European Journal of Soil Science, December 1998, **49,** 649–659

Nitrate leaching: modifying the loss from mineralized organic matter

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Summary

The impact on nitrate leaching of agronomic practices designed to immobilize nitrogen in autumn and winter was investigated over 4 years. Experimental treatments (reducing tillage depth, incorporating harvest residues, reducing fertilizer N by growing unfertilized grass or by spring-sown rather than autumn-sown crops) were compared with a control treatment in which autumn crops were sown after burning harvest residues, mouldboard ploughing and seedbed preparation. Winter cover cropping was also compared with winter fallowing. In the first year, incorporation of harvest residues or reducing tillage depth significantly decreased nitrate leaching compared with the control. Unfertilized grass did not affect leaching in the first winter but significantly decreased it in years 2 and 3. When winter cover crops were grown, nitrate leaching was never less than that under an autumn-sown cereal, and in the subsequent year leaching could be significantly greater. Winter fallowing caused the most nitrate leaching over the year. In the winter following a spring-sown crop, leaching under an autumn-sown crop greatly increased. Summed over 4 years, most leaching occurred with the winter fallow–spring cropping treatment; it was 18% more than where a winter cover crop preceded the spring crop. Reducing tillage depth or incorporating harvest residues did not significantly decrease leaching. Unfertilized grass ley followed by an autumn-sown cereal in the fourth year was the only treatment that significantly reduced leaching loss compared with the control. Incorporating harvest residues resulted in a balance between annual N inputs and outputs. All other treatments required substantial net annual N mineralization to balance annual inputs and outputs.

Introduction

In temperate regions the loss of fertilizer nitrogen (N) by leaching after spring top-dressing is usually less than the loss of N released by the mineralization of organic matter in autumn and winter, provided that good agronomic practices are adopted (Addiscott *et al.*, 1991; Goss *et al.*, 1993). By contrast, N applied in autumn, either as mineral fertilizer (Goss *et al.*, 1993) or as animal manure (Thompson *et al.*, 1987; Younie *et al.*, 1996), is vulnerable to leaching in winter. The magnitude of the leaching loss of N released by mineralization in autumn and winter depends on the method of tillage, the nutrient uptake by the current crop, the volume of through drainage, and the previous crop. Thus Goss *et al.* (1993) showed that ploughing increased the loss by 21% compared with no-till, and that wheat (*Triticum aestivum* L.) removed less N in autumn than did oilseed rape (*Brassica napus* L.). Furthermore, in the following winter the loss of N by leaching was three times greater after the harvest of oilseed rape than after oats (*Avena sativa* L.).

Fast-growing winter cover crops can reduce leaching of nitrate because increased evapotranspiration of water compared with bare fallowing results in less drainage, and because of uptake of nitrate by the crop. However, models of the turnover of soil organic matter have suggested that the rate of mineralization is less in the presence of living plant roots, and this was confirmed experimentally by Reid & Goss (1982) for maize (*Zea mays* L.) and by Sparling *et al.* (1982) for barley (*Hordeum vulgare* L.). Thus after allowing for plant uptake, cropped land should release less mineral N than land under bare fallow. In early spring there are differences in rooting density between various autumn-sown crops (Barraclough, 1989; Goss *et al.*, 1989), but little is known about their effect on the leaching of nitrate. Similarly, the incorporation of crop residues, straw and stubble, can apparently immobilize mineral N (Martinez & Guiraud, 1990; Laurent & Mary, 1992; Francis *et al.*, 1995; Wyland *et al.*, 1995), but the duration of the effect, the time required for soil microbes to establish a new

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Received 28 October 1997; revised version accepted 14 May 1998

equilibrium rate for organic matter turnover and the consequences for nitrate leaching have not been established. Davies *et al.* (1996) recorded less leaching of nitrate under a cover crop of winter rye (*Secale cereale* L.) than under bare fallow, but they did not consider how either treatment compared with autumn-sown cereals grown in rotation. They found no effect on nitrate leaching of incorporating post-harvest straw residues compared with removing them by burning or baling.

In this paper we report an investigation of the effects on nitrate leaching of agronomic practices that were expected to modify the turnover of soil organic matter and consequently the mineralization of N during autumn and winter. The experiment started in 1988 and was planned to continue for 4 years. In the first 3 years it compared leaching losses of N under autumn-sown and spring-sown crops, the latter following winter cover crops and winter fallowing. The effects of straw incorporation were compared with straw and stubble burning, and the effect of tillage depth was also investigated in a 2-year comparison of shallow-tine cultivation with mouldboard ploughing. In the fourth year, winter barley was sown on all plots to compare the availability of N following the previous treatments. Because of the unusually dry conditions in the third and fourth years, measurements continued for a fifth year (1992–93) when all plots were bare fallowed over the winter and oats were sown in the spring.

Experimental design and methods

The experiment was at Brimstone Farm, Oxfordshire, UK, on a gleyed clay soil (clay fraction 0.54, silt fraction 0.39, sand fraction 0.07) with a poorly permeable subsoil. It used the hydrologically isolated plots described by Cannell *et al.* (1984). The facility consists of 20 plots arranged in five blocks aligned with the slope. Each plot measures 59 m × 41 m and contains hydrological catchments of about 0.2 ha. Water movement from plot to plot down the 2% slope was prevented by a trench 1000 mm deep, filled with gravel to the level of the soil surface and with a pipe drain at its base. Movement across the slope was prevented by vertical, 500-gauge polythene barriers extending from the surface to either 1100 mm or 1300 mm depth, which had bentonite plugs placed alongside at regular intervals to prevent preferential flow along their lengths. Movement of water to depth below these barriers was negligible because of very slowly permeable clay subsoil.

