3

Nitrogen and Phosphorus Losses from Legume-supported Cropping

Michael Williams,[1]* Valentini A. Pappa[2] and Robert Rees[3]

[1]*Trinity College Dublin, Ireland;* [2]*Texas A&M University, Texas, USA;* [3]*Scotland's Rural College, Edinburgh, UK*

Abstract

The loss of nutrients from agricultural systems is recognized as a major environmental problem, contributing to air pollution and nutrient enrichment in rivers and oceans. The use of legumes within agriculture provides an opportunity to reduce some of these losses in ways which maintain or enhance agricultural productivity. This chapter considers the role of legumes in crop rotations, legumes in intercrops and legume-based green manures in influencing nutrient loss and turnover. Nitrous oxide emissions are particularly important here given that they are the largest contributor to greenhouse gas emissions from many agricultural systems. There are many circumstances in which the use of legume-supported cropping systems can reduce overall nitrous oxide emissions and the biological nitrogen fixation process associated with legumes can replace synthetic nitrogen fertilizer use.

Introduction

The efficiency of nitrogen (N) fertilizer application in agroecosystems is often no higher than 50% with 45–50% of the N applied being taken up by the crop for growth and the remaining N being lost primarily through the combined processes of denitrification, ammonia volatilization and leaching (Smil, 1999; Crews and Peoples, 2004). Using legumes in cropping systems reduces reliance on inorganic N fertilizer but in many cases the problem of low efficiency of N use remains. Through their ability to fix N, legumes play a significant role in N supply in both natural ecosystems and agriculture/agroforestry contributing as much as 500 kg N/ha/year (Briggs *et al.*, 2005). The potential environmental and agronomic implications of biological fixation have been reviewed recently by Jensen and

*willimsm@tcd.ie

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Hauggaard-Nielson (2003), Muňoz *et al.* (2010) and Jensen *et al.* (2011). Positive environmental effects of legume cropping arise from a reduced reliance on inorganic N fertilizer and improvements in soil structure from residue incorporation. Negative effects are primarily associated with N losses to the atmosphere and groundwater where peaks in available N from mineralization of N-rich residues occur at periods of low crop growth or high rainfall. Soil acidification may also prove problematic, eventually leading to decreases in crop productivity, but here liming of soils is an effective treatment although affecting N losses too (Galbally *et al.*, 2010). This chapter provides a review of recent literature on N losses from legume crops and highlights management options that may reduce nitrous oxide (N_2O) emissions to the atmosphere. In addition enhanced phosphorus (P) uptake is considered particularly in respect to legume intercropping.

Nitrous Oxide Production in Agricultural Soils

Agriculture, forestry and other land use are estimated to account for 24% of anthropogenic greenhouse gas (GHG) emissions (Edenhofer *et al.*, 2014). The agricultural sector is a particularly important source of emissions of methane (CH_4) and N_2O globally, these two GHGs being approximately 25 and 298 times more effective at causing warming of the climate than carbon dioxide (CO_2). In addition atmospheric N_2O plays a significant role in depletion of the tropospheric ozone layer.

Analysis of air trapped in ice cores shows that levels of N_2O range from interglacial values of 270 parts per billion by volume (ppbv) to lower glacial values of 200 ppbv (Sowers, 2001; Fluckiger *et al.*, 2004). Since approximately 1850 though, the concentration of N_2O increased to over 280 ppbv by 1905, to over 300 ppbv by the mid-1970s and currently the atmospheric concentration of N_2O exceeds 320 ppbv, representing approximately 6% of the present-day greenhouse effect (IPCC, 2007) and 60% of global agricultural emissions of GHGs (Prather *et al.*, 2001; Smith *et al.*, 2007).

A measure of the present-day imbalance between sources and sinks for N_2O is provided in Fowler *et al.* (2009), and serves to highlight the role of agriculture in N_2O production (Table 3.1). Of the imbalance between sources and sinks, 70% can be attributed to increased N_2O production from agriculture, primarily a consequence of the addition of reactive N fertilizer to soils (Kroeze, 1999). Synthetic N fertilizer use has increased by over 800% between the years 1960 and 2000 (Fixen and West, 2002) and this trend will probably continue. Agricultural N_2O emissions are predicted to rise by 30–60% over the next 20 years, driven by a steadily increasing population and subsequent stresses on food demand leading to increased N inputs into agricultural systems through synthetic fertilizers, manure, human waste and N_2 fixing crops (Smith, 1997; Bruinsma, 2003).

N_2O production in soils reflects both the oxidation and the reduction of inorganic N forms by a wide range of soil microorganisms (fungi, bacteria and archea). These have evolved to use inorganic N compounds as essential components of energy-coupled, electron transport systems. The rate of N_2O production is determined by a wide range of factors, but primarily the microbial capacity of the soil, temperature, pH, substrate supply and the degree of oxygenation of the soil (Flessa *et al.*, 2002; Khalil *et al.*, 2002; Šimek and Cooper, 2002; Smith *et al.*, 2003; Malhi *et al.*, 2006; Ding *et al.*, 2007). In addition, the diffusive properties of the soil will affect the flux rate of N_2O to the atmosphere (Fig. 3.1). Water-filled pore space (WFPS) is frequently highlighted in the literature as the most important controlling variable in agricultural soils as it is directly linked with aeration and oxygen availability (Davidson, 1991; Davidson *et al.*, 2000; Smith *et al.*, 2003). In general, N_2O production is thought to be greatest at intermediate WFPS values in the range of 50–80% (Davidson, 1991; Dobbie and Smith, 2003a) with peak denitrification rates (N reduction pathways) being favoured by high WFPS values (80–85%) where reduced oxygen availability is also coupled to increased solubility

Table 3.1. Sources and sinks of nitrous oxide (N_2O) accumulation in the atmosphere. (Adapted from Fowler *et al.*, 2009.)

Sources	10^6 t N_2O/year	Sinks	10^6 t N_2O/year	Source–sinks 10^6 t N_2O/year
Oceans	3.8 (1.8–5.8)	Stratosphere	12.5 (1.8–5.8)	
Atmosphere	0.6 (0.3–1.3)	Soils	1.5–3.0	
Soils	6.6 (3.3–9.0)			
Agriculture	*2.8 (1.7–4.8)*			
Biomass burning	0.7 (0.2–1.0)			
Energy and industry	0.7 (0.2–1.8)			
Others	2.5 (0.9–4.1)			
Total sources	*17.7 (8.5–27.7)*	*Total sinks*	*14.0 (11.5–18.0)*	*3.7*

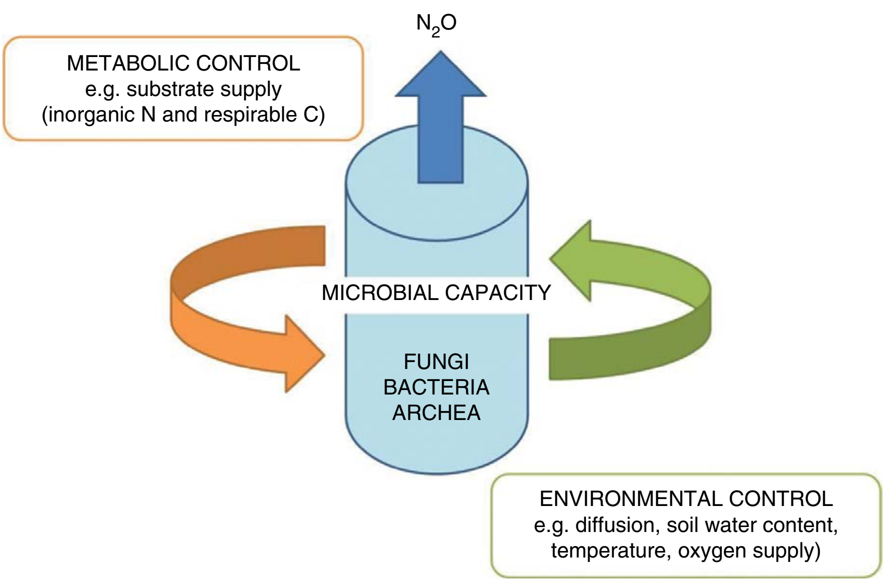

Fig. 3.1. Limiting factors on nitrous oxide (N_2O) production in the soil.

of organic carbon and nitrate (Bowden and Bormann, 1986). Nitrification (N oxidation pathways) may also prevail at WFPS values above 50%, while above 75% denitrification is the major pathway for N_2O production (Well *et al*., 2006).

