The Brimstone Farm Experiment

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4: Nitrate Leaching

Rothamsted Research

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4. NITRATE LEACHING

4.1 BACKGROUND

An intensive programme of water sampling to study nitrate leaching was started at Brimstone Farm because of the interest generated by the Royal Commission on Environmental Pollution (Fraser and Chilvers 1981) and the European Community Drinking Water Directive (Anon. 1980). In Phase I samples were taken from the surface flow, interflow and drainflow of 4 plots in 1978-80, 6 in 1980-84 and 12 in 1984-88. In Phases II and III they were from the drainflow and surface layer flow (combined surface flow and interflow). Total leaching losses of N are always calculated by integration of the Rothamsted nitrate concentrations and ADAS flow rates.

Table 9 Effect of tillage on mean total losses of nitrate-N through the collector systems of drained and undrained plots, harvest years 1981-88.

	Surface flow		Interflow		Drainflow		Total	
	P	DD	P	DD	P	DD	P	DD
Drained[1]	1.1	1.8	1.7	1.0	36.1	28.9	38.9	31.7
Undrained[2]	1.1	4.6	2.8	3.7	-	-	3.9	8.3

[1] 1981-88; [2] 1981, 1982, 1984, 1987, 1988; P = ploughed, DD = direct drilled
(see text for statistical assessment of confidence in these values)

4.2 RESULTS FOR PHASE I

4.2.1 Nitrate losses from drained plots

In 1978/79 and 1979/80, when wheat was established after tine cultivation to 25 cm and the addition of some fertilizer to the seedbed (Table 4), about 90% of the nitrate leached was in the drainflow (Harris *et al.* 1984). In the three following years again about 90% of the nitrate leached was in the drainflow from both ploughed and direct drilled plots (Dowdell *et al.* 1987). However, the total nitrate lost from direct drilled plots was 24% less than from ploughed plots. In the more intensively sampled period from 1984/85 to 1987/88, about 95% of the nitrate lost was in the drainflow, and total losses (in surface flow, interflow and drainflow) from ploughed land were on average 21% greater than from direct drilled land (Goss *et al.* 1993). For the years 1980/81 to 1987/88 the average annual total loss from ploughed land (39 kg N/ha) was 23% greater than from direct drilled land (Table 9), and was equivalent to 22% of the fertilizer-N applied, though the losses cannot be attributed entirely to fertilizer applications (see Section 4.2.3).

The concentration of nitrate-N in drainflow often exceeded the EC limit (11.3 mg/l) for drinking water (Fig. 13). In each year concentrations generally declined from the first flows of autumn to those just before spring top-dressing, which were usually similar to or less than the EC limit. When flow continued after top-dressing (as in 1985 and 1987),

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the concentrations reached maxima exceeding 60 mg/l. The concentrations in drainflow from direct drilled plots were less than those from ploughed plots except for the period after spring top-dressing to oilseed rape in 1985. Under the succeeding winter wheat crop the drainflow concentration remained well in excess of the EC limit on both ploughed and direct drilled plots. However, in 1987/88 when wheat followed oats, the nitrate concentrations were much less than in 1985/86 (wheat after oilseed rape).

