 4 to 5 m wide alleys.

for experimental plots (50–90%, Table 8). There are a number of possible reasons for this:

(i) Although some investigations have monitored legume growth and N_2 fixation over several years (e.g. Brockwell et al., 1994; Gault et al., 1995; Heichel et al., 1985; Peoples et al., 1994d; Vallis and Gardner, 1985), most measures of N_2 fixation by forages have been determined shortly after establishment of a legume-dominant sward. Unfortunately, the high legume contents common in research studies are not necessarily representative of farmers' pastures. The botanical composition of pastures can fluctuate widely in response to rainfall patterns, grazing pressure, and elapsed time after pasture establishment (Wilson and Simpson, 1993). The data shown in Table 12 reflect, in part, the effect of pasture age (3–30 years after initial establishment) and pasture quality on BNF.

(ii) Experimental determinations have almost invariably been undertaken in the absence of grazing animals. Apart from being an integral part of most- farming systems, livestock can affect pasture growth and composition, and negatively impact upon BNF by introducing localized N-rich sites via urine patches and faeces (Ledgard and Steele., 1992; Peoples et al., 1994d).

Green manures

Azolla. The aquatic fern *Azolla* is probably used as a green manure on <2% of the world's rice crop, but

Table 10. Global change in yield of major cereals and crop legumes during the past decade[a]

Crop	Yield 1981 ($t\ ha^{-1}$)	Yield 1991 / 1992 ($t\ ha^{-1}$)	Change in yield over 10 years (%)
Cereals			
Wheat	1.86	2.51	35
Rice	2.75	3.55	29
Maize	3.34	3.98	19
Crop legumes			
Soybean	1.70	1.92	13
Groundnut	0.99	1.16	16
Chickpea	0.62	0.71	13
Common bean	0.55	0.64	16

[a] FAO (1993).

this still represents around 2 to 3 million ha (Giller and Wilson, 1991). Under optimal conditions, *Azolla* doubles in biomass every 3 to 5 days and one crop can be expected to accumulate between 70 and 110 kg N ha^{-1} (Ventura and Watanabe, 1993). With experimental values of P_{fix} commonly >70% (Kumarasinghe and Eskew, 1993; Roger and Ladha, 1992), *Azolla* represents a potentially important source of N for flooded rice. However, there is little information available concerning inputs of N by *Azolla* in farmers' fields. Since growth and N_2-fixing capacity of *Azolla* can be affected by many environmental variables, mineral nutrition (particularly phosphorus), insect predators and pathogens, it is uncertain whether experimental potentials are ever realized in farmers' paddies (Giller and Wilson, 1991).

Legumes. The principal source of information on legume green manures in farmers' fields comes from measures of P_{fix} for perennial cover-crops in commercial rubber and oilpalm plantations in Malaysia (Faizah and Peoples, unpublished data). The range of values were wide (9–91%, Table 12), but the mean (57%) was close to previous experimental determinations in plantation systems (Giller and Wilson, 1991). The levels of P_{fix} observed tended to be inversely related to the age of the cover-crop, and presumably reflected the change in light penetration through the plantation canopy and the accumulation of organic N in the interrow space between the trees.

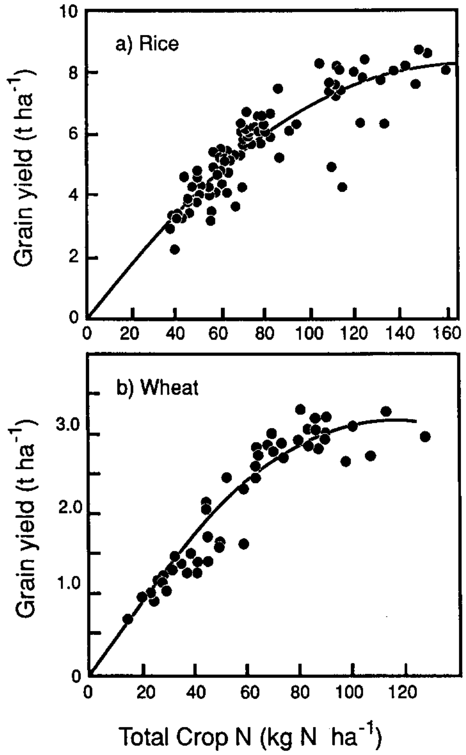

Fig. 2. Relationship between total crop N and grain yield for (**a**) rice (data from 12 rice genotypes; Ladha, unpubl.) and (**b**) wheat (data derived from Strong et al., 1986; Herridge and Doyle, 1988; Doyle et al., 1988; McDonald, 1992).

Agroforestry systems

Almost all measurements of BNF by N_2-fixing trees, either on farms or as part of natural communities, have been restricted to estimates of P_{fix} from studies or surveys undertaken in Africa, Australia, Brazil, Indonesia, the Philippines, Thailand or USA (Table 12). Although amounts of N_2 fixed cannot be calculated in most cases because tree biomass was not determined, the inputs of N could be substantial because of the large annual yields of dry matter and N of woody species (from 150-850 kg N ha^{-1}) in natural communities (Sandhu et al., 1990; Torrey, 1982), in alley cropping systems (Ladha et al., 1993; Sanginga et al., 1995), or where trees and shrubs are cut for forage (Blair et al., 1990).