In this study only 12 plots were used for six treatments, randomized such that plots of each treatment pair occupied different positions on the slope. Each plot had two systems for collecting drainage water. Water moving horizontally on or in the topsoil (surface-layer flow) was intercepted at the lower end of each hydrological catchment by a shallow trench 250 mm deep. Water drained from the trench into a pipe placed at the bottom of a sump and thence to a weir. Water draining through the subsoil (drainflow) was collected by a secondary mole drainage system at 550 mm depth and 2 m lateral spacing connected to a pipe drain (900 mm deep) at the lower end of each plot through gravel fill above the drain. As drainflow could be collected in only 10 plots of the original facility (Cannell *et al.*, 1984), we installed the pipe drain and secondary drainage system in two plots that previously had collectors only for surface-layer flow. At the same time the secondary drainage system was renewed in the other 10 plots.

To determine the mass of nitrate lost by leaching the volumes of water intercepted by the surface-layer and drainflow collectors were measured and sampled for chemical analysis. The water from the two collectors in each plot passed through closed pipes to separate V-notch weirs where flow was determined from the height of the water in the weir chamber. This was recorded autographically using a float with a pen attachment, and also on magnetic tape as the resistance across a potentiometer was varied by the movement of a thread connected to the float (Harris *et al.*, 1993). Samples of water for analysis were automatically collected at 3-h intervals from a U-bend trap at the end of the closed pipe immediately before the water entered the weir chamber. The samplers used for water collection serially drew 250 ml into glass bottles, which were taken to the laboratory for analysis of nitrate on a flow injection system. Nitrate was reduced to nitrite using a cadmium column, and an azo dye was formed with N-1-napthylethylenediamine, which was then measured with a spectrophotometer. In a previous experiment at the site amounts of ammonium and nitrite measured in drainflow and surface-layer flow were very small, so they were ignored in this experiment.

The amount of nitrate N lost through each plot collector was estimated for each period of flow. The nitrate-N concentration in the water was estimated at each half hour (to match the flow records) using simple linear interpolation. The total nitrate N lost in each time period was then estimated by approximate integration based on Simpson's Rule.

The details of treatments, including crops grown and the associated agronomic practices, are summarized in Table 1. Two major plant families, the Graminaceae and the Cruciferae, were identified by Meisinger *et al.* (1991) as especially able to recover nitrate under cool conditions. Unfertilized grass has been recommended as a particularly effective crop for reducing nitrate leaching (Ryden *et al.*, 1984; Chilton & Foster, 1991), and was used as treatment 6 (Table 1). Two species of Cruciferae, white mustard (*Sinapsis alba* L.) and forage rape (*Brassica napus* L.), were selected as autumn-sown cover crops, and these were followed by a spring-sown crop (treatment 4). A bare-soil winter fallow followed by a spring-sown crop (treatment 5) was used for comparison with the cover crop treatment. Incorporation of crop residues was also selected as a means of immobilizing nitrate in the autumn (treatment 3). The effect of reducing the depth of tillage as another possible

Table 1 Treatments and associated agronomic practices in the five treatment years

Treatment	1988–89	1989–90	1990–91	1991–92	1992–93
1 Control (plots 10 & 20)	Crop residues burnt Ploughed Winter crop oats Spring fertilizer (100 kg N ha^{-1})	Crop residues burnt Ploughed Winter crop wheat Spring fertilizer (150 kg N ha^{-1})	Crop residues burnt Ploughed Winter crop wheat Spring fertilizer (179 kg N ha^{-1})	Crop residues burnt Ploughed Winter crop barley Spring fertilizer (122 kg N ha^{-1})	Crop residues burnt Ploughed Winter fallow Spring crop oats (No fertilizer)
2 Shallow tillage (plots 4 & 18)	Crop residues burnt Shallow-tine tillage Winter crop oats Spring fertilizer (100 kg N ha^{-1})	Crop residues burnt Shallow-tine tillage Winter crop wheat Spring fertilizer (150 kg N ha^{-1})	Crop residues burnt Shallow-plough tillage Winter crop beans	Crop residues incorporated Ploughed Winter crop barley Spring fertilizer (122 kg N ha^{-1})	Crop residues burnt Ploughed Winter fallow Spring crop oats (No fertilizer)
3 Harvest residues incorporated (plots 6 & 19)	Crop residues incorporated Ploughed Winter crop oats Spring fertilizer (100 kg N ha^{-1})	Crop residues incorporated Ploughed Winter crop wheat Spring fertilizer (150 kg N ha^{-1})	Crop residues incorporated Ploughed Winter crop wheat Spring fertilizer (179 kg N ha^{-1})	Crop residues incorporated Ploughed Winter crop barley Spring fertilizer (122 kg N ha^{-1})	Crop residues burnt Ploughed Winter fallow Spring crop oats (No fertilizer)
4 Autumn-sown cover crop and spring-sown crop (plots 7 & 9, 1988–89) (plots 5 & 16, 1990–91)	Crop residues burnt Shallow-tine tillage Winter crop white mustard White mustard killed in spring No tillage Spring crop wheat Spring fertilizer (100 kg N ha^{-1})	Crop residues burnt Ploughed Winter crop barley Spring fertilizer (150 kg N ha^{-1})	Crop residues burnt Shallow-tine tillage Winter crop forage rape Forage rape killed in spring No tillage Spring crop beans	Crop residues incorporated Ploughed Winter crop barley Spring fertilizer (122 kg N ha^{-1})	Crop residues burnt Ploughed Winter fallow Spring crop oats (No fertilizer)
5 Autumn/winter fallow and spring-sown crop (plots 5 & 16, 1988–89) (plots 7 & 9, 1990–91)	Crop residues burnt Shallow-tine tillage Winter crop none No tillage Spring crop wheat Spring fertilizer (100 kg N ha^{-1})	Crop residues burnt Ploughed Winter crop barley Spring fertilizer (150 kg N ha^{-1})	Crop residues burnt Shallow-tine tillage Winter crop none No tillage Spring crop beans	Crop residues incorporated Ploughed Winter crop barley Spring fertilizer (122 kg N ha^{-1})	Crop residues burnt Ploughed Winter fallow Spring crop oats (No fertilizer)
6 Unfertilized grass (plots 1 & 15)	Crop residues burnt Shallow-tine tillage Autumn-sown grass	Grass No tillage Grass mown and removed	Grass No tillage Grass mown and removed	Grass residues killed Ploughed Winter crop barley Spring fertilizer (122 kg N ha^{-1})	Crop residues burnt Ploughed Winter fallow Spring crop oats (No fertilizer)