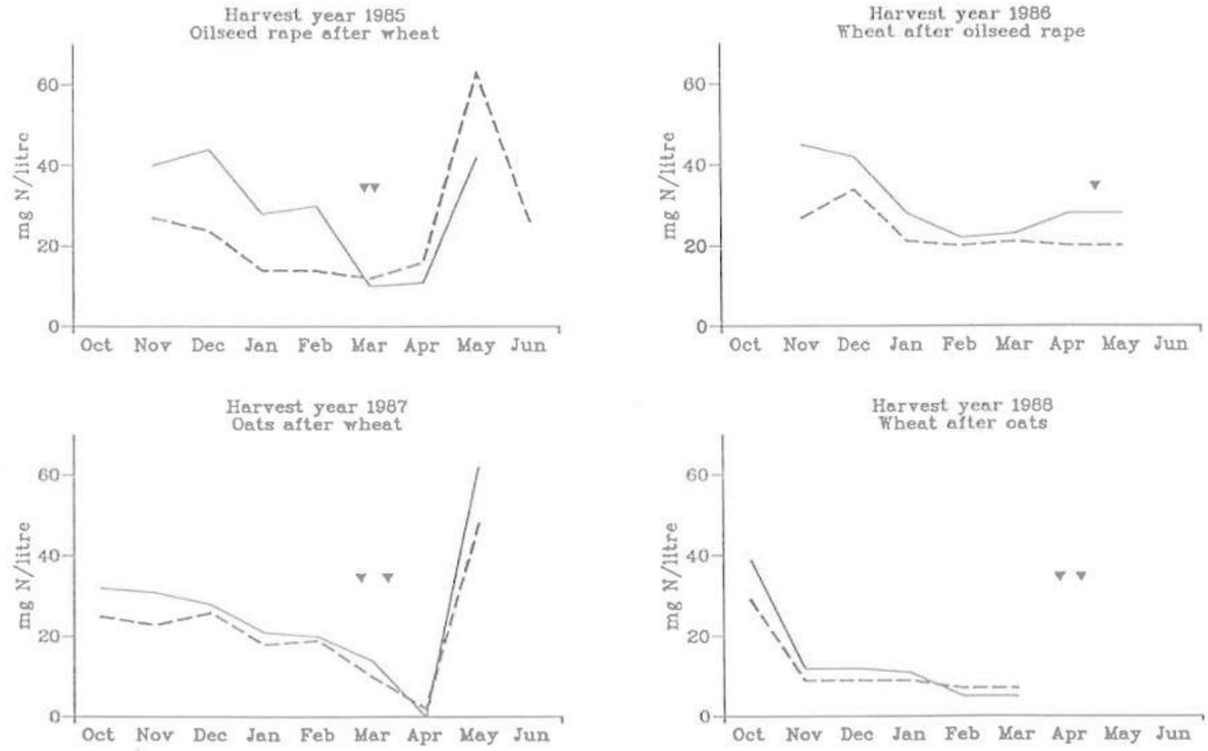

Fig. 13. Flow-weighted mean monthly concentrations of nitrate-N in drainwater, harvest years 1985-88. Arrows indicate date/s of spring top dressings, solid line - ploughed plots, dashed line - direct drilled plots.

4.2.2 Nitrate losses from undrained plots

Annual measured losses by surface flow and interflow from undrained plots (Table 9) were much less than the total losses from drained plots, though we cannot be sure that they represent total losses because of the incomplete winter water balance of undrained plots (Section 2.4). Losses from direct drilled plots were greater than from ploughed plots, i.e. the opposite relationship to drained plots.

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4.2.3 Sources of nitrate lost between harvest and spring top-dressing

Table 10. Effects of hydrology and tillage on nitrate-N losses by drainflow (kg/ha) between the harvest of one crop and spring top dressing of the next.

Harvest year	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Winter drainflow (mm)	163	219	198	198	183	73	144	227	190	207
Winter rainfall (mm)	208	365	407	449	409	324	399	447	401	434
Soil water deficit before cultivation (mm)	0[1]	112	114	129	152	137[2]	170[2]	92	180	155
Winter losses of nitrate-N (kg/ha)										
Tined	40.1	55.3	-	-	-	-	-	-	-	-
Ploughed	-	-	11.5	41.7	54.0	5.1	40.8	50.4	32.0	17.9
Direct drilled	-	-	10.4	25.9	33.5	2.3	26.9	46.2	26.7	11.3
SED	-	-	7.3	5.6	14.5	2.2	13.1	7.2	5.4	3.2

1 Assumes a fully drained profile

2 Calculated from deficit under grass at Brimstone and adjusted for a tall crop using factors for a similar crop on a nearby site

Losses of nitrate in drainflow during the winter periods of Phase I were very variable (Table 10), and were weakly correlated with rainfall. In the years when no nitrogen fertilizer was applied in autumn (1980/81, 1985/86, 1986/87 and 1987/88), the nitrate lost over winter must have been derived from (a) residues of fertilizers applied to previous crops, (b) mineralization of soil organic matter, including residues of the previous crop, and (c) atmospheric deposition. Fertilizer residues probably made little contribution because (a) there is no correlation between winter leaching losses and amounts of fertilizer-N applied the previous spring, (b) in 1987/88 there was no difference in the mineral-N content of the soil to 1.5 m depth over the winter between harvest and just before spring top-dressing; if any mineral-N had been left over from previous fertilizer applications, a decrease would have occurred because of leaching or crop uptake, and (c) in experiments elsewhere using ^{15}N-labelled fertilizer, the measured residues from spring applications are very small at harvest.

