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Management practices for minimising nitrate leaching after ploughing temporary leguminous pastures in Canterbury, New Zealand

G.S. Francis

New Zealand Institute for Crop & Food Research Limited, Private Bag 4704, Christchurch, New Zealand

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Abstract

Winter leaching losses of nitrate following the ploughing of temporary leguminous pastures in late summer or early autumn are a major concern in mixed cropping rotations on the Canterbury Plains of New Zealand. Field experiments showed that pastures ploughed in early autumn (March) and left fallow accumulated 107–142 kg ha^{-1} N of mineral-N in the soil profile by the start of winter, with 72–106 kg ha^{-1} N lost through leaching in the first winter. Delaying the ploughing of pasture until late autumn (May) reduced the accumulation of mineral-N to 42–120 kg ha^{-1} N and the leaching loss to 8–52 kg ha^{-1} N.

In situations where early cultivation cannot be avoided, growing winter cover crops or using the nitrification inhibitor dicyandiamide (DCD) both have the potential to reduce leaching compared with fallow soil. DCD increased the amount of mineral-N present in the soil as ammonium and reduced leaching losses by 25–50% without affecting the yield of the following spring wheat crop.

Cover crops only reduced leaching losses (by up to 60%) when they were sown early in the autumn and they had taken up considerable amounts of soil mineral-N before drainage occurred. When cover crops were grazed before incorporation in spring, there was an increased risk of leaching from urine patch areas. If residues were incorporated without grazing, however, the yield of the following spring wheat crop was depressed by 20–30% due to extensive net N immobilization during decomposition of the residues.

In Canterbury conditions, the most reliable way to minimise N leaching losses is to delay the ploughing of pasture for as long as possible in autumn or winter. Where pastures are ploughed early, the relative effectiveness of using DCD or growing winter cover crops varies mainly in relation to rainfall distribution.

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1. Introduction

Mixed cropping (pasture/arable) is a major land use on the Canterbury Plains of New Zealand, an area of ~ 750,000 ha. Grazed ryegrass (*Lolium perenne* L.)–white clover (*Trifolium repens* L.) pastures or grass and/or clover seed crops are commonly grown for 2–5 years before they are ploughed in and followed by 2–5 years of arable crops (Haynes and Francis, 1990). Many "sustainable" cropping systems that are currently being promoted throughout the world are based on similar rotations that partly rely on legumes to fix N_2 and restore soil structure (Keeney, 1990).

The N fertility of the soil increases during the pastoral phase of the rotation, mainly due to the large amount of symbiotic N_2 fixation by the clover. As a result, net N mineralization of organic-N (of plant and soil origin) is usually sufficient to meet the requirements of the arable crop grown in the first year after pasture is ploughed. The N fertility of the soil gradually declines, and N fertilizer is commonly applied to arable crops at a rate of 50 kg ha^{-1} N in the second year and at 100–150 kg ha^{-1} N in the third and subsequent years (Haynes and Francis, 1990). Despite this cyclical change in soil-N fertility, changes in total-N content are often not detectable (Haynes et al., 1991). This is not surprising as a decrease in the total-N in the plough layer of 0.01% is not likely to be analytically or statistically significant, yet it represents > 200 kg ha^{-1} N.

An apparent deficiency of this mixed pasture/arable system is that a substantial amount of nitrate (NO_3^--N) can be leached from the soil. As a result, concentrations of NO_3^--N in potable water in Canterbury (Adams et al., 1979) often exceed the World Health Organization recommended limit of 10 mg L^{-1} NO_3^--N (WHO, 1978). In Canterbury, most of the NO_3^--N in groundwater is thought to arise from winter leaching after the ploughing of temporary leguminous pastures in late summer or autumn (Haynes and Francis, 1990).

This paper reviews the recent research carried out in our laboratory on NO_3^--N leaching losses under mixed cropping rotations. We have measured the extent of nitrate leaching losses over autumn and winter and investigated possible approaches to minimize these leaching losses. These include delaying the time of pasture incorporation until late autumn or early winter; using different cultivation methods; growing cover crops during winter; and using a nitrification inhibitor. Most of the research has been conducted in the first winter after pasture is ploughed, although some experiments have investigated leaching losses in the second, third and fourth winters after the initial cultivation of pasture. We have also measured winter leaching losses after a number of leguminous and non-leguminous grain crops during the arable phase of the rotation.