means of decreasing the mineralization of soil organic matter in the autumn was also investigated but only for the first 2 years (treatment 2). The control (treatment 1) was an autumn-sown winter grain crop (oats, wheat or barley in different years), with harvest residues (straw and stubble) burnt, and autumn ploughing as primary tillage. This control treatment allowed comparison of the results for the different treatments from year to year, identification of any carry-over from season to season, and also comparison of results with those of Goss *et al.* (1993). In all treatments, seedbeds were prepared by appropriate secondary cultivations. All crops were sown at commercial seed rates, and crop protection measures were applied as required. To avoid any unrecognized carry-over effects, the two plots that formed treatment 4, being sown with a cover crop in year 1 (1988–89), were switched to treatment 5 in year 3 (1990–91), and so were bare-fallowed over autumn and winter. Similarly, the two plots that were bare-fallowed over autumn and winter in year 1 (1988–89) were sown with a cover crop in year 3 (1990–91). For the remaining treatments the same pairs of plots were used throughout the experiment.

The effect of the experimental treatments on leaching loss was analysed from the regression of N loss on flow. To separate impacts of year-by-year treatments, dummy variables (storing 0 or 1) were used to represent each combination of treatment and year, except for all years of the control treatment (ploughed and harvest residues burnt) (level 1). The model fitted was a straight line through the origin for the control treatment, and deviations from this line were determined for the other treatment year combinations.

The mineral-N content (nitrate N + ammonium N) of the Ap horizon (≈0–200 mm depth) of the soil was measured in the autumn immediately after harvest, and again in spring just before top-dressing with nitrogen fertilizer. Two cores 76 mm in diameter were collected from each plot in the first 3 years of the experiment, and 12 auger samples from each plot in years 4 and 5. A third core was extracted to measure the bulk density and water content. Mineral N was extracted using 2 M KCl from either one or two cores from each plot. To minimize errors caused by variation in bulk density, the mass of soil in the Ap horizon was determined from the mean of all the seasons' assessments of bulk density in the Ap horizon, and this was used to calculate the mineral-N content as kg N ha^{-1}.

The uptake of N into the aerial tissue of crops was determined from six random samples per plot, each at least 0.09 m^2. Samples were gathered from all crops immediately before the first top-dressing of N fertilizer to any cereal in spring and at final harvest of the crop. The N content of the unfertilized grass was also measured at each cutting required in the zero-grazing regime. The N content of the cover crops was measured immediately before they were killed off by herbicide in preparation for the drilling of the spring-sown crop. All samples were dried at 80°C and ground to pass through a 1-mm sieve before their total N content was assessed using Kjeldahl digestion.

Results and discussion

Nitrate leaching in winter

In each of the first 4 years of the experiment rainfall was less than the average for the previous 10 years reported by Goss *et al.* (1993) (Figure 1), but there were considerable differences from year to year. Total annual drainflow was also very variable.

Over the period from harvest to top-dressing in the following spring, the total nitrate N leached each year (in kg N ha^{-1}) in surface-layer flow and drainflow from the control treatment (1) was combined (Y_w) and regressed against the total flow (X_w) in mm (Figure 2). There was some indication that N loss was more variable with increasing flow rate, but standard model-checking techniques suggested this was not serious. The regression fitted was

$$Y_w = 0.11\ X_w, \qquad (1)$$

the standard error of the slope being 0.011, and this accounted for 83% of the variance. A similar approach was adopted by Kolenbrander (1969). His results for leaching from cropped arable soil with a clay content of 0.23 g g^{-1} give a value for the regression coefficient of 0.105 kg N mm^{-1} drainflow. For fallow soil his results gave a value of 0.415 kg N mm^{-1} flow. For a drainflow of 192 mm, the average of the nine values of normal drainflow reported for the previous experiment on the site (Goss *et al.*, 1993), the predicted value of nitrate N leached using Equation (1) was 21.9 kg N ha^{-1}. This was similar to the value of 21.8 kg N ha^{-1} calculated for similar conditions (i.e.