Omitting data for the dry winter of 1983/84 when there was very little drainflow, the amounts of nitrate lost in winter drainflow from tined or ploughed plots under cereal crops following cereals (L_p) are correlated with amounts of seedbed fertilizer-N (F) in excess of 21.8 kg N/ha (Fig. 13). The regression equation

$$L_p = 21.8 + 1.09F$$

accounts for 71% of the variance. The value 21.8 kg N/ha (s.e. 6.0) when no seedbed fertilizer was applied represents the mean loss of nitrate derived from mineralization of soil organic matter and atmospheric deposition. The slope of 1.09 (s.e. 0.30) indicates

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that for each unit of fertilizer-N applied there was an approximately equivalent weight of nitrogen leached.

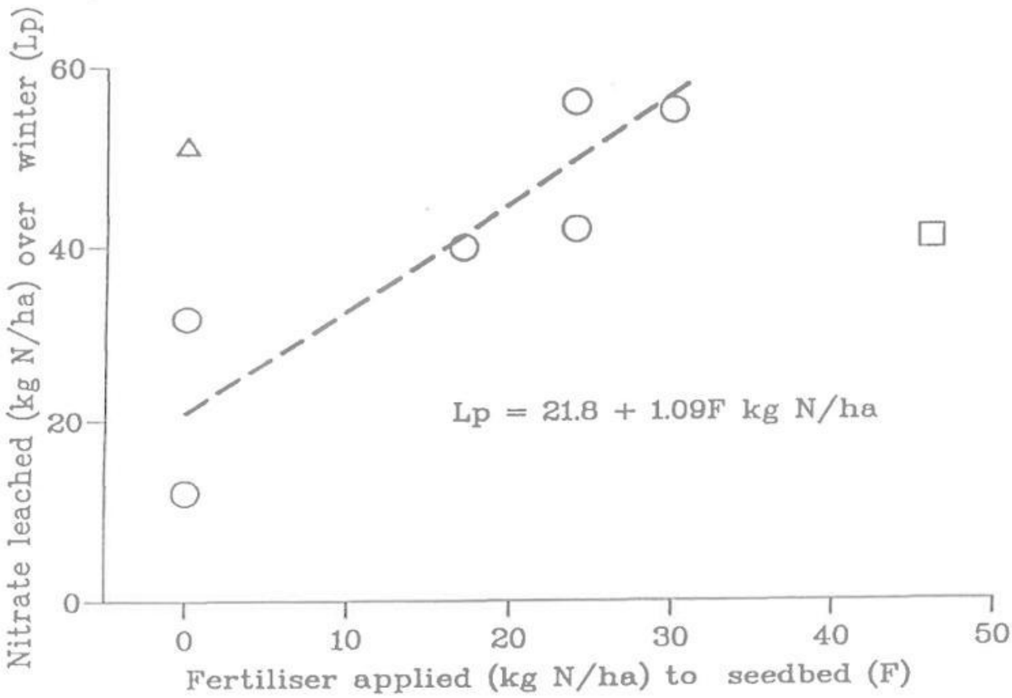

Fig. 13. Relationship between amount of autumn-applied fertiliser-N and nitrate leached over the winter period. The regression is fitted to results for cereals following wheat or barley on tilled plots (circles). Values for oilseed rape following wheat (square) and wheat following oilseed rape (triangle) also shown.

In the winter of 1984/85 the loss under oilseed rape departed from the relationship for cereals following cereals, as it was 31 kg N/ha less than the calculated mean for cereals given the same amount of autumn N (46 kg/ha). Unlike cereals, not all of the N applied to the rape was leached. However, in the following winter the loss of nitrate under winter wheat was larger than that predicted for cereals following cereals. This suggests that residues from the oilseed rape crop released more nitrogen than cereal residues; no fertilizer-N was applied to the wheat, but the loss was equivalent to that when 26 kg N/ha autumn was applied.