2. Materials and methods

This review presents data from field experiments in which plots were commonly ~ 100 m^2 and individual treatments were replicated three or four times in randomized block designs. All experiments were conducted on freely-draining Templeton silt loam soils (Udic Ustochrept, USDA Soil Taxonomy), which are common in the region (Kear et al., 1967). Under pasture, the soils had a total-N content of ~ 0.23% and an organic

C content of ~ 2.7%. Except where specifically stated, pastures were incorporated by mouldboard ploughing to a depth of 150–200 mm. Soil mineral-N content was measured on samples bulked from four replicate soil cores (i.d. 25 mm) taken from each plot. Soil solution nitrate concentrations were measured on samples collected in duplicate porous ceramic samplers (25 mm wide × 55 mm long) installed at 600-mm depth. Soil solution samples were collected from autumn to spring after significant (> 20 mm) rainfall events. Mean annual rainfall in the study area is 680 mm, which is relatively evenly distributed throughout the year (Cox, 1978). Long-term meteorological records show that soil drainage usually only occurs in winter and spring (July–September) (Cox, 1978). Soil temperature at the 100-mm depth steadily decreases from 10–12°C in March to a minimum of 2–3°C in June, and then increases to 7–8°C in September.

Long-term, mean, April–September rainfall is 353 mm (Cox, 1978). In the years of our experiments (1989–1994), rainfall varied markedly during this period from 298 mm in 1994 to 481 mm in 1992 (Fig. 1). The distribution of rainfall also varied between years. In some years, major rainfall events occurred in autumn (April–May), while in other years major rainfall events occurred at the end of winter or beginning of spring (August–September). Soil drainage was calculated using a simple water balance model, with soil moisture in each plot measured using time–domain reflectometry (0–200-mm depth) and neutron probe (200–800-mm depth) techniques.

Leaching losses of mineral-N during autumn and winter were measured by several methods. We obtained very good agreement on these soils between leaching losses calculated from either sequential soil core samples or porous soil solution samplers and drainage estimates (Francis et al., 1992, 1994). Similarly, direct measurements of drainage and nitrate leaching from large (800-mm diameter × 800-mm deep), undisturbed lysimeters installed at the experimental site correlated very well with estimates of

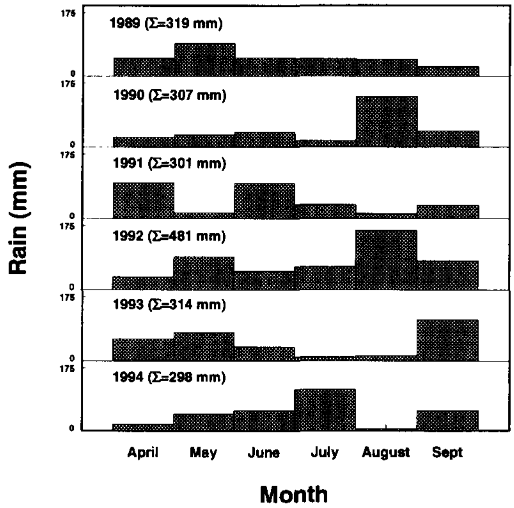

Fig. 1. Monthly rainfall during autumn–spring (April–September) in 1989–1994.

drainage and N leaching obtained from field plots (G.S. Francis, unpublished data, 1993).

3. Results and discussion

3.1. Effect of date of ploughing pastures

In 1990–1992 we investigated the effect of the date of ploughing temporary leguminous pastures on the extent of NO_3^--N leaching losses during the first winter following cultivation. Pastures were ploughed either in March (early autumn), May (late autumn), August (early winter) or October (spring). When pastures were ploughed in March, there was extensive net N mineralization of organic-N (in pasture residues and readily-mineralizable soil organic matter) before the start of winter. This mineralization was favoured by the relatively warm soil temperatures at incorporation and the long period for mineralization before the start of winter leaching events. Consequently, a large amount of mineral-N accumulated in the profile before the onset of leaching (Table 1). Decomposition studies of ^{14}C-labelled residues in cores (100-mm diameter × 150-mm deep) in the field suggested that ~ 30% of the total-N in the incorporated pasture residues mineralized by the start of the winter (Francis et al., 1992). The remainder of the accumulated mineral-N came from the mineralization of readily-mineralizable soil organic matter.

