Plant and Soil **252:** 177–186, 2003.

How can increased use of biological N_2 fixation in agriculture benefit the environment?

Erik Steen Jensen[1] & Henrik Hauggaard-Nielsen
Organic Farming Unit, Department of Agricultural Sciences, The Royal Veterinary and Agricultural University, DK-2630 Taastrup, Denmark. [1]*Corresponding author**

Key words: biological diversity, biological nitrogen fixation, fertilizer N, gaseous N losses, leaching of nitrate, nitrogen cycling, soil fertility

Abstract

Asymbiotic, associative or symbiotic biological N_2 fixation (BNF), is a free and renewable resource, which should constitute an integral part of sustainable agro-ecosystems. Yet there has been a rapid increase in use of fertiliser N and a parallel decline in the cultivation of leguminous plants and BNF, especially in the developed world. Fertilisers have boosted crop yields, but intensive agricultural systems have increasingly negative effects on the atmospheric and aquatic environments. BNF, either alone or in combination with fertilisers and animal manures, may prove to be a better solution to supply nitrogen to the cropping systems of the future. This review focuses on the potential benefit of BNF on the environment especially on soil acidification, rhizosphere processes and plant CO_2 fixation. As fertiliser N has supplanted BNF in agriculture the re-substitution of BNF is considered. What is the consequence of fertiliser N production on energy use? The effect of fertiliser use on the release of the greenhouse gas CO_2 is estimated at approximately 1% of the global anthropogenic emission of CO_2. The role of BNF on nitrogen cycling, ammonia volatilisation, N_2O emission and NO_3 leaching suggests that BNF is less likely than fertilisers to cause losses during pre-cropping and cropping. Sometimes however the post-harvest losses may be greater, due to the special qualities of legume residues. Nevertheless, legumes provide other 'ecological services' including improved soil structure, erosion protection and greater biological diversity.

Introduction

Global terrestrial biological N_2 fixation (BNF) is between 100 and 290 million tonnes of N year^{-1} (Cleveland et al., 1999), 40–48 million tonnes year^{-1} of which is fixed by agricultural crops in fields (Galloway et al., 1995; Jenkinson, 2001). In comparison, 83 million tonnes year^{-1} are fixed industrially in fertiliser production (Jenkinson, 2001). BNF in various agro-ecosystems has been extensively reviewed (Boddey et al., 1998; Giller and Wilson, 1991; Ladha, 1998; Ledgard, 2001; Peoples et al., 1995).

Since atmospheric N_2 is a renewable resource, BNF in agricultural systems is a sustainable source of N in cropping systems (Bohlool et al., 1992). In contrast to the large amounts of fossil energy used for fertiliser N production in the Haber-Bosch process, the energy that drives BNF is virtually 'free' and derived from photosynthesis. For these reasons, BNF is the most 'environmentally friendly' approach to supplying N to agro-ecosystems.

As BNF is largely restricted to legumes in agro-ecosystems, replacing fertilizer N with symbiotically fixed N_2 may require a legume crop to be grown before, e.g. maize, as a green manure, intercropped with maize or grown alone. N_2 fixed by heterotrophic diazotrophs, e.g., in sugarcane (Boddey et al., 1995; this volume) or *Azolla–Anabena* introduced in flooded rice may complement soil and fertilizer N sources for these crops. Table 1 summarizes the major potential benefits and problems related to BNF on the environment.

Effect of the BNF process per se

Plants that assimilate $NH_4{}^+$ and legumes that fix N_2absorb more cations than anions, because as un-

---

* FAX No.: +45-35282175. E-mail: esj@kvl.dk

Table 1. Potential effects of biological N_2 fixation (BNF) on environmental parameters: ↑ – increase, ↓ – decrease

BNF process per se	Effect of reduced fertilizer production and application	Effect of BNF crops on N cycling of cropping systems	Non-N effects of BNF organisms
Soil acidification	↓ Fossil energy use	Pre-cropping/cropping period	Soil structure
↑ CO_2 fix./mol N ass.	↓ CO_2 emission	↓ N_2O emission	Break-crop effect
↑ Soil N uptake	↓ NO_x emission	↓ Ammonia volatilisation	Soil erosion control
		↓ N leaching risk	Deep rooting
		↓ Risk of N loss from GM[1] than NF[2]	Carbon sequestration
		Post-harvest period	Biodiversity
		↑ N_2O emission	
		↑ Ammonia volatilisation	
		↑ N leaching risk in intensive systems	
		↑ N-benefit to next crop	
		Long-term effects of BNF	
		↑Soil fertility building	
		↑Soil N supply power	
		↑Risk of N losses intensive systems	

[1] GM – Green manure/*Azolla*.
[2] NF – N-fertilizer (mainly ammonia or urea).

charged N_2 enters the root protons are excreted to balance the internal pH (Raven, 1986). Thus symbiotic N_2 fixation and ammonium assimilation cause soil acidification, whereas plants that assimilate nitrate raise the soil pH. As an example, a nitrogen-fixing alfalfa crop that yields 10 t ha^{-1} of green matter acidifies the soil to such an extent that 600 kg $CaCO_3$ ha^{-1} $year^{-1}$ would need to be applied to maintain constant soil pH (Israel and Jackson, 1978). Although the effect of BNF on soil pH is lower that that observed during ammonium assimilation (Marschner, 1995), both cause increased leaching of Ca and Mg ions.