Values of P_{fix} for the non-legume tree *Casuarina*, were uniformly high, ranging from 65 to 90% (mean 81%) under different environments and soil types (Table 12). Estimates of P_{fix} for tree legumes on the other hand ranged from 0 to 100%. Although P_{fix} values for a number of legume trees and shrubs indicated that 60% or more of their N requirements

Table 11. Proportion (P_{fix}) and amount of plant N derived from N_2 fixation by crop legumes growing in farmers' fields, and potential contributions of fixed N to soil reserves following seed harvest[a]

Species	Crop N	N_2 fixation		Seed N	N-balance	Reference
		P_{fix}	Amount			
	(kg N ha^{-1})	(%)	(kg N ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	
Cool-season						
Pea	220 - 227	60 - 81	133 - 183	135 - 162	-2 to +21	Peoples et al. (1995)
Lupin	46 - 199	65 - 91	36 - 181	nd[b]	nd	Unkovich (1991)
	241 - 372	78 - 88	188 - 327	126 - 170	+62 to +157	Unkovich et al. (1994)
Faba bean	61 - 171	62 - 76	38 - 130	42 - 74	-460 + 56	Rochester, Gault and Peoples, unpubl.
Warm-season						
Soybean	33 - 132	45 - 74	15 - 98	nd	nd	Bhromsiri and Peoples, unpubl.
	330 - 348	13 - 72	44 - 250	178 - 181	-134 to +69	Peoples et al. (1994b)
Green gram	nd	6 - 81	nd	nd	nd	Bushby and Lawn (1992)

[a] Apart from the data of Bhromsiri and Peoples, which relate to soybean grown in farmers' fields during the late rainy season in northwest Thailand, all other measurements come from commercial crops in Australia.
[b] nd = not determined.

were met by N_2 fixation, some fell below 25% (Table 12). Many of these low measurements were reported for *Acacia* spp. In one instance (Hamilton et al., 1993), low P_{fix} values and small inputs of fixed N reflected recovery of the understory legumes after burning and a low density of acacia within the temperate forest. Other examples of low reliance of *Acacia* upon N_2 fixation come from arid, harsh conditions (e.g. Schulze et al., 1991; Shearer et al., 1983), however, species such *Prosopis glandulosa* demonstrated a higher symbiotic capacity in these same environments (Table 12). In the study of Shearer et al. (1983), in a desert ecosystem in California, estimates of P_{fix} for *P. glandulosa* were 40 to 60% at 6 of the 7 sites examined. Growth and N accumulation was monitored at one of the sites where 60% of the plant N was calculated to be from N_2 fixation, and an annual input of 40 kg N ha^{-1} was calculated. This represented a remarkable contribution by BNF in an inhospitable environment.

In general, levels of N_2 fixation tended to be highest in humid, more favorable environments where trees were actively managed to provide mulch or animal forage and where, presumably, N demand was greater than in undisturbed or other low productivity ecosystems.

Contributions of BNF to the soil N pool and associated rotational effects

The increased crop yields that are widely observed following N_2-fixing associations may arise from breaking cycles of pests and diseases, through changes in soil microbial, chemical or physical characteristics or through encouraging the activity of soil macrofauna such as earthworms (Kundu and Ladha, 1994; Peoples and Craswell, 1992; Wani et al., 1995). But most often rotational benefits can be attributed to an improvement in the N economy of soils. The key to the long-term sustainability and productivity of soils is organic matter, in particular organic C and N. Examples are presented of the use of legumes in Australian agriculture to illustrate the role played by BNF in contributing N to soil.

In the western and southern parts of the Australian wheat belt, annual pasture legumes (predominantly subterranean clover and medics) were introduced into pastures grown in rotation with crops in the 1940's and 50's (Reeves, 1991). More recently perennial legumes, in particular lucerne, have also been used. These legume-based pasture systems can be very successful in increasing total (organic) soil N (Dalal et al., 1994). Annual increments of soil N of between 25 and 100 kg N ha^{-1} appear to be common in subterranean clover-based pastures (e.g. Fig. 3; Simpson et al., 1973a), but average rates of soil N accretion much greater than 100 kg N ha^{-1} have been report-

Table 12. Proportion (P_{fix}) and amount of plant N derived from N_2 fixation for legume forages and cover crops, and for N_2-fixing trees growing in farmers' fields or commercial plantations

Species	Legume N-yield (kg N ha^{-1})	N_2 fixation P_{fix} (%)	N_2 fixation Amount (kg N ha^{-1})	Reference
Forage legumes				
Lucerne - grazed	174	42	74[b]	Peoples and Gault, unpubl.
- cut for hay	185	57	105[b]	
Medicago spp.	nd[a]	7 - 100		Sanford et al. (1994)
Subterranean clover	nd	0 - 100		Sanford et al. (1994)
	11 - 141	68 - 90	10 - 95[c]	Peoples and Gault, unpubl.
Trifolium michelianum var. *balansae*	nd	0 - 100		Sanford et al. (1994)
Lotus spp.	nd	1 - 100		Sanford et al. (1994)
Centrosema spp.	nd	37 - 71		Peoples, unpubl.
Legume cover-crops				
Calopogonium/ Peuraria spp.	nd	9 - 91		Faizah and Peoples, unpubl.
Trees and shrubs				
Acacia spp.	<1	21 - 48[d]	<1[d]	Hamilton et al. (1993)
	nd	34 - 95		Peoples, unpubl.
	nd	2 - 71		Schulze et al. (1991)
	nd	0		Yoneyama et al. (1993) / Shearer et al. (1983)
Albizia falcataria	nd	43 - 80		Peoples, unpubl.
Aeschynomene spp.	nd	75 - 94		Yoneyama et al. (1990)
Casuarina spp.	nd	65 - 90		Yoneyama et al. (1990)
Calliandra	nd	20 - 47		Peoples, unpubl.
Gliricidia	nd	32 - 88		Peoples, unpubl.
	nd	0		Yoneyama et al. (1993)
Leucaena	nd	59 - 100		Yoneyama et al. (1990, 1993)
Sesbania spp.	nd	61 - 100		Yoneyama et al. (1990, 1993)
Prosopis glandulosa	nd	31		Schulze et al. (1991)
	nd	2 - 61	40[c]	Shearer et al. (1983)

[a] nd = not determined.
[b] Dryland lucerne, one year after establishment under a wheat crop receiving different management in adjacent fields. Measurements of N_2 fixation represent cumulative data from 5 samplings taken during a growth period of 135 during spring and summer (September to February).
[c] Averaged over entire growing season.
[d] The range in P_{fix} values reflect different periods after fire (12–27) months). Amount of N_2 fixed were low due to low plant density and slow growth of understorey legumes in the temperate forest.

ed under lucerne despite the removal of large amounts of shoot N by grazing animals or as hay (Gault et al., 1995; Holford, 1981). However, once the pasture phase is replaced by cereal cropping, N fertility quickly declines (Fig. 3). Thus, the system demands alternating pasture-cropping phases.