Due to variable rainfall amounts in the years of the experiment, soil drainage from pastures ploughed in March ranged from 131 to 270 mm (Table 1). The extent of leaching loss was determined by the amount of drainage from the soil and the soil-NO_3^--N concentration when drainage occurred. Consequently, leaching losses from pasture ploughed in March ranged from 72 to 106 kg ha^{-1} N in relation to rainfall

Table 1
Effect of the time of ploughing of pasture on pasture residue N content, soil mineral-N accumulation before the start of winter leaching, drainage, and N leaching loss from soil fallowed during winter

Time of ploughing	Pasture residue total-N content [a] (kg ha^{-1} N)	Pre-leaching soil mineral-N content [b] (kg ha^{-1} N)	Drainage (mm)	N leaching loss (kg ha^{-1} N)
Early autumn (March)	145–175	107–142	131–270	72–106
Late autumn (May)	171–222	42–100	116–250	8– 52
Early winter (August) [c]	231	20	78	6
Spring (October)	201–287	18– 24	58–220	2– 15
SED[d]	±11.1– 18.4	±4.7– 13.3	±4.5– 10.2	±6.7– 10.1

Data from Francis et al. (1992, 1994), G.S. Francis (unpublished data, 1994).

[a] Sum of above and below ground residues.

[b] 0–600-mm depth in June.

[c] Treatment only imposed in one experimental year (1990).

[d] Standard error deviation of individual treatment means in each year.

Table 2

Soil mineral N content (0–1-m depth), dry matter (DM), N content of cover crop herbage before winter leaching and in spring 1993, and yield of the subsequent spring wheat crop

Treatment	Before winter leaching			In spring			Spring wheat yield [a, b] (t ha^{-1})
	soil mineral-N (kg ha^{-1} N)	herbage-DM (t ha^{-1})	herbage-N (kg ha^{-1} N)	soil mineral-N [a] (kg ha^{-1} N)	herbage-DM (t ha^{-1})	herbage-N (kg ha^{-1} N)	
Fallow	100	0	0	129	0	0	5.6
Oats	51	3.1	80	27 (68)	9.9	297	4.0 (5.4)
Italian ryegrass	58	1.7	53	19 (62)	6.2	109	3.9 (5.8)
Mustard	45	2.9	71	44 (64)	5.3	160	4.5 (5.0)
Lupins	73	1.4	50	35 (164)	9.0	269	5.9 (5.4)
SED	±16.4	±0.13	±5.1	±12.5	±0.68	±22.3	±0.58

Data from G.S. Francis (unpublished data, 1994). 1 t = 1 metric tonne = 10^3 kg. SED = standard error deviation.

[a] Figures in brackets are for the mean of ± urine patch areas of grazed plots. Urine patch areas were estimated to cover 50% of the soil area during grazing (Haynes and Williams, 1993).

[b] Nil N fertilizer plots.

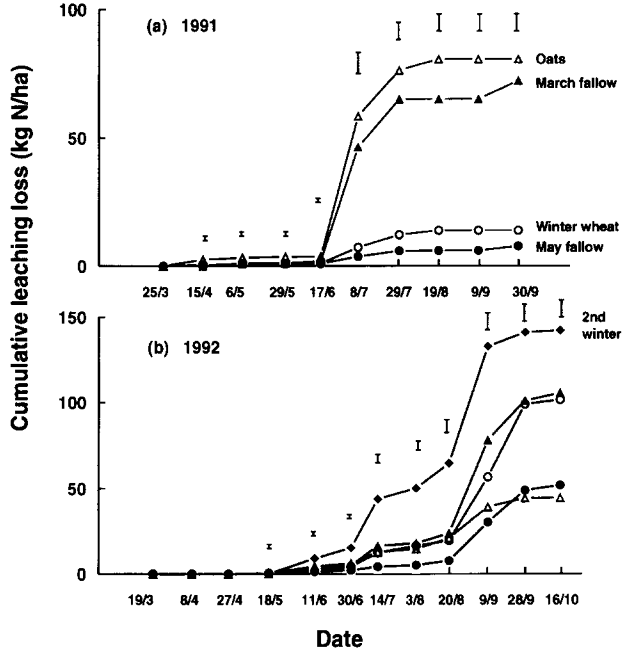

Fig. 2. Cumulative nitrate leaching losses from March fallow, oats, May fallow and winter wheat treatments during the first autumn and winter after ploughing in (a) 1991 and (b) 1992. Losses during the second autumn and winter under March fallow are also shown. *Vertical bars* represent SED's.

amount and distribution. Losses were greatest in 1992 when there was a large amount of drainage that occurred in late winter after a large amount of mineral-N had accumulated in the soil profile (Fig. 2).

The impacts of a delay in ploughing pasture became more pronounced the longer it was delayed. Due to continued pasture growth during autumn and winter, the amount of soil mineral-N incorporated into plant residues increased when the ploughing of pasture was delayed (Table 1). Cooler soil temperatures at incorporation and a shorter time for net N mineralization reduced the accumulation of soil mineral-N before the start of winter drainage. Soil drainage was also reduced when the fallow period was shorter as evapotranspiration losses from pasture were greater than evaporation from bare soil. When the ploughing of pasture was delayed, the combination of reduced drainage and lower mineral-N accumulation resulted in reduced leaching losses of NO_3^--N (Table 1).

