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THE
BRIMSTONE FARM
EXPERIMENT

A guide for visitors to a field
experiment for studying leaching
of nutrients and
pesticides

Operated jointly by ADAS and
IACR-Rothamsted

Funded since 1978 by Ministry of
Agriculture, Fisheries and Food

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1. INTRODUCTION TO THE SITE AND THE EXPERIMENT

Brimstone Farm was established as an experimental site in 1978 and has become one of the UK's best facilities for field leaching studies. Based on a series of hydrologically isolated plot lysimeters, which are large enough for normal agricultural operations to be undertaken, it has achieved international acclaim for its work on water transport, nitrate and pesticide residue leaching.

The first phase of the experiment (1978-88) investigated the effects of drainage on crops established by direct drilling or after ploughing; losses of nitrogen in the field drainage system and the effects of ploughing and direct drilling on water losses and catchment hydrology were also studied.

In Phase II (1988-93) various crop management strategies for minimising losses of nitrate and pesticide residues were studied, and the data used to validate models of water, nitrate and pesticide movement in clay soils; the effects of different drainage systems on removal of water and losses of agrochemicals were also investigated.

In the current phase (Phase III, 1993-97) the effects of drainflow restrictors on the leaching of nitrate, nitrite, phosphate and pesticides are being assessed.

1.1 BACKGROUND TO PHASE I

Clay soils provide some 45% of the cereal-growing land in England and Wales, but they are slowly permeable (< 0.1 m/day) and require artificial drainage. On ploughed clay land the preferred drainage treatment has been mole drains at 2 m spacing to maintain the water table at about 0.5 m depth within 24 hr of the cessation of rainfall (Trafford and Oliphant 1977).

During the early 1970s farmers were encouraged to adopt direct drilling and other minimal tillage systems on clay soils, because they decreased input costs and helped avoid soil structural damage (compaction in wet seasons and cloddy seedbeds in dry autumns) resulting from ill-timed seedbed preparation by conventional methods. Work at the ARC Letcombe Laboratory and elsewhere had shown that, with good management, similar crop yields could be achieved on clayey arable soils whatever the cultivation regime. However, the effect of minimal tillage on drainage was unknown. Goss *et al.* (1984) reported that the water table is often closer to the surface of direct drilled than ploughed soils, and that the mole drains deteriorate more rapidly, so it seemed that direct drilled soils needed a more intensive drainage system.

Despite the absence of direct supporting evidence, improved field drainage was often cited as the cause of frequent flooding and of increasing nitrate concentrations in surface waters. The Brimstone Farm Experiment was designed to examine these allegations.

1.1.2 Principal objectives

1.1.2.1 To investigate the effects of drainage in a clay soil on crops established by direct drilling and after ploughing.

1.1.2.2 To measure the loss of nitrogen by a field drainage system.

1.1.2.3 To investigate the relative amounts of rainfall lost by surface flow, interflow (movement in the cultivated layer of the soil) and drainflow (through a mole and pipe drainage system), and the effects on catchment hydrology.

1.1.3 Site characteristics

To examine these aspects the experimental site needed to be uniform, representative of UK clay lowland in terms of climate, soil and topography and gently sloping for reliability of hydrological monitoring. After an 18 month search for a suitable site, which involved uniformity trials at four possible locations, the experimental facility at Brimstone Farm (National Grid Reference SU 248946) on the National Trust's Coleshill Estate near Faringdon, Oxfordshire, was established jointly by ADAS Field Drainage Experimental Unit and the then ARC Letcombe Laboratory. With the closure of Letcombe Laboratory in 1985, their responsibility was transferred to Rothamsted Experimental Station.

Throughout the experiment the responsibilities have been:
ADAS: Supervision and installation of all drainage and hydrological equipment; collection of hydrological data.
Letcombe and Rothamsted: Agronomy; measurement of plant growth and soil physical conditions; nitrate concentrations in the drainage water.

In Phase III the emphasis is on work on pesticide leaching and nutrient losses.

The experimental site is on a heavy clay of the Denchworth series derived from Upper Jurassic Oxford Clay. In the top 0.2 m of the profile the soil contains 54% clay (< 2 μm), 39% silt (2-60 μm) and 7% sand (> 60 μm). An initial auger survey, soil cores collected on a grid pattern between the proposed plot areas and five soil pits (Cannell *et al.* 1984) all demonstrated good soil uniformity across the site. The altitude is 100-106 m O.D. and the slope is approximately 2% (Fig. 1). Relief was surveyed on a 20 m x 10 m grid in 1979. The mean annual rainfall is 680 mm.

The records of earlier drainage systems were not found before deciding the plot layout. Exploratory trenching identified numerous clay pipe drains of different layouts and careful recording later established the existence of three systems within the experimental area and five within the whole field (Cannell *et al.* 1984). Initial recording in spring 1978 indicated reasonable uniformity in the depth to the water table.

1.1.4 Experimental design

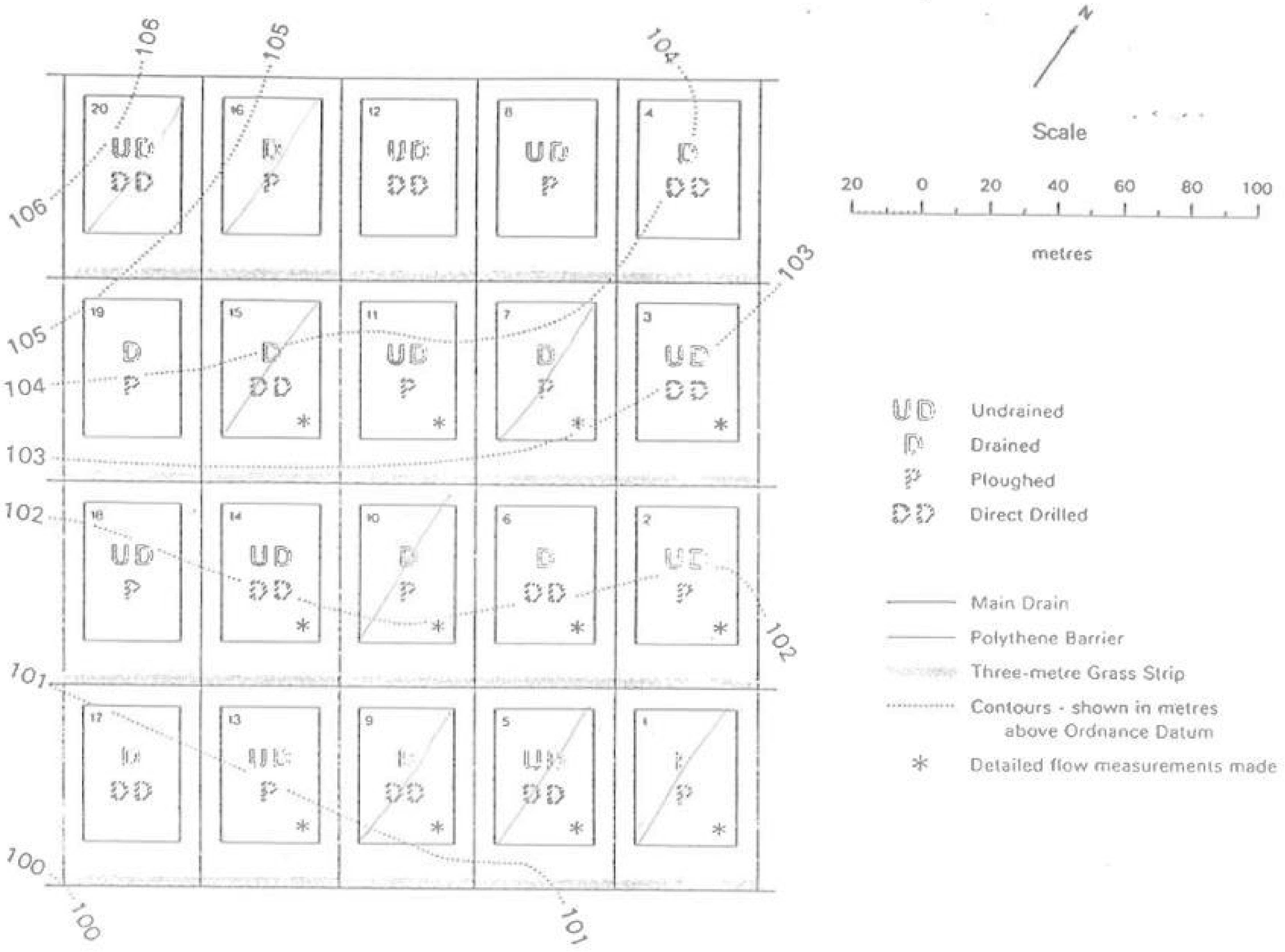


Fig. 1 Layout of plots, site topography, treatments and facilities for hydrological separation.

In Phase I there were four treatments, each replicated five times (Fig. 1), established in a 4 x 4 latin square (Plots 1-16) with a fifth block (Plots 17-20). The treatments were:
undrained, direct drilled (UD/DD)
undrained, ploughed to 0.2 m (UD/P)
drained, direct drilled (D/DD)
drained, ploughed (D/P).

There were thus ten drained and ten undrained plots. Direct drilling was a simplified system in which seeds were planted with minimum soil disturbance.

Each year crop residues were burnt and the ash incorporated with the least possible soil disturbance using the same discs or tines on all plots. From autumn 1984 the ash was incorporated within 36 hr.

1.1.5 Plot isolation

Each plot is 59 m x 41 m (0.24 ha), but with discard margins around a central agronomic area of 40 m x 28 m (0.112 ha). In 1978 the whole experimental area was hydrologically isolated to 1.3 m depth around the site perimeter, and plots were isolated to 1.1 m depth using continuous polythene membrane placed in trenches extending up and down the slope in the discard areas between plots. The trenches were then refilled with soil. Experience on other clay sites had shown that water movement in clay soils is almost entirely in the top 1.0 m. Water moving downslope is prevented from reaching the next plot by pipe drains located at 1.0 m depth in trenches 0.1 m wide and filled to the surface with coarse gravel (Fig. 2). These interceptor trenches are separated from the marginal plot discard areas by 3 m wide grass strips. The polythene barriers and interceptor trenches together create what are in effect field plot lysimeters.