Nitrous Oxide Emissions from Legume-supported Cropping Systems

Monocrop legumes, legumes in rotation, legumes as intercrops and legumes grown as cover crop/green manures will all influence N_2O emissions from the soil through their input of biologically fixed N into the soil. In addition, root nodules may contribute directly to N_2O emissions via the inherent capacity of some rhizobial species/strains to reduce nitrite to nitrous oxide. In practice, the contribution of legume cropping to soil N_2O emissions may be divided into three separate processes:

- rhizobial denitrification within the nodules;
- nitrification and denitrification of biologically fixed N; and
- decomposition of N-rich residues to provide inorganic N.

Of these three processes, the addition of N-rich legume residues to soils is the most critical for peak N_2O emissions.

Rhizobial denitrification and N_2O production

The process of biological N fixation does not lead directly to N_2O emissions, but it has long been suspected that the enzyme responsible (nitrogenase) may contribute to some production of N_2O from reduction of nitrates present in root nodules. Isolated legume nodules and rhizobia bacteroids from a range of plant species have been shown to produce N_2O at limiting concentrations of oxygen and with nitrate as their source of nitrogen (Daniel *et al*., 1980; O'Hara and Daniel, 1985; Coyne and Focht., 1987; Bedmar *et al*., 2005; Monza *et al*., 2006). Not all rhizobia share this property, indeed denitrification has been shown in only a few genera of N_2-fixing bacteria and a majority of the species/strains studied lack a full complement of denitrification genes (Monza *et al*., 2006).

Whatever the distribution and function of denitrification enzymes among symbiotic rhizobia, the extent of N_2O production from legume nodules in the field is not clear. Early work on upscaling laboratory rates of denitrification highlighted a considerable potential of N_2-fixing bacteria to remove nitrate from agricultural soils. In the case of *Rhizobium lupini*, a measured bacterial density of 10^4 cells/g soil was calculated to give initial rates of denitrification of the order of 20 kg N removed/ha (O'Hara *et al*., 1984), this loss of nitrogen being of a similar magnitude to field rates of N_2 fixation (O'Hara and Daniel, 1985). Despite such concerns, evidence for high rates of denitrification by legume nodules in the field is scarce (Zhong *et al*., 2009). Given the considerable uncertainty in upscaling laboratory rates of N_2O flux by isolated nodules or symbiotic bacteria to the field, useful experiments would be those incorporating suitable controls to compare N_2O flux from inoculated and non-inoculated plants. In the case of both pea and lentil, little difference in N_2O emissions has been determined between plants inoculated with strains of *Rhizobium leguminosarum* and control plants, and even between inoculated plants and soils planted with wheat (Zhong *et al*., 2009). This suggests that N_2O emissions are not directly related to biological N_2 fixation by grain legumes, as further illustrated in soil box experiments incorporating wetting and drying cycles with pea and lentil crops and *R. leguminosarum* (Zhong *et al*., 2011). Taking the lack of field-based data into consideration, N_2 fixation by legumes as a source of N_2O is no longer considered important by the Intergovernmental Panel on Climate Change (IPCC) and has been dropped from their emission calculation guidelines (Rochette and Janzen, 2005; IPCC, 2006).

Nitrification and denitrification of biologically fixed N

A comparison of N_2O emissions from different cropping systems by Muñoz *et al*. (2010) is summarized in Table 3.2 and highlights the range of N_2O emissions recorded.

Table 3.2. Nitrous oxide (N_2O) fluxes from different soil use and management. (From Muñoz *et al*., 2010.)

System	Range N_2O flux (kg N_2O-N/ha/year)	Country	References
Cropping			
Continuous and rotation crops	0–44	Brazil, Canada, Denmark, New Zealand	Wagner-Riddle and Thurtell (1998), Gregorich *et al*. (2005), Metay *et al*. (2007), Saggar *et al*. (2008), Chirinda *et al*. (2010), Allen *et al*. (2010)
Leguminous crop	0.3–4.7	Canada	Gregorich *et al*. (2005)
Rice	0–36	Australia, USA, Japan, China, Philippines, Indonesia, Taiwan, India	Majumdar (2009)
Shrub land/ natural landscape	0–21	New Zealand, Finland	Malijanen *et al*. (2006), Saggar *et al*. (2008)
Pasture			
Animal waste applied	0–156	Canada, New Zealand, England, the Netherlands, Japan, Canada, Denmark, USA	Gregorich *et al*. (2005), Saggar *et al*. (2009)
Grazing	0.1–183	UK, New Zealand, Australia	Saggar *et al*. (2008), Cardenas *et al*. (2010), Galbally *et al*. (2010), Matthews *et al*. (2010)

Pastures

Grazed grass/clover pastures have the largest recorded N_2O emissions with fixed nitrogen being released into the soil through both decay of leaf, stem and root litter and transfer to the soil N pool via faeces and urine from the grazing animals. Leaching of N and acidification of soils is a common problem here (Bouwman *et al.*, 2002), the drop in soil pH due to the acidifying effects of the nitrogenase reaction. This eventually leads to a decline in productivity of the grassland (Williams, 1980) hence liming of grasslands is a common solution (Galbally *et al.*, 2010). As N_2O emissions are reduced when soil pH values fall below pH 5.5, liming may lead directly to decreases in N_2O flux although field data on the effect of liming is scarce. Galbally *et al.* (2010) found no significant effect of liming on N_2O emissions from grazed legume pastures typical of Australia. Laboratory incubations of limed soils with urine added as a source of N also show little effect of raising the soil pH above 5.5 on N_2O emissions (Zaman *et al.*, 2007, 2008). Clover density may also be assumed to affect N_2O emissions in such systems through increasing N inputs into the soil but, as with the case of liming, few field data are available. A study of N_2O emissions from high- and low-density clover patches concluded that spatial heterogeneity in clover abundance may have very little impact on field-scale N_2O emissions in fertilized grasslands (Klumpp *et al.*, 2011).