Delaying the ploughing of pasture was most effective at reducing leaching losses when rainfall occurred early in the autumn or winter before a significant amount of mineral-N had accumulated in the soil profile. For example, delaying pasture incorporation until May reduced leaching losses to 8 kg ha^{-1} N in 1991, but to only 52 kg ha^{-1} N in 1992 when leaching occurred much later in the winter (Fig. 2). In the Canterbury climate, delaying ploughing of pasture until May is an option, but ploughing in August is often impossible due to wet soil conditions.

3.2. Leaching in the second and subsequent winters after pasture

When short-term pastures are incorporated, leaching losses of N are usually greater during the first winter following their incorporation than in the second and subsequent winters (Webster and Dowdell, 1986; Davies and Barraclough, 1989). In our experiments, plots ploughed in March had a similar accumulation of mineral-N in the profile at the start of winter in 1992 both in their first (107 kg ha^{-1} N) and second (112 kg ha^{-1} N) year after incorporation (Francis et al., 1995a). This result was somewhat surprising, because more readily-mineralizable N was incorporated as pasture residue in plots before the first winter than as burned wheat stubble before their second winter. The contribution of pasture residue decomposition to mineral-N accumulation in the second winter would have been small, because 60–70% of pasture residues would have decomposed in the first year after incorporation (Francis et al., 1992). Most of the mineral-N in the soil in the second winter after pasture was presumably derived from the mineralization of soil organic-N that had accumulated under pasture. However, some mineral-N probably remained in the profile after the harvest of the first spring wheat crop. Indeed, there was a greater amount of mineral-N below 400-mm depth at the start of the second winter ($\sim$ 45 kg ha^{-1} N) than at the start of the first winter after pasture ($\sim$ 30 kg ha^{-1} N). This mineral-N had probably been leached to that depth by heavy rainfall in late summer after significant N uptake by the first spring wheat crop had ceased. The greater mineral-N content below 400-mm depth at the start of the second winter partially explains the more rapid and greater cumulative leaching losses in the second (142 kg ha^{-1} N) than in the first winter (106 kg ha^{-1} N) after pasture (Fig. 2b).

There was little residual effect of reducing leaching losses in the first winter on N leaching losses during the second winter after pasture. This is because in this high N fertility soil, differences in leaching losses between treatments in the first winter were small compared with the total amount of N present in the plough layer ($\sim$ 4500 kg ha^{-1} N), and presumably compared with the size of the readily-mineralizable pool of organic-N.

In 1994, we compared soil solution nitrate concentrations at 600-mm depth in fallow soil which was in its first to fourth winter after pasture had been ploughed. Concentrations were greatest during most of the autumn and winter in plots in their first and second winter after pasture (Fig. 3). By the third and fourth winters after pasture, the pool of readily-mineralizable soil organic-N would have declined significantly. Consequently, soil solution NO_3^--N concentrations were generally smaller in the third and fourth winters after pasture compared with the first or second winters. The potential for leaching loss thus declined with time from the second winter after pasture onwards.

3.3. Effect of cultivation method

The most common practice for pasture incorporation on the Canterbury Plains is to bury most of the above-ground pasture residues at 150–200-mm depth by mouldboard ploughing. Pastures are sometimes chisel-ploughed instead, which disrupts soil to a similar depth, but leaves most of the above-ground pasture residues at the 0–100-mm

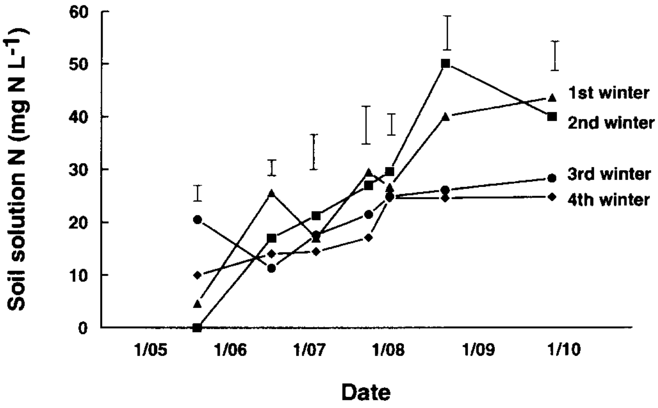

Fig. 3. Soil solution nitrate concentration at 600-mm depth during the first, second, third and fourth winters after initial ploughing of pasture. *Vertical bars* represent SED's.

depth. Alternatively, pastures may be sprayed with herbicide and the following crop established using no-tillage methods.