1.1.6 Plot drainage

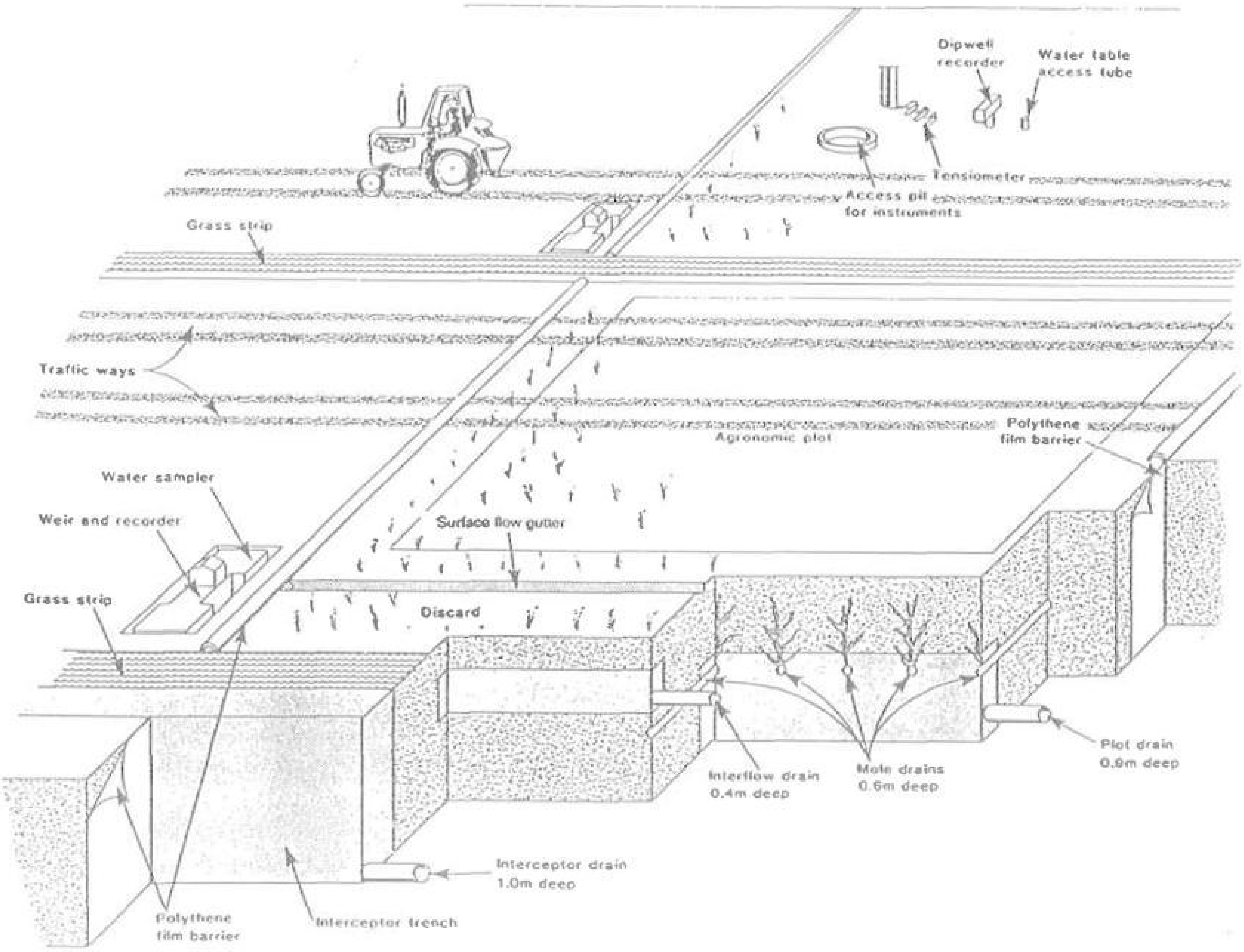


Fig. 2 Plot layout showing location of drainage and hydrological flow monitoring equipment.

The hydrologically monitored area covers the full plot width of 41 m, and extends 46 m downslope from the interceptor drain at the top of each plot. The remaining 13 m of each plot has no subsurface drainage (Fig. 3). The effective drainage on each of the ten drained plots was therefore a pipe drain 46 m downslope from the interceptor drain and at 0.9 m depth, covered with permeable backfill to connect with 19 mole channels 2 m apart and at 0.6 m depth. To intercept plough layer flow (interflow) a pipe drain was also installed at 0.35 depth in a polythene-lined trench and covered with permeable backfill. This was located 3 m downslope of the plot drain to allow for pull-out of the mole drains.

Originally a 0.1 m wide PVC gutter was laid across the plot 1.5 m downslope of the agronomic plot boundary to collect surface flow. However, difficulties with distortion of the PVC by frost heave, achieving a uniform level across the plot and movement of soil into the gutter prevented accurate measurement of flow. A second system of rectangular gutters in either galvanized metal or reinforced glass fibre with polythene sheeting laid under the soil upslope was more successful, but had to be removed for autumn cultivations. Eventually only 8 plots retained surface flow collectors across one third of the plot width.

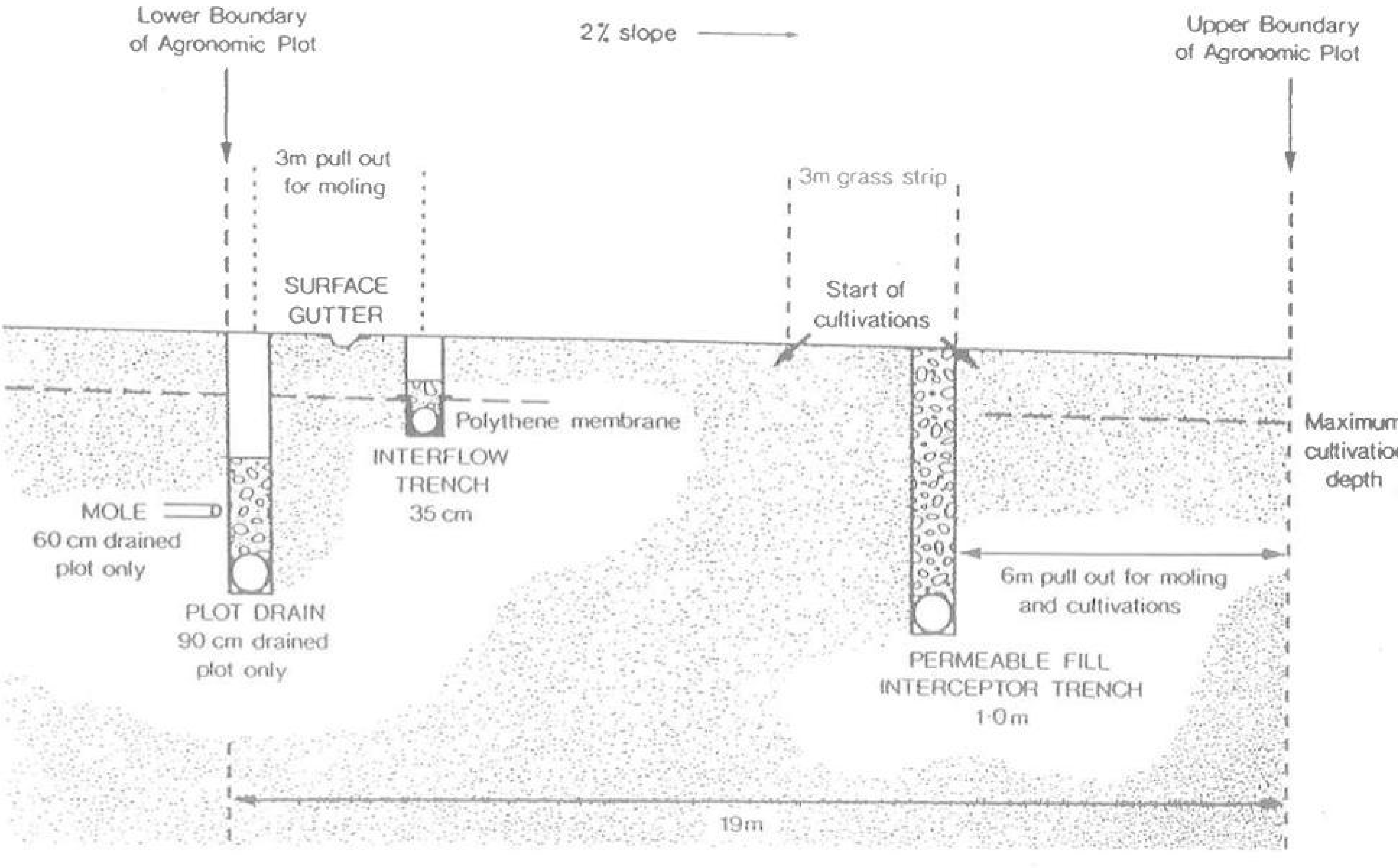


Fig. 3 Cross-section across plots showing collector systems and discard for machinery operations between drained Plots 6 and 7 (after Cannell et al. 1984).

As lateral movement below the depth of the interflow collectors could not be measured on undrained plots without draining them, it was estimated from piezometers on undrained land outside the experimental area. Because of deep seepage observed below some of the plot isolation trenches, Plots 3, 7, 11 and 15 were further isolated to 1.8 m depth in 1984.

1.2 UNIFORMITY TRIALS

After installation of the mole drainage system on the drained plots in autumn 1978, all 20 plots were tine cultivated and sown to winter wheat to assess uniformity of the treatments. Over the winter no difference was observed in mean depth to the water table between the drainage treatments, and in 1979 crop growth and yield were similar on all plots.

Examination of soil profiles in summer 1979 showed the presence of a discontinuous cultivation pan. This limited soil water movement and caused a perched water table during rain. However, water movement to the drains was possible through the leg slot crack produced by mole draining. The pan was removed by shallow subsoiling across the plots in autumn 1979 and the uniformity trial repeated, all plots again being tine cultivated. Subsequent measurements showed that the pan had been successfully removed; the depth to the water table was increased by typically 0.2 m and crop yields reflected the improved soil aeration.