Obviously, the acidifying effect of BNF may be beneficial in alkaline soils by solubilising nutrients, which would otherwise remain fixed. For example, more P may become available from rock phosphates due to the acidifying effect of legumes (Israel and Jackson, 1978), and in this sense legumes promote P use efficiency. As many tropical and other soils are already acid, further acidification may provoke aluminium and other toxicities (Israel and Jackson, 1978). Liming is an obvious solution to this problem but calcium carbonates are not always available. Other means such as recycling of crop residues are available (Greenwood, 1989), but the long-term effects of BNF on the soil acidification, *Rhizobium* survival and aluminium toxicity need to be addressed (Graham and Vance, 2000).

Acquisition of N_2, nitrate and ammonium requires energy and the reduction of between 6 to 12 kg of photosynthetic carbon is required to fix 1 kg N in the legume symbiosis (Marschner, 1995), though legumes are able to compensate the carbon cost of their microbial symbionts by increased photosynthesis (Paul and Clark, 1989). Some plants are able to assimilate a large amount of the nitrate taken up in the leaves, which significantly reduces the carbon cost (Marschner, 1995). Nevertheless, field experiments in which a number of legumes have been grown with or without abundant fertilizer N, consistently show that symbiotic yields are not lower than those of legumes fed with fertilizer nitrogen (Boddey et al., 2003; Sagan et al., 1993; Weber, 1966a and b).

It is well known that N_2 fixing plants exude greater amounts of amino acids into the rhizosphere than non-legumes (e.g., Brophy and Heichel, 1989; Rovira, 1956). Similarly, nodulated soybeans take up more soil N than non-nodulated and fertilised soybeans (Jensen and Sørensen, 1988), suggesting that BNF may enhance soil N use efficiency in certain cases. The effect may be the result of different compositions of plant root exudates of nodulated and non-nodulated soybeans. If the C/N ratio of exudates of the nodulated plants are lower than those of non-nodulated soybeans, less soil N will be immobilized in the nodulated rhizosphere and more could be taken up (Jensen and Sørensen, 1988). However, it may also be related to the so-called ‘starter-N’ effect in which the root growth, of legumes growing in soil at low mineral N contents, may be stimulated during early growth stages, resulting in an enhanced water and nutrient uptake and photosynthesis during later growth stages (Voisin et al., 2002)

Effects of fertiliser N manufacture, transport and application on the environment

At the cost of environmental degradation, fertiliser N has contributed to increased productivity of cropping systems. Special concerns include: (a) leaching of nitrate to groundwater, rivers, surface water and seas, resulting in eutrophication and gaseous losses via ammonia and nitrous oxide (N_2O); (b) losses of ammonia increase N deposition in natural ecosystems influencing nutrient balances and reducing biological diversity; (c) nitrous oxide is a powerful greenhouse gas, which contributes to depletion of tropospheric ozone; (d) the manufacture, transport and spread of fertiliser N consumes more energy than any other process in agricultural plant production in many areas of the world.

Global fertilizer N use was about 83 million tonnes of N in 1997/98 and it has been quite static in North America and Europe during the last decade (Figure 1). Most of the increase from 61 million tones year^{-1} in the early eighties to 83 million tones year^{-1} in 1998 was in Asia (Jenkinson, 2001, Peoples et al., 1995). As a result Africa, Latin America and Asia now used about 55% of the total fertilizer N produced (Peoples et al., 1995).

Reduced fossil energy use in crop production

Due to the high temperatures (up to 1200 °C) and high pressures (100–300 bar) required, reduction of N_2 to ammonia in the Haber-Bosch process is an energy demanding process, and the product, ammonia, is the basis of most commercial fertilizers. Natural gas is the main source of both feedstock and fuel for about 80% of the world's ammonia production, although in some parts of the world, e.g., China, coal is still used as the feedstock (Jenkinson, 2001). The amount of energy required to produce 1 kg of N in ammonia or urea is around 55 and 80 MJ, respectively, whereas ammonium nitrate is intermediate with 73 MJ per kg N (Mudahar and Higgnet, 1987). Approximately 60% of the total energy is used in the form of feedstock, 37% in heating the furnaces where hydrogen and carbon monoxide are produced from methane and steam. In 1988/89 the global energy use for fertilizer N production, packaging, transport and application (78 million t N) was estimated to be 6590 million GJ of which 83% was used in the production (Mudahar and Higgnet, 1987).

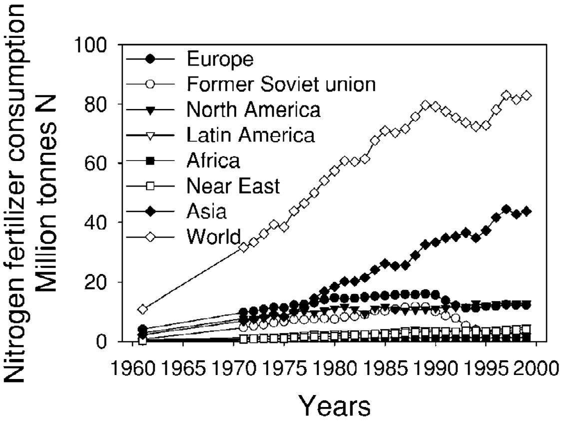

Figure 1. World nitrogen fertiliser production (1960–1998). Source: The International Fertilizer Industry Association (1998).

Even though fertilizer N manufacture, distribution and application constitutes only 1–2% of the total world energy consumption it is worth noting that agriculture complements fossil energy with energy from renewable energy sources. Nevertheless, reduced fertiliser application and increased reliance on BNF are worthwhile environmental goals. However, in soils of low fertility (Giller et al., 1997), it may not be possible to completely substitute fertiliser N with BNF.