^{14}C-labelled residue decomposition studies in cores in the field showed that the extent of residue decomposition was very similar following mouldboard or chisel ploughing of pasture. In both cases, $> 50\%$ of pasture residues had decomposed by the first spring after incorporation (Francis et al., 1992). However, in field plots there was a difference in the initial distribution of mineral-N in the profile between mouldboard and chisel-ploughed soil. The accumulation of mineral-N following cultivation in May is shown in Fig. 4. The greatest amount of mineral-N in the chisel-ploughed soil on 30 July was at 0–100-mm depth, whereas in the mouldboard-ploughed soil the greatest accumulation was at 100–200-mm depth. This different initial distribution of mineral-N had very little effect on leaching losses over winter or on mineral-N distribution in the profile in spring (September). For pasture ploughed in March, the leaching loss from mouldboard-ploughed soil was 78 kg ha^{-1} N and from chisel-ploughed soil was 76 kg ha^{-1} N

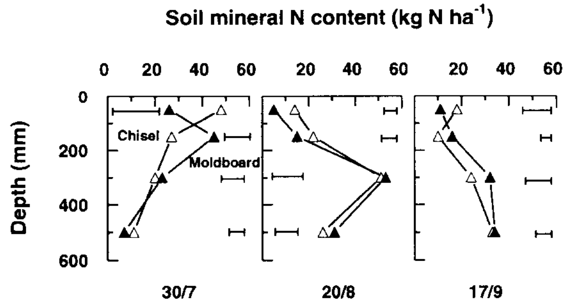

Fig. 4. Mineral-N profiles in soil cultivated out of grass–clover pasture in May by mouldboard or chisel ploughing. *Horizontal bars* represent SED's.

(SED = ±8.9, $n = 4$). Corresponding losses following mouldboard and chisel ploughing in May were 44 and 36 kg ha^{-1} N, respectively (SED = ±8.9, $n = 4$).

Net N mineralization in autumn and winter is slower following no-tillage than ploughing, due to less soil disturbance (Francis and Knight, 1993). Thus in a field experiment where wheat (*Triticum aestivum* L.) was established in May after temporary pasture, soil solution NO_3^--N concentrations during the winter at 600-mm depth were almost twice as large following mouldboard ploughing (30–55 mg L^{-1} NO_3^--N) than following no-tillage (20–35 mg L^{-1} NO_3^--N) (G.S. Francis, unpublished data, 1994). As a result, in years with significant drainage, no-tillage could reduce leaching losses during the first winter after pasture compared with ploughing. Within grass/arable rotations, the long-term effects of adopting no-tillage on winter leaching losses are unknown. Conservation of organic-N through reduced leaching losses for several years may result in the build-up of a large pool of readily-mineralizable soil organic matter and an associated increased potential for leaching in subsequent winters. However, long-term studies in the U.K. have shown consistently lower leaching losses following no-tillage than ploughing (Goss et al., 1993). This is an area of research we are currently pursuing.

3.4. *Effect of cover crops*

The potential of cover crops to reduce NO_3^--N leaching losses has received considerable attention (e.g., Hargrove, 1991). Cover crops grown during winter can reduce leaching losses by removing substantial amounts of mineral-N from the soil profile before winter drainage starts or by reducing drainage through increased evapotranspiration losses compared with bare soil evaporation (Schröder et al., 1992; Alvenäs and Marstorp, 1993).

Our initial experiments showed that, under Canterbury conditions, neither wheat nor oats (*Avena sativa* L.) grown over winter as cover crops reduced drainage compared with fallow soil (Francis et al., 1995a). This result is attributed to the fact that evapotranspiration from the cover crops during autumn and winter was similar to bare soil evaporation as the cover crops did not produce adequate leaf area to increase evapotranspiration until daily evaporative demand was small. Thus, cover crops were only effective at reducing leaching losses when they were sown early in the autumn.

Winter wheat sown in May (after cultivation in May in 1991, but in March in 1992) reduced neither the accumulation of mineral-N by the start of winter drainage nor the winter leaching loss in any experimental year (Francis et al., 1995a) (Fig. 2). In contrast, an oats cover crop was planted early in the autumn (March). This reduced leaching losses, but only when substantial drainage occurred late in the winter, and after considerable amounts of mineral-N had been removed from the soil profile by the plants. This phenomenon occurred in 1992 (Fig. 2b) when major drainage events occurred in September and leaching losses were reduced by ~ 60% by the presence of an oat cover crop. In contrast, oats did not affect leaching losses in 1991 (Fig. 2a) when major leaching events occurred in early winter (June), before the oats had removed the bulk of the soil NO_3^--N.