Legume monocrops

These show the least emissions of N_2O in the published literature (Table 3.2) but care must be taken in interpretation of short-term studies. Nitrification and denitrification of biologically fixed N may represent a significant source of N_2O from agricultural systems in the long term where incorporation and mineralization of legume residues may lead to peaks in available nitrate. The majority of studies on legume monocrops are limited at best to 1 year and hence focus on the short term. Under these conditions with removal of a high proportion of biologically fixed N to the grain during growth and harvest, short-term measurements of N_2O emissions will fail to incorporate the effect of carryover of the remaining plant nitrogen in the soil (Evans *et al.*, 2001; Peoples *et al.*, 2001). Some authors consider the stubble of grain legumes to be a minor source of N_2O through mineralization given its low organic N content (Lemke *et al.*, 2007; Peoples *et al.*, 2009). For grass–clover stands or stands of forage legumes long-term dynamics of N loss are important. Carter and Ambus, (2006) found only 2% of the total N_2O-N emissions of biologically fixed N lost as N_2O in the short term, highlighting the importance of the long-term mineralization of plant material for N_2O emissions compared with recently fixed N. Accepting these limitations, Table 3.3 illustrates the mean and range of N_2O emissions as summarized by Jensen *et al.* (2011) and using additional data from the Legume Futures project, for a range of specific legume and non-legume crops. The apparent trend would be that grain legumes, forage legumes and grass–clover stands receiving minimal inorganic N fertilizer have lower emissions of N_2O than N-fertilized pastures and non-legume crops, but higher emissions than non-fertilized, non-legume crops (Rochette *et al.*, 2004; Jensen *et al.*, 2011).

In the case of legume systems showing higher N_2O emissions than non-legume crops grown with no added fertilizer, this would reflect N inputs provided by the

Table 3.3. Comparison of nitrous oxide (N_2O) emissions from legume and non-legume crops.

Crop	Total N_2O emissions per year or growing season (kg N_2O-N/ha)	
	Jensen *et al*. (2011)	Legume Futures project
Grassland		
N-fertilized pasture (grass)	4.5 (0.3–18.6)	
Mixed pasture sward (grass–clover)	0.5 (0.1–1.3)	
Pure legume stands		
Lucerne	2.0 (0.7–4.6)	0.6
White clover	0.8 (0.5–0.9)	
Galega		1.3 (1.1–1.4)
Grain legumes		
Faba bean	0.4	0.6 (0.02–1.5)
Field bean		0.08 (0.06–0.12)
Mung bean		0.4
Lupin	0.05	0.4
Lentil		0.06 (0.05–0.07)
Chickpea	0.06 (0.03–0.16)	
Field pea	0.7 (0.4–1.7)	1.0 (0.08–3.0)
Soybean	1.6 (0.3–7.1)	1.1 (0.9–1.2)
Mean of all legumes	*1.3*	*0.6*
N-fertilized crops		
Wheat	2.7 (0.09 –1.6)	
Maize	2.7 (0.16–12.7)	
Canola	2.7 (0.13–8.6)	
Mean N-fertilized crops	*3.2*	
Soil (no legumes or fertilizer)	1.2 (0.03–4.8)	

legumes. As an example, Dick *et al.* (2006) in a comparison of soils from N-fixing and non-N-fixing trees found both higher N_2O emissions and pool of available N (NH_4^+ and NO_3^-) in the soil from those trees fixing N_2 from the atmosphere.

There are a few exceptions in the literature where very high emissions of N_2O have been recorded from legume monocrops, such as lucerne (alfalfa) (Rochette *et al.*, 2004) and soybean (Parkin and Caspar, 2006), but here the influence of previous land management and sources of N other than biologically fixed N must be considered.

Before inorganic N fertilizers, soil fertility in farms was typically managed using legume-rich pastures, cover crops or rotation. These management systems are seen by some as a means of increasing productivity in poorer areas of the globe and also to increase sustainable agricultural production (Crews and Peoples, 2004). For instance: (i) cereal–legume intercropping is a common crop production system in Africa; (ii) incorporation of groundnut into rice-based cropping systems increases productivity and income of smallholders in South-east Asia (Whitmore *et al.*, 2000); (iii) rotation of crops with fast-growing tree, shrub and herbaceous N_2-fixing legume species is widely adopted for soil fertility management in the humid tropics (Millar *et al*., 2004); and (iv) in southern Brazil the use of legume cover crops is increasingly common in no-tillage systems (Mielniczuk *et al*., 2003).

Decomposition of N-rich residues to provide inorganic N

Both legume crops in rotation and their use as cover crops involve the incorporation of high-N plant residues into the soil. It is this aspect to legume systems, the incorporation of organic N into soils which following mineralization will provide sufficient substrate for nitrification and denitrification, which represents a significant source of N_2O. This may be further compounded by the higher N content and lower C:N ratios of legume tissues compared with other plant material.

In general, plant residues with high C:N ratios will immobilize soil N during initial microbial decomposition. In the short term, this has the effect of delaying the availability of inorganic nitrate for nitrification/denitrification but also for crop growth. In the long term though, plant-available N, yield and N uptake increase following straw addition with mineralization being extended (Cassman *et al*., 1996; Eagle *et al*., 2000). Inorganic N tends to be released from plant residues once excess C has been consumed by microbial growth. For legume residues this will occur rapidly due to both the high N content and the low C:N ratio of the tissue. A threshold C:N value of 20–25 has been proposed below which rapid N mineralization occurs (Frankenberger and Abdelmagid, 1985; Myers *et al*., 1994).

The typical N content values for a variety of plant residues taken from data presented in Jensen *et al*. (2011) shows that C:N values vary from approximately 26:1 to 10:1 for legume tissues and from approximately 26:1 to 105:1 for non-leguminous tissues (Fig. 3.2). Both the high overall N content and low C:N ratios of legume residues will result in more rapid net N mineralization, providing an excess of mineral N with respect to microbial growth and increased substrate for the combined processes of nitrification and denitrification. In general, therefore, greater N_2O emissions are measured after incorporation of high-N plant residues (Baggs *et al*., 2000; Millar *et al*., 2004; Kaewpradit *et al*., 2008; Gomes *et al*., 2009; Frimpong *et al*., 2011, 2012), with the peak in N_2O emissions occurring early after incorporation. Imbalances between the timing, availability and amount of newly mineralized N from legume residues and the onset of plant growth are therefore critical with respect to N_2O emissions, particularly if the legume is a cover crop and ploughed in as a green manure (Baggs *et al*., 2000) or part of an improved ley ploughed over before cereal planting (Pu *et al*., 1999).

To illustrate these points further, Table 3.4 provides a comparison of the percentage change effect on N_2O emissions of legumes grown in rotation versus legumes as green manure/cover crops. Accepting that few published studies provide suitable control values, the limited data available highlight the significant increase in N_2O flux possible where high N residues are incorporated into the soil. Irrespective of the scale of the percentage effect observed, the largest recorded flux values are comparable with those measured from crops fertilized with inorganic N. This comes in contrast to savings in both cost to the farmer in reducing fertilizer usage and environmental costs of reducing fertilizer manufacture, and further benefits of N carryover into the following crop.

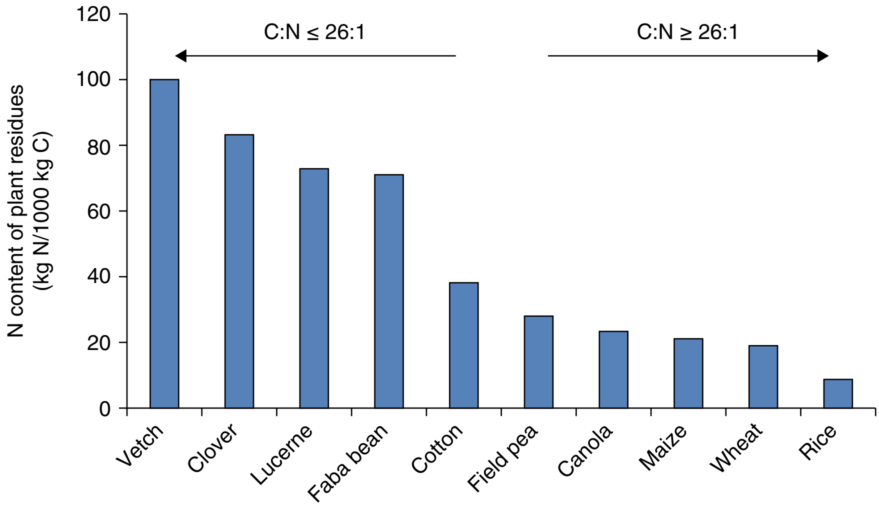

Fig. 3.2. N content and C:N ratios for legume and non-legume plant residues. (Adapted from Jensen *et al.*, 2011.)