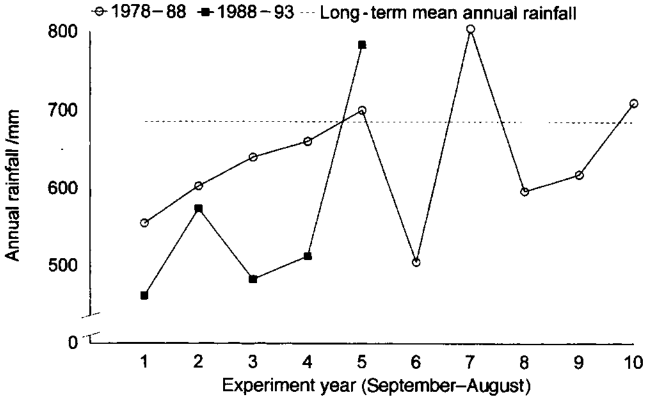

Figure 1 Comparison of annual rainfall (September–August) in this experiment (1988–93) with that in the previous 10 years (1978–88) at Brimstone Farm.

ploughed land under autumn-sown crops of barley and wheat with no fertilizer N applied to the seedbed) over the previous 9 years at the site (Goss *et al.*, 1993). The earlier value was obtained from the relation between fertilizer applied to the seedbed and the mass of nitrate leached, so the methods of calculating the two similar values were different. As the value obtained from the regression on drainflow for the control plots for the period 1988/89–1991/92 (Figure 2) is similar to that from the earlier work, we assumed that any divergence from the regression in Equation (1) resulted from the treatments. Equation (1) was therefore used to judge the effects of the experimental treatments intended to modify leaching losses over the autumn and winter period. The regression analysis used treatment and year as a single factor.

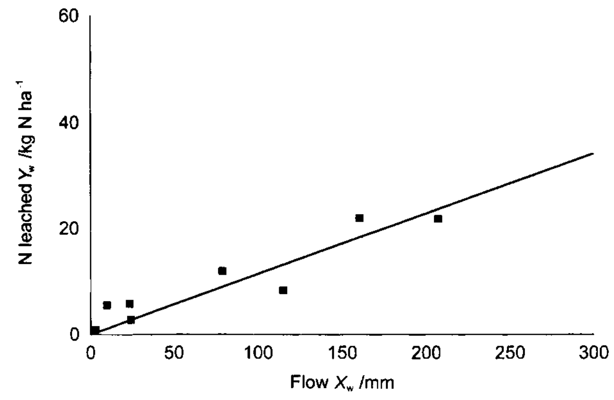

Figure 2 Relation between the nitrate-N loss by leaching in winter under autumn-sown cereals and the total winter drainflow. Results are for plots 10 and 20 (control treatment) over years 1988–92.

Shallow tillage (treatment 2) had a significant effect on nitrate leaching compared with the ploughed control treatment but only in the first year when the N loss was less ($P < 0.05$) than predicted from Equation (1) (Figure 3a). In the second year there was no significant effect and the treatment was then discontinued to allow winter beans to be sown by ploughing (Table 1).

Incorporating harvest residues (treatment 3) also significantly reduced nitrate leaching over winter in the first season ($P < 0.001$), but in subsequent years nitrate loss was similar to that of the control treatment where the straw was burnt (Figure 3b). Averaged over the 4 years incorporation