Despite the fact that the substitution of fertiliser N with BNF will only have minor effects on the global energy balance, energy balances on farms may change significantly. Table 2 shows the energy use in grass silage production in organic and conventional production systems (Refsgaard et al., 1998). In the organic system, BNF in a grass–clover pasture is exploited, whereas fertiliser N is used in the conventional system. About 70% of the energy use in conventional silage production is for fertiliser N production, transport and application. Taking into account the difference in yield between the organic BNF-based and the conventional fertiliser-based grass production 0.7 versus 2.3 MJ is required per unit of feed produced (Table 2). Similarly, the energy costs of barley production were 18% lower per kg grain in the organic system while fertilizer N use consumed 33% of the energy of cereal production (Refsgaard et al., 1998).

Table 2. Energy consumption in organic and conventional grass–clover silage and spring barley production on a clay soil measured in MJ ha^{-1}. After Refsgaard et al. (1998)

Energy input (MJ ha^{-1})	Grass–clover		Barley	
	Organic	Convent.	Organic	Convent.
Electricity, drying etc.	0	0	239	311
Diesel oil	425	168	613	521
Establishment and plant protection	137	322	1399	1568
Harvest and transport	1942	2196	577	577
Diesel extra	255	363	1170	1208
Direct energy, total	2759	3050	3995	4186
Seeds	94	65	459	358
Fertilizer	0	9128	0	3178
Pesticides	0	72	0	218
Lime	150	150	150	150
Machinery	1134	1381	1968	1936
Indirect energy, total	1378	10796	2577	5798
Energy, total	4137	13846	6572	9983
Yield, feed units or tonnes ha^{-1}	6100	6900	3.3	4.3
Energy costs MJ/FU or tonnes	0.7	2.0	2000	2322

Reduced CO_2 emission due to reduced production, transportation and application of fertilizers

Human activities have significantly increased the emission of greenhouse gasses such as CO_2, CH_4, N_2O, CFCs. Other gasses such as NO_x, CO, SO_2, which are not greenhouse gasses in the strict sense can be converted to greenhouse gasses via chemical reactions in the atmosphere.

It is estimated that 0.7 m^3 $CO_2$is produced per kg ammonia-N in modern fertiliser plants that use natural gas (Dybkjær, 1994). In global terms, this is equivalent to 58×10^9 m^3CO_2 (or 31×10^6 t CO_2-C) per year, and represents about 0.5% of the 6.3×10^9 tons of CO_2-C released by industrial activity in 1996. Jenkinson (2001) has suggested, however, that the real amount of CO_2 emitted is probably close to 1%, when the additional energy requirements of transport, packaging, and application are considered. Other factors like leakage of CH_4 into the atmosphere during fertilizer N production, the formation of NO_x ($NO+NO_2$) during manufacture, transport and application fertilisers should also be considered (Mosier, 2001).

Effects of BNF on the N cycling and N losses in cropping systems

It is impossible to avoid some losses of nitrogen via the volatilisation of ammonia, denitrification and leaching of nitrate from agro-ecosystems. About 54 million tons of ammonia was volatilised from the earth surface in 1990, 65% of which probably came from agricultural systems (animals, plants and soils) (Mosier, 2001). Significant losses of ammonia occur when ammonium bicarbonate or urea are applied to soil. Ammonia loss through volatilisation also occurs when slurries derived from animal residues are spread over soils. If this ammonia is not re-absorbed by plants it contributes to acidification of ecosystems when nitrified (Mosier, 2001) which in turn provokes eutrophication (Jenkinson, 2001).

Global denitrification from agricultural soils, measured in terms of nitrous oxide production (N_2O), represents about 2.1 million tons N $year^{-1}$. A similar amount is lost through animal production (excreta and waste management). Additionally, 2 million t N are leached or eroded from the site of application (Mosier, 2001). As N_2O is a potent green-house gas and has a long half-life (130 years in the atmosphere), badly managed agricultural processes contribute to global warming (Jenkinson, 2001). Nitric oxide (NO_x) is very active chemically and has an important role in the oxidation of ozone (Campbell et al., 1995). It is assumed that ammonium- and urea-based fertilisers contribute to NO_x emission, since NO is formed during nitrification and denitrification of ammonium in soil. Nevertheless, only about 15% of global NO_x emissions derive from soils. The dominant source of NO_x remains the combustion of fossil fuels (Mosier, 2001).

Leaching of nitrogen (especially NO_3) to the groundwater or drainage system, may occur when precipitation (or water from irrigation) exceeds evapotranspiration. Whether this occurs periodically or continuously depends on the region, climate, soil type, and management factors. Nitrate being lost by leaching contaminates the groundwater and aquatic environments; resulting in eutrophication and reduced quality of the drinking water. Unused fertiliser N is also leached from agricultural soils, but improved management can minimise these losses (Jenkinson, 2001). As a rule of thumb, the crop uses only 50% of the fertilizer N applied, but some of the remainder may be immobilized in soil organic matter. Undoubtedly some of this immobilized N is later mineralized, e.g., in the autumn and winter, where crop growth is limited (see also Recous and Machet, 1999).

Pre-cropping phase

To protect emerging seedlings, animal manure and fertilisers are often applied immediately after planting. Losses of N are particularly acute at this time because the amounts of N are high when the crop cannot absorb them. Even though the timing and rate of fertilizer/manure application can be managed to match crop N demand, the risk of denitrification and ammonium volatilisation remains. Losses are closely correlated to the amounts of water held in the soil during the 3 weeks after N application (Addiscott and Powlson, 1992). In these studies the total loss averaged 16% of the fertilizer N supplied, of which 10% was attributed to denitrification.

Use of legumes or *Azolla* as green manure stimulates rice yields (Ladha, 1998, 2003). In addition to fixing N_2, the green 'manure' plants absorb soil nitrate and reduce leaching. Management of the green manure crop is critical in limiting N losses via ammonia volatilisation, denitrification and leaching (Becker et al., 1995; Boddey et al., 1998; Giller and Wilson, 1991). Intense tillage to incorporate green 'manure' for example provokes greater losses of N (Boddey et al., 1998). This is because both the low C/N ratios of both *Azolla* and legumes favor high rates of mineralisation and volatilisation.