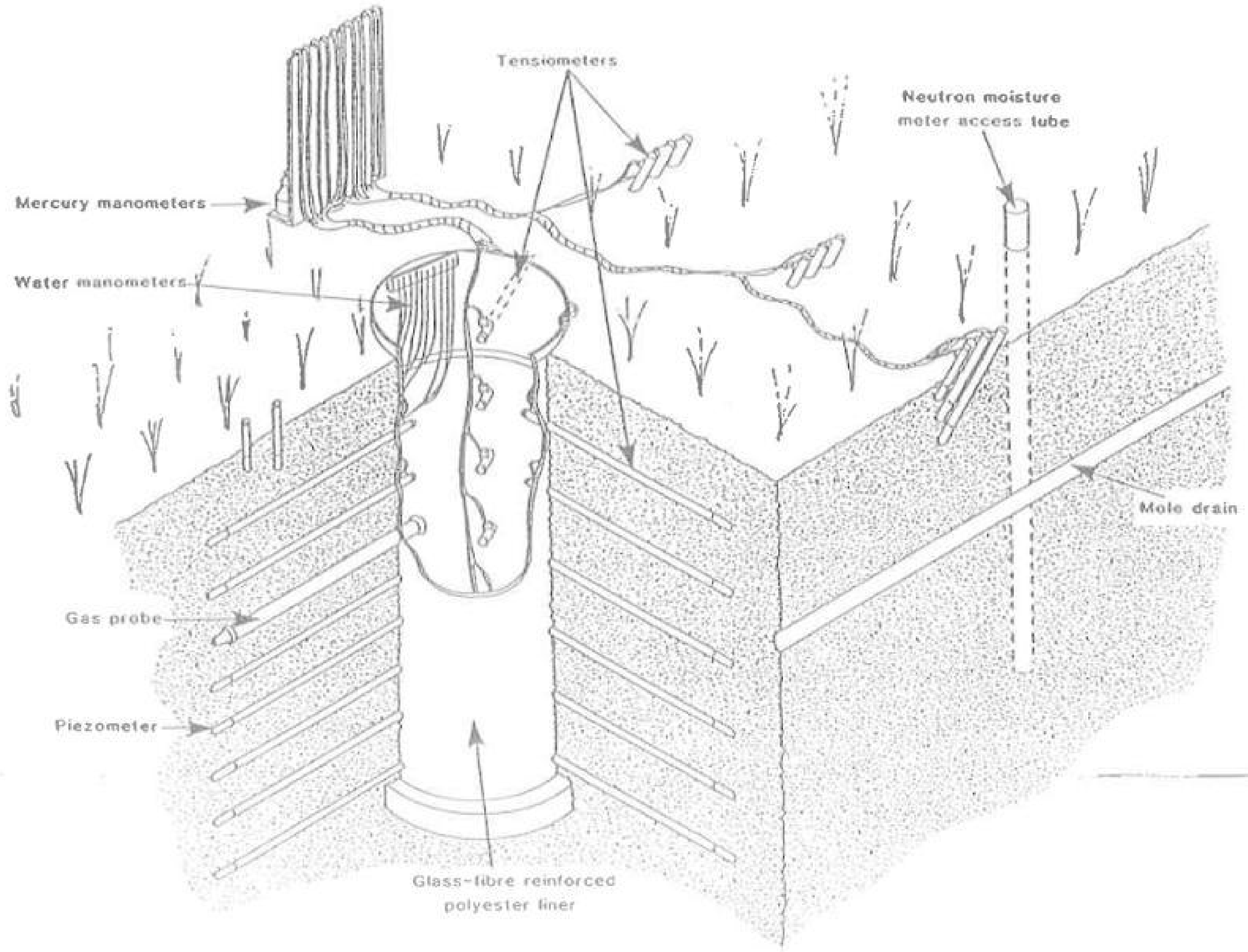


Fig. 4 Cut-away section showing soil properties instrumentation.

1.3 MONITORING IN PHASE I

1.3.1 Crop growth

Combined yield and components of yield (grain and straw) were recorded every year from 1979 to 1988. In some years crop growth (roots and shoots) and uptake of nutrients were also measured.

1.3.2 Soil physical measurements

The intention was to measure short- and long-term changes in soil conditions associated with both the drainage and cultivation treatments and their influence on crop growth. The water balance of crops is determined from meteorological measurements, drainage losses, soil water content measured by calibrated neutron moisture meter and soil water potential measured by tensiometers. To avoid repeated disturbance of the plots, tensiometers and piezometers were permanently installed at 0.2 m intervals to a depth of 2 m through the walls of lined access pits (Fig. 4), which can be temporarily covered to permit soil cultivations (Howse and Goss 1982). Water table depth is measured by dipwells and autographic water table meters. Soil structure was assessed with particular reference to root growth by measurements of soil water characteristics and hydraulic conductivity. Soil strength was assessed in relation to slaking and trafficability by measurements of aggregate stability and cone penetrometer resistance.

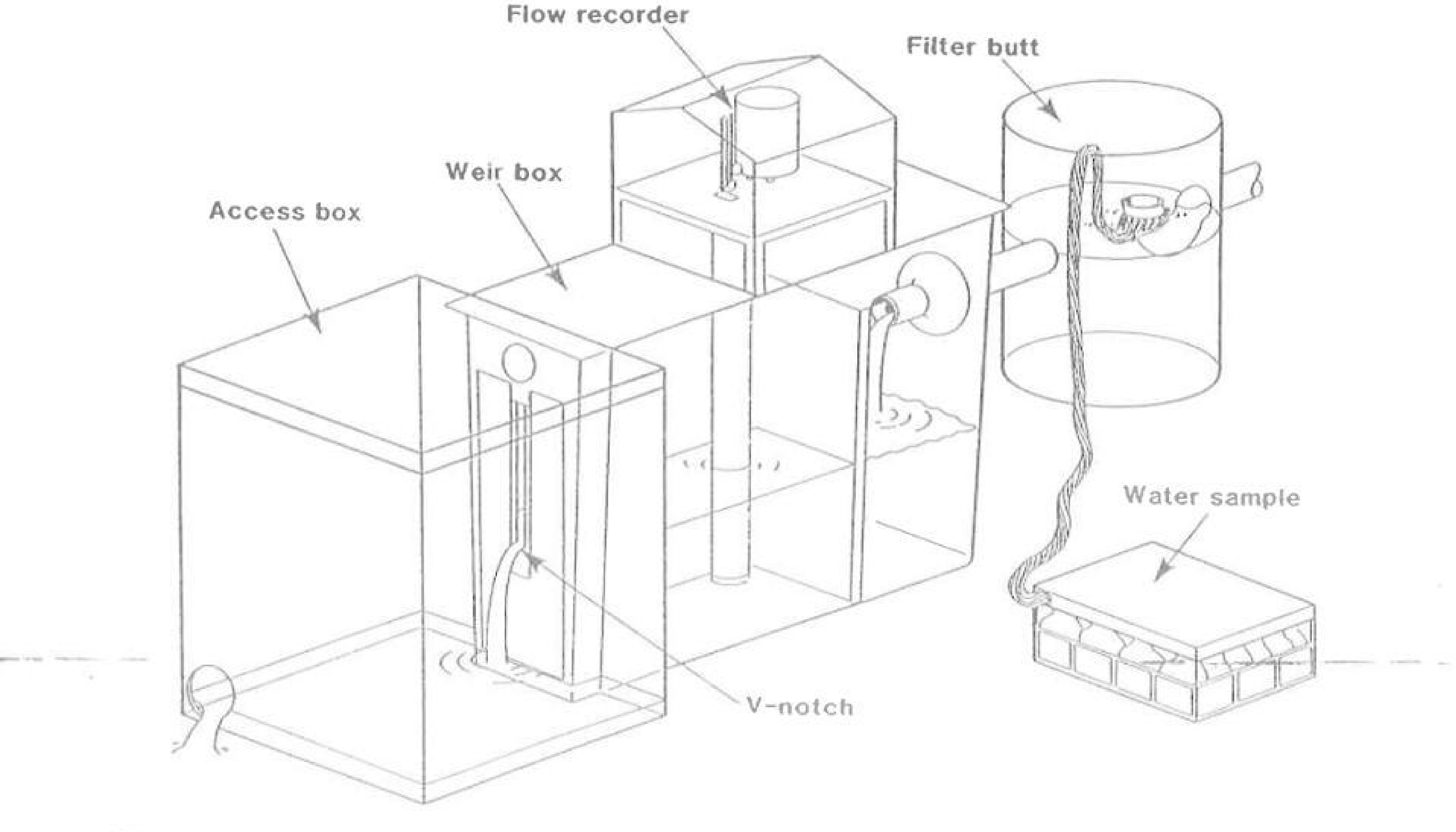


Fig. 5 Drainflow metering and water sampling equipment (after Harris et al. 1984).

1.3.3 Meteorological measurements

A fully automatic weather station (AWS) was installed in 1979. Additional logged and autographic rainfall recorders at various positions in the field showed up to a 10% variation in rainfall, and so a second AWS was installed in 1983.

1.3.4 Drainflow rates

Water movement in surface flow and interflow (later combined into cultivated layer flow) and drainflow is measured using V-notch weirs (Fig. 5) with a flow range of 0 - 7.0 litre/sec (Talman 1980). The head level is recorded autographically using a float system linked to chart recorders and later also to potentiometers connected by buried cabling to a data logger housed in the site hut. In addition, in several years flow from paired mole channels was measured by tipping bucket recorders also linked to the site logger.

1.3.5 Losses of nutrients

Water samples are taken from a U-bend located in a filter bin immediately upstream of the V-notch weir (Fig. 5). In Phase I evacuated sample bottles were connected individually by rubber and polythene tubing to the U-bend, and a variable timer triggered sampling by releasing the vacuum at preset intervals. Since 1990 this sampling system has been progressively replaced by EPIC programmable samplers. In 1979-84 the usual sampling frequency was once every 24 hr, but it was increased to once every 3 hr from 1985 onwards. The water samples were originally analysed for nitrate, nitrite and ammonium, but nitrite and ammonium occurred in very small amounts and were later abandoned as they contributed little to the nitrogen balance. Nitrite measurements were resumed at the start of Phase III in autumn 1993.