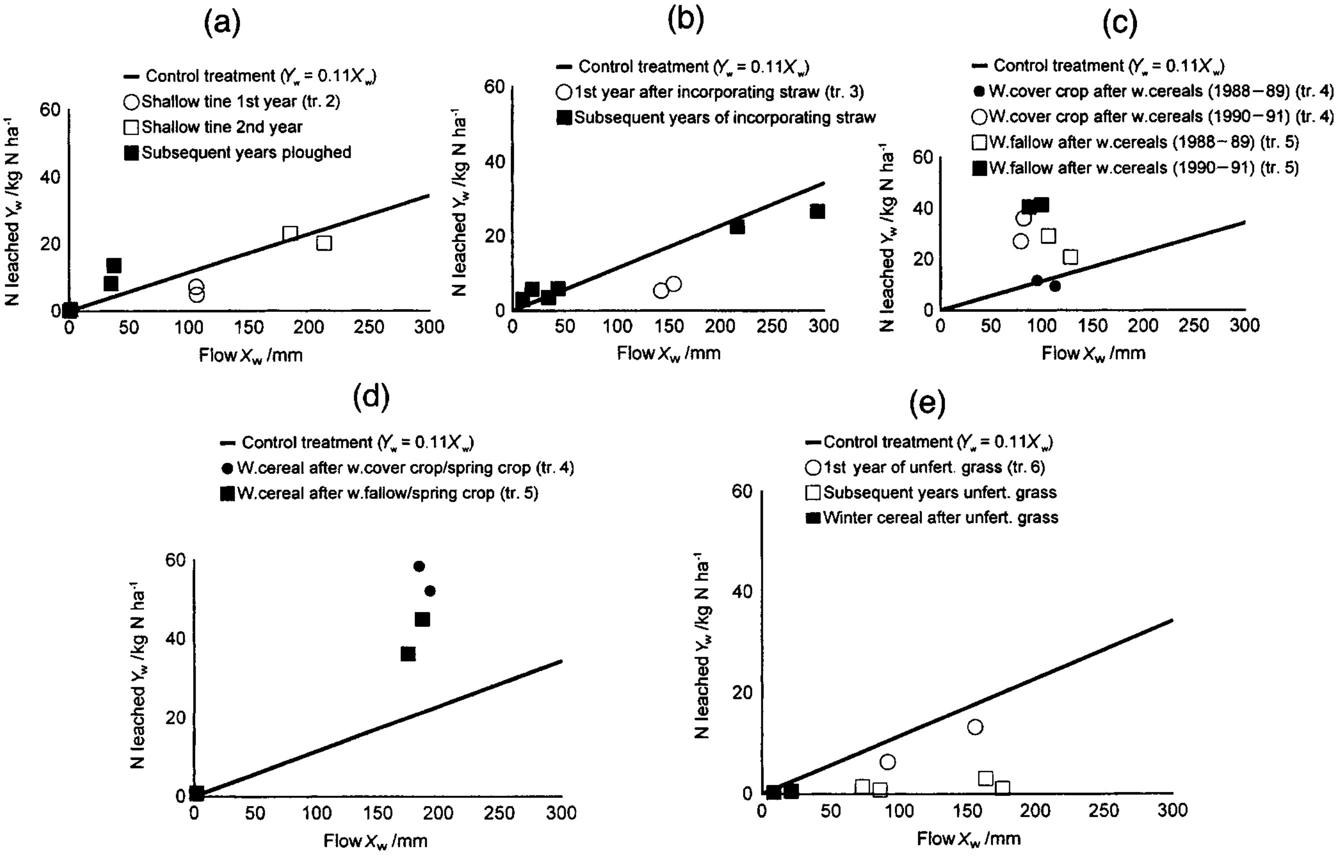

Figure 3 (a)–(e) Effect of treatments on the relationship between winter nitrate-N loss and drainflow. Results for individual plots over years 1988–92 are compared with the control treatment regression line.

Table 2 Grain yield and N uptake by spring crops following winter fallowing or winter cover cropping. SE, standard error

Treatment	Year	Cover crop	Plots	Spring crop	Grain yield /t ha^{-1} ± SE	N uptake in crop /kg N ha^{-1} ± SE
Fallow	1989	None	5, 16	Wheat	3.12 ± 0.49	147.9 ± 14.0
	1991	None	7, 9	Beans	4.15 ± 0.01	377.2 ± 43.6
Cover crop	1989	White mustard	7, 9	Wheat	3.38 ± 0.22	129.6 ± 26.9
	1991	Forage rape	5, 16	Beans	4.04 ± 0.28	339.0 ± 64.5

of residues did not reduce leaching of nitrate significantly, a result consistent with that of Davies *et al.* (1996), except that they observed no significant impact of the treatment in any year.

The effects of spring cropping after winter fallowing or growing winter cover crops (treatments 4 and 5) were more complex (Figure 3c,d). In the first year, when white mustard (*Sinapsis alba* L.) was sown as a cover crop on plots 5 and 16, the mass of nitrate leached was similar to that of the control treatment but less than in treatment 5 where the soil was left bare (Figure 3c). When the cover crop of forage-rape (*Brassica napus* L.) was sown on plots 7 and 9 in the third year of the experiment (1990–91), more nitrate leached than on the control plots, but again less than under the winter fallow. Thus in the periods in which they were growing, cover crops decreased nitrate leaching by 36% compared with leaving the land fallow over the autumn and winter, but were less effective in decreasing nitrate loss than an autumn-sown cereal. Davies *et al.* (1996) reported reductions in nitrate leaching of between 23% and 94% compared with bare fallowing in the years that cover crops were grown.

Over the autumn and winter of the year after the first comparison of winter fallowing and cover crop (i.e. in 1989–90) the leaching losses from treatments 4 and 5 were significantly greater ($P < 0.001$) than those under the control treatment with autumn-sown cereals (Figure 3d). The loss from plots where the cover crop had been grown the previous winter was greater than that where the land had been fallowed, suggesting that some of the N released from the cover crop residues was still present in the soil after growth of the spring cereal. In the fourth year of the experiment, when the same comparisons were made, the total flows (<4 mm) and the leaching losses (<2 kg N ha^{-1}) were too small for any significant effects of the third-year cover crop or fallow to be detected. However, as in year 2, the results suggested that some of the extra N released by mineralization of the cover crop residues was still present in the soil and available for leaching after the spring-sown crop had been harvested. The results for years 2 and 4 also showed greater nitrate leaching under treatments 4 and 5 than that after the autumn-sown cereal control (year 2 $P < 0.001$, year 4 not significant $P > 0.05$).