Loss of *Azolla* N is normally no more than 0-10%, whereas 30% of the urea N fertilizers may be lost (Watanabe et al. 1989). Similarly Becker et al. (1995) reviewed studies of urea and green manure N losses in lowland rice and they found the average urea-N losses to be 35% compared to 14% for green 'manures'. If the green manure is a cash-crop, other economic benefits might also accrue. In seasonal systems the incorporation of green 'manure' may provoke mineralisation during the winter (Campbell et al., 1995) and enhance the losses of nitrate via leaching to surface and ground waters.

Cropping season

During the cropping season N losses via denitrification or ammonia volatilisation are less in associative or symbiotic N_2 fixation systems than in those supplied with synthetic fertilizer N or animal manure. Little information is available on the effects of N_2 fixing versus non-fixing plants on denitrification. Apparently due to the greater amounts of soluble carbon, Wheatley et al. (1990) and Bertelsen (1991) reported that the denitrification potential, determined at non-limiting concentrations of nitrate, is greater in soils under peas than in soil cropped to non-legumes. Presumably, however, soil nitrate concentrations may only be high during early growth of legumes.

Dense mats of *Azolla* floating on the surface of the floodwater in rice may decrease the pH by about 2 units and reduce losses of fertilizer and soil N via ammonia volatilisation (Kumarasinghe and Eskew, 1993). As a result the overall fertilizer loss was reduced by 35–55% when *Azolla* was incorporated (Giller and Wilson, 1991).

Ammonia can volatilise from crop canopies. In temperate arable systems, annual emissions are about 5 kg N ha^{-1}. Pea crops do not seem to emit more than winter wheat, oil seed rape or spring barley (Schjoerring and Mattsson, 2001). In a dry season, Bertelsen and Jensen (1992) observed that about 30% of the pea plant N, amounting to ca. 50 kg N ha^{-1}, were apparently lost from the canopy during the last weeks of growth. Since shedding of leaves in pea is unusual and the N was not recovered in roots, it was suggested that this N was lost by ammonia volatilisation from the

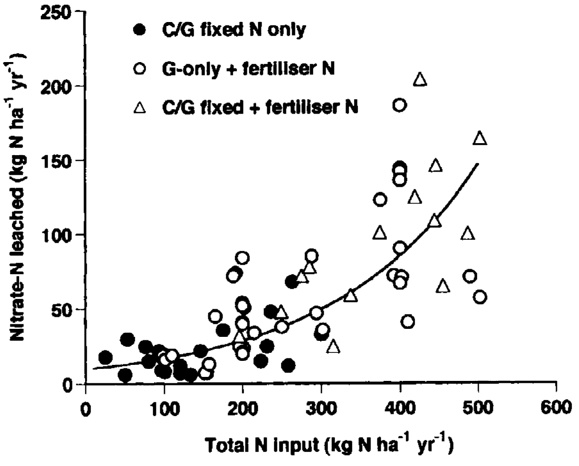

Figure 2. Nitrate leaching from grazed clover–grass or grass only pastures as affected by total N input from N_2 fixation or N fertiliser application. C – Clover; G – Grass. Data are summarised from studies in New Zealand, France and UK. Source: Ledgard (2001).

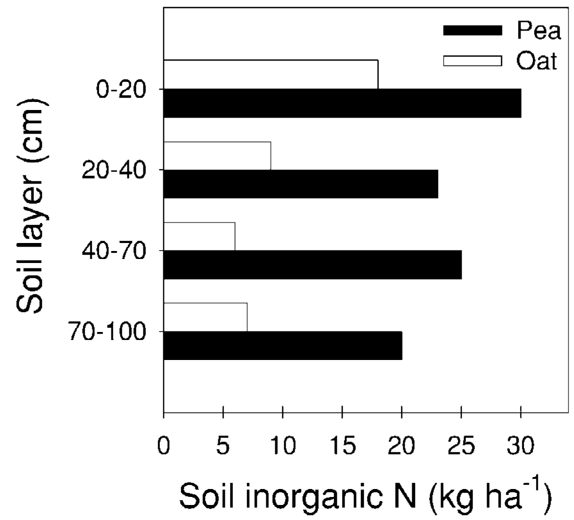

Figure 3. Nitrate and ammonium in the soil profile 0–14 days after harvest of peas and oats on a sandy loam in Denmark. Data are means of 4 years of experiments. Source: Jensen (1997).

canopy in this year where climatic conditions during the seed filling phase are suboptimal. Similar losses are observed in non-legumes too (Schjoerring et al., 1989).

In temperate regions, leaching of nitrate is limited after crop establishment as a result of the balance between evapotranspiration and precipitation. Nevertheless, in perennial pastures there may be periods with less growth and high precipitation, resulting in both leaching of N and denitrification (Figure 2). Ledgard (2001) presented data on N balances from dairy and sheep pasture grazing systems of varying intensities in New Zealand. The data show that the more intensively (e.g., via N fertilizer use), the pasture system is managed, the greater are the losses of N via denitrification, ammonia volatilisation and leaching (Table 3). Similarly, Owens et al. (1994) showed that when alfalfa replaced ammonium nitrate as the N source in a grassland system, $NO_3{}^-$ concentrations in the subsurface water decreased to 30% of the levels found during N-fertilization. In systems dependent on BNF the effects on the environment are much less than in intensively managed systems, but managing nitrate leaching may become increasing difficult with N_2 fixing crops, due to crops residues of high N concentration.