4.2.4 Sources of nitrate lost between spring top-dressing and harvest

Losses of nitrate-N in drainflow in the summer periods of Phase I were on average equal to 3% of the spring fertilizer applications (Goss *et al.* 1993). They exceeded 1 kg N/ha in only 3 of the 10 years; no losses were detected in 3 years (Table 11). Losses were strongly correlated with drainflow and therefore dependent on rainfall. For example, cumulative nitrate losses occurring over a protracted period in the wet spring of 1983 were strongly correlated with cumulative rainfall (Fig. 14). The regression line for ploughed and direct drilled plots combined accounts for 91% of the variance; it has a slope of 0.115 (s.e. 0.004) and an intercept of -0.32 (s.e. 0.12), which suggests that only 3 mm of rain was required to initiate leaching losses.

Table 11. Effect of tillage on nitrate-N losses by drainflow (kg/ha) between the first spring application of nitrogen and harvest.

Harvest year	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Drainflow (mm)	0	0	24	6	93	0	50	8	3	0
Tine cultivated	0.0	0.0	-	-	-	-	-	-	-	-
Ploughed	-	-	6.0	0.8	19.1	0.5	7.8	0.5	0.5	0.0
Direct drilled	-	-	5.1	0.5	27.7	0.4	13.0	0.5	0.9	0.0
SED	-	-	2.1	0.2	3.0	0.2	4.1	0.3	0.5	-

The relationship between summer rainfall for each year and nitrate-N losses expressed as percentages of the fertilizer-N applied shows that 100 mm rain resulted in an average loss of 31% of the fertilizer-N applied in spring. The loss of nitrate-N per mm rain was 18% greater on direct drilled than on ploughed plots (i.e. the opposite relationship to that for the winter period and for the year as a whole).