Effects of annual crop legumes on soil N are not so clear cut. A number of trials (Dalal et al., 1994; Reeves et al., 1984; Strong et al., 1986) were unable to detect consistent effects of prior legume crop on levels of total soil N. On the other hand, Rowland (1987) reported that total soil N increased in long-term lupin-wheat rotations. There are a number of reasons why

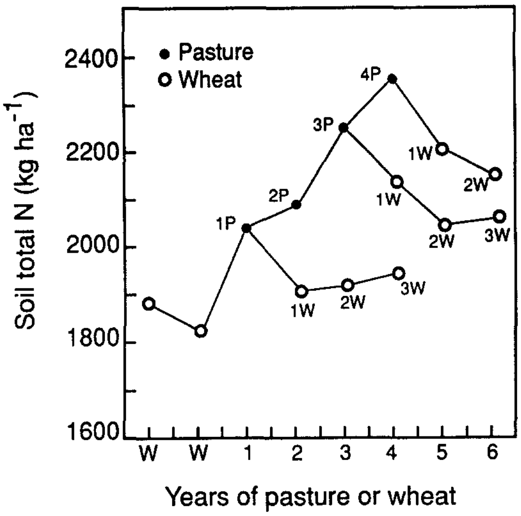

Fig. 3. Changes in levels of total soil N in the southern wheat belt of Australia following different numbers of years of legume-based pasture (P), or wheat (W) (redrawn from Reeves, 1991).

the net effects of crop legumes on total soil N may be difficult to observe:

(i) In virtually all studies of crop legume-cereal rotations, the legumes have been grown for a single season. By comparison, pasture legumes are more likely to be grown for a number of seasons. Holford (1981) found that 2 to 3 years of lucerne was required to increase levels of total soil N significantly. The study of Rowland (1987), in which lupin increased total soil N, was long-term, not a one-year experiment. Thus, it may. be unreasonable to expect to detect significant differences in soil N following a single legume crop.

(ii) Measurements of the small increments in total soil N, likely to accrue a in one-year or a short-term experiment, is technically very difficult.

(iii) Soils are normally cultivated in the fallow period between the legume crop and the following cereal crop, thereby encouraging rapid transformations of the N in legume residues to mineral forms.

(iv) Grain legumes are usually grown in soils that have been cultivated and fallowed. Consequently, nitrate levels may be sufficiently high to inhibit or delay nodulation and so depress N_2 fixation potential.

(v) A large proportion of the N accrued by the legume during growth is removed with the harvested seed (see equation (1) and related discussion above).

There may be more appropriate indices of the benefits of legumes on the soil N pool than measurement of total soil N. A number of rotational trials has demonstrated that legumes can increase the capacity of soils to supply plant-available N regardless of whether there are detectable changes in total soil N or not. The ability of legumes to improve soil reserves of readily mineralizable organic N have been reported for crop legumes (Dalal et al., 1994; Herridge et al., 1993; Wani et al., 1994), temperate and tropical pasture species (Bromfield and Simpson, 1973; Dalal et al., 1994; Thomas and Lascano, 1994), and alley cropping systems (Haggar et al., 1993).

One of the most consistent effects of both crop and pasture legumes is to increase plant-available (nitrate) N in the soil (Table 13). In the studies summarized in Table 13, nitrate-N levels in soil immediately following legumes were between 14 and 77 kg N ha^{-1} greater than the levels after non-legumes (usually measured to a depth of 60 or 120 cm). This extra nitrate, detectable even during growth of the legume, results from a reduced use of soil nitrate ("nitrate-sparing", Evans et al., 1991; Herridge et al., 1994b; Herridge and Bergersen, 1988), the possible release of products of N_2 fixation from nodulated roots (Ofosu et al., 1992, 1993; Pothet al., 1986; Sawatsky and Soper, 1991), or from N mineralized from fallen leaves or roots and nodules lost during growth and development. After a period of time the differences in levels of soil nitrate between legume and non-legume plots usually increase as N contained in the legume residues is released (Table 13).

Few studies have attempted to quantify the relative benefits of fixed or spared N, but one investigation (Chalk et al., 1993) concluded that in the case of a lupin crop, fixed N from fallen leaves and roots, and unutilized soil nitrate contributed in approximately equal proportions to the N benefit to a subsequent cereal crop. However, another study of the residual benefit of vetch (Danso and Papastylianou, 1992), attributed the 61% improvement in N accumulated in barley (*Hordeum vulgare*) following vetch compared to barley after oats (*Avena sativa*), to a reduced uptake of soil N by vetch rather than a release of fixed N.

The combination of conserved soil N, greater mineralization potential and return of fixed N might explain why the benefits of crop legumes to subsequent non-legume crops can be considerable (e.g. Doyle et al., 1988; Peoples and Craswell, 1992; Wani et al., 1995), even when there are apparently only modest returns of fixed N in vegetative residues (Evans et al., 1991; Herridge et al., 1994b). However, rotational benefits might also be greater than expected from calculations of the apparent return of fixed N to soil because estimates of

Table 13. Examples of the increased levels of soil nitrate often detected after growth of a legume

Species	Additional soil nitrate[a] (kg N ha^{-1})		Reference
	Post-harvest	Pre-sowing	
Crop legumes			
Chickpea	+14	+46	Herridge et al. (1994b)
Lupin	+34	nd[b]	Reeves et al. (1984)
Pea	+28 to +38	nd	Jensen and Haahr (1960)
Soybean	+23	+62	Herridge (1987)
Green gram	+26	+57	Doughton and Mackenzie (1984)
Black gram	+38	+68	Doughton and Mackenzie (1984)
Pigeon pea	+15 to +59	nd	Ladha et al. (1995)
Forage legumes			
Subterranean clover	nd	+100 to +150[c]	Angus, Koetz and Peoples, unpubl.
Medicago scutellata	+24[d]	+46[d]	Ladd et al. (1986)
Siratro	+26[e]	nd	Ladha et al. (1995)
Crotalaria	+19 to +77[e]	nd	Ladha et al. (1995)
Clitoria	+25 to +54[e]	nd	Ladha et al. (1995)