Loss of nitrogen by denitrification was also measured in certain years by determining amounts of nitrous oxide after blocking further reduction to nitrogen gas with acetylene.

1.4 SITE CHANGES FOR PHASE II

As the Phase I experiment progressed it was evident that Brimstone Farm provided a valuable facility for further studies, so a new experiment was designed for the period 1988-93.

1.4.1 Principal objectives

1.4.1.1 To investigate alternative drainage systems, such as modifications to existing mole plough design to produce mole channels with different longevities, and to compare their effectiveness for removing excess water and the leaching of agrochemicals.

1.4.1.2 To develop soil and crop management strategies for minimising runoff of nitrate and pesticides.

1.4.1.3 To provide data to validate models of water, nitrate and pesticide movement.

Table 1. Phase II, drainage and crop rotations for harvest years 1989-1991.

Secondary treatment Plot no.	1989	1990	1991
Moled conventional (4,18)	Winter oats	Winter wheat	Winter beans
Moled frequent (5,16)	Bare fallow/ Spring wheat	Winter barley	Forage rape/ Spring beans
Moled, large exp. (6,19)	Winter oats	Winter wheat	Winter wheat
Moled, no-expander (10,20)	Winter oats	Winter wheat	Winter wheat
Moled, wide space (17)	Winter oats	Winter barley	Winter wheat
Gravel moles (1,15)	Grass ley	Grass ley	Grass ley
Pipes (35 mm) (7,9)	White mustard/ Spring Wheat	Winter barley	Bare fallow/ Spring beans
Undrained control (14)	Spring oats	Winter wheat	Winter wheat

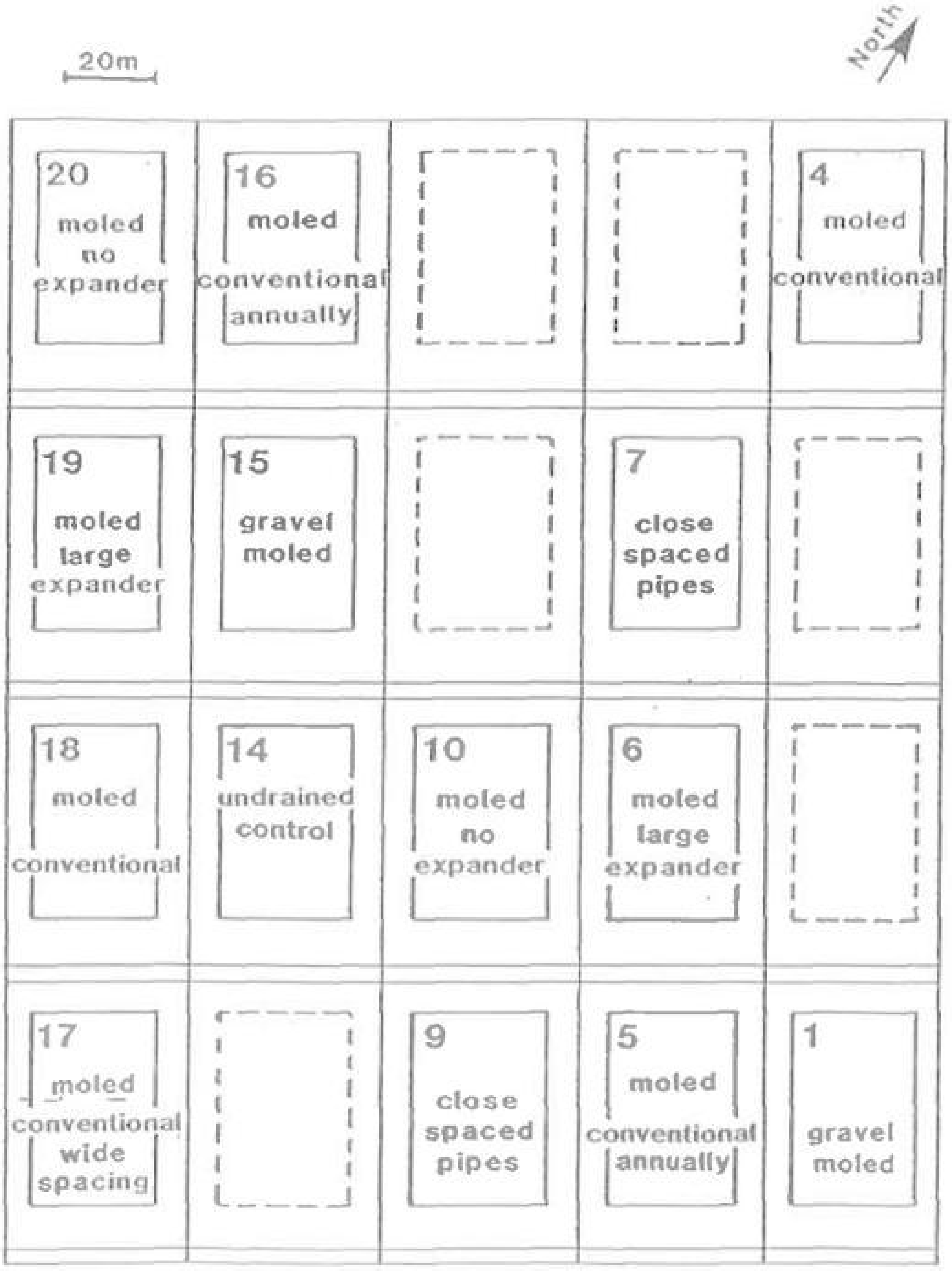


Fig. 6. Drainage treatments, Phase II, 1988-93. Plots shown with pecked borders are undrained cropped plots, not incorporated into the experiment, but available for soil physical monitoring.

1.4.1.4 To measure soluble phosphate and total phosphorus losses in individual flow events.

1.4.2 Revised plot layout

Six pairs of plots had different drainage treatments and cropping systems (Table 1 and Fig. 6). An additional plot (14) was retained as an undrained control, and another (17) measured the effect of mole drains at 4 m spacing (twice that of the other secondary treatments on the site). As in Phase I, each of the 14 experimental plots was managed individually.

1.4.3 Collection of field data

The instrumentation remained similar except that surface flow and interflow were combined as surface layer flow collected in a deep plough furrow. Improvements to data capture include an upgraded data logger to record flow rates and a telemetry system for remote interrogation of data from ADAS, Cambridge. The physical state of mole channels, siltation in gravel-filled mole drains and any slot blockage in closely spaced plastic pipes have been assessed periodically. The nitrogen balance in the crop and soil was studied by determinations of soil organic matter, total and mineral nitrogen and the total dry matter and nitrogen content of the crop.

Water samples for analysis of pesticide residues were originally bulked from the small (300 ml) samples collected for determination of nitrate. This meant that few data were available on variations within individual flow events. To improve the sampling over storm periods, the programmable samplers were added to the site facilities in 1990 and 1991. The pesticides studied (isoproturon, mecoprop, triadimenol, prochloraz, propiconazole, simazine) are those commonly reported in surface watercourses. With respect to modelling, emphasis has been placed on isoproturon.

1.5 COLLABORATIVE STUDIES

Throughout its life the Brimstone Farm site has been used by many researchers working in collaboration with RES and ADAS.

1.5.1 Phase I projects

Rothamsted Experimental Station, Department of Soil Science (Dr D.S. Powlson). Use of ^{15}N-labelled fertilizer to study uptake and leaching losses of nitrogen in spring.

Birkbeck College, London, Department of Geography (Mr A.W. Warren). Effects of seasonal drying on soil structure and self-mulching properties.

Reading University, Department of Soil Science (Dr D. Payne). Changes in soil surface relief by shrinking and swelling.

Silsoe College, Department of Applied Soil Physics (Prof G. Spoor). Stability of mole drains.

Soil Survey and Land Research Centre (Prof A. Thomasson). Land management and water depletion studies.

1.5.2 Phase II projects

Rothamsted Experiment Station, Department of Insecticides and Fungicides (Dr R.H. Bromilow). Pesticide degradation and movement in the soil.

Institute of Aerosol Sciences, Essex University and Department of Biological Sciences, Birmingham University (Mr A.B. Turnbull). Atmospheric deposition of pesticides.

Lancaster University, Institute of Biological and Environmental Sciences (Mr A.J. Beck). Column and lysimeter studies of pesticide movement.

MAFF CSL Application Hazards Unit, Harpenden (Mr G. Bell). Appraisal of pesticide application equipment and arable spraying mass-balance studies.

MAFF CSL Pesticides Analysis Group, Cambridge (Mr D.J. Mason). Analysis of pesticide residues in water samples.

Reading University, Department of Soil Science (Prof R. Swift). Transport of pesticides by association with mobile soil organic constituents.

NERC Institute of Hydrology (Dr P. Whitehead). Modelling nitrate leaching to surface waters.

1.5.3 Phase III projects

Rothamsted Experimental Station, Department of Biological and Environmental Chemistry (Dr R.H. Bromilow). Pesticide degradation, sorption and modelling.

Reading University, Department of Soil Science (Dr S. Nortcliff). Assessment of soil structure and water movement.

Silsoe College, Water Research Centre (Medmenham), Soil Survey and Land Research Centre, Horticulture Research International. Modelling of pesticide and nitrate leaching.

2. HYDROLOGY AND SOIL PHYSICS STUDIES

2.1 BACKGROUND

Movement of water and transport of agrochemicals in clay soils is strongly influenced by the development of macropores such as root channels and seasonal desiccation cracks (Germann and Beven 1981). When the Brimstone Experiment was started in 1978 it was known that the cultivated layer of a ploughed soil is more porous and has a greater hydraulic conductivity than the soil to the same depth in direct drilled land. It was also known that in clay soils water moves laterally in the plough layer if no attempt has been made to modify the subsoil, but that untilled soils have continuous vertical channels which persist from year to year and can enhance infiltration of water. However, it was not known whether these differences affect the total runoff from clay soils or their drainage requirements.