There are few other reports of the effects of cover crops on nitrate leaching in seasons after the first year. Davies *et al.* (1996) observed no additional leaching in the year after growing a cover crop, and in a lysimeter system McCracken *et al.* (1994) found less nitrate leached when rye or hairy vetch (*Vicia hirsuta* L.) were grown for cover every year after corn (*Zea mays* L.) than where soil was fallowed. The availability of N from the cover crop to the next crop is often small (Doran & Smith, 1991), and there may even be so much N immobilized following incorporation that yield of the subsequent crop is impaired (Doran & Smith, 1991; Laurent & Mary, 1992; Davies *et al.*, 1996). Davies *et al.* (1996) reported that a rye cover crop depressed the yield of a spring-sown cereal compared with that grown on land previously fallowed. Consequently it is possible that in the autumn after the cover crop was incorporated, more of the spring fertilizer-N application was left in the soil and available for leaching than where land was bare fallowed. Alternatively, mineralization of N in the incorporated cover crop residues might have occurred too late to benefit the spring cereal and again contributed to the pool of mineral N available for leaching in the autumn. The cover crops had no significant effect on yield (Table 2), and although N uptake by the spring crop tended to be more following a cover crop than after a winter fallow the differences were not significant ($P > 0.05$).

After it was sown in September 1988, the unfertilized grass did not decrease nitrate leaching during the first winter compared with the control plots (Figure 3e), but in the following 2 years the loss under grass was much less ($P < 0.01$). After ploughing up the grass in the winter of 1991–92 drainflow and leaching loss were too small to detect any additional loss resulting from the release of nitrate by mineralization of grass residues.

Nitrate leaching in spring and summer

For the period from spring top-dressing to harvest leaching losses of nitrate were much less than over winter, consistent with the findings of Goss *et al.* (1993). The total nitrate N lost in this period each year through leaching in surface-layer flow and drainflow from the control treatment with autumn-sown

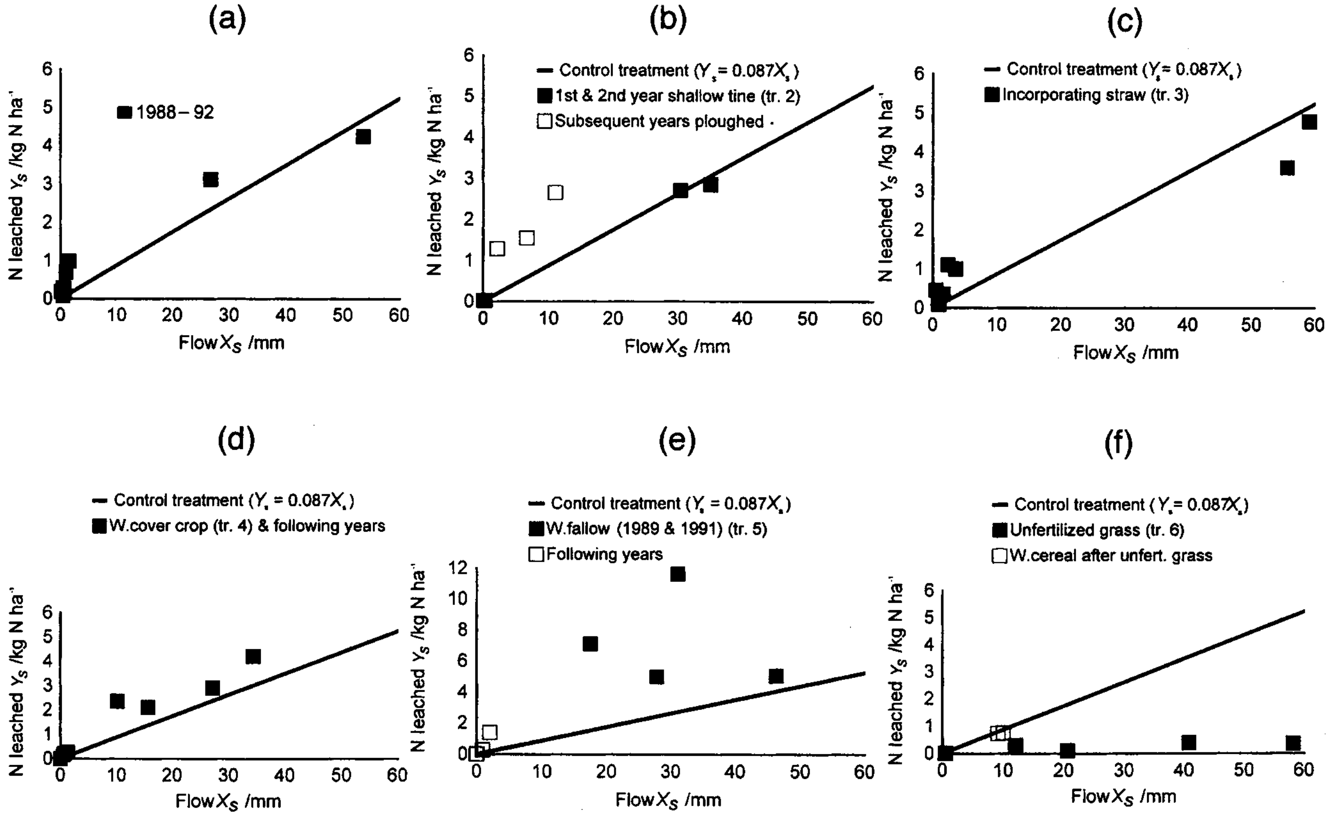

Figure 4 (a) Relation between nitrate-N loss by leaching in spring and summer under autumn-sown cereals and the total spring and summer drainflow. Results are for plots 10 and 20 (control treatment) over years 1988–92. (b)–(f) Effect of treatments on the relation between spring and summer nitrate-N loss and drainflow. Results for individual plots over years 1988–92 are compared with the control treatment regression line.

cereals was combined (Y_s, kg N ha^{-1}) and regressed against the combined flow (X_s, mm) (Figure 4a):

$$Y_s = 0.087\ X_s, \tag{2}$$

with a standard error of 0.0087, and this accounted for 90% of the variance. This regression was then used as a base against which to compare the results of the other experimental treatments over the spring and summer (Figure 4b–f).