[a] Calculated as the difference between the levels of soil nitrate after a legume and after a cereal crop or a period of fallow. Measurements were taken either immediately after growth of a legume, or just prior to sowing a following crop.
[b] nd = not determined.
[c] Difference between autumn buildup of soil nitrate after growth of subterranean clover-dominant pasture or following a period of bare-fallow the previous spring (i.e. no legume growth). The range in soil nitrate levels reflect different clover contents (70–100%) that resulted from use of selective herbicides.
[d] Results were similar irrespective of whether levels of soil nitrate after a pure legume sward were compared with a mixed legume-grass pasture, or wheat.
[e] Levels of soil nitrate at the end of the growing season (following the last cut) were compared with soil under a weedy fallow.

N_2 fixation have almost always been based solely on measurements of shoot N. The contributions of roots and nodules have often been overlooked as a potential source of N. Estimates of amounts of N present in nodulated roots determined from field excavations of root systems of various crop legumes have ranged from < 15 kg N ha^{-1} (Bergersen et al., 1989; Kumar Rao and Dart, 1987) to between 30 and 50 kg N ha^{-1} (Chapman and Myers, 1987; Unkovich et al., 1994). Commonly, such amounts of root N represent < 15% of total plant N. Yet a recent study on lupin using ^{15}N has indicated that the total below-ground N may be almost three-fold higher than might be calculated from N contained in recoverable root material (Russell and Fillery, 1994a). If this finding is applicable to a range of other legumes, then past determinations of the return of fixed N to soil have been greatly underestimated. There could also be considerable rotational benefits from using abundantly nodulated legume genotypes (Song et al., 1994; Wani et al., 1995) simply because they partition relatively more crop N below-ground (Song et al., 1994).

Although this discussion has focussed on the positive aspects of legumes on the N-economy of soils, it should also be acknowledged that there are potential risks associated with a buildup of soil mineral N. The accelerated acidification of many soils under legume-based improved pastures and crop legume-cereal rotations in the winter-dominant rainfall regions of Australia (Coventry and Slattery, 1991; Ridley et al., 1990ab; Willlams, 1980) has largely been attributed to the mismanagement of legume-derived N, inefficient utilization of plant-available soil N and leaching of nitrate (Helyar, 1991). Based on the assumption that nitrate leaching accounts for that proportion of observed soil acidification not attributable to the addition of organic acids or ion removal in agricultural produce, it has been estimated that between 14 and 80 kg nitrate-N ha^{-1} yr^{-1} might be leached from soils in the

500 to 800 mm rainfall belt of southeastern Australia. This proposition is supported by:

(i) The finding that soils acidify more slowly under perennial than annual pastures (Ridley et al., 1990b) - it is presumed that perennials have a greater capacity to utilize soil nitrate and water throughout the year and so the opportunity for nitrate loss is minimized.

(ii) The pattern of nitrate distribution under annual subterranean clover-based pastures - there are regular flushes of mineral N in the soil surface as legume residues decompose following each growing season (Table. 13). The appearance of "nitrate bulges" at depth (Peoples et al., 1995) strongly suggests leaching processes.

That the mismanagement of legume N could have such an impact on soil chemistry in a temperate environment is reason for caution in the humid tropics where there is rapid decomposition of legume residues and a high potential for nitrate leaching (George et al., 1993). Where it is intended that BNF will be used as a primary source of N to improve soil fertility, the legume-derived N will need to be managed well and attention should be given to closing "windows for nitrate loss" (Helyar, 1991).

Utilization of fertilizer or organic sources of N

Maximizing N gains through the use of legumes or *Azolla* not only entails maximizing N_2 fixation, but also requires that recovery of N is optimized. The N transformations occurring during breakdown of leguminous or *Azolla* material are influenced by residue management and soil physical and chemical properties. In rice cropping systems, the dominant N transformations will be depend on whether soils are flooded immediately or remain aerobic (George et al., 1992). The rate of decomposition may be modified by lignin and polyphenol, content (Becker et al., 1994b; Fox et al., 1990; Handayanto et al., 1994) and soil pH, but it is the tissue N concentration (C:N ratio), soil temperature and water status which are the primary factors influencing mineralization and release of legume and *Azolla* N (Peoples and Craswell, 1992; Sandhu et al., 1990; Watanabe et al., 1991). This section compares the recovery of N derived from *Azolla* or legume sources with fertilizer N for a number of important agronomic systems.

Cropping systems

Tropical and warm season crops

Upland rice. In a study in Indonesia, Sisworo et al. (1990) compared the utilization by upland rice of 2 sources of legume N (cowpea and soybean) and urea. Up to 28% of the cowpea N was recovered by a following crop of upland rice and a further 45% was recovered by 5 successive crops over a 2-year period (Table 15). This compared with a total recovery of the soybean or urea N of only 23% over 2 years. Utilization of fertilizer by upland crops elsewhere in the tropics have ranged from 12 to 74%, with poor recoveries reportedly occurring under both dry and very wet conditions (Myers, 1988).

Flooded rice. When a legume is grown as a green manure, either the entire crop is returned, or quantities of leaf mulch are applied to soil. The amount of N and the N concentration in such material is generally high and rates of decomposition can be very rapid following incorporation in tropical flooded soils (Becker et al., 1994a; Ventura and Watanabe, 1993). Studies comparing recoveries of ^{15}N-labelled leguminous green manure with urea fertilizer indicate that between 21 and 62% of the legume N and 24 to 51% of the fertilizer N can be taken up by a following rice crop (Table 14). Not only was the recovery of legume N by rice either comparable or superior to that of inorganic fertilizer N, but it appeared also to be less subject to loss than urea-N (Table 14).