Intercropping promises more sustainable plant production in many agricultural systems (Giller and Wilson, 1991; Vandermeer, 1989). Intercropping annual legumes and cereals may be beneficial to the environment, since the planned diversity of the crop community can more efficiently exploit the available nutrients, reduce pest and diseases, and reduce the need for synthetic fertilizer and pesticides.

Sharing of N sources between the fixing- and non-fixing plant contributes to a better overall use of N and reduces the post-harvest soil N availability, which in some agro-ecosystem may be easily leached to the ground water. In the majority of low input farming systems soil N is a limiting resource (Hauggaard-Nielsen et al. 2001, 2002; Jensen, 1996).

Short-term post-harvest effects

Post-harvest soil N dynamics vary between legumes and non-legumes. The differences are mainly due to (A) greater levels of soil inorganic N at harvest after legumes compared to cereals (Figure 3, Chalk et al., 1993; Herridge et al, 1995; Peoples et al., 1995), and (B) the greater amounts of N in crop residues compared to cereals. The former effect is often called ‘N-sparing’, indicating that legumes are less efficient than cereals in recovering soil inorganic N during the growth season. Many factors contribute to these differences including the depths of the rooting systems and differential rates of N mineralisation-immobilisation turnover in the legume and non-legume (Jensen, 1997).

To alleviate the increased levels of soil inorganic N in the autumn associated with temperate legumes, efficient N- cash crops may be included in the ro-

Table 3. Animal stocking rate, pasture production N inputs and outputs from intensive dairy farm systems based on legume–grass pastures in New Zealand. Comparison is made with (400 kg N ha^{-1} $year^{-1}$ as urea) and without N application . Values in brackets are the range of N flows measured over five years. After Ledgard (2001)

System component	Without N application	Application of 400 kg N
Cows ha^{-1}	3.3	4.4
Total pasture (t Dm ha^{-1} $year^{-1}$)	16	20
% Clover in pasture	15	5
N inputs (kg ha^{-1} $year^{-1}$)		
Clover BNF	160 80–210)	40 (15–115)
Asymbiotic BNF + deposition	5	5
Fertilizer	0	400
Purchased feed	0	41
N outputs (kg ha^{-1} $year^{-1}$)		
Milk and meath	76 (68–83)	114 (90–135)
Transfer of excreta to roads	53 (41–63)	77 (72–91)
Denitrification	5 (3–7)	25 (13–34)
NH_3 volatilisation	15 (15–17)	68 (47–78)
Leaching	30 (12–14)	130 (109–137)
Immobilisation fertilization N	0	70 (60–84)
N balance (kg N ha^{-1} $year^{-1}$)	–16 (–17 to +47)	12 (–11 to +24)
Kg N lost/ kg N in product	1.4	2.6

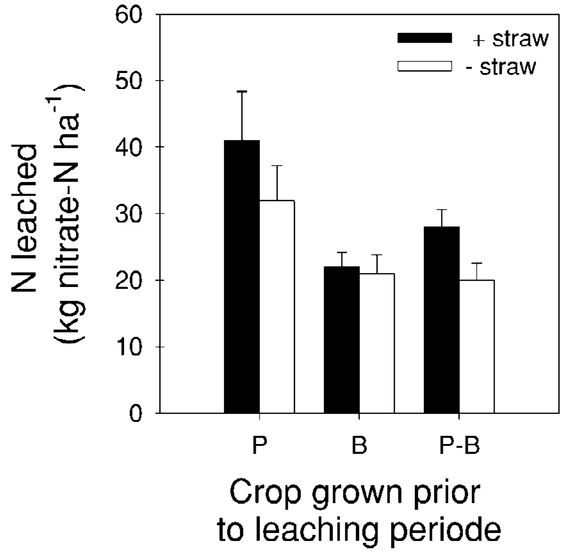

Figure 4. Nitrate leaching in lysimeters after peas (P), barley (B) and a 50–50% pea–barley intercrop (P–B) on a sandy loam soil in Denmark. Source: Hauggaard-Nielsen (2001).

tations or legumes can be intercropped with cereals (Hauggaard-Nielsen, 2001). Hauggaard-Nielsen showed that NO_3^- leaching after pea was 3.6 g N m^{-2}, whereas after a 50:50% pea-barley intercrop it was only 2.4 g N m^{-2} (Figure 4). Heavy fertilisation of non-legumes provokes N-leaching and gaseous losses (e.g. Owens et al., 1995). The incorporation of clover into the soil enhances denitrification (Aulakh et al., 1983).

Nevertheless, the nitrogen derived from BNF contributes substantially to the N economy of the subsequent crop (Armstrong et al., 1997; Jensen, 1997; Peoples et al., 1995, 2001). Ploughing under a legume-based pasture results in a massive nutrient flush. Danish studies on the effect of grass or grass-clover pasture incorporation showed that spring ploughing and N cash crops are efficient in conserving the pasture N in the systems while benefiting subsequent crops without increasing leaching (Eriksen, 2001). As a result the fertilization of the succeeding crop can be reduced and environmental benefits gained.

Long-term effects of BNF on soil fertility As discussed above pastures that include N_2 fixing forage legumes probably have the greatest positive impact on soil fertility (Campbell, 1978). Typically 100–200 kg of N are fixed ha^{-1} year^{-1} (Ledgard, 2001; Peoples et al., 2001) and only a minor proportion is removed by grazing. Giller et al. (1997) suggest that the best approaches for building soil nitrogen capital in Africa is improved legume fallows, legume/grass leys and minimum tillage systems. Incorporation of the residues from grain legumes helps maintain soil N levels (Campbell et al., 1995; Jensen, 1997), but the overall benefit is much less than from legume-based pastures (Paustian et al., 1997).