Losses from the plots given the autumn treatments of shallow tillage (treatment 2) (Figure 4b), straw incorporation (treatment 3) (Figure 4c), and cover crops (treatment 4) (Figure 4d) were similar to those of the control treatment. However, winter fallowing (treatment 5) significantly increased ($P < 0.05$) nitrate leaching in the following spring compared with that from the control plots (Figure 4e), and leaching under unfertilized, cut grass (treatment 6) was significantly less ($P < 0.001$) than that from the control (Figure 4f).

Annual leaching losses

In those years when land was winter fallowed, the combined leaching losses (autumn, winter, spring and summer) of nitrate were 40 ± 6.2 kg N ha^{-1} year^{-1}, greater than where cover crops were grown prior to a spring cereal (24 ± 6.0 kg N ha^{-1} year^{-1}). However, if leaching in the year after the cover crops were grown was included, the difference was reduced to less than 5 kg N ha^{-1} year^{-1}.

The leaching losses of nitrate in the fourth year of the experiment (1991–92) were small because of a prolonged drought. However, some effects of the treatments were evident in the following year when residues were burnt on all plots before ploughing, the land was bare fallowed over autumn and winter, and oats were sown in the spring. Drainage then exceeded 300 mm from all plots, and for most plots the nitrate N leached over autumn and winter was the largest value recorded in any year of the experiment (Table 3). The largest losses in the final winter were from plots where harvest residues had previously been incorporated or where the tillage was shallow, and the smallest from the control plots (previously winter cereals after ploughing).

N balance

The N balance over the period from September 1988 to September 1993 was calculated on an annual basis from

Table 3 Total loading of nitrate in autumn and winter drainage water in the 5th year of the experiment (1992–93)

	Autumn and winter loading (SE in parentheses)	
Treatment	/mm	Nitrate load /kg N ha^{-1}
1 Control	424 (50)	45.4 (14.7)
2 Shallow tillage	383 (125)	58.7 (29.5)
3 Residues incorporated	438 (24)	60.1 (0.4)
4 and 5 Winter cover crop and winter fallow	362 (34)	52.2 (5.9)
6 Grass	474 (35)	50.1 (13.0)

measured values of the mineral-N content of the Ap horizon of the soil, the crop N content, N fertilizer applied, drainage loss of nitrate N, and estimates of atmospheric N deposition (Goulding, 1990) and N fixation by free-living soil microorganisms. The last were based on Barry *et al.* (1993) and Witty *et al.* (1979) for blue-green algae and on Wild (1988, p. 663) for heterotrophs, allowing for their greater activity because of the large clay and organic matter contents of the soil at Brimstone. Nitrogen fixation by the beans was estimated from a regression on grain yield based on the results of Hauser (1987); the amounts were similar to those reported by Roughley *et al.* (1983) for faba beans grown at Rothamsted. No measurements of denitrification or volatilization were made or estimates of loss included. Net mineralization of N was assumed to account for outputs exceeding inputs, and net immobilization for inputs exceeding outputs.

For the control plots (ploughed with straw burnt) an average net annual mineralization of about 22 kg N ha^{-1} year^{-1} over all 5 years was required to complete the N balance (Table 4). Over the autumn and winter net mineralization on these plots averaged 15 kg N ha^{-1} year^{-1}. Consistent with the aims of the experiment, reducing the depth of tillage, incorporating crop residues and sowing unfertilized grass generally decreased net mineralization of N over autumn and winter in the first 4 years. However, planting a winter cover crop tended to increase net mineralization over winter, and winter fallowing decreased it. In the final autumn and winter, when all plots were treated equally, net mineralization was least in the control plots (Table 4).

Only where straw residues were incorporated in the autumn (treatment 3) was there an apparent net annual balance between input and output of N from the cropping system over the 5 years, and this was essentially the result of a large net immobilization of N in the first year of the treatment (Table 4). Nyborg *et al.* (1995) observed net immobilization of N in the first 2 years after straw incorporation, but thereafter found no effect. In our experiment where straw was incorporated the average N removed in the grain (139 kg N ha^{-1} year^{-1}) was slightly greater than that applied as fertilizer (110.2 kg N ha^{-1} year^{-1}). The original source of the N that accounts for the average of 23 kg N ha^{-1} year^{-1} leached from this treatment may have been atmospheric deposition as well as fertilizer. However, this N may well have been converted into crop or microbial biomass before being returned to the mineral-N pool in the soil by mineralization.