4.2.5 Nitrogen budgets for Phase I (1980-88)

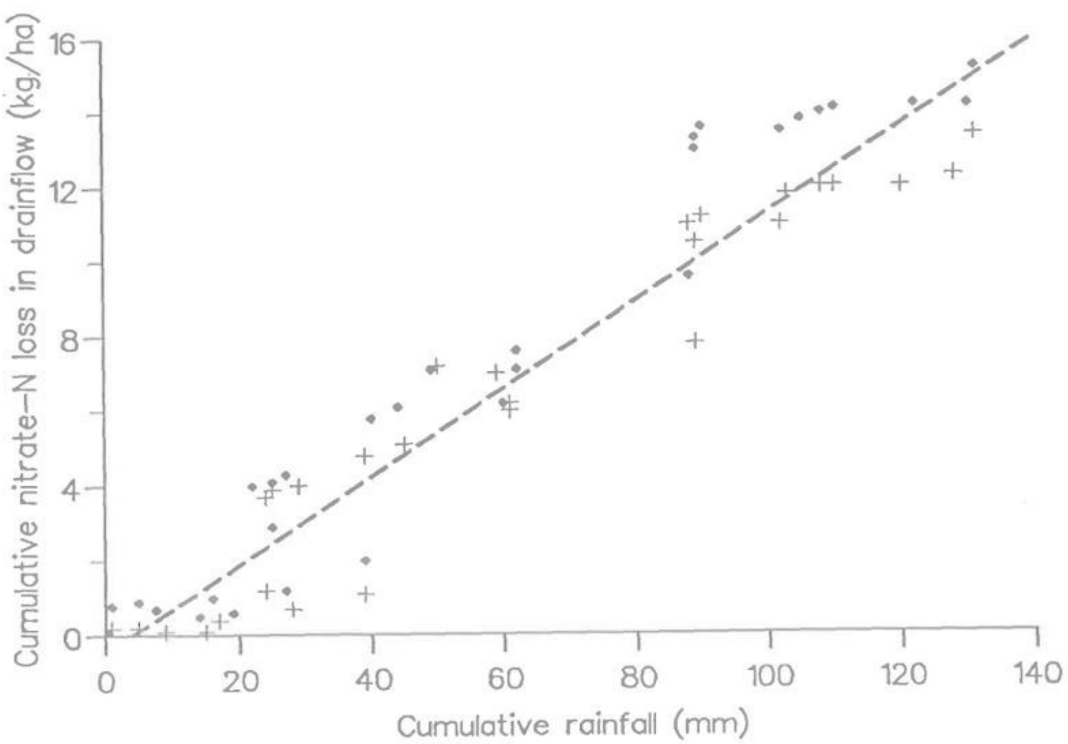

Fig. 14. Relationship between rainfall in the period after spring top-dressing 1983 and nitrate-N in drainflow (circles, direct drilled plots; crosses, ploughed plots).

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Budgets for ploughed and direct drilled drained plots (Fig. 15) were constructed by Goss *et al.* (1993) from the total runoff losses, amounts of applied fertilizer-N and crop offtakes in grain and straw measured each year (Ellis *et al.* 1984, Cannell *et al.* 1986), estimates of denitrification losses in certain years (Colbourn *et al.* 1984, Colbourn and Harper 1987), measurements of wet and dry aerial deposition at Harwell in 1986 (Goulding 1990) and an estimate of mineralization for 1987/88 based on the change in mineral-N content of the soil over the year, uptake by the wheat crop and the loss of nitrate-N by total runoff and denitrification. Some components are therefore estimated more precisely than others.

Losses (leaching + denitrification) averaged 43 kg N/ha/yr from both direct drilled and ploughed plots, but leaching losses were greater from ploughed plots and denitrification losses were greater from direct drilled land. The inputs of non-fertilizer-N (aerial deposition, N-fixation by free-living soil organisms and seed) were 45 kg N/ha/yr, slightly greater than the losses, and crop uptakes exceeded fertilizer inputs by 12 kg/ha/yr on direct drilled plots and 18 kg/ha/yr on ploughed plots. The balance of 16 kg/ha/yr on ploughed plots, 10 kg/ha/yr on direct drilled plots, was met by net annual release of nitrogen from the soil organic matter. Gross annual release from the organic matter was 83 kg/ha/yr from ploughed plots, 67 kg/ha/yr from direct drilled plots, but this was partly offset by immobilization of 67 kg and 57 kg, respectively, in the form of root and other crop residues incorporated into the soil.