Table 3.4. Effect of legume crop on N_2O emissions.

	Effect of legume crop on N_2O emissions compared with cereal crop/control (percentage change)	
	Legume crop in rotation (some residue incorporation)[a]	Legume crop as cover crop/green manure (significant residue incorporation)[b]
Mean	1.6	679
Minimum	–59	7.8
Median	–8	236
Maximum	113	1888

[a]Data from: MacKenzie *et al.* (1997), Dick *et al.* (2006), Drury *et al.* (2008), Halvorson *et al.* (2008), Guo *et al.* (2009) and Barton *et al.* (2013).
[b]Data from: Baggs *et al.* (2003), Millar *et al.* (2004), Kaewpradit *et al.* (2008), Gomes *et al.* (2009) and Frimpong *et al.* (2011).

Improving the synchrony between N availability and crop growth in these management systems would be critical in reducing N_2O flux and maybe N fertilized systems where top-dressings can match supply of N to demand are better than legume rotations in this respect (Cassman *et al.*, 2002; Crews and Peoples, 2004). One strategy that may prolong mineralization of legume residues through the season would be to manipulate the overall C:N ratio of the plant material applied. This may be achieved by mixing high-C cereal residues with high-N legume residues to allow for some measure of N immobilization (Myers *et al.*, 1994; Vinten *et al.*, 1998; Schwendener *et al.*, 2005; Kaewpradit *et al.*, 2008; Frimpong *et al.*, 2011).

Nitrate Leaching from Legume Crops

Leaching of nitrate from agricultural land is another important route of N loss from field soils reflecting both excess N in the soil comparative to crop growth requirements and the amount of water held by the soil immediately following N application (Addiscott and Powlson, 1992; Ledgard, 2001; Jensen and Hauggaard-Nielsen, 2003). In Europe, nitrate pollution of surface water and groundwater is a significant environmental problem with the annual nitrate concentration of approximately 30% of groundwaters exceeding the European Commission (EC) threshold value of 50 mg/l (Al-Kaisi and Licht, 2004; Hooker *et al.*, 2008). In legume-supported systems, particularly legume-rich pastures, leaching may be less of a problem than intensively managed systems (Owens *et al.*, 1994), although field data are lacking. Legume crops in rotation, or legume cover crops/green manures may still be associated with significant nitrate leaching from the soil due to both the lack of synchrony between N availability and crop growth and the amount of N provided through mineralization of the low C:N plant residues. As almost 75% of legume cover crop biomass is killed and left on the soil surface as a mulch which may be decomposed after 120 days, the potential for N leaching is high (Quemada *et al.*, 2004). Comparable field data on the effect of legume cropping on nitrate leaching is scarce in the literature. Beaudoin *et al.* (2005) observed the highest rates of nitrate leaching in crop rotations including pea for northern France due to the higher N content of plant biomass and lower N uptake rates from the soil, while one recent study on the use of legumes as cover crops in *Capsicum* production showed both high N leaching and a linear correlation between the N accumulated in the legume biomass and the total amount of nitrate leached (Campiglia *et al.*, 2011). Targeting the reduction of mineral N accumulation in soil, synchronizing N inputs with crop growth and crop N uptake and avoiding the buildup of excess N in soils would contribute towards decreased leaching (Mosier *et al.*, 2002) and one possible way to achieve this would be through intercropping of legumes with cereals, a form of low-N input agriculture popular in the tropics and now receiving interest in Europe.

Nitrogen and Phosphorus Losses from Intercropping of Legumes

Intercropping of legumes and cereals offers an opportunity to increase the input of fixed N into an agroecosystem both in the short term through direct N transfer (Patra *et al.*, 1986; Xiao *et al.*, 2004), and in the long term through mineralization of residues (Olesen *et al.*, 2002; Thorsted *et al.*, 2006). This may be achieved without compromising N uptake by the cereal crop or crop yield/stability (Hauggard-Nielsen *et al.*, 2001), and in terms of economic yield may even prove beneficial (Willey, 1979; Hauggaard-Nielsen *et al.*, 2001). As intercropping involves both a reduction in applied inorganic N and, by virtue of the legume and non-legume plants growing in close proximity, a more efficient use of N, emissions of N_2O may be expected to be lower than for monocrops. However, as with N leaching, there is a scarcity of information whereby direct comparisons between intercrops and monocrops can be made. Dyer *et al.* (2012) reported short-term N_2O emissions from a temperate maize–soybean intercropping system which was compared with monocropped maize and soybean. Emissions of N_2O were significantly lower from the intercrop treatments (11.5–12 μg N_2O-N m^2/h) than either the soybean or maize crops (13.5 μg N_2O-N m^2/h and 14 μg N_2O-N m^2/h, respectively). Only one study has reported cumulative emissions for legume–cereal intercropping (Pappa *et al.*, 2011). This study included both barley–pea and barley–clover intercrops and also looked at varietal differences in N_2O emission and N leaching (Table 3.5). As the barley monocrop received no added N other than that provided from the previous grass crop, inclusion of the clover and pea (cv. Nitouche) crops increased annual N_2O emission by 211% and 267%, respectively. Of significant interest, however, was the observation that one of the second pea varieties (cv. Zero 4) reduced the annual N_2O emission by 22% and that unlike barley–clover, the barley–pea intercrops reduced nitrate leaching.

Intercropping may also have positive effects on plant phosphorus (P) uptake. Phosphorus is an essential plant nutrient but is a relatively immobile element in soils. Following adsorption by soil surfaces and organic matter it forms stable largely insoluble compounds that cannot be removed from soils by leaching or volatilization. Small amounts of phosphorus are, however, released into the soil solution in the form of phosphate ions and it is these that become available for plant uptake and potential loss through drainage.

In many Western countries, fertilizer phosphorus inputs over many years have led to the enrichment of soil with phosphorus in immobile pools. Utilization of this excess phosphorus can be improved by selecting rotational designs to include crops or intercrops that optimize phosphorus uptake (Edwards *et al.*, 2010). Brassicas have been shown to be particularly effective at mobilizing phosphorus from the soil, possibly as a consequence of their root exudates (Walker *et al.*, 2012). There is considerable evidence that the use of legume-based intercropping systems improves the efficiency of soil phosphorus utilization and it has been suggested that this may be also a consequence of mycorrhizal associations with the roots of legume species (Ren *et al.*, 2013). It is considered likely that legume roots are able to alter the pH of the soil and influence phosphorus availability accordingly (Betencourt *et al.*, 2012; Li *et al.*, 2013). Legume-supported

Table 3.5. N losses from spring barley–clover and barley–pea intercrops. (Adapted from Pappa *et al.*, 2011.)