As cover crops were only effective at reducing leaching losses when sown early in the autumn, later experiments only investigated the ability of a range of cover crops sown in March to reduce leaching losses during winter. We used oats, Italian ryegrass (*Lolium multiflorum* L.), mustard (*Sinapis alba* L.) and lupins (*Lupinus angustifolius* L.). The ability of non-legumes to reduce leaching losses depends largely on their ability to produce dense root systems and large amounts of dry matter under cool conditions. Brassicas are well known for these abilities, but are not as winter hardy as grasses. Legumes often have higher N concentrations than non-legumes, so have a greater potential to reduce soil mineral-N content for the same production of dry matter if they do not fix extensive amounts of N (Meisinger et al., 1991).

The uptake of mineral-N by cover crops varied from year to year, with significant uptake before the start of winter only in years when there was rapid early growth of the crops. In 1993, there was a large variation in the amount of dry matter (DM) produced by the different cover crops before winter leaching. As a result, the amount of N in the herbage ranged from 50–80 kg ha^{-1} N (Table 2). Nitrogen uptake by the non-leguminous cover crops reduced soil mineral-N content by ~ 50 kg ha^{-1} N compared with the fallow treatment. The soil mineral-N content under lupins was only ~ 25 kg ha^{-1} N less than under fallow, as some plant-N content was derived from biological N_2 fixation. Leaching losses in this year were largely unaffected by treatment, however, due to low amounts of winter rainfall (Fig. 1). By spring, all cover crops had produced a large weight of dry matter and had removed considerable amounts of mineral-N from the soil. Mineral-N remaining in the soil in spring (19–44 kg ha^{-1} N) was much less than that in the fallow soil (129 kg ha^{-1} N). When non-leguminous cover crops were incorporated in the spring, the yield of the following spring wheat crop was reduced by 20–30% (Table 2) and N uptake was reduced by 30–40% compared with the fallow treatment. These effects were largely due to inadequate N supply to the spring wheat crop caused by extensive net N immobilization during the initial decomposition of the cover crop residues (Haynes, 1986; Francis et al., 1994). A spring fertilizer application of 50 kg ha^{-1} N overcame the resulting yield depressions (Francis et al., 1995a). Incorporation of the lupin cover crop did not affect the yield of the following wheat crop, although the N concentration of the lupin herbage residue in the spring was similar to that of oats and mustard.

Short-term net N immobilization may be avoided by using the common local farming practice of grazing cover crops once or twice during winter before their incorporation in spring. This also provides valuable winter feed for livestock, when pasture growth is poor. When cover crops are grazed, ~ 60–70% of the ingested herbage N is returned to the soil in urine, mainly as readily-available urea-N (Haynes and Williams, 1993). The urine is unevenly distributed over the soil surface, with N application rates in urine patches of ~ 500 kg ha^{-1} N (Haynes and Williams, 1993). Urea-N is very mobile in the soil and susceptible to leaching, but it undergoes rapid hydrolysis to NH_4^+-N, which is subsequently nitrified to NO_3^--N. Thus, the potential exists for substantial N leaching losses from urine patch areas if there is significant drainage after grazing.

In two experimental years (1993 and 1994) when little drainage occurred after grazing, we measured very similar leaching losses when cover crops were either grazed or incorporated (G.S. Francis, unpublished data, 1994). Nonetheless, soil mineral-N contents were much greater in the spring where cover crops were grazed (62–164 kg ha^{-1} N) than incorporated (19–44 kg ha^{-1} N) (Table 2), as the amount of N returned to the soil in urine patch areas was greater than the cover crop requirement. During a urination event, macropore flow of urine often occurred to a depth of 150 mm (Haynes and Williams, 1993). In these two years there was little subsequent movement of NO_3^--N to 600-mm depth over the winter (G.S. Francis, unpublished data, 1994). Even so, in years when substantial rainfall occurs late in the winter, the potential for leaching losses would be greater where cover crops were grazed than where they were incorporated.