In Phase I the effects of the different cultivation and drainage treatments on the flow paths by which excess water is removed, the timing of movement and the total volume removed provided key support for measuring leaching losses of nitrate. In Phase II the imposition of different drainage treatments and cropping sequences allowed more detailed investigation of the processes determining movement of agrochemicals. In Phase III these are being continued, and the influence of drainflow restrictors (rotatable U-bends in the pipework carrying drainwater from the mole drains to the flow meters and water samplers) on water tables and agrochemical leaching is being studied.

2.1.1 Objectives

In Phase I the main hydrological objectives were:

2.1.1.1 To compare the drainage requirements of ploughed and direct drilled land.

2.1.1.2 To compare surface flow, interflow and drainflow on ploughed and direct drilled land and their effect on total flood runoff.

2.1.1.3 To provide a detailed hydrological database to support nitrate leaching studies.

The hydrological objectives of the different soil drainage and crop management strategies in relation to leaching and surface layer flow of pesticides in Phase II are given in section 5.1.1.

2.1.2 Drainage design standards

The drainage for the site conformed to general recommendations for clay soils in the late 1970s. The diameter of plastic or clay pipe recommended for such soils was 75 mm, but because the total drain length on each plot was only 41 m, the capacity of each drain considerably exceeded the design standard for the site. However, this allowed the peak drainflows to be fully recorded under all weather conditions experienced.

2.2 RAINFALL PATTERNS IN PHASE I

The weather over the 10 year period of Phase I was very variable. In most winters the rainfall totals were within 15% of the long-term average, but there were two very dry summers (1983 and 1984) each having < 50% of the average rainfall (Table 2). In several summers soil drying led to surface and subsurface cracking.

Table 2. Rainfall expressed as a percentage of the long term average, 1978-88.
(+) Oct-Nov, (*) Gauge suspended - end of Phase I.

	78/ 79	79/ 80	80/ 81	81/ 82	82/ 83	83/ 84	84/ 85	85/ 86	86/ 87	87/ 88
Sep-Nov		51	95	111	135	73	143	46	101	123
Dec-Mar	21^+	121	100	112	83	96	81	114	79	108
Jun-Aug	116	114	76	91	44	40	141	73	90	-*
	67									
Total		85	93	96	102	74	117	87	91	-
	-									

mm 456 578 632 653 694 503 796 593 619 789 Mea
63

The network of 10 check raingauges installed in the early years of Phase I showed up to 10% variability in rainfall across the site. Greater rainfall was recorded on north-western parts of the site, especially with prevailing westerly winds in winter. Values from the various gauges were averaged to produce agreed daily, weekly and monthly figures. Heavy snowfalls also resulted in different surface accumulations between plots, and 'rainfall' for each plot then had to be adjusted to correct the water-balances.

2.3 COMPONENTS OF FLOW IN PHASE I

2.3.1 Surface flow

On all plots surface flow depends on rainfall; on the drained plots it also depends on the effectiveness of the mole drainage system. In Phase I there was no difference in surface flow between tine cultivated (1978/79 and 1979/80) and ploughed (1980/81 onwards) plots, but the change to direct drilling (1980/81 onwards) led to peaky hydrographs (Figs 7 and 8) and an increase in surface flow on both drained and undrained plots (Table 3). On direct drilled plots surface flow often occurred after 3-4 mm rainfall in winter, and the lag time between peak rainfall and peak flow was on 15-30 mins. In contrast on the ploughed plots, surface flow occurred less in response to low rainfall amounts, and the lag time between peak rainfall and peak flow was usually 30 mins (Figs 7 and 8).

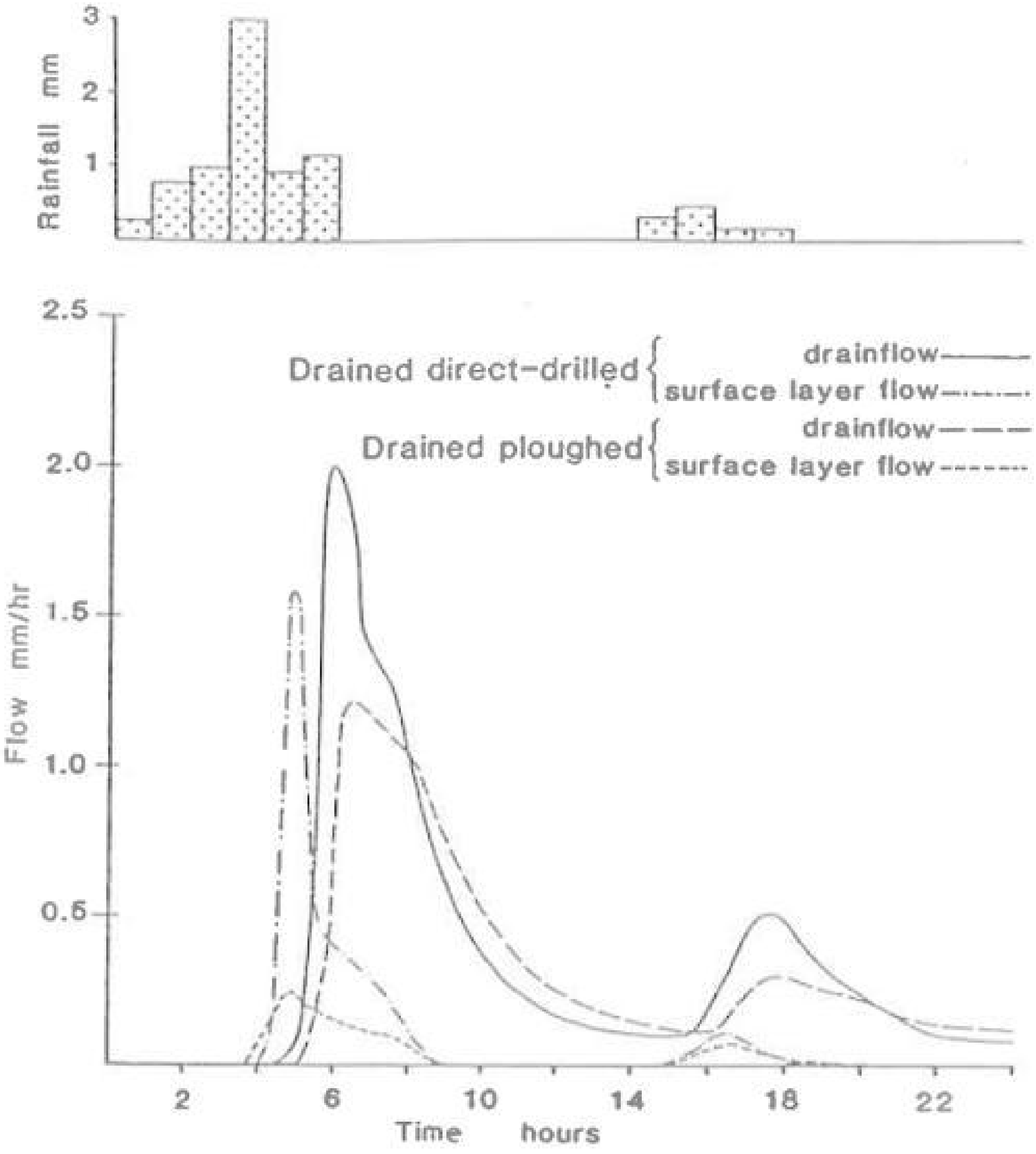


Fig. 7. Typical surface flow and interflow response to a winter rainfall event on a drained plot for direct drilled and ploughed treatments (after Arrowsmith et al. 1989).

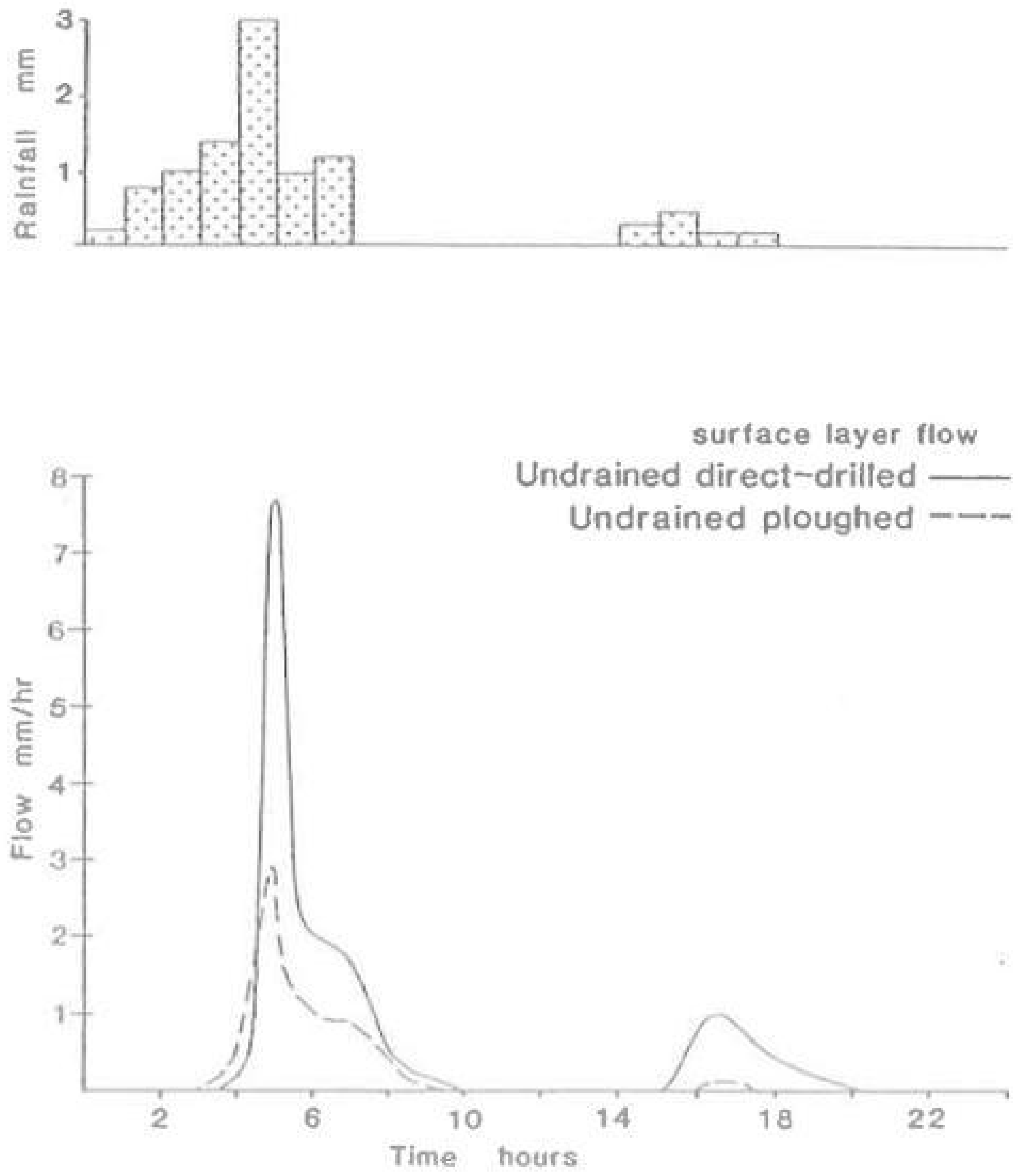


Fig. 8. Typical surface flow ~~and~~ ~~interflow~~ response to a winter rainfall event on an undrained plot for direct drilled and ploughed treatments (after Arrowsmith et al. 1989).