Crop	N_2O flux (kg N_2O-N/ha)	Change compared with control (%)	Nitrate leached (kg NO_3^--N/ha)	Change compared with control (%)
Barley	0.9		0.3	
Barley–clover	2.8	+ 211	1.3	+ 333
Barley–pea cv. Nitouche	3.3	+ 267	0.2	–33
Barley–pea cv. Zero 4	0.7	–22	0.1	–66

rotations (including intercrops) are of particular value in soils with lower phosphorus content or in circumstances where phosphorus is applied in insoluble forms. For example, organic farming regulations preclude the use of soluble phosphorus fertilizers, preferring instead to use composts or manure or other forms of phosphorus input such as rock phosphate. However, extreme phosphorus deficiency (often encountered in low pH soils) could possibly result in reduced growth of legumes in rotation as this becomes the next most limiting nutrient after nitrogen.

Conclusions

In terms of N loss from the soil via N_2O flux and NO_3^- leaching then available evidence indicates that the use of legumes as cover crops/green manure and surface mulches lead to high risks of losses of reactive nitrogen to the environment. Legumes in rotation, forage legumes and legumes as intercrops are more likely to be beneficial both in terms of reducing fertilizer inputs and in terms of cumulative N_2O emissions, but in the case of nitrification/denitrification, N_2O flux would be dependent on N inputs through mineralization of the previous crop.

Insufficient field data allows a definitive statement on N leaching and in terms of variable results from intercropping may reflect deeper rooting varieties (Pappa *et al.*, 2011). However, of the four cropping systems considered, the greatest potential for N loss would be the green manure/cover crop/mulch option.

Although legumes are known to mobilize phosphate pools, this comes at a cost of soil acidification that requires liming and may lead to some drainage losses.

Improvement of soil quality through soil structure and carbon sequestration would be pronounced both in long-term legume forage systems and in direct application of legume residues to soils as green manures/surface mulches.

References

Addiscott, T.M. and Powlson, D.S. (1992) Partitioning losses of nitrogen fertilizer between leaching and denitrification. *Journal of Agricultural Science* 118, 101–107.

Al-Kaisi, M. and Licht, M.A. (2004) Effect of strip tillage on corn nitrogen uptake and residual soil nitrate accumulation compared with no-tillage and chisel plough. *Agronomy Journal* 96, 1164–1171.

Allen, D.E., Kingston, G., Rennenberg, H., Dalal, R.C. and Schmidt S. (2010) Effect of nitrogen fertilizer management and waterlogging on nitrous oxide emission from subtropical sugarcane soils. *Agriculture Ecosystems and Environment* 136, 209–217.

Baggs, E.M., Rees, R.M., Smith, K.A. and Vinten, A.J.A. (2000) Nitrous oxide emissions from soils after incorporating crop residues. *Soil Use and Management* 16, 82–87.

Baggs, E.M., Stevenson, M., Pihlatie, M., Regar, A., Cook, H. and Cadisch, G. (2003) Nitrous oxide emissions following application of residues and fertiliser under zero and conventional tillage. *Plant and Soil* 254, 361–370.

Barton, L., Murphy, D.V. and Butterbach-Bahl, K. (2013) Influence of crop rotation and liming on greenhouse gas emissions from a semi-arid soil. *Agriculture, Ecosystems and Environment* 167, 23–32.

Beaudoin, N., Saad, J.K., Van Laethem, C., Machet, J.M., Maucorps, J. and Mary, B. (2005) Nitrate leaching in intensive agriculture in Northern France: effect of farming practices, soils and crop rotations. *Agriculture, Ecosystems and Environment* 111, 292–310.

Bedmar, E.J., Robles, E.F. and Delgado, M.J. (2005) The complete denitrification pathway of the symbiotic, nitrogen-fixing bacterium *Bradyrhizobium japonicum*. *Biochemical Society Transactions* 33,145–148.

Betencourt, E., Duputel, M., Colomb, B., Desclaux, D. and Hinsinger, P. (2012) Intercropping promotes the ability of durum wheat and chickpea to increase rhizosphere phosphorus availability in a low P soil. *Soil Biology & Biochemistry* 46, 181–190.

Bouwman, A.F., Boumans, L.J.M. and Batjes, N.H. (2002) Emissions of N_2O and NO from fertilized fields: summary of available measurement data. *Global Biogeochemical Cycles* 16, 6–1.

Bowden, W.B. and Bormann, F.H. (1986) Transport and loss of nitrous oxide in soil water after forest clear-cutting. *Science* 233, 867–869.

Briggs, S.R., Cuttle, S., Goodlass, G., Hatch, D., King, J., Roderick, S. and Shepherd, M. (2005) Soil nitrogen building crops in organic farming – Defra research project OF0316 project publication. Department for Environment, Food and Rural Affairs (Defra), London.

Bruinsma, J. (2003) *World Agriculture: Towards 2015/2030*. *An FAO Perspective*. Earthscan Publications Ltd, London.

Campiglia, E., Mancinelli, R., Radicetti, E. and Marinari, S. (2011) Legume cover crops and mulches: effects on nitrate leaching and nitrogen input in a pepper crop (*Capsicum anuum* L.). *Nutrient Cycling in Agroecosystems* 89, 399–412.

Cardenas, L.M., Thorman, R., Ashlee, N., Butler, M., Chadwick, D., Chambers, B., Cuttle, S., Donovan, N., Kingston, H., Lane, S., Dhanoa, M.S. and Scholefield, D. (2010) Quantifying annual N_2O emission fluxes from grazed grassland under a range of inorganic fertiliser nitrogen inputs. *Agriculture Ecosystems and Environment* 136, 218–226.

Carter, M.S. and Ambus, P. (2006) Biologically fixed N_2 as a source for N_2O production in a grass–clover mixture as measured by $^{15}N_2$. *Nutrient Cycling in Agroecosystems* 74, 13–26.

Cassman, K.G., de Datta, S.K., Amarante, S.T., Liboon, S.P., Samson, M.I. and Dizon, M.A. (1996) Long-term comparison of the agronomic efficiency and residual benefits of organic and inorganic nitrogen sources for tropical lowland rice. *Experimental Agriculture* 32, 427–444.

Cassman, K.G., Dobermann, A.D. and Walters, D. (2002) Agroecosystems, nitrogen-use efficiency, and nitrogen management. *Ambio* 31, 132–140.

Chirinda, N., Carter, M.S., Albert, K.R., Ambus, P., Olesen, J.E., Porter, J.R. and Petersen, S.O. (2010) Emissions of nitrous oxide from arable organic and conventional cropping systems on two soil types. *Agriculture Ecosystems and Environment* 136, 199–208.

Coyne, M.S. and Focht, D.D. (1987) Nitrous oxide reduction in nodules: denitrification or N_2 fixation? *Applied Environmental Microbiology* 53, 1168.

Crews, T.E. and Peoples, M.B. (2004) Legumes versus fertilizer sources of nitrogen: ecological tradeoffs and human needs. *Agriculture, Ecosystems and Environment* 102, 279–297.

Daniel, R.M., Smith, I.M., Phillip, J.A.D., Ratcliffe, H.D., Drozd, J.W. and Bull, A.T. (1980) Anaerobic growth and denitrification by *Rhizobium japonicum* and other rhizobia. *Journal of General Microbiology* 120, 517–521.