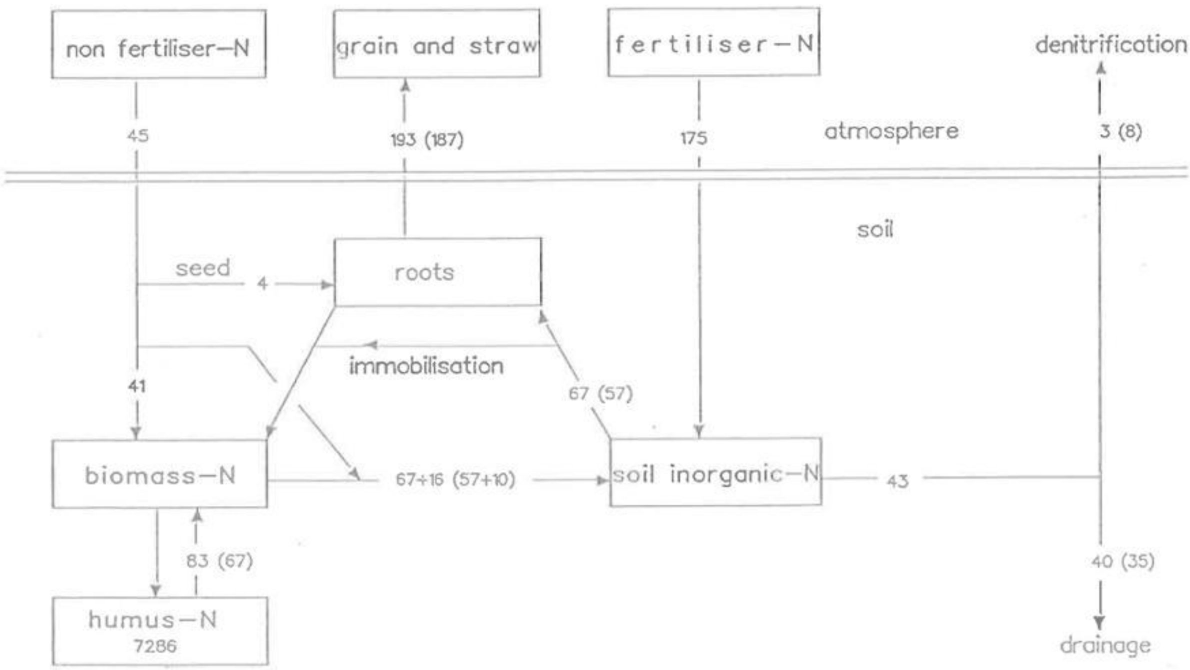

Fig. 15. Nitrogen budget for drained, tilled plots, 1980-88. Values given in kg/ha/yr. Values for drained direct drilled plots are shown in parenthesis where they differ from those of tilled plots.

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4.3 DISCUSSION OF PHASE 1 RESULTS

Approximately five times more nitrate was lost from drained land than from undrained, though the total amount of water collected from drained land was less than twice that from undrained (Harris *et al.* 1991). The greater leaching losses from drained land probably resulted mainly from the greater depth of soil leached, though increased denitrification in less aerobic undrained soil and greater mineralization of organic matter in the more aerobic drained soil may have contributed to the difference. Uptake of nitrogen by crops was less on undrained plots (Cannell *et al.* 1986), so differential uptake does not help explain the greater loss of nitrate from drained land.

The mean winter loss in drainflow of 21.8 kg N/ha additional to any loss of autumn applied fertilizer-N is similar to values calculated by Lawes *et al.* (1882) for Broadbalk Field at Rothamsted. They also found that almost 100% of autumn applied fertilizer-N was lost in drainflow.

4.4 SUMMARY OF FACTORS INFLUENCING NITRATE LEACHING

Nitrate-N losses by drainflow from tined and ploughed plots were determined by five factors (Goss *et al.* 1993):

1. Amount of drainflow determined by excess rainfall over evapotranspiration.
2. Amount of fertilizer-N applied to the seedbed in autumn.
3. Amount of rainfall following spring top-dressing.
4. Uptake of nitrogen by the crop.
5. Mineralization of soil organic matter, including residues of previous crops.

All except 3 influenced the major losses occurring between the harvest of one crop and top-dressing of the next. Factors 1, 3, 4 and 5 determined the smaller losses in spring and summer.

For both winter and summer losses Factor 1 was the most important but, as evapotranspiration is greater in summer and rainfall more variable, summer leaching losses were more variable than those in winter. In the years when nitrogen was applied to the seedbed, the amount (Factor 2) strongly influenced winter losses. Winter losses also depended upon mineralization of soil organic matter (Factor 5); together with a proportion of the non-fertilizer inputs, this contributed a mean loss of 21.8 kg N/ha/yr on tined and ploughed plots under cereals. Crop uptake (Factor 4) mainly explained the usually small leaching losses after spring top-dressing.

The factors controlling leaching losses under direct drilled crops were less clearly identified than those influencing losses from ploughed land. Mineralization under direct drilling is usually less than under crops established after ploughing (Dowdell and Cannell 1975, Powlson 1980), but this does not entirely account for the difference in leaching losses between these two treatments.

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4.4.1 Effects of soil structure

Differences in the pattern of water movement in ploughed and direct drilled soils may account for the smaller winter leaching losses from direct drilled land (Goss *et al.* 1988). Nitrate released by mineralization of organic matter in autumn and winter occurs mainly in fine pores within the soil matrix and is not readily removed by water flowing in macropores. In direct drilled land the water reaching the mole drains flows mainly in the macropores, which have greater continuity between topsoil and subsoil than in ploughed land; consequently it does not remove as much of the nitrate as in ploughed land, where the water percolates slowly through finer pores between the cultivated topsoil and the mole drains.