Decomposition of *Azolla* is also rapid and up to 66% of *Azolla*-N has been recovered in subsequent rice crops depending upon the method and time of incorporation, and the amount of *Azolla* applied. In some experiments, rice uptake of N derived from *Azolla* was greater than fertilizer (39–63% cf 27–48% respectively) because of reduced losses of *Azolla*-N (0–11% cf 30–32%; Watanabe et al., 1989), but a series of co-ordinated studies across 6 rice-growing countries showed that the recoveries of N from both sources were similar when averaged across a wide range of environmental and soil conditions (Kumarasinghe and Eskew, 1993; Table 14).

In flooded systems, fertilizer-N is predominantly lost via ammonia volatilization and denitrification. Factors such as fertilizer composition, rate, time and method of application, floodwater depth, and algal growth exert their influences on these two loss processes through the primary variables - ammoniacal N

Table 14. Recovery of N from organic and inorganic sources by tropical-warm season cereal crops

Crop	Organic residue	Plant uptake of N (% of applied)	N Loss (% applied)	Fertilizer[a]	Plant uptake of N (% of applied)	N Loss (% applied)	Reference
Rice							
Upland	Cowpea	28 (1st crop)		Ur	19 (1st crop)		Sisworo et al. (1990)
		73 (over 2 yr)			23 (over 2 yr)		
	Soybean	14 (1st crop)					
		23 (over 2 yr)					
Flooded	*Crotalaria*	21	29	Ur	24	36	Roa and Shinde (1991)
	Aeschynomene	42 - 49	7 - 9	Ur	28 - 31	31 - 50	Diekmann et al. (1993)
	Sesbania spp.	40 - 47	13 - 16				
		12 - 34	0 - 15	Ur	20 - 31	30 - 33	Becker et al. (1994a)
		34	28	Ur	24	36	Rao and Shinde (1991)
		62[b]		Ur	51[b]		Ventura and Watanabe (1993)
	Green manures		14[c]	Ur		35[c]	Becker et al. (1995)
	Azolla	66[b]					Ventura and Watanabe (1993)
		39 - 63	0 - 11	Ur	27 - 48	30 - 32	Watanabe et al. (1989)
		40[d]		Ur	36[d]		Kumarasinghe and Eskew (1993)
				Ur	5 - 57	14 - 85	Peoples et al. (1994e)
Maize							
Broad-acre	Groundnut	6–10					McDonagh et al. (1993)
	Lucerne	17 - 25	25 - 32				Harris and Hesterman (1990)
	Lucerne - shoot	51 - 63[e]		AS	45 - 65		Hesterman et al. (1987)
	Lucerne - root	36 - 44[e]					
	Soybean	18 - 19[e]					
				AN	45 - 53	14 - 41	Peoples et al. (1994e)
Alley crop	*Erythrina*	12					Haggar et al. (1993)
	Gliricidia	27					
	Leucaena	5 - 9	25 - 34	AS	43 - 50	14 - 35	Xu et al. (1993a,b)
		6 - 18					Sanginga et al. (1995)

[a] Ur - urea; AS = ammonium sulphate; AN = ammonium nitrate; KN = potassium nitrate.
[b] Mean of 9 rice crops.
[c] Mean of 18 observations from 10 studies using various legume green manure sources.
[d] Mean under a wide range of environmental and soil conditions across 6 countries.
[e] Uptake of fixed N represented 33–40% and 3–5% of the N applied as lucerne or soybean respectively.

concentrations, the pH and temperature of floodwater, and windspeed (Buresh and DeDatta, 1991; Peoples et al., 1994e). The extent of losses from fertilizer N in rice-based systems can range from 14 to 85% (Table 15). Several field experiments have shown that adding leguminous or *Azolla* green manure with urea to flooded rice can enhance grain yield and reduce, but not eliminate, loss of urea N (Becker et al., 1994a; Buresh and De Datta., 1991; Diekmann et al., 1993; Kumarasinghe and Eskew, 1993). Application of green manure reduced floodwater pH and partial pressure of ammonia, and consequently reduced the potential for ammonia volatilization. The lower floodwater pH was attributed to production of CO_2 during decomposition of organic matter (Diekmann et al., 1993).

Maize. While uptake of fertilizer N by maize can be in the range of 40 to 50% regardless of whether it is grown as an alley crop or not (Table 14), the potential for losses of fertilizer N can be substantial (particularly in tropical soils, e.g. 36–153 kg N ha^{-1} leached below 150 cm, Poss and Saragoni, 1992), and up to 30 to 40% of the N applied might be lost from the plant-soil system (Table 14). Direct comparisons of total recoveries of legume N and fertilizer N (plant uptake of N + N remaining in soil) have been undertaken for tree legume prunings (Xu et al., 1993ab), and lucerne

Table 15. Recovery of N from organic and inorganic sources by temperate cereals

Crop	Organic residue	Plant uptake of N (% of applied)	N Loss (% applied)	Fertilizer[a]	Plant uptake of N (% of applied)	N Loss (% applied)	Reference
Wheat							
	Lupin	9 - 27	0 - 13				Russell and Fillery (1994b)
	Pea	26		AN	42		Rees et al. (1993)
	Lentil residues	6	0	AS	34	30	Bremer and van Kessel (1992)
	Lentil green manure	19	24				
	Medics	20 - 28	3 - 20				Ladd et al. (1983)
		16 - 19	15 - 17	Ur/KN/AS	41 - 50	16 - 22	Ladd and Amato (1986)
	Subterranean clover	6	0				Peoples et al. (1994a)
				KN/AS/AN	38 - 45	7 - 40	Peoples et al. (1994e)
				Ur	20 - 58	23 - 46	Peoples et al. (1994ae)
Barley							
	Pea	15	10				Jensen (1994b)
		6 - 16	5 - 19				Jans-Hammermeister et al. (1994)
	Common bean	17	1				Müller and Sundman (1988)
	White clover	24	11				
	Red clover	20	6				
	Subterranean clover	18	5				
				KN	53 - 62	10 - 14	Peoples et al. (1994e)
				Ur	13 - 54	9 - 36	
Oats							
	Soybean	6 - 8					Bergersen et al. (1992)

[a] Ur = urea; AS = ammonium sulphate; AN = ammonium nitrate; KN = potassium nitrate.