Davidson, E.A. (1991) Fluxes of nitrous oxide and nitric oxide from terrestrial ecosystems. In: Rogers, J.E. and Whitman, W.B. (eds) *Microbial Production and Consumption of Greenhouse Gases: Methane, Nitrogen Oxide and Halomethanes*. American Society for Microbiology, Washington, DC, pp. 219–235.

Davidson, E.A., Keller, M., Erickson, H.E., Verchot, L.V. and Veldkamp, E. (2000) Testing a conceptual model of soil emissions of nitrous and nitric oxides. *Biosciences* 50, 667–680.

Dick, J., Kaya, B., Soutora, M., Skiba, U., Smith, R., Niang, A. and Tabo, R. (2006) The contribution of agricultural practices to nitrous oxide emissions in semi-arid Mali. *Soil Use and Management* 24, 292–301.

Ding, W.X., Cai, Y., Cai, Z.C., Yagi, K. and Zheng, X.H. (2007) Nitrous oxide emissions from an intensively cultivated maize–wheat rotation soil in the North China Plain. *Science of the Total Environment* 373, 501–511.

Dobbie, K.E. and Smith, K.A. (2003) Nitrous oxide emission factors for agricultural soils in Great Britain: the impact of soil water-filled pore space and other controlling variables. *Global Change Biology* 9, 204–218.

Drury, C.F., Yang, X.M., Reynolds, W.D. and McLaughlin, N.B. (2008) Nitrous oxide and carbon dioxide emissions from monoculture and rotational cropping of corn, soybean and winter wheat. *Canadian Journal of Soil Science* 88, 163–174.

Dyer, L., Oelbermann, M. and Echarte, L. (2012) Soil carbon dioxide and nitrous oxide emissions during the growing season of maize–soybean intercropping and sole cropping systems. *Journal of Plant Nutrition and Soil Science* 175, 994–400.

Eagle, A.J., Bird, J.A., Horwath, W.R., Linquist, B.A., Brouder, S.M., Hill, J.E. and van Kessel, C. (2000) Rice yield and nitrogen utilization efficiency under alternative straw management practices. *Agronomy Journal* 92, 1096–1103.

Edenhofer, O., Pichs-Madruga, R.N., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S. and Eickemeier, P. (2014) Climate change 2014: Mitigation of climate change. Contribution of working group III to the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge.

Edwards, A.C., Walker, R.L., Maskell, P., Watson, C.A., Rees, R.M., Stockdale, E.A. and Knox, O.G.G. (2010) Improving bioavailability of phosphate rock for organic farming. In: Lichtfouse, E. (ed.) *Genetic Engineering, Biofertilisation, Soil Quality and Organic Farming*. Springer Science+Business Media BV, Dordrecht, the Netherlands.

Evans, R.D., Rimer, R., Sperry, L. and Belnap, J. (2001) Exotic plant invasion alters nitrogen dynamics in an arid grassland. *Ecological Applications* 11, 1301–1310.

Fixen, P.E. and West, F.B. (2002) Nitrogen fertilizers: meeting contemporary challenges. *AMBIO: A Journal of the Human Environment* 31, 169–176.

Flessa, H., Russa, R., Schilling, R., Loftfield, N., Munch, J.C., Kaiser, E.A. and Beese, F. (2002) N_2O and CH_4 fluxes in potato fields: automated measurement, management effects and temporal variation. *Geoderma* 105, 307–325.

Flückiger, J., Blunier, T., Stauffer, B., Chappellaz, J., Spahni, R., Kawamura, K., Schwander, J., Stocker, T.F. and Dahl-Jensen, D. (2004) N_2O and CH_4 variations during the last glacial epoch: insight into global processes. *Global Biogeochemical Cycles* 18, doi:10.1029/2003GB002122.

Fowler, D., Pilegaard, K., Sutton, M.A., Ambus, P., Raivonen, M., Duyzer, J., Simpson, D., Fagerli, H., Fuzzi, S., Schjoerring, J.K., Grainer, C., Neftel, A., Isaksen, I.S.A., Laj, P., Maione, M., Monks, P.S., Burkhardt, J., Daemmgen, U., Neirynck, J., Personne, E., Wichink-Kruit, R., Butterbach-Bahl, K., Flechard, C., Tuovinen, J.P., Coyle, M., Gerosa, G., Loubet, B., Altimir, N., Gruenhage, L., Ammann, C., Cieslik, S., Paoletti, E., Mikkelsen, T.N., Ro-Poulsen, H., Cellier, P., Cape, J.N., Horvath, L., Loreto, F., Niinemets, U., Palmer, P.I., Rinne, J., Misztal, P., Nemitz, E., Nilsson, D., Pryor, S., Gallagher, M.W., Vesala, T., Skiba, U., Brueggemann, N., Zechmeister-Boltenstern, S., Williams, J., O'Dowd, C., Facchini, M.C., de Leeuw, G., Flossman, A., Chaumerliac, N. and Erisman, J.W. (2009) Atmospheric composition change: ecosystems–atmosphere interactions. *Atmospheric Environment* 43, 5193–5267.

Frankenberger, W.T. and Abdelmagid, H.M. (1985) Kinetic parameters of nitrogen mineralisation rate of leguminous crops incorporated into soil. *Plant and Soil* 87, 257–271.

Frimpong, K.A., Yawson, D.O., Baggs, E.M. and Agyarko, K. (2011) Does incorporation of cowpea–maize residue mixes influence nitrous oxide emission and mineral nitrogen release in a tropical luvisol? *Nutrient Cycling in Agroecosystems* 91, 281–292.

Frimpong, K.A., Yawson, D.O., Agyarko, K. and Baggs, E.M. (2012) N_2O emission and mineral N release in a tropical acrisol incorporated with mixed cowpea and maize residues. *Agronomy* 2, 167–186.

Galbally, I.E., Meyer, M.C.P., Wang, Y.-P., Smith, C.J. and Weeks, I.A. (2010) Nitrous oxide emissions from a legume pasture and the influences of liming and urine addition. *Agriculture, Ecosystems and Environment* 136, 262–272.

Gomes, J., Bayer, C., de Sousa Costa, F., de Cássia Piccolo, M., Zanatta, J.A., Vieira, F.C.B. and Six, J. (2009) Soil nitrous oxide emissions in long-term cover crops-based rotations under subtropical climate. *Soil and Tillage Research* 106, 36–44.

Gregorich, E.G., Rochette, P., Vandenbygaart, A.J. and Angers, D.A. (2005) Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada. *Soil and Tillage Research* 83, 53–72.

Guo, Z.L., Cai, C.F., Li, Z.X., Wang, T.W. and Zheng, M.J. (2009) Crop residue effect on crop performance, soil N_2O and CO_2 emissions in alley cropping systems in subtropical China. *Agroforestry Systems* 76, 67–80.

Halvorson, A.D., Del Grosso, S.J. and Reule, C.A. (2008) Nitrogen, tillage and crop rotation effects on nitrous oxide emissions from irrigated systems. *Journal of Environmental Quality* 37, 1337–1344.

Hauggaard-Nielsen, H., Ambus, P. and Jensen, E.S. (2001) Temporal and spatial distribution of roots and competition for nitrogen in pea–barley intercrops – a field study employing 32P technique. *Plant and Soil* 236, 63–74.

Hooker, K.V., Coxon, C.E., Hackett, R., Kirwan, L.E., O'Keefe, E. and Richards, K.G. (2008) Evaluation of cover crop and reduced cultivation for reducing nitrate leaching in Ireland. *Journal of Environmental Quality* 37, 138–145.