Natural regulation of fixed N inputs into cropping systems also seems to occur (Ledgard and Steele, 1992; Schwinning and Parsons, 1996). When the soil N reaches certain levels in, e.g., a grass–clover pasture, net mineralisation of N will cause the grass to out compete the clover or reduce nodulation of the clover. After sufficient N has been removed from the system, the clover often re-colonizes the pasture.

Probably similar situations exist in N_2-fixing cover crops such as *Calopogonium, Centrosema* and *Pueraria,* in rubber and oil palm plantation. Deposition of N by the cover crop will gradually increase the level of soil N and thus reduce the proportion of plant biomass derived from N_2 fixation (Vesterager et al., 1995). In turn, the non-legume species will become more competitive and the legumes will gradually give way to the plantation crops (Broughton, 1977). During their life, BNF from the cover-crop will have contributed more than 200 kg N ha^{-1} year^{-1} (Broughton, 1976; 1977).

The amount of carbon in the roots of grass–clover pastures can be two to four times more than the carbon in fertilized cereal roots and stubble (Jenkinson, 1981). Nitrogen fixing crops are therefore an integral part of strategies to maintain high levels of soil organic N and C in both temperate and tropical cropping systems.

Non-nitrogen effect of N_2 fixing crops

Sometimes it is difficult to discern whether the beneficial effect of legumes, N_2 fixing non-legumes or *Azolla* results directly from BNF or whether it is related to other characteristics of the organism. Legume-based pastures have the ability to rehabilitate degraded land by improving the physical, chemical and biological characteristics of the soil. This is mainly due to improved soil aggregation (Karlen et al., 1994). Legumes stimulate the activity of a plethora of soil organisms include earthworms (Parker, 1985), which significantly affect soil structure. Legume cover crops help prevent erosion during the establishment of the plantations (Broughton, 1977; Giller and Wilson, 1991) (Figure 5).

Figure 5. Newly established rubber plantation in Malaysia. The cover crop *Pueraria phaseoloides* protects against soil erosion, conserves water and fixes N_2. Photo: E.S. Jensen.

It is well known that legumes may act as break-crops in cereal rich rotations to reduce the survival of nematode populations, suppress leaf and root diseases such as take-all fungus, and reduce weeds (Herridge, 1992; Stevenson and van Kessel, 1996). An analysis of a pea–wheat rotation in comparison with continuous wheat, showed that 91% of the yield advantage of wheat succeeding pea was associated with non-N benefits, mainly reduced leaf disease (Stevenson and van Kessel, 1996). Surprisingly, only 9% of the advantage was associated with the increased soil N levels. Consequently, including legumes in the cropping system can reduce the need for pesticides, so diminishing pollution. However, it is important to design rotations in a way that there is not an overabundance of legumes, since too frequent presence can stimulate diseases and pest in the system.

Some legumes, such as alfalfa have roots that grow to depths of greater than 5 m in some soils. These deep roots are able to absorb nitrate, water and nutrients that are unavailable to other plants (Karlen et al., 1994). N_2 fixing trees serve a similar role acting as 'nutrient pumps' while concomitantly reducing leaching losses (Altieri, 1999).

Future developments

In many parts of the world food security is more important than the environment. In the long-term sustainable food production depends on well-managed agriculture. Serious treats to the local environment need to be eliminated. Research and development of management methods to conserve nitrogen and carbon in cropping systems will rely heavily on the application of BNF, which may give benefits beyond those of an enhanced nitrogen fertiliser supply.

References

Addiscott T M and Powlson D S 1992 Partitioning losses of nitrogen fertilizer between leaching and denitrification. J. Agric. Sci. Camb. 118, 101–107.

Altieri M A 1999 The ecological role of biodiversity in agroecosystems. Agric. Ecosyst. Environ. 74, 19–31.

Armstrong E L, Heenan D P, Pate J S and Unkovich M J 1997 Nitrogen benefits of lupins, field pea, and chickpea to wheat production in southeastern Australia. Aust. J. Agric. Res. 48, 39–47.

Aulakh M S, Rennie D A and Paul E A 1983 The effect of various clover management practices on gaseous N losses and mineral N accumulation. Can J. Soil Sci. 63, 593–605.

Becker M, Ladha J K and Ali M 1995 Green manure technology: Potential, usage, and limitations. A case study for lowland rice. Plant Soil 174, 181–194.

Bertelsen F 1991 Denitrification and the cultivation of legumes. Ph.D. Thesis. Risø National Laboratory. 72 p.

Bertelsen F and Jensen E S 1992 Gaseous nitrogen losses from field plots grown with pea (*Pisum sativum* L.) or spring barley (*Hordeum vulgare* L.) estimated by ^{15}N mass balance and acetylene inhibition techniques. Plant Soil 142, 287–295.

Boddey R B, Oliveira O C de, Urquiaga S, Reis V M, Olivares F L de, Baldani V L D and Döbereiner J 1995 Biological nitrogen fixation associated with sugar cane and rice: Contributions and prospects for improvement. Plant Soil 174, 195–209

Boddey R M, Giller K E, Cadisch G, Alves B J R and Urquiaga S 1998 Contribution of biological nitrogen fixation to tropical agriculture: actual and potential. *In* Biological Nitrogen Fixation for the 21st Century. Eds. C Elmerich, A Kondorosi and W E Newton. pp. 599–604. Kluwer Academic Publishers, Dordrecht, The Netherlands

Boddey R M, Urquiaga S, Alves B J R and Reis V 2003 Endophytic nitrogen fixation in sugarcane: present knowledge and future applications. Plant Soil 252, 139–149.