In several years peak surface flow on direct drilled plots exceeded drainflow, and resulted in shallow erosion rills.

2.3.2 Interflow

Amounts of interflow were small in all years, especially on drained plots. Except during very intense rainfall, hydrographs were much less peaky than those of the surface flow, with peak flow occurring 1-1½ hrs after peak rainfall.

2.3.3 Drainflow

Drainflow was continuous through most of each winter, with trickle flows lasting for several weeks after cessation of rainfall. Peak flow rates in direct drilled soils were often greater than those in tilled (tine or ploughed) plots, particularly with newly drawn mole channels (1978, 1982, 1985). The difference was greatest in early autumn and late spring when soil cracking was most evident. For the drainflow events that exceeded 0.85 mm/hr (the UK design rate for sub-surface drainage at Brimstone) the peak drainflows from direct drilled plots were on average 30% greater than those from ploughed plots. The lag time between peak rainfall and peak drainflow was typically 2-3 hrs for ploughed plots but only 1½-2 hrs for direct drilled plots; the latter also exhibited a faster hydrograph recession (Fig. 9).

Table 3. Mean flow for each cultivation treatment as a percentage of total runoff for December to March inclusive, each year, 1978-88.

Year	Undrained Surface Flow		Drained Surface Flow		Drained Mole + Pipe Drainflow	
	Ploughed	Direct Drilled	Ploughed	Direct Drilled	Ploughed	Direct Drilled
1978/79	47*	-	1*	-	91*	-
1979/80	55*	-	5*	-	90*	-
1980/81	68	5	14	74	80	-
1981/82	77	81	8	23	83	64
1982/83	76	89	5	17	93	82
1983/84	19	57	10	3	82	95
1984/85	30	69	7	3	91	94
1985/86	54	81	3	11	96	81
1986/87	77	79	3	3	94	93
1987/88	83	93	3	20	91	78

* all plots tine cultivated.

Means 52·6 69·3 5·9 19·3

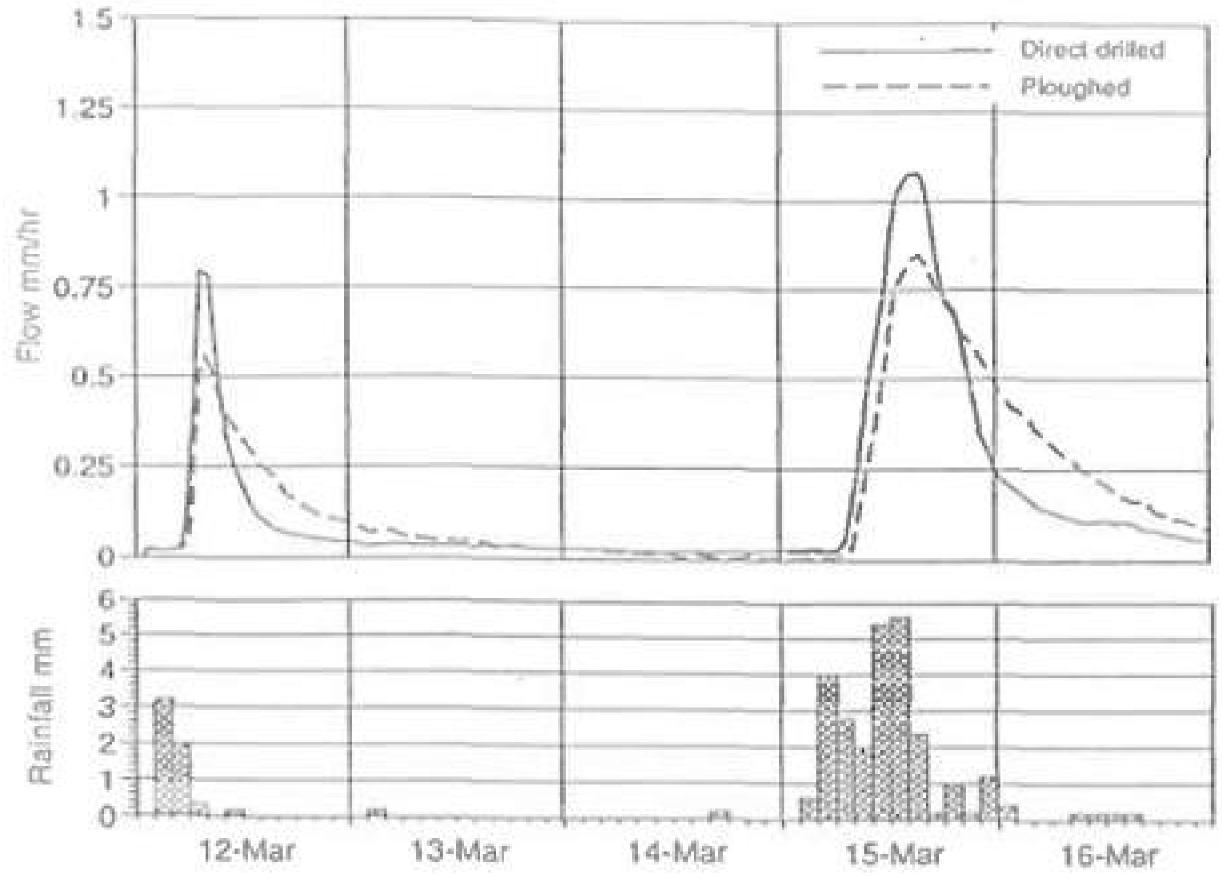


Fig. 9. Comparison of typical drainflow response, direct drilled and ploughed treatments, March 1982

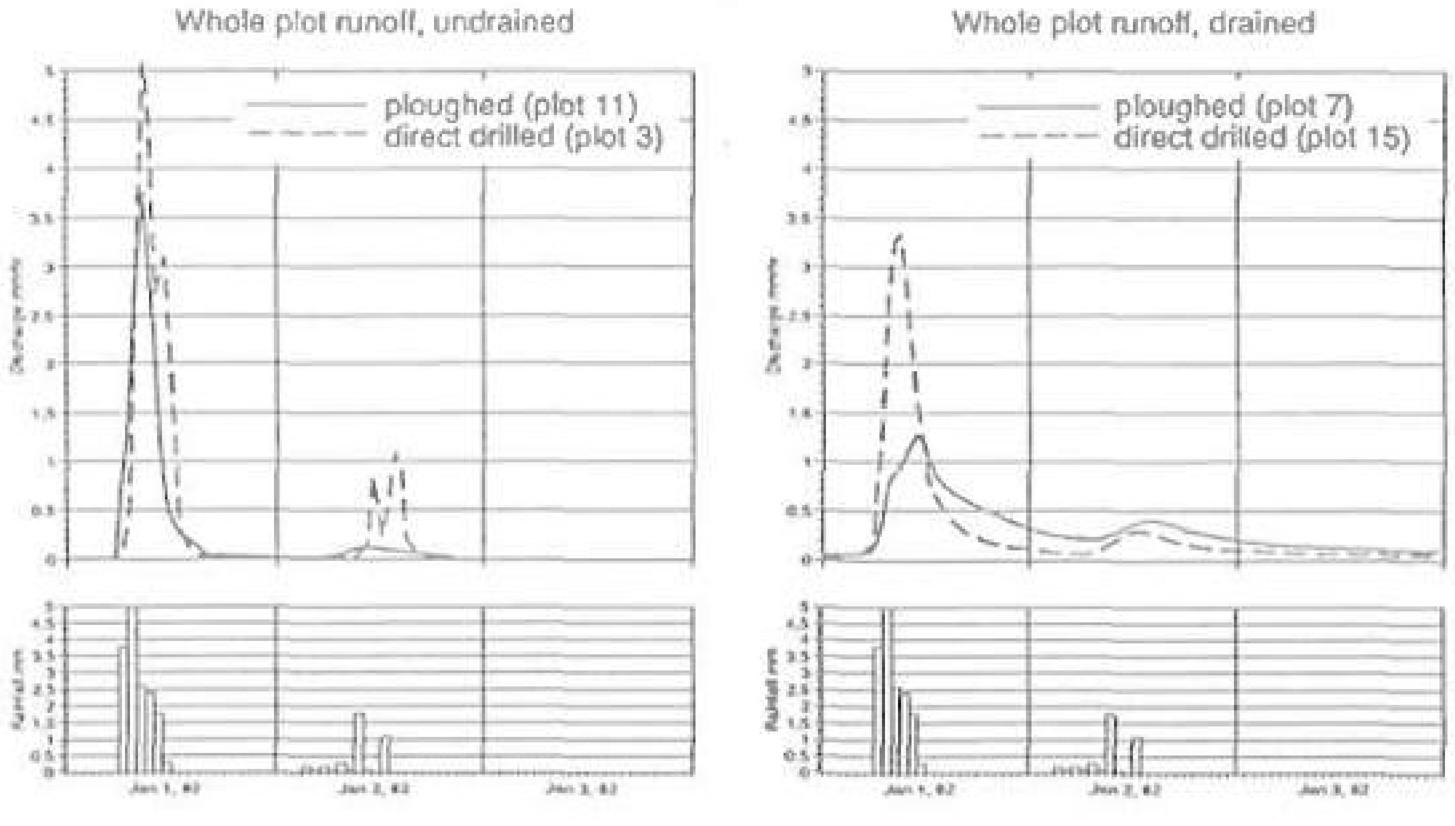


Fig. 10. Total runoff response from drained and undrained land showing effect of drainage on overall flood risk for a typical winter event.