Intergovernmental Panel on Climate Change (IPCC) (2006) 2006 IPCC guidelines for national greenhouse gas inventories. In: Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T. and Tanabe, K. (eds) *Agriculture, Forestry and Other Land Use*. Prepared by the National Greenhouse Gas Inventories Programme, Vol. 4. Institute for Global Environmental Strategies (IGES), Japan.

Intergovernmental Panel on Climate Change (IPCC) (2007) Climate change 2007: The scientific basis. Contribution of working group 1 to the fourth assessment report of the IPCC. Cambridge University Press, Cambridge.

Jensen, E.S. and Hauggaard-Nielson, H. (2003) How can increased use of biological N_2 fixation in agriculture benefit the environment? *Plant and Soil* 252,177–186.

Jensen, E.S., Peoples, M., Boddey, R.M., Gresshoff, P.M., Hauggard-Nielsen, H., Alves, B.J.R. and Morrison, M.J. (2011) Legumes for the mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review. *Agronomy for Sustainable Development* 32, 329–364.

Kaewpradit, W., Toomsan, B., Vityakon, P., Limpinuntana, V., Saenjan, P., Jogloy, S., Patanothai, A. and Cadisch, J. (2008) Regulating mineral N release and greenhouse gas emissions by mixing groundnut residues and rice straw under field conditions. *European Journal of Soil Science* 59, 640–652.

Khalil, M.K., Rosenani, A.R., Van Cleemput, O.V.C., Boeckx, P.B., Shamshuddin, J.S. and Fauziah, C.F. (2002) Nitrous oxide production from an ultisol of the humid tropics treated with different nitrogen sources and moisture regimes. *Biology and Fertility of Soils* 36, 59–65.

Klumpp, K., Bloor, J.M.G., Ambus, P. and Soussana, J.-F. (2011) Effects of clover density on N_2O emissions and plant–soil N transfers in a fertilised upland pasture. *Plant and Soil* 343, 97–107.

Kroeze, C. (1999) Closing the global N_2O budget: a retrospective analysis 1500–1994. *Global Biogeochemical Cycles* 13, 1–8.

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

Lemke, R.L., Zhong, Z., Campbell, C.A. and Zentner, R. (2007) Can pulse crops play a role in 580 mitigating greenhouse gases from North American agriculture? *Agronomy Journal* 99, 1719–1725.

Li, X.P., Mu, Y.H., Cheng, Y.B., Liu, X.G. and Nian, H. (2013) Effects of intercropping sugarcane and soybean on growth, rhizosphere soil microbes, nitrogen and phosphorus availability. *Acta Physiologiae Plantarum* 35,1113–1119.

MacKenzie, A.F., Fan, M.X. and Cadrin, F. (1997) Nitrous oxide emissions as affected by tillage, corn–soybean–alfalfa rotations and nitrogen fertilization. *Canadian Journal of Soil Science* 77, 145–152.

Majumdar, D. (2009) Past, present and future of nitrous oxide emissions from rice field: a treatise. In: Sheldon, A.I. and Barnhart, E.P. (eds) *Nitrous Oxide Emissions Research Progress*. Environmental Science, Engineering and Technology Series. Nova Science Publishers, New York, pp. 179–252.

Malhi, S.S., Lemke, R., Wang, Z.H. and Chhabra, B.S. (2006) Tillage, nitrogen and crop residue effects on crop yield, nutrient uptake, soil quality and greenhouse gas emissions. *Soil and Tillage Research* 90, 171–183.

Malijanen, M., Nykänen, H., Moilanen, M. and Martikainen, P.J. (2006) Greenhouse gas fluxes of coniferous forest floors as affected by wood ash addition. *Forest Ecology and Management* 237, 143–149.

Matthews, R.A., Chadwick, D.R., Retter, A.L., Blackwell, M.S.A. and Yamulki, S. (2010) Nitrous oxide emissions from small scale farmland features of UK livestock farming systems. *Agriculture Ecosystems and Environment* 136, 192–198.

Metay, A., Oliver, R., Scopel, E., Douzet, J.M., Alves Moreira, J.A., Maraux, F., Feigl, B.J. and Feller, C. (2007) N_2O and CH_4 emissions from soils under conventional and no-till management practices in Goiania (Cerrados, Brazil). *Geoderma* 141, 78–88.

Mielniczuk, J., Bayer, C., Vezzani, F.M., Lovato, T., Fernandes, F.F. and Debarba, L. (2003) Manejo de solo e culturas e sua relação com os estoques de carbono e nitrogênio do solo. *Tópicos em ciência do solo* 3, 209–248.

Millar, N., Ndufa, J.K., Cadisch, G. and Baggs, E.M. (2004) Nitrous oxide emissions following incorporation of improved–fallow residues in the humid tropics. *Global Biogeochemical Cycles* 18, doi: 10.1029/2003GB002114.

Monza, J., Irisarri, P., Díaz, P., Delgado, M.J., Mesa, S. and Bedmar, E.J. (2006) Denitrification ability of rhizobial strains isolated from *Lotus* sp. *Antonie Van Leeuwenhoek, International Journal of General and Molecular Microbiology* 89, 479–484.

Mosier, A.R., Bleken, M.A., Chaiwanakupt, P., Ellis, E.C., Frenzy, J.R., Howarth, R.B., Matson, P.A., Minami, K., Naylor, R., Weeks, K.N. and Zhu, Z.-L. (2002) Policy implications of human-accelerated nitrogen cycling. *Biogeochemistry* 57, 477–516.

Muňoz, C., Paulino, L., Monreal, C. and Zagal, E. (2010) Greenhouse gas (CO_2 and N_2O) emissions from soils: a review. *Chilean Journal of Agricultural Research* 70, 485–497.

Myers, R.J.K., Palm, C.A., Cuevas, E., Gunatilleke, I.U.N. and Brossard, M. (1994) The synchronisation of nutrient mineralisation and plant nutrient demand. In: Woomer, P.I. and Swift, M.J. (eds) *The Biological Management of Tropical Soil Fertility*. Wiley, Chichester, UK, pp. 81–116.

O'Hara, G. and Daniel, R.M. (1985) Rhizobial denitrification: a review. *Soil Biology and Biochemistry* 17, 1–9.

O'Hara, G.W., Daniel, R.M., Steele, K.W. and Bonish, P.M. (1984) Nitrogen losses from soils caused by *Rhizobium*-dependent denitrification. *Soil Biology and Biochemistry* 16, 429–431.

Olesen, J.E., Rasmussen, I.A., Askegaard, M. and Kristensen, K. (2002) Whole-rotation dry matter and nitrogen grain yields from the first course of an organic farming crop rotation experiment. *Journal of Agricultural Science* 139, 361–370.

Owens, L.B., Edwards, W.M. and Van Keuren, R.W. (1994) Groundwater nitrate levels under fertilized grass and grass legume pastures. *Journal of Environmental Quality* 23, 752–758.

Pappa, V.A., Rees, R.M., Walker, R.L., Baddeley, J.A. and Watson, C.A. (2011) Nitrous oxide emissions and nitrate leaching in an arable rotation resulting from the presence of an intercrop. *Agriculture, Ecosystems and Environment* 141, 153–161.

Parkin, T.B. and Kaspar, T.C. (2006) Nitrous oxide emissions from corn–soybean systems in the Midwest. *Journal of Environmental Quality* 35, 1496–1506.

Patra, D.D., Sachdev, M.S. and Subbiah, B.V. (1986) ^{15}N studies on the transfer of legume-fixed nitrogen to associated cereals in intercropping systems. *Biology and Fertility of Soils* 2, 165–171.