Bohlool B B, Ladha J K, Garrity D P and George T 1992 Biological nitrogen fixation for sustainable agriculture: A perspective. Plant Soil 141, 1–11.

Brophy L S and Heichel G H 1989 Nitrogen release from roots of alfalfa and soybean grown in sand culture. Plant Soil 116, 77–84.

Broughton, W J 1976. Effect of various covers on the performance of *Elaeis guineensis* (jacq.) on different soils. *In* Eds. D A Earp and W Newall *International Oil Palm Developments*. pp. 501–525. Kuala Lumpur: Incorp. Soc. Planters.

Broughton W J 1977 Effect of various covers on soil fertility under *Hevea brasiliensis* Muell. Arg. and on growth of the tree. Agro-Ecosystems 3, 147–170.

Campbell C A 1978 Soil organic carbon, nitrogen and fertility. *In* Soil Organic Matter. Eds. M Schnitzer and S U Khan. pp. 173–271. Elsevier, Amsterdam.

Campbell C A, Myers R J K and Curtin D 1995 Managing nitrogen for sustainable crop production. Fertil. Res. 42, 277–296.

Chalk P M, Smith C J, Hamilton S D and Hopmans P 1993 Characterization on the N benefit of a grain legume (*Lupinus angustifolius* L.) to a cereal (*Hordeum vulgare* L) by an *in situ* ^{15}N isotope dilution technique. Biol. Fertil. Soils 15, 39–44.

Cleveland C C, Townsend A R, Schimel D S, Fisher H, Howarth R W, Hedein L O, Perakis S S, Latty E F, Von Fischer J C, Elseroad A and Watson M F 1999 Global patterns of terrestrial biological nitrogen (N_2) fixation in natural ecosystems. Global Biogeochem. Cycles 13, 623–645.

Dybkjær I 1994 Haldor Topsøe. Personal communication.

Eriksen J 2001 Nitrate leaching and growth of cereal crops cultivation of contrasting temporary grasslands. Journal of Agricultural Science 136, 271–281.

Galloway J N, Schlesinger W H, Levy II H, Michaels A and Schnoor J L 1995 Nitrogen fixation: Anthropogenic enhancement–environmental response. Global Biochem. Cycles. 9, 235–252.

Giller K E and Wilson K 1991 Nitrogen Fixation in Tropical Cropping Systems. CAB International. Wallingford UK, 313 pp.

Giller K E, Cadish G, Ehaliotis C, Adams E, Sakala W D and Mafongoya P 1997 Building soil nitrogen capital. *In* Replenishing Soil Fertility in Africa. Eds. R J Buresh and P A Sanchez. SSSA Special Publication 51, SSSA, Madison WI.

Graham P H and Vance C P 2000 Nitrogen fixation in perspective: an overview of research and extension needs. Field Crops Res. 65, 93–106.

Greenwood D J 1989 Plant nutrition and human welfare: The world scene. J. Sci. Food Agric. 48, 387–410.

Hardy R W F, Heytler P G and Rainbird R M 1983 Status of new nitrogen inputs for crops. *In* Better Crops for Food, pp. 28–52. Pitman, London, UK.

Hauggaard-Nielsen H, Ambus P and Jensen E S 2001. Interspecific competition, N use and interference in pea-barley intercropping. Field Crops Res. 70, 101–109.

Hauggaard-Nielsen H, Ambus P and Jensen E S 2002 The comparison of nitrogen use and leaching in sole cropped versus intercropped pea and barley. Nutr. Cycling Agroecosyst. (In press).

Herridge D F 1982 Crop rotations involving legumes. *In* Nitrogen Fixation in Legumes. Ed J M Vincent, pp. 253–261. Academic Press, Sydney.

Herridge D F, Marcellos H, Felton W L, Turner G L and Peoples M B 1995 Chickpea increases soil N fertility in cereal systems through nitrate sparing and N_2 fixation Soil Biol. Biochem. 27, 545–551.

Israel D W and Jackson W A 1978 The influence of nitrogen nutrition on ion uptake and translocation by leguminous plants. *In* Mineral Nutrition of Legumes in Tropical and Subtropical Soils. Eds. C S Andrew and E J Kamprath. pp. 113–129. Commonwealth Scientific and Industrial Research Organization, Melbourne, Australia

Jenkinson D A 1981 The fate of plant and animal residues in soil. *In* The Chemistry of Soil Processes. Eds. D J Greenland and M H B Hayes. pp. 505–561. Wiley and Sons, Chichester.

Jenkinson D A 2001 The impact of humans on the nitrogen cycle, with focus on temperate arable agriculture. Plant Soil 228, 3–15.

Jensen E S 1996 Grain yield, symbiotic N_2 fixation and interspecific competition for soil inorganic N in pea-barley intercrops. Plant Soil 182, 25–38.

Jensen E S 1997 The role of grain legume N_2 fixation in the nitrogen cycling of temperate cropping systems. D.Sc. Thesis. Risø National Laboratory. R-885(EN). 86 pp.

Jensen E S and Sørensen L H 1988 Uptake of soil nitrogen by soybean as influenced by symbiotic N_2 fixation or fertilizer N supply. Soil Biol. Biochem. 20, 921–925.

Karlen D L, Varvel G E, Bullock D G and Cruse R M 1994 Crop rotations for the 21st century. Adv. Agron. 53, 1–45.

Kumarasinghe K S and Eskew D L 1993 Isotopic studies of *Azolla* and nitrogen fertilization of rice. Kluwer Academic Publishers, Dordrecht, 145 pp.

Ladha J K 1998 Role of Biological nitrogen fixation in replenishing soil nitrogen pool in cropping systems. *In* Biological Nitorgen Fixation for the 21st Century. Eds. C Elmerich, A Kondorosi and W E Newton. pp. 605–608. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Ladha J K and Reddy P M 2003 Nitrogen fixation in rice systems: state of knowledge and future prospects. Plant Soil 252, 151–167.