(Harris and Hesterman, 1990): These studies suggested that losses of N from both the tree legume mulch and lucerne were similar to fertilizer N (Table 14). However, in alley-cropping systems, some of the N lost from the rooting zone of the interrow maize might be captured by the roots of neighbouring tree hedgerows and so be retained within the system (Sanginga et al., 1995).

While uptake of fertilizer and legume N can be similar in some maize cropping systems, the utilization of legume N by maize may be relatively poor in other circumstances (commonly <20% of the N applied, Table 14). This appears to contradict the higher productivity and increased N harvest in maize crops commonly observed where legume residues have been returned (Giller and Wilson, 1991; McDonagh et al., 1993; Xu et al., 1993b). It would seem that even though the immediate transfer of legume N to a following crop might be restricted, the accumulation of a readily-mineralizable organic N pool in soil and higher N availability becomes a more important determinant of productivity than timing of release (Haggar et al., 1993).

Temperate crops

Wheat, barley and oats. Although utilization of N from crop and pasture legume residues by temperate cereals (6–28%, Table 15) are less than those reported for warm season and tropical crops (Table 14), this might still represent 20 to 40 kg N ha^{-1} (Ladd et al., 1983; Russell and Fillery, 1994b), and contributions of legume N to the N-economy of a following crop may be high (up to 33% of a cereal's N requirements; Bergersen et al., 1992). A comparison of recoveries of pasture legume residues and fertilizer N under Mediterranean climatic conditions (i.e. cool wet winter, hot dry summer, Ladd and Amato, 1986) indicated that a following wheat crop utilized more fertilizer N (41–50%) than legume N (16–19%, Table 15). Similar conclusions were obtained from comparisons of wheat recoveries of fertilizer or crop legume N (Bremer and van Kessel, 1992; Rees et al., 1993). However, despite a smaller uptake of legume N in a following crop (Table 15), large quantities of the applied legume N appear to be immobilized in microbial biomass and semi stable organic materials in soil during decomposition (Ladd et al., 1986; Jensen, 1994a,b), so that losses of N from plant and soil pools during growth of a subsequent crop (typically < 15%) can be smaller than from fertilizer in similar environments (up to 30–50% of the N applied, Table 15). Nonetheless, some studies indicate that significant losses of legume N can occur in unplanted soils (Jensen, 1994a; Russell and Fillery, 1994b), or when applied as a green manure mulch rather than returned as crop residues (Bremer and van Kessel, 1992; Table 15).

Forage systems

Appreciable amounts of organic N can accumulate in soils under legume-based pastures (Holford, 1981; Fig. 3; Simpson et al., 1974a; Vallis, 1972), but legumes also improve forage quality and intake and increase overall productivity of, and nutrient cycling within, pastures (Peoples and Craswell, 1992; Thomas and Lascano, 1994). Legumes also have the ability to rehabilitate degraded land by improving the physical, chemical and biological characteristics of soil (Thomas, 1995). Many of the benefits have been attributed to the ability of legumes to release N to soil and transfer N to grasses in a pasture (Ledgard and Steele, 1992). Determinations of the importance of transfer of fixed N to associated grasses range from agronomically insignificant amounts (< 10 kg N ha^{-1}) to > 100 kg N ha^{-1}; representing between 1 and 48% of the N_2 fixed (Table 16). Some of the upper estimates of N transfer seem surprisingly large; however, between 40 and 70% of total plant N can be below-ground in pasture legumes (Zebarth et al., 1991), and there may be a considerably larger pool of fixed N available for release than might be determined from measurements of shoot N.

There are some methodological problems in interpreting N-isotope data from experiments such as those presented in Table 16 (Chalk and Smith, 1994), but it appears that transfer of legume N could play an important role in meeting a proportion of the N requirements of grasses in pasture systems (Table 16). However, the rate at which transfer occurs may not always be rapid or the amount large (Vallis, 1983; Ledgard et al., 1985). The extent of N transfer is likely to be influenced by environmental factors, pasture nutrition and growth potential, and grazing management (Simpson et al., 1974a,b).

Fixed N could be returned to soil in a pasture or transferred to neighboring grasses via a number of different pathways.

Below-ground:
(i) Excretion of N into the legume rhizosphere (Ta et al., 1986)
(ii) Decomposition of roots and nodules sloughed off during growth (Russelle et al., 1994)
(iii) Direct interconnection of grass and legume roots via mycorrhizal fungi (Haystead et al., 1988)
(iv) Via the action of soil macro- and micro-fauna grazing legume roots and nodules.

Above-ground:
(i) Decomposition of leaf litter on the soil surface
(ii) Leaching of compounds from herbage as rainwater passes through the canopy
(iii) Volatile losses of ammonia from legume foliage reabsorbed by grass (Denmead et al., 1976)
(iv) Via excreta from grazing animals.

Only one of the studies summarized in Table 16 considered the return of fixed N in dung and urine from grazing animals (Ledgard, 1991). Despite the opportunities for losses ranging from 3 to 50% of the N excreted by the annual which arise from localized return of high rates of N (Bussink, 1992; Peoples et al., 1994e; Steel and Vallis, 1988; Vallis et al., 1985), some 60 kg N ha^{-1} yr^{-1} was estimated to have been transferred (22% of BNF and 48% of total N transferred, Table 16) from white clover to perennial ryegrass (*Lolium perenne*) under grazing by dairy cattle.