Management of the cover crop had a marked effect on the yield of the following spring wheat crop. When cover crops were grazed before incorporation, extensive net N immobilization did not seem to occur as yields of the spring wheat crop were similar to those for the fallow treatment (Table 2). Indeed, soil mineral-N contents were still greater in the grazed (62–103 kg ha^{-1} N) than incorporated plots (~ 30 kg ha^{-1} N) after harvest of the spring wheat crop (G.S. Francis, unpublished data, 1994). This result suggests that net N immobilization occurred for some significant period after cover crop residues were incorporated. Such results emphasise the important role that grazing animals play in influencing soil fertility in these mixed cropping systems.

3.5. *Effect of nitrification inhibition*

A large amount of NH_4^+-N is produced through net N mineralization of organic N when pastures are ploughed. The inhibition of the nitrification of this NH_4^+-N has the potential to reduce leaching losses of N because NH_4^+-N is relatively immobile in the soil, whereas NO_3^--N is very mobile. Dicyandiamide (DCD) is one of the most widely studied inhibitors; its mode of action is the specific inhibition of the ammonium oxidizer *Nitrosomonas* (Amberger, 1989).

We investigated over two years (1991/1992) the effect of surface-applying an aqueous solution of DCD (20 kg ha^{-1}) to pasture the day before its ploughing in either March or May. DCD did not appear to affect the activity of the heterotrophic soil microflora (Guiraud et al., 1989), as the extent of net N mineralization was not affected by its application (Francis et al., 1995b). However, DCD significantly inhibited nitrification, with a greater accumulation of NH_4^+-N and a lesser accumulation of NO_3^--N in the soil before the start of winter leaching. This effect was most evident at the depth of DCD incorporation (100–200 mm). The effect was also greater when DCD was applied in March than in May as there was a longer period for inhibition and for the accumulation of NH_4^+-N before the start of winter (Fig. 5). DCD was effective at reducing leaching losses from pasture ploughed in March in both experimental years. Untreated plots lost ~ 100 kg ha^{-1} N in each year, while DCD-treated plots lost only 56–74 kg ha^{-1} N. DCD also reduced leaching losses from pasture ploughed in May 1992 to 78 kg ha^{-1} N when major leaching events occurred in late winter. DCD was most effective at reducing leaching losses when pasture was ploughed early in autumn and leaching occurred late in the winter. In such situations, the large amount of mineral-N that accumulated in the soil was dominantly present as the relatively immobile NH_4^+-N rather than mobile NO_3^--N.

Although DCD reduced leaching losses, it did not affect spring wheat yield at this high N fertility site. There has also been no yield response to DCD in other experiments

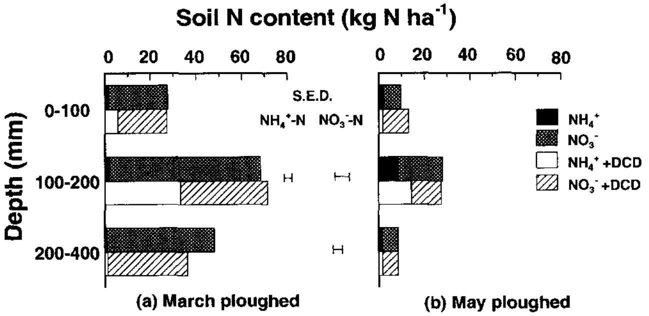

Fig. 5. The effect of dicyandiamide (DCD) on soil profile distributions of ammonium (NH_4^+-N) and nitrate (NO_3^--N) before winter leaching in 1992 after ploughing of pasture in (a) March and (b) May. *Horizontal bars* represent SED's for significant sampling times.

where DCD reduced leaching losses (Bronson et al., 1991). This result has been attributed to increased microbial uptake and N immobilization where DCD is applied because microorganisms tend to prefer NH_4^+-N to NO_3^--N as their N source (Guiraud et al., 1989; Hauck, 1990). However, even for this soil with high N fertility, there was a trend towards greater total-N removal in the spring wheat grain and straw at harvest when DCD was applied (165–191 kg ha^{-1} N) than in the control treatments (149–150 kg ha^{-1} N) (Francis et al., 1995b). Under Canterbury conditions, there is little economic benefit in the use of DCD, as the cost of its application is similar to the cost of replacing with fertilizer the N otherwise leached from the soil. However, there is an environmental benefit from the use of DCD in terms of reduced potential for groundwater pollution.

3.6. Effect of arable crops on leaching losses

In Canterbury, grain legumes are often grown in the third or fourth year of the arable phase of a mixed cropping rotation to maintain or improve soil N fertility. Grain legumes often have beneficial effects on the yields of following non-leguminous grain crops by increasing levels of soil mineral-N and reducing the incidence of crop disease. However, when leguminous residues with relatively high N contents are ploughed in after harvest in early autumn, there may be extensive net N mineralization before the start of winter. Thus, in situations where winter drainage occurs, much of this mineral-N may be lost from the soil and may not be available to the following crop.