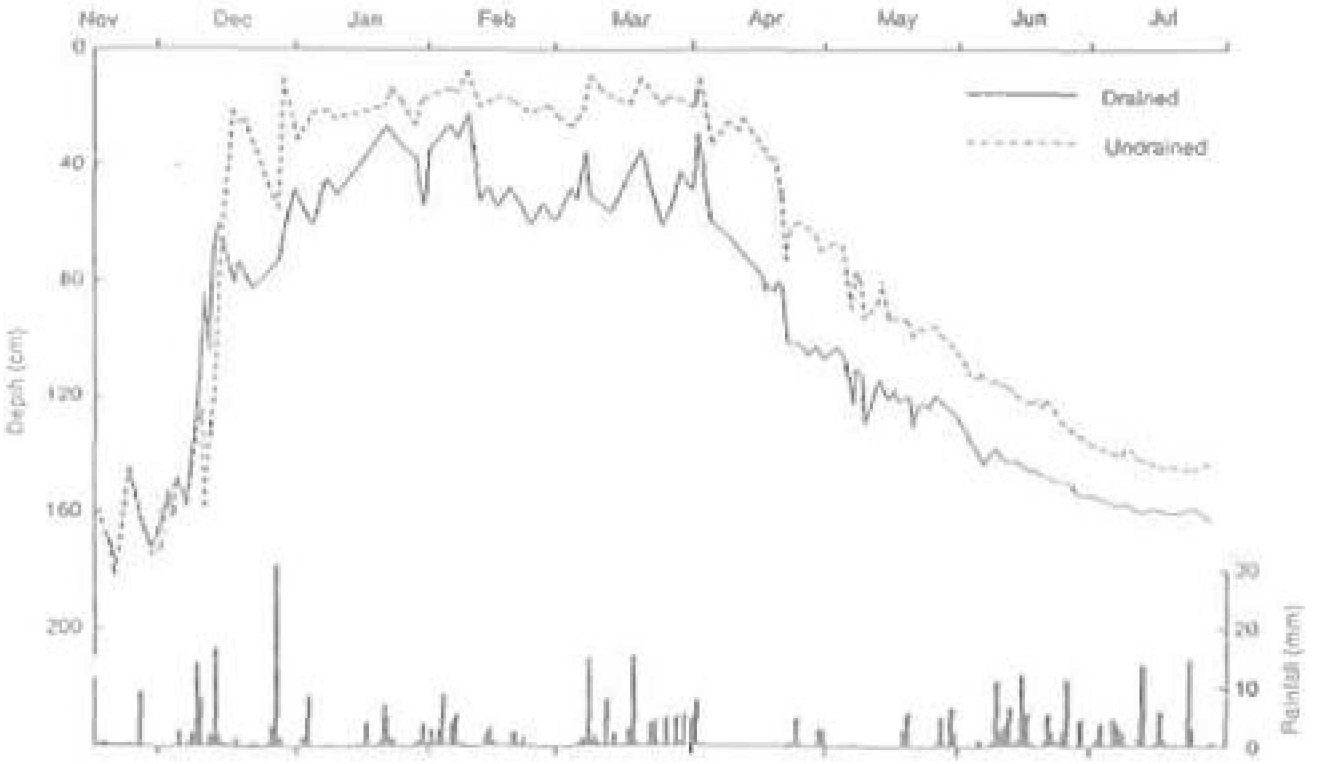


Fig. 11. Mean depth to the water table, for drained and undrained central eight plots, 1979-80 (after Harris et al. 1984). Data from tensiometers.

Whereas direct drilling resulted in greater runoff at peak flow than ploughing, and therefore increased the risk of flooding downstream, drainage decreased peak total runoff (Fig. 10). This is because it increased the depth to water table (Fig. 11) and provided opportunities for excess water to be temporarily stored in upper soil horizons. A computer model developed to examine the implication of the increased peak drainflows under direct drilling showed that surcharging of systems designed to current standards could occur, with water backing up in pipes and mole channels, and that flood problems could result nationally.

2.4 WATER BALANCES

Daily, monthly and winter water balances were produced from rainfall, evapotranspiration and total runoff values. Poor balances were obtained in early years, but improved plot separation and settlement of drainage trenches gave better balances in later years. Winter water balances were then almost 100% on the drained plots and up to 70% on undrained plots.

2.5 MOLE CHANNEL DETERIORATION AND SOIL STRUCTURE

In most years mole channel deterioration occurred equally under ploughing and direct drilling. The roof and walls gradually collapsed over 3-4 years, so the channels were redrawn in 1982 and 1985. However, after dry periods in 1983 and 1986 deep cracking allowed topsoil to infill the channels, especially on the direct drilled plots. In the dry summer of 1984 extensive roof collapse occurred on all plots, but on the direct drilled plots a continuous void up to 100 mm in diameter developed along the old roof; this later provided effective drainage, though the water table control was less than that offered by the original mole channel.

The soil structure around mole channels was better developed under direct drilling, with more continuous vertical cracks likely to encourage downward water movement. This increased the effectiveness of the channels and extended the life of the system by at least 25% compared with that on ploughed plots. Earthworm populations were small on both ploughed and direct drilled plots and few were found deep in the soil, so it is unlikely that they account for the structural and drainage differences.

2.6 WATER TABLE CONTROL

In 1978/79 drainage gave no water table or crop yield benefit because of the cultivation pan. Once this had been removed the drainage system increased the depth to the water table by 0.25 m in 1979/80 (Fig. 11) and by 0.15 - 0.20 m in subsequent winters, as indicated by both water table meters and tensiometers (Thackeray *et al.* 1987). On the drained, direct drilled plots the improved soil structure lowered the water table more rapidly and for longer periods than on ploughed plots. On undrained direct drilled plots the dense cultivated soil resulted in a shallower aerated zone, with water held nearer to the surface and the crop, than on undrained ploughed land.

3. CROP YIELDS AND UPTAKE OF NITROGEN

3.1 RESULTS FOR PHASE I

3.1.1 Agronomy

After the uniformity trials in 1978/79 and 1979/80 when all plots were tine cultivated, 10 plots were ploughed each year, their seedbeds prepared with equipment appropriate for the soil conditions and seed was sown on a common date for all plots. Conventional sowing methods were used on ploughed land except in the wet autumn of 1982, when seed was broadcast in November, because the soil would not support a tractor without suffering severe wheel marking. Crop residues were burnt *in situ* after each harvest, but the burn was incomplete in 1983 and 1986, so the remainder was then incorporated by shallow tillage.

Winter wheat was grown in the uniformity trials of 1978/79 and 1979/80 and in the two following years. It had also been grown by the farmer in 1977/78, so by 1982 take-all was affecting the crop. Thereafter rotational cropping was adopted (Table 4).

Table 4. Agronomic details Phase I and Phase II

Phase 1				Spring Nitrogen		
Year	Crop (autumn sown)	Sowing date	Autumn fertilizer NPK kg/ha	Date of 1st application	Amount kg/ha and splits ( )	Total N for crop kg/ha
1978/79	Wheat	2 Oct. 78	17 26 21	7 March 89	116 (3)	133
1979/80	Wheat	5-9 Oct. 79	24 21 0	11 April 80	140 (2)	164
1980/81	Wheat	1-2 Oct. 80	0 25 0	1 April 81	149 (2)	149
1981/82	Wheat	8 Oct. 81	24 21 0	24 March 82	148 (3)	172
1982/83	Oats	11 Nov. 82	30 26 0	8 March 83	111 (3)	141
1983/84	Wheat	17 Sept.83	17 25 0	5 April 84	223 (3)	240
1984/85	Oilseed rape	1 Sept.84	46 16 30	11 March 85	239 (2)	285
1985/86	Wheat	10 Oct. 85	0 29 54	30 April 86	130 (1)	130
1986/87	Oats	15 Oct. 86	0 29 55	10 April 87	100 (2)	100
1987/88	Wheat	12-13 Oct. 87	-	12 April 88	194 (2)	194
Phase II				Spring Nitrogen		
Year	Crop	Sowing date	PK fertilizer kg/ha	Date of 1st application	Amount kg/ha and splits ( )	Total N for crop kg/ha
1988/89	Grass	21 Sept.88				
	White mustard	21 Sept.88	29.55	14 March 89	100 (3)	100
	Winter oats	5 Oct. 88	5 May 89			
	Spring wheat	28 Mar.89				
1989/90	Winter wheat	6 Oct. 89	-	8 March 90	150 (2)	150
	Winter barley	9 Oct. 89	-			

Crop protection chemicals and growth regulators have been used since 1978. Sprays and fertilizers are applied using tramlines re-established in the same positions each year. Amounts of fertilizer applied were assessed from soil analyses for P and K and by the index system of MAFF (1973) for N (Table 4). To assess plant populations, shoot density, components of yield and nutrient content of aerial dry matter, plants were collected from 6 locations in each plot. Grain yields were measured in four cuts 2.2 m wide and 24 m long across each plot, and adjusted to 85% dry matter for cereals and 86% dry matter for oilseed rape.

3.1.2 Yields in uniformity trials

Because of the cultivation pan (Section 1.2) there was no significant difference in grain yields between the drained and undrained plots (all tine cultivated) in 1978/79. After disruption of the pan, the yield at harvest 1980 was 6% greater on drained than on undrained plots (Table 5).