N-fertilizers are often applied to pastures in intensively grazed systems to promote growth during the late autumn to early spring. Rates exceeding 200 kg N ha^{-1} are not uncommon (particularly in Europe, Bussink, 1992; FAO, 1992b). Annual losses from 4 to 90 kg fertilizer-N ha^{-1} have been reported from fertilized pastures under a range of different environmental conditions, depending upon the form of fertilizer used and its application rate (Black et al., 1985; Bussink, 1992; Catchpoole et al., 1983; Jordan, 1989; Ruz-Jerez et al., 1994). A number of grazing trials have compared N losses from fertilized grass swards with those from clover-based pastures. Although consistent differences in leaching losses between fertilizer or legume N sources have not been observed (Cuttle et al., 1992), less N was lost in absolute terms as gaseous emissions from the clover-grass swards (Jarvis et al., 1989; Parsons et al., 1990; Ruz-Jerez et al., 1994),

Table 16. Transfer of legume N to associated grasses in mixed pasture swards via shoot residues, belowground organs, or the action of grazing animals

Species	N_2 fixed	N transferred			Reference
		Amount	As % BNF	% grass N	
	(kg N ha^{-1})	(kg N ha^{-1})	(%)	(%)	
Lucerne	54	7	13	68	Brophy et al. (1987)
	58 - 258	1 - 27	1 - 10	5 - 56	Ledgard and Steele (1992)
White clover	227 - 283	11 - 52	5 - 18	14 - 55	Boller and Nosberger (1987)
	269	70	26	27	Ledgard (1991)
(*via animals*)		(*60*)[a]	(*22*)	(*23*)	
Red clover	165 - 373	14 - 42	4 - 25	47 - 48	Boller and Nosberger (1987)
Birdsfoot trefoil	31	5	10	17	Brophy et al. (1987)
Desmodium spp.	na[b]	5 - 7	na	1 - 2	Vallis (1982)
Siratro	na	7 - 9	na	2 - 3	

[a] Italicised data in parentheses represent additional transfer via animal excreta, i.e. total transfer (below-ground + animal contribution) = 130 kg N or 48% of N estimated to be fixed.
[b] na = not available.

which has important implications for minimizing agriculture's contribution to the release of "greenhouse" and ozone depleting gases in the form of oxides of N (Peoples et al., 1994e). However, if denitrification was expressed as a proportion of annual N inputs, losses may be similar irrespective of whether N was supplied to pastures by N_2 fixation or fertilizer (Ruz-Jerez et al., 1994).

Agroforestry systems

Apart from the use of N_2-fixing trees as a N source in the alley cropping systems (above) woody species are an invaluable source of high-quality forage, fuel and timber, and are used to regenerate degraded, or erodable agricultural land (Giller and Wilson, 1991). N_2-fixing trees can also play an important role in providing N in traditional farming practices. *Casuarina* for example is planted in cleared areas of the highlands in Papua New Guinea and grown for 5 to 10 years until cleared for firewood or timber. The land is then planted to yams and other crops which benefit from the N buildup (Torrey, 1982).

While comparisons between the recovery and utilization of fertilizer N or leaf litter N have not be undertaken for agroforestry systems outside alley cropping, some information is available concerning the return and release of N from woody species. Measurements taken in stands of *Leucaena* in the dry tropics and *Casuarina* in temperate environments indicate that leaf and litterfall can contribute 10 to 25 t ha^{-1} of organic matter to soil annually, representing 250 to 290 kg N (Sandhu et al., 1990; Torrey, 1982). Although decomposition of this litter under generally harsh conditions is likely to be slower than in the intensive agricultural systems described above, a high proportion of the total litterfall N might be expected to be released to the soil each year (Sandhu et al., 1990), representing a major contribution to the cycling of N in degraded and infertile environments.

Can the use of BNF as a source of N improve farm profitability?

Yield increases by crops following *Azolla* or legumes are often equivalent to applications of between 30 and 80 kg fertilizer N ha^{-1} (Jensen and Haahr, 1990; McDonagh et al., 1993; Peoples and Craswell, 1992; Watanabe, 1982). Equivalence values of 100 kg fertilizer N ha^{-1} or greater have also been reported (Becker et al., 1995; Herridge, 1987; Ladha et al., 1988; Wani et al., 1995), depending upon the amount of N returned to the soil in organic material, or whether the N_2-fixing system is grown for only 1, or for 2 or more consecutive years prior to planting a cereal (Paré et al., 1993). These measures of fertilizer equivalence can provide a site- and season-related estimate of the potential economic value of BNF in a rotation. There are however, other factors that should be considered such as costs of production, opportunity costs of alternative actions, and return from saleable produce. When such an exercise was undertaken for *Azolla* in flooded rice systems, it was concluded that *Azolla* was not a cost-effective substitute for urea fertilizer while fertilizer prices remain low (Rosegrant and Roumzasset, 1988). High labor costs and high opportunity costs of land use were identified as two of the major constraints to the economic feasibility of using *Azolla* as a green manure. This may also be true for other sources of green manures, if grown at the expense of an alternative cash or food crop. Nonetheless, there are situations where the potential contributions of green manures may be very important, and where fertilizer N is not a viable option. One such example may be in single-crop rainfed lowland systems where flood-tolerant legumes can provide valuable sources of green manure N. In these areas, short-term waterlogging occurs during the transition between dry and wet seasons. Alternative crops cannot be grown and farmers are reluctant to apply fertilizer N because of adverse climatic conditions and lack of consistent fertilizer response (Ladha et al., 1992). Another example might be in rubber and oil palm plantations where the beneficial effects of perennial legume cover crops can extend for up to 20 years after planting and be equivalent to the total application of between 840 and 1100 kg fertilizer N ha^{-1} (Giller and Wilson, 1991; Peoples and Herridge, 1990).

It should be much easier to demonstrate the financial benefits of utilizing BNF as a source of N in systems where the N_2-fixing component itself contributes directly to the production of a saleable commodity (seed from crop legumes, livestock production from legume-based pastures). To illustrate this point, a case study is presented below from an important cropping region of Australia.