A field experiment with a range of leguminous and non-leguminous grain crops showed that the accumulation of soil mineral-N by the start of winter leaching depended on the previous crop. Mineral-N contents in the winter were least after barley (*Hordeum vulgare* L.) and oilseed rape (*Brassica napus* L.) and greatest after field peas (*Pisum sativum* L.), field beans (*Vicia faba* L.) and lentils (*Lens culinaris* Med.) (Table 3). The greater mineral-N content at the start of winter following leguminous crops was partly due to the greater amount of mineral-N remaining in the soil at their harvest, as the crops provided some of their N requirement through symbiotic N_2 fixation (Francis et al., 1994). In addition, the extent of net N mineralization following the incorporation of

Table 3
C/N ratio and dry matter content of residues, soil mineral-N contents in winter before leaching and N leaching loss

Preceding crop	Residue C/N ratio [a]	Residue DM [a] (t ha^{-1})	Soil mineral-N in winter [b] (kg ha^{-1} N)	N leaching loss (kg ha^{-1} N)
Barley	57	5.1	79	45
Rape	50	4.5	82	30
Lupins	50	9.0	88	25
Lentils	36	3.0	124	75
Field beans	23	4.4	125	75
Field peas	29	2.3	123	75
Fallow			197	110
SED			±11.9	±7.9

Data from Francis et al. (1994). 1 t = 1 metric tonne = 10^3 kg. SED = standard error deviation.
[a] Weighted mean of above and below ground residues.
[b] 0–600-mm depth.

the grain crop residues was greater for legumes (35–54 kg ha^{-1} N) than non-legumes (27–31 kg ha^{-1} N) due to their lower C/N ratios and subsequently shorter period when net N immobilization occurred.

The lupin treatment was the anomaly; after a cover crop of lupins the soil mineral-N content was similar to that of barley and rape by the start of winter leaching. Compared with the other legumes, the lupin crop removed more mineral-N from the soil during growth due to its high N harvest index. In addition, lupins produced a much larger amount of low-quality (i.e. low N content) post-harvest residues than the other legumes (Table 3). Thus, there was a longer period of net N immobilization during the decomposition of the lupin residues compared with other leguminous residues (Francis et al., 1994). As a result, the soil mineral-N content following lupins before winter leaching was much lower than for the other grain legumes.

Winter leaching losses were related to soil mineral-N content before winter leaching started. Except for the lupins, cumulative losses were greater following leguminous (75 kg ha^{-1} N) than non-leguminous grain crops (30–45 kg ha^{-1} N). Losses following lupins (25 kg ha^{-1} N) were similar to losses following barley and rape.

The use of legumes as cover crops, which produce large amounts of low N content residues (e.g., lupins), has obvious advantages in reducing autumn/winter leaching losses through extensive net immobilization of soil N in the autumn.

4. Summary and conclusions

Compared with the practice of fallowing soil during winter after ploughing pasture in early autumn (March), the relative effectiveness of delaying ploughing, growing winter cover crops or using a nitrification inhibitor varied between years, mainly in relation to rainfall distribution. Delaying the ploughing of pasture until late winter most effectively reduced leaching losses in years when leaching occurred early in the winter, before a significant amount of NO_3^--N had accumulated in the profile.

Cover crops only significantly reduced leaching losses when they were sown early in the autumn and major drainage events occurred late in winter. The common local practice of using winter wheat as a cover crop sown in late autumn did not reduce winter leaching due to its small mineral-N uptake by the start of winter.

DCD reduced leaching losses whenever pasture was ploughed. It was more effective, however, when pasture was ploughed early in the autumn and leaching occurred late in the winter when there was a long period for the accumulation of relatively-immobile NH_4^+-N.

It appears that the most reliable way to reduce leaching losses is to delay ploughing pasture for as long as possible in autumn or winter. In cases where early cultivation is needed (e.g., if the soil would be too wet to cultivate in late autumn or winter), DCD is more reliable than an early-sown cover crop in reducing losses.

If cover crops are grown during winter, then care must be taken in the management of their residues. If cover crops are incorporated, the yield and N uptake of the following spring crop is often depressed due to extensive net N immobilization. This net N immobilization can be overcome by grazing cover crops before their incorporation, although this practice has the associated risk of elevating leaching losses from urine patch areas.

The use of no-tillage instead of mouldboard ploughing has the potential to reduce leaching losses following pasture, although the long-term effects of this approach require investigation.

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