Ledgard S F 2001 Nitrogen cycling in low input legume-based agriculture, with emphasis on legume/grass pastures. Plant Soil 228, 43–59.

Ledgard S F and Steele K W 1992 Biological nitrogen fixation in mixed legume/grass pastures. Plant Soil 141, 137–153.

Marschner H 1995 Mineral Nutrition of Higher Plants, Academic Press, London, UK. 889 pp.

Mosier A 2001 Exchange of gaseous nitrogen compounds between agricultural systems and the atmosphere. Plant Soil 228, 17–27.

Mudahar M S and Hignett T P 1987 Fertilizer and energy use. *In* Energy in Plant Nutrition and Pest Control. Ed. Z R Helsel. pp 1–24. Elsevier, Amsterdam.

Owens L B, Edwards W M and van Keuren R W 1994 Groundwater nitrate levels under fertilized grass and grass-legume pastures. J. Environ. Qual. 23, 752–758.

Owens L B, Edwards W M and Shipitalo M J 1995 Nitrate leaching though lysimeters in a corn–soybean rotation. Soil Sci. Soc. Am. J. 59, 902–907.

Parker C A 1985 Legumes and nitrogen fixation; their importance for farming in the future. Impact Sci. Soc. 142, 153–164.

Paul E A and Clark F E 1989 Soil Microbiology and Biochemistry. Academic Press, San Diego, CA. 273 p.

Paustian K, Collins H P and Paul E A 1997 Management controls on soil carbon. *In* Soil Organic Matter in Temperate Agroecosystems, Eds. E A Paul, E T Elliott, K Paustian and C V Cole, pp. 15–49, CRC Press, Boca Raton, FL.

Peoples M B, Herridge D F and Ladha J K 1995 Biological nitrogen fixation: An efficient source of nitrogen for sustainable agricultural production. Plant Soil 174, 3–28.

Peoples M B, Bowman A M, Gault R R, Herridge D F, McCallum M H, McCormick K M, Norton R M, Rochester I J, Scammell G J and Schwenke 2001 Factors regulating the contributions of fixed nitrogen by pasture and crop legumes to different farming systems of eastern Australia Plant Soil 228, 29–41.

Raven J A 1986 Biochemical disposal of excess H^+ in growing plants. New Phytol. 104. 175–206.

Recous S and Machet J-M 1999 Short term immobilisation and crop uptake of fertilizer nitrogen applied to winter wheat: effect of date of application in spring. Plant Soil 206, 137–149.

Refsgaard K, Halberg N and Kristensen E S 1998. Energy utilisation in crop and dairy production in organic and conventional livestock production systems. Agric. Syst. 57, 599–630.

Rolfe B G, Verma D P S, Potrykus I, Dixon, McCully M, Sautter C, Denarie J, Sprent J, Reinhold-Hurek B, Vanderleyden J and Ladha JK 1998 Agriculture 2020: 8 billion people. *In* Biological Nitrogen Fixation for the 21st Century. Eds. C Elmerich, A Kondorosi and W E Newton. pp. 685–692. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Rovira A D 1956 Plant root excretions in relation to the rhizosphere effect. I. The nature of root exudate from oats and peas. Plant Soil 7, 178–194.

Sagan M, Ney B and Duc G 1993 Plant symbiotic mutants as a tool to analyse nitrogen nutrition and yield relationship in field-grown peas (*Pisum sativum* L.). Plant Soil 153, 33–45.

Schjoerring J K and Mattsson M 2001 Quantification of ammonia exchange between agricultural cropland and the atmosphere: measurements over tow complete growth cycles of oil seed rape, wheat, barley and pea. Plant Soil 228, 105–115.

Schjoerring J K, Nielsen N E, Jensen H E and Gottschau A 1989 Nitrogen losses from field-grown spring barley plants as affected by rate of nitrogen application. Plant Soil 116, 167–175.

Schwinning S and Parsons A J 1995 Analysis of coexistence mechanisms for grasses and legumes in grazing systems. J. Ecol. 84, 799–813.

Stevenson F C and van Kessel C 1996 A landscape-scale assessment of the nitrogen and non-nitrogen rotation benefit to pea. Soil Sci. Soc. Am. J. 60, 1797–1805.

Vandermeer J 1989 The Ecology of Intercropping. Cambridge University Press, Cambridge, UK. 237 p.

Vesterager J M, Østerby S, Jensen E S and Schjørring J K 1995 Symbiotic nitrogen fixation by the cover crop *Pueraria phaseoloides* as influenced by litter mineralization. Plant Soil 177, 1–10.

Voisin A-S, Salon C, Munier-Jolain N G and Ney B. 2002. Effects of mineral nitrogen nutrition and biomass partitioning between the roots and shoots of pea (*Pisum sativum* L). Plant Soil (In press).

Watanabe I, Ventura W, Mascarina G and Eskew D L 1989 Fate of *Azolla* spp. and urea nitrogen applied to wetland rice (*Oryza sativa* L.). Biol. Fertil. Soils 8, 102–110.

Weber C R 1966a Nodulating and non-nodulating soybean isolines: Agronomic and chemical attributes. Agron. J. 58, 43–46.

Weber C R 1966b Nodulating and non-nodulating soybean isolines: II Response to applied nitrogen and modified soil conditions. Agron. J. 58, 46–49.

Wheatley R, Ritz K and Griffiths B 1990 Microbial biomass and mineral N-transformations in soil planted with barley, ryegrass, pea or turnip. Plant Soil 127, 157–167.