All treatments other than straw incorporation required significant net mineralization of N to complete the average annual N balance (Table 4). Where plots were shallow-tine cultivated in 1988 and 1989 and ploughed thereafter there was an average net mineralization of about 40 kg N ha^{-1} year^{-1} (Table 4), mainly because of a very large increase in net mineralization to 200 kg N ha^{-1} in the first year of ploughing. When spring crops were grown in alternate years preceded by a winter cover crop, the average net mineralization required was about 41 kg N ha^{-1} year^{-1}, similar to where the land was fallowed in the autumn, when the average net mineralization was about 40 kg N ha^{-1} year^{-1} (Table 4). These last three cropping systems all included beans in the rotation, and any underestimation of the N fixation by these legumes would enhance the difference between output and input that must be met by mineralization. We took no account of any gaseous loss of N that might have occurred, but Goss *et al.* (1993) reported that on this site denitrification accounted for only 3 kg N ha^{-1} year^{-1} in ploughed soil. However, for all treatments any N losses by denitrification or volatilization would also have required additional mineralization to complete the balance.

Conclusions

Reducing the depth of autumn tillage, incorporating crop residues or sowing grass, which received no N fertilizer, generally decreased mineralization of N over autumn and winter compared with the control treatment. Surprisingly, winter fallowing also appeared to decrease the mass of N mineralized during the winter, although annual mineralization was greater than on the control in years 1 and 3. Planting a cover crop in autumn tended to increase mineralization over winter compared with the control treatment.

Only unfertilized grass resulted in a consistent and significant reduction in nitrate leaching during autumn and winter. Reducing the depth of tillage from 200 mm to about 100 mm, or incorporating harvest residues, reduced leaching only in the first season. Thereafter it returned to the same amount as in the control. Sowing a cover crop and winter fallowing both resulted in increased leaching of nitrate compared with the control. The effects on leaching of fallowing or of growing a winter cover crop were not confined to the cropping year in which the treatment was applied, but were also apparent in the autumn and winter of the following year under an autumn-sown crop. In this second year, increased leaching resulted from either residual N

Table 4 Effect of treatments on soil N balance in kg N ha^{-1} over 5 years (1988/89–1992/93)

	Treatment	1 Control	2 Shallow tillage	3 Residues incorporated	4 Winter cover crop	5 Winter fallow	6 Unfertilized grass
Inputs							
N in seed	Year 1	2	2	2	5	5	1
	Year 2	5	5	5	4	2	0
	Year 3	6	6	6	13	12	0
	Year 4	4	4	4	4	4	4
	Year 5	3	3	3	3	3	3
N in crop residues	Year 1	0	0	50	34	0	0
	Year 2	0	0	35	0	0	0
	Year 3	0	0	13	32	0	0
	Year 4	0	98	53	80	84	0
	Year 5	0	0	0	0	0	0
Atmospheric N deposition/year		34	34	34	34	34	34
Non-symbiotic N fixation/year		3	3	3	3	3	3
N fixation by beans	Year 3	–	198	–	205	211	–
N fertilizer applied	Year 1	100	100	100	100	100	0
	Year 2	150	150	150	150	150	0
	Year 3	179	0	179	0	0	0
	Year 4	122	122	122	122	122	122
	Year 5	0	0	0	0	0	0
Outputs							
N in crop	Year 1	121	93	124	130	148	85
	Year 2	177	168	170	124	118	34
	Year 3	218	408	261	339	377	19
	Year 4	203	238	195	258	223	136
	Year 5	50	50	44	60	60	54
N leached	Year 1	14	9	10	14	30	10
	Year 2	22	22	25	55	41	2
	Year 3	5	13	6	34	50	1
	Year 4	4	1	5	1	2	1
	Year 5	53	66	70	61	61	60
Net mineralization of N in autumn and winter[a,b]	Year 1	17	14	–55	33	–19	–3
	Year 2	21	23	–15	50	13	3
	Year 3	12	–12	–1	22	–5	6
	Year 4	21	–94	–46	–64	–59	–4
	Year 5	2	21	18	8	8	28
	Mean	15	–10	–20	10	–12	6
Net annual mineralization of N[a]	Year 1	–14	–40	–69	–2	21	37
	Year 2	21	4	–23	10	–26	–2
	Year 3	6	200	41	112	160	–21
	Year 4	54	–21	–10	34	–12	–10
	Year 5	41	58	60	53	55	74
	Mean	22	40	0	41	40	16

[a] Values allow for changes in soil N content; any spring-sown seed N; any crop N residues incorporated.

[b] Assumes 2 kg N ha^{-1} non-symbiotic N fixation and 17 kg N ha^{-1} deposition over winter.

fertilizer unused by the spring cereal, or from mineralization of cover crop residues. Winter fallowing also increased leaching under the following spring-sown cereal crop, probably because the soil was wetter in the spring than it was where an autumn-sown crop had been growing.

Only in soil where crop residues were incorporated annually were N inputs in balance with crop offtake and N losses. For all other cropping systems a net mineralization of N was required to account for the N removed. Nitrate leaching was therefore not simply a consequence of excess fertilizer application, but resulted mainly from the lack of synchrony between mineralization of soil organic matter and crop demand for the nutrients released.

Acknowledgements

We thank the Ministry of Agriculture Fisheries and Food for continuing financial support for the Brimstone Farm Experiment and the Biotechnology and Biological Sciences Research Council for its grant to Rothamsted. We also thank the National Trust and Michael Berry, landlord and tenant, respectively, of Brimstone Farm, for their help and cooperation in allowing access to the Brimstone site, Donald Brockie, Rosalie Nicol and Nicola Yates for technical assistance and Peter Lane for invaluable support in the statistical analysis of the data.

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