The greater continuity of vertical macropores also explains the increased leaching of fertilizer-N from direct drilled crops in spring. Fertilizer lies on or near the soil surface and dissolves quickly in rainwater, which then moves more rapidly to the mole drains in direct drilled soil than in ploughed soil. This may explain why greater applications of spring nitrogen are often required to achieve heavy yields when crops are direct drilled (Cannell 1985).

4.5 RESULTS FOR PHASE II

The results of Phase I suggested that with good husbandry (avoiding autumn applications of fertilizer and carefully timing split spring applications in relation to soil moisture content and expected rainfall) the main leaching losses occurred in autumn as a result of mineralization of soil organic matter. One of the objectives of Phase II therefore was to investigate various crop management strategies thought to minimize losses resulting from autumn mineralization. Denitrification and aerial deposition were not measured in Phase II, but the other components of the nitrogen budget continued to be investigated. Rainfall and drainflows in the winter of 1989/90 were similar to the means for Phase I (Tables 2 and 3), but the winters of 1988/89, 1990/91 and 1991/92 were much drier, and this limits the conclusions that can be drawn with respect to the effects of treatments on mineralization of organic matter, though the results for these dry years may be relevant to future climatic scenarios.

4.5.1 Winter leaching losses

The greatest leaching losses in drainflow in the winters of 1988/89 and 1990/91 were from the fallowed plots (Table 12). The winter cover crops (mustard in 1988/89 and forage rape in 1990/91) decreased these losses by only 53% and 31%, respectively. This poor performance of the cover crops resulted at least partly from management difficulties on the clay soil. The mustard was killed off on 9 February and 60% of the drainflow occurred after that date but before spring wheat could be sown on the wet soil, and the rape germinated and developed very slowly in the dry soil conditions of autumn 1990. The unfertilized grass also established slowly, especially on Plot 1, and so lost almost as much nitrate in the winter of 1988/89 as the mustard cover crop, but in later years when the grass had become established the losses were much less than from any of the other crops (Catt *et al.* 1992).

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Table 12. Total annual losses of nitrate (kg N/ha) in drainflow and cultivated layer flow 1988/89-1992/93.

Plots	1988/89		1989/90		1990/91	
	Crop	N loss	Crop	N loss	Crop	N loss
1 & 15	Grass	10.2	Grass	2.1	Grass	1.3
5 & 16	Fallow/S.wheat	30.0	W.barley	40.5	F.rape/S.beans	33.2
7 & 9	Mustard/s.wheat	14.1	W.barley	55.3	Fallow/S.beans	48.0
10 & 20	W.oats (P,B)	10.2	W.wheat (P,B)	22.0	W.wheat (P,B)	4.3
6 & 19	W.oats (P,I)	6.3	W.wheat (P,I)	24.6	W.wheat (P,I)	4.7
4 & 18	W.oats (T,B)	6.0	W.wheat (T,B)	21.6	W.beans (P,B)	12.7
	1991/92		1992/93		Total N loss	
	Crop	N loss	Crop	N loss	1988/89 - 1992/93	
1 & 15	W.barley	1.2	Fallow/S.oats	33.6	48.2	
5 & 16	W.barley	1.1	Fallow/S.oats	30.5	134.8	
7 & 9	W.barley	1.6	Fallow/S.oats	37.6	156.6	
10 & 20	W.barley (P,B)	3.5	Fallow/S.oats	12.9	56.2	
6 & 19	W.barley (P,I)	4.8	Fallow/S.oats	30.3	75.5	
4 & 18	W.barley (P,B)	0.9	Fallow/S.oats	36.7	80.6	

P = ploughed; T = shallow tined; B = previous crop residues burnt; I = straw incorporated

Losses under winter oats in 1988/89 were larger from plots where crop residues had been burnt and ploughed in than where unburnt residues were incorporated by ploughing or where burnt residues were incorporated by shallow tine cultivation. These results accord with the ideas that straw incorporation can decrease leaching losses of nitrate and that shallow cultivation achieves a similar effect by preserving the continuity of macropores into the subsoil so that less nitrate is leached from the soil matrix. However, the differences were not repeated under winter wheat in the next two years or under winter barley in 1991/92 and spring oats in 1992/93 (Table 12).