In the northern wheat belt of New South Wales, an area of around 1 million ha, farmers have traditionally produced large tonnages of high protein wheat with little use of either pasture or grain legumes, or fertilizer N. Many of the soils of the region, particularly the deep, friable black earths, were initially naturally fertile and there seemed no need to add additional N (McGarity, 1975). However, evidence that soils were becoming progressively less able to supply N for cereal production can be found in the results of fertilizer N trials conducted over a 30 year period. In the early 1960's, there was only a low frequency (22%) of economic responses in wheat to applied fertilizer (Colwell and Esdaile, 1966). Ten years later, this figure had almost doubled to 40% (Doyle, 1977), and by the 1980's, responses had risen to 70% (Holford et al., 1992).

A survey of farms in the region between 1983–85 estimated that cereal yield was depressed by 45% because of N deficiency (Martin et al., 1988). Investigations of management practices revealed that 45% of farmers used fertilizer N, but rates of application were generally low (8–11 kg N ha^{-1}). Not more than 8% of farmers surveyed used fertilizer N at realistic rates of 30 to 60 kg N ha^{-1}. Farmers practiced rotations, but for the most part, legumes were not included.

Thus, there was a need to change the agronomic practices that had become inappropriate once soil fertility was no longer high, and to promote the concepts of N management. In response to the crisis of widespread N-deficiency, and to farmer reluctance to use fertilizer N, a series of on-farm trials were commenced to examine the potential of chickpea as a commercial crop in the region and to assess its role as a rotation crop in wheat production systems. In these trials, yields of wheat were increased by 26 to 144% following chickpea (Herridge et al., 1994a). Following chickpea, and also long fallow, benefits were observed in the first wheat crop, but not in the second. These rotational experiments showed clearly that the improved wheat yields following chickpea could be explained in terms of increased availability of soil N (Herridge et al., 1994b).

The average yield figures for experiments conducted in the region between 1987 and 1992 were used to prepare an economic comparison of cropping systems based on wheat monoculture (W-W-W), chickpea (CP-W-W), or long fallow (F-W-W) (Table 17). Although the return from wheat following fallow was almost similar to wheat following chickpea, no income was generated in the first year so that the gross margin over 3-year period was identical to a continuous wheat system (Table 17). The economic analysis of the benefits of chickpea on wheat production indicated that the gross margin more than doubled over 3 years when chickpea was included (Table 17). For an average farmer in the region cropping 200 ha, replacement of every third crop with chickpea would, on current commodity prices, result in the overall farm gross margin increasing from A$26,600 to A$61, 900 (A$1.00 = US$ 0.74).

While similar average yield benefits from chickpea (around 40%) could be achieved with fertilizer applications of 60 to 80 kg N ha^{-1}, the net financial return from the additional wheat (A$ 125–130 ha^{-1} less fertilizer costs of A$50–65 ha^{-1} each annum) would still fall short of the impact of chickpea on farm profitability because of the price differential between the value

Table 17. Returns, costs and gross margins for three cropping systems in the northern cereal belt of New South Wales, Australia. Yields are averaged from on-farm experiments conducted over 5 years[a]

Item	Rotations based on					
	Wheat (W-W-W)		Chickpea (CP-W-W)		Fallow (F-W-W)	
	Yield ($t\ ha^{-1}$)	Value (A$)	Yield ($t\ ha^{-1}$)	Value (A$)	Yield ($t\ ha^{-1}$)	Value (A$)
Year 1	2.33	314	2.02	727	-	-
Year 2	2.24	302	3.18	429	3.37	455
Year 3	2.47	333	2.51	339	2.59	350
Total		949[b]		1495[b]		805[b]
Less fixed costs[c]		105		105		105
Less variable costs[d]		444		461		296
Gross margin over 3 years		400		929		404

[a] Wheat yields ranged from 1.43 to 4.34 $t\ ha^{-1}$ and chickpea yields ranged from 1.29 to 2.90 $t\ ha^{-1}$ (Herridge et al., 1994a).
[b] Based on 1993 on-farm selling prices for Australian standard white (A$135 t^{-1}), and chickpea (A$360 t^{-1}). [A$1 = US$0.74]
[c] Calculated at A$35 ha^{-1} $annum^{-1}$.
[d] Calculated at A$148 ha^{-1} for wheat and A$165 ha^{-1} for chickpea.

of wheat and chickpea (Table 17). However, even if total farm profits resulting from the use of fertilizer N matched or exceeded that achieved with chickpea or other legume rotations (Dalal et al., 1994), there would be eventual problems with buildup of cereal diseases, herbicide resistance of weeds and soil structural decline associated with a N-fertilized monoculture, which would provide sufficient economic justification in the long term to choose the BNF option.

Conclusions

Considerable inputs of biologically-fixed N can be achieved in almost all agricultural ecosystems through the activity of many different symbiotic associations. While the short term recovery of N from these biological sources may not always match fertilizer (particularly in temperate environments), there are consistent rotational benefits to subsequent cereal crops and evidence of significant transfers of fixed N to associated grasses in pastures. Without doubt, BNF improves the N economy of soils. This does not mean that these systems will always make large net contributions of N to soils in which they grow. What it does mean is that the N balance for a legume-cereal sequence for example will be more positive than for a cereal-cereal sequence in the same soil.

Evidence indicates that N derived from legume or *Azolla* sources might be less susceptible to losses than fertilizer N, and that long-term use of these organic materials results in the build-up of a reserve of readily mineralizable organic N. The use of BNF in a farming system can represent a profitable approach to arrest the decline of soil N fertility that inevitably accompanies intensive agriculture.

The nitrate "spared" and N released from crop legume residues and short duration green manures may be capable of meeting only part of the N demand of high-yielding cereal crops and supplementary fertilizer N applications may be required to provide optimal nutrition. However, the amount of N accrued in soil under pasture-ley systems, or where perennial legume cover-crops and tree legume leaf mulch are used, may be sufficient to satisfy subsequent crop requirements. Therefore, it should be possible to manage BNF to provide a renewable source of N to supplement or replace fertilizer N, and redress the deterioration of agriculture's resource base.

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