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, G.D. (2001) Factors regulating the contributions of fixed nitrogen by pasture and crop legumes to different farming systems of eastern Australia. *Plant and Soil* 228, 29–41.

Peoples, M.B., Brockwell, J., Herridge, D.F., Rochester, I.J., Alves, B.J.R., Urquiaga, S., Boddey, R.M., Dakora, F.D., Bhattarai, S., Maskey, S.L., Sampet, C., Rerkasem, B., Khan, D.F., Hauggard-Nielsen, H. and Jensen, E.S. (2009) The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. *Symbiosis* 48, 1–17.

Prather, M.J., Ehhalt, D., Dentener, F.J., Derwent, R., Dlugokencky, E.J., Holland, E.A., Isaksen, I., Katima, J., Kirchhoff, V., Matson, P.A., Midgley, P., Wang, M. and Al, E. (2001) Atmospheric chemistry and greenhouse gases. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., Van der Linden, P.J., Dai, X., Maskell, K. and Johnson, C.A. (eds) *Climate Change 2001: The Scientific Basis*. Cambridge University Press, Cambridge,

Pu, G., Saffigna, P.G. and Strong, W.M. (1999) Potential for denitrification in cereal soils of northern Australia after legume or grass–legume pastures. *Soil Biology and Biochemistry* 31, 667–675.

Quemada, M. and Cabrera, M.L. (2004) Predicting crop residue decomposition using moisture adjusted time scales. *Nutrient Cycling in Agroecosystems* 70, 283–291.

Ren, L.X., Lou, Y.S., Zhang, N., Zhu, X.D., Hao, W.Y., Sun, S.B., Shen, Q.R. and Xu, G.H. (2013) Role of arbuscular mycorrhizal network in carbon and phosphorus transfer between plants. *Biology and Fertility of Soils* 49, 3–11.

Rochette, P. and Janzen, H.H. (2005) Towards a revised coefficient for estimating N_2O emissions from legumes. *Nutrient Cycling in Agroecosystems* 73, 171–179.

Rochette, P., Angers, D.A., Bélanger, G., Chantigny, M.H., Prevost, D. and Levesque, G. (2004) Emissions of N_2O from alfalfa and soybean crops in eastern Canada. *Soil Science Society of America Journal* 68, 93–506.

Saggar, S., Tate, K.R., Giltrap, D.L. and Singh, J. (2008) Soil–atmosphere exchange of nitrous oxide and methane in New Zealand terrestrial ecosystems and their mitigation options: a review. *Plant and Soil* 309, 25–42.

Saggar, S., Luo, J., Giltrap, D. and Maddena, M. (2009) Nitrous oxide emissions from temperate grasslands: processes, measurements, modelling and mitigation. In: Sheldon, A.I. and Barnhart, E.P. (eds) *Nitrous Oxide Emissions Research Progress*. Environmental Science and Technology Series. Nova Science Publishers, New York, pp. 1–66.

Schwendener, C.M., Lehmann, J., de Camargo, P.B., Luizão, R.C.C. and Fernandes, E.C.M. (2005) Nitrogen transfer between high- and low-quality leaves on a nutrient-poor oxisol determined by 15N enrichment. *Soil Biology and Biochemistry* 37, 787–794.

Šimek, M. and Cooper, J.E. (2002) The influence of soil pH on denitrification: progress towards the understanding of this interaction over the last 50 years. *European Journal of Soil Science* 53, 345–354.

Smil, V. (1999) Nitrogen in crop production: an account of global flows. *Global Biogeochemical Cycles* 13, 647–662.

Smith, K. (1997) The potential for feedback effects induced by global warming on emissions of nitrous oxide by soils. *Global Change Biology*, 3, 327–338.

Smith, K.A., Ball, T., Conen, F., Dobbie, K.E., Massheder, J. and Rey, A. (2003) Exchange of greenhouse gases between soil and atmosphere: interactions of soil physical factors and biological processes. *European Journal of Soil Science* 54, 779–791.

Smith, P., Martino, D., Cai, C., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B. and Sirotenko, O. (2007) Agriculture. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R. and Meyer, L.A. (eds) Climate change 2007, mitigation. Contribution of working group 111 to the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge.

Sowers, T. (2001) N_2O record spanning the penultimate deglaciation from the Vostok ice core. *Journal of Geophysical Research–Atmospheres* 106, 31903–31914.

Thorsted, M.D., Olesen, J.E. and Weiner, J. (2006) Width of clover strips and wheat rows influence grain yield in winter wheat/white clover intercropping. *Field Crops Research* 95, 280–290.

Vinten, A.J.A., Davis, R., Castle, K. and Baggs, E.M. (1998) Control of nitrate leaching from a nitrate vulnerable zone using paper mill waste. *Soil Use Management* 14, 44–51.

Wagner-Riddle, C. and Thurtell, G.W. (1998) Nitrous oxide emission from agricultural fields during winter and spring thaw as affected by management practices. *Nutrient Cycling in Agroecosystems* 52, 151–163.

Walker, R.L., Edwards, A.C., Maskell, P., Watson, C.A., Rees, R.M., Knox, O.G.G. and Stockdale, E.A. (2012) The effect of co-composted cabbage and ground phosphate rock on the early growth and P uptake of oilseed rape and perennial ryegrass. *Journal of Plant Nutrition and Soil Science* 175, 595–603.

Well, R., Kurganova, I., Lopes de Gerenyu, V. and Flessa, H. (2006) Isotopomer signatures of soil-emitted N_2O under different moisture conditions, microcosm study with arable loess soil. *Soil Biology and Biochemistry* 38, 2923–2933.

Whitmore, A.P., Cadisch, G., Toomsan, B., Limpinuntana, V., van Noorwijk, M. and Purnomosidhi, P. (2000) An analysis of the economic values of novel cropping systems in N.E. Thailand and S. Sumatra. *Netherlands Journal of Agricultural Science* 48, 1055–1114.

Willey, R.W. (1979) Intercropping: its importance and research needs. Competition and yield advantages. *Field Crop Abstracts* 1, 1–10.

Williams, C.H. (1980) Soil acidification under clover pasture. *Australian Journal of Experimental Agriculture* 20, 561–567.

Xiao, Y., Li, L. and Zhang, F. (2004) Effect of root contact on interspecific competition and N transfer between wheat and faba bean using direct and indirect ^{15}N techniques. *Plant and Soil* 262, 45–54.

Zaman, M., Nguyen, M.L., Matheson, F., Blennerhassett, J.D. and Quin, B.F. (2007) Can soil amendments (zeolite or lime) shift the balance between nitrous oxide and dinitrogen emissions from pasture and wetland soils receiving urine or urea-N? *Australian Journal of Soil Research* 45, 543–553.

Zaman, M., Nguyen, M.L. and Saggar, S. (2008) N_2O and N_2 emissions from pasture and wetland soils with and without amendments of nitrate, lime and zeolite under laboratory condition. *Australian Journal of Soil Research* 46, 526–534.

Zhong, Z., Lemke, R.L. and Nelson, L.M. (2009) Nitrous oxide emissions associated with nitrogen fixation by grain legumes. *Soil Biology and Biochemistry* 41, 2283–2291.

Zhong, Z., Nelson, L.M. and Lemke, R.L. (2011) Nitrous oxide emissions from grain legumes as affected by wetting/drying cycles and crop residues. *Biology and Fertility of Soils* 47, 687–699.