Leaching losses under winter barley in the winter of 1989/90 were considerably more than those from any of the winter wheat plots. This was probably because the four plots under barley (5, 7, 9 and 16) had been under fallow or the mustard cover crop in the previous winter, and the intervening spring wheat crop had not taken up the excessive amounts of mineral-N resulting from mineralization under bare fallow or mineralization of the incorporated cover crop residues.

Plots 5 and 20, previously undrained and direct drilled respectively in Phase I, were disrupted for the first time in autumn 1988, when mole drains were drawn and the soil was cultivated. This probably stimulated mineralization of organic matter that had accumulated near the soil surface, as there were greater winter leaching losses of nitrate from these plots in 1988/89 than from their replicates (Plots 10 and 16, respectively), which had previously been cultivated for at least 10 yr. The differences did not recur in 1989/90. However, in 1990/91 the greater loss of nitrate from Plot 4 than from Plot 18 (both under winter beans) can also be related to the cultivation difference in Phase I, and here the effect had persisted through two years of tine cultivation.

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Over the five years of Phase II total nitrate loss was least from the grass ley (Table 12). By far the largest total losses were from the plots with winter cover crops or winter fallow in 1988/89 and 1990/91. Among the three pairs of plots that grew cereals in all five years, the least total nitrate was lost from those which were ploughed after burning the straw of the previous crop.

4.5.2 Concentration of nitrate in drainflow

Most of the drainflow samples collected from the 14 monitored plots in Phase II had nitrate concentrations greater than the EC drinking water limit. As in Phase I, the initial autumn flows contained the most (24-73 mg N/l) and concentrations then declined through each winter. The drainflow from the unfertilized grass plots was initially richer in nitrate than that from the other plots, but once the grass was established the drainflow contained less nitrate than from any of the other plots, and remained less than the EC limit from February 1989 to spring 1991. After the grass had been ploughed in autumn 1991 there were large increases in nitrate concentrations especially in the wet winter of 1992/93. The nitrate concentrations in drainflow from plots under winter cereals were decreased by straw incorporation and shallow tining, but only for 1-2 years; thereafter the concentrations from these plots were greater than from the winter cereal plots which were ploughed after straw had been burnt.

4.5.3 Numbers of drainwater samples exceeding EC limit

The percentages of water samples per year with nitrate concentrations exceeding the EC drinking water limit (50 mg NO_3/l) were approximately proportional to the total annual loadings of nitrate leached. For example, in 1989/90, when the mean annual losses from Plots 1 and 15 (grass), 5 and 16 (winter barley after fallow/spring wheat), 7 and 9 (winter barley after cover crop/spring wheat) and 6 and 19 (winter wheat after winter oats) were 2.1, 40.5, 55.3 and 24.6 kg N/ha, the percentages of water samples exceeding the drinking water limit were 6.1, 96.0, 99.5 and 57.5, respectively.

4.6 DISCUSSION OF PHASE II RESULTS

The results for Phase II suggest that some crop management strategies for minimizing winter leaching of nitrate, such as winter cover crops, straw incorporation and shallow tine cultivation, are slightly effective but only for 1-2 years. Cover crops can be difficult to establish in dry autumns and difficult to incorporate in wet springs on the clay soil at Brimstone; also the nitrate released by mineralization of their residues is incompletely taken up by spring cereals and consequently increases leaching losses in the following winter. Spring wheat also failed to take up all the nitrate released by a winter fallow. Once established, unfertilized grass was very effective in decreasing losses, but this is not a productive crop, and ploughing led to rapid mineralization and a large flush of leached nitrate. Ploughing of soil which had been direct drilled for several years in Phase I also resulted in increased mineralization and leaching, but shallow tine cultivation did not have the same effect.

Use of direct drilling, shallow tine cultivation, straw incorporation, grass leys or winter cover crops to minimize nitrate leaching are all likely to have short-term benefits, but they may only be techniques for slowing mineralization and storing organic-N in the soil

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on a temporary basis. In the long term the best option for minimizing nitrate losses in productive agriculture was continuous cultivation of cereals after straw burning and mouldboard ploughing.

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