Table 5. Yield of winter wheat grown during the uniformity trial period 1979-80

Harvest Year	Cultivation	Yield (t/ha 85% DM)		SED
		Drained	Undrained	
1979	Tine 25cm Disc Harrow	5.20	5.14	0.110
1980	Progressive Tine Cultivation to 25cm	7.33	6.52	0.139 ***

*** = Statistically significant $P < 0.001$

3.1.3 Effects of drainage on yield, harvests 1981-88

Averaged over the 8 years of the drainage/cultivation comparison in Phase I, drainage had a greater influence on yield than did cultivation. Cereal yields of drained land were significantly greater than those of undrained land at harvest 1982, 1983 and 1988 (Table 6). In 1982 this was a result of better root and shoot growth in early spring, and in the other two years when the soil had been waterlogged in the previous autumn periods there were more plants on the undrained plots.

Table 6. Effect of Drainage on crop yield after Ploughing (P) or Direct Drilling (DD)
Results based on 16 plot comparison, Phase I.

		Treatment				Statistical Significance (FTEST)			
Harvest Year	Winter Crop	Cultivation	Drained t/ha	Undrained t/ha	Percent change due to drainage	Between drainage treatments	Between cultivation treatments	Cultivation and drainage interaction	SED
1981	Wheat	P	8.01	8.17	- 2	N.S.	N.S.	N.S.	0.316
		DD	8.58	7.90	9				
		Mean	8.29	8.03	3				
1982	Wheat	P	6.91	5.62	23	* * *	* *	N.S.	0.208
		DD	7.95	6.00	32				
		Mean	7.43	5.81	28				
1983	Oats	P	7.17	5.89	22	* * *	* *	* *	0.450
		DD	7.04	3.19	121				
		Mean	7.11	4.54	57				
1984	Wheat	P	11.41	11.42	-	N.S.	N.S.	*	0.221
		DD	11.96	11.19	7				
		Mean	11.68	11.30	3				
1985	Oilseed Rape	P	3.84	3.51	9	N.S.	N.S.	*	0.112
		DD	3.44	3.57	- 4				
		Mean	3.64	3.54	3				
1986	Wheat	P	7.49	7.99	- 6	N.S.	N.S.	*	0.167
		DD	7.83	7.74	1				
		Mean	7.66	7.86	- 2				
1987	Oats	P	6.02	6.60	- 9	N.S.	N.S.	* * *	0.128
		DD	6.70	6.23	8				
		Mean	6.36	6.42	- 1				
1988	Wheat	P	7.55	7.33	3	*	*	N.S.	0.353
		DD	7.22	6.13	18				
		Mean	7.39	6.73	10				

N.S. = Not significant; * P = < 0.05; ** P = < 0.01; *** P = < 0.001.

3.1.4 Effects of cultivation on yield, harvests 1981-88

Yields were greater on direct drilled plots in five years (Table 6) when rainfall in the preceding autumn was equal to or less than average, and were greater on ploughed plots in three years (1983, 1985, 1988), all of which were preceded by wet autumns.

After the poor burn in 1986, volunteer wheat affected the subsequent crop of winter oats, and was especially abundant on direct drilled plots. At harvest 1987 the contamination of the grain was 20% on direct drilled plots and only 3% on ploughed plots. Ploughing had buried the unburnt residues and therefore limited the problem of volunteers. But, as elsewhere (Christian and Bacon 1990), cultivation otherwise had very little effect on yield.

3.1.5 Interaction between drainage and cultivation

The benefit of drainage to yield was greater for direct drilled crops (mean of 1.12 t/ha/yr) than for crops established after ploughing (0.23 t/ha/yr), and was greater for oats than for wheat or oilseed rape. This was because sowing of the first of the two oat crops in 1982 was delayed by wet weather, which prevented the preparation of seedbeds on ploughed plots. The late sowing penalized the direct drilled crop, especially on undrained plots where waterlogging probably caused many seeds and seedlings to die (Cannell and Belford 1982). Without the restriction of a common sowing date for all treatments, the direct drilled crop could have been sown earlier and might not have suffered in this way.

3.1.6 Nitrogen uptake

Table 7. The nitrogen content of shoots (kg/ha) before nitrogen fertilizer was applied and at harvest

	Drained		Undrained		
	Plough	Direct drill	Plough	Direct drill	SED
1985/OSR[a]					
Spring	119	126	117	129	28.8
Harvest[b]	262	220	245	210	30.6
1986/WW[a]					
Spring	35	37	25	26	2.2
Harvest	220	223	233	202	18.6
1987/WO[a]					
Spring	48	56	34	48	3.7
Harvest	144	124	141	121	5.4
1988/WW[a]					
Spring	25	20	16	10	4.4
Harvest	254	239	231	213	13.2

[a] OSR = winter oilseed rape; WW, winter wheat, WO, winter oats

[b] Total in grain and straw

Uptake of nitrogen in the last four years of Phase I was usually greater on drained plots than undrained (Table 7). Uptake by oilseed rape over the winter of 1984/5 was several times that by winter cereals in the three following years. The rape received 46 kg N/ha in autumn and the cereals all received no autumn N, but the increased uptake by oilseed rape was approximately twice its seedbed dressing in autumn, so the rape made greater demands on non-fertilizer sources of N than did the cereal crops. However, at maturity differences in N content between crops and treatments had decreased, and total uptakes exceeded amounts applied as fertilizer (cf. Tables 4 and 7).

Results for winter oats in 1986/87 are confused by the presence of volunteer wheat plants. The spring N content includes both sown and volunteer plants, but the amounts at maturity are for areas where volunteers had been removed by hand roguing in the early summer.

3.2 RESULTS FOR PHASE II

3.2.1 Agronomy

The different crop rotations on the 14 plots used in Phase II are shown in Table 1. Different methods of tillage and straw disposal were also involved (Table 8). The policy of crop protection was continued but modified to suit the pesticide leaching studies (Section 5). Cereal yields were estimated as in Phase I (Section 3.1.1) and grass growth was estimated by cutting the sward on several occasions each year.

3.2.2 Crop yields

The autumn of 1988 was very dry (Fig. 12), so crop establishment was slow. For example on Plot 1 the grass grew more slowly than on Plot 15, and by July 1989 there was a 40% difference in dry matter production (Table 8). This difference had narrowed to 5% by spring 1990. On Plot 14 patches of sterile brome affected the growth of winter oats; as this would have jeopardized future experimentation on the plot, all the vegetation was killed by spraying in spring and the plot was resown to spring oats. Yields on the remaining 7 plots carrying winter oats averaged 5.75 t/ha and were not influenced by secondary drainage, tillage or method of straw disposal (Table 8).

Two pairs of plots were used to assess nitrate leaching under winter cover crops. In the winter of 1988/89 Plots 7 and 9 were sown with white mustard and the other pair (5 and 16) was fallow. The mustard established slowly. It was killed by spraying in late February 1989 but wet weather prevented the sowing of spring wheat for three weeks. The average yield of spring wheat after the cover crop was 8% heavier than after fallow.

In autumn 1989 all plots except those in grass (1 and 15) were sown with either winter wheat or barley. The average yields of these crops was 7.5 t/ha and 5.4 t/ha, respectively (Table 8). The average yield of Plots 7 and 9 (cover crops in 1988/89) was 12% more than on Plots 5 and 16 (winter fallow in 1988/89); this increase probably resulted from the nutrients released from residues of the winter cover crop.

For each of the crops involved the plots which had been direct drilled in Phase I (1980-88) yielded more in 1989 and 1990 than those that had been ploughed.

Table 6. Phase II yield of crops and uptake of nitrogen 1989 and 1990

Plot number	Mole drainage treatment	Tillage methods	Straw disposal	Crop 1989	Yield	Nitrogen uptake kg/ha		Crop 1990	Yield	Nitrogen uptake kg/ha		Previous drainage/tillage
						Spring[c]	Harvest			Spring	Harvest	
1 15	Gravel filled	-	-	grass	3.49 4.88	12 22	62 108	grass	4.30 4.54	11 9	32 36	D[e]-P D-DD
5 16	Frequent moling	tine	burnt	fallow/ spring wheat	3.46 2.77	-	158 138	winter barley	5.31 4.18	12 5	136 100	UD-DD D-P
7 9	Closed spaced drainage	tine	burnt	white mustard/ spring wheat	3.22 3.53	23[a] 26[a]	111 148	winter barley	5.31 5.83	7 9	105 143	D-P D-DD
10 20	moled, no expander	plough	burnt	winter oats	5.70 5.96	31 29	122 121	winter wheat	7.64 7.44	7 7	172 182	D-P UD-DD
6 19	moled, large expander	plough	incorporated	winter oats	6.05 5.60	25 21	128 120	winter wheat	7.64 7.19	7 5	192 148	D-DD UD-P
4 18	moled conventional	tine	burnt	winter oats	5.88 5.21	24 30	94 93	winter wheat	7.64 7.19	7 7	170 166	D-DD UD-P
14	undrained	direct-drilled	burnt	spring oats[f]	-	19_b	68	winter wheat	7.81	5	185	UD-DD
17	moled extended interval	tine	burnt	winter oats	5.86	16	117	winter barley	6.45	6	157	D-DD

[a] N in white mustard when it was incorporated

[b] N in vegetation when killed in spring

[c] Assessment made before nitrogen was applied in spring.

[e] D denotes drained; UD = undrained; P = ploughed; DD = direct drilled

[f] Originally sown with winter oats

3.2.3 Nitrogen uptake

Because the white mustard cover crop established poorly in autumn 1989, the amount of N it took up was less than that taken up by winter oats (Table 8), even though the oats had been sown one week later. The difference in N uptake between the two grass plots (1 and 15) in 1988/89 reflected the better establishment and growth on the plot which had been direct drilled in Phase I. By harvest 1990 the difference in N uptake had almost disappeared.

In 1988/89 and 1989/90 the total amount of nitrogen in crops (Table 8) exceeded the amounts applied as fertilizer (Table 4), except on Plots 4 and 18 in 1988/89 (winter oats) and 5, 7, 16 and 19 in 1989/90 (winter barley). Although winter wheat and winter barley received the same amount of N in spring 1990, there was more N in the wheat crop.

Greater N uptake occurred on several plots which had been direct drilled in Phase I than on plots that had been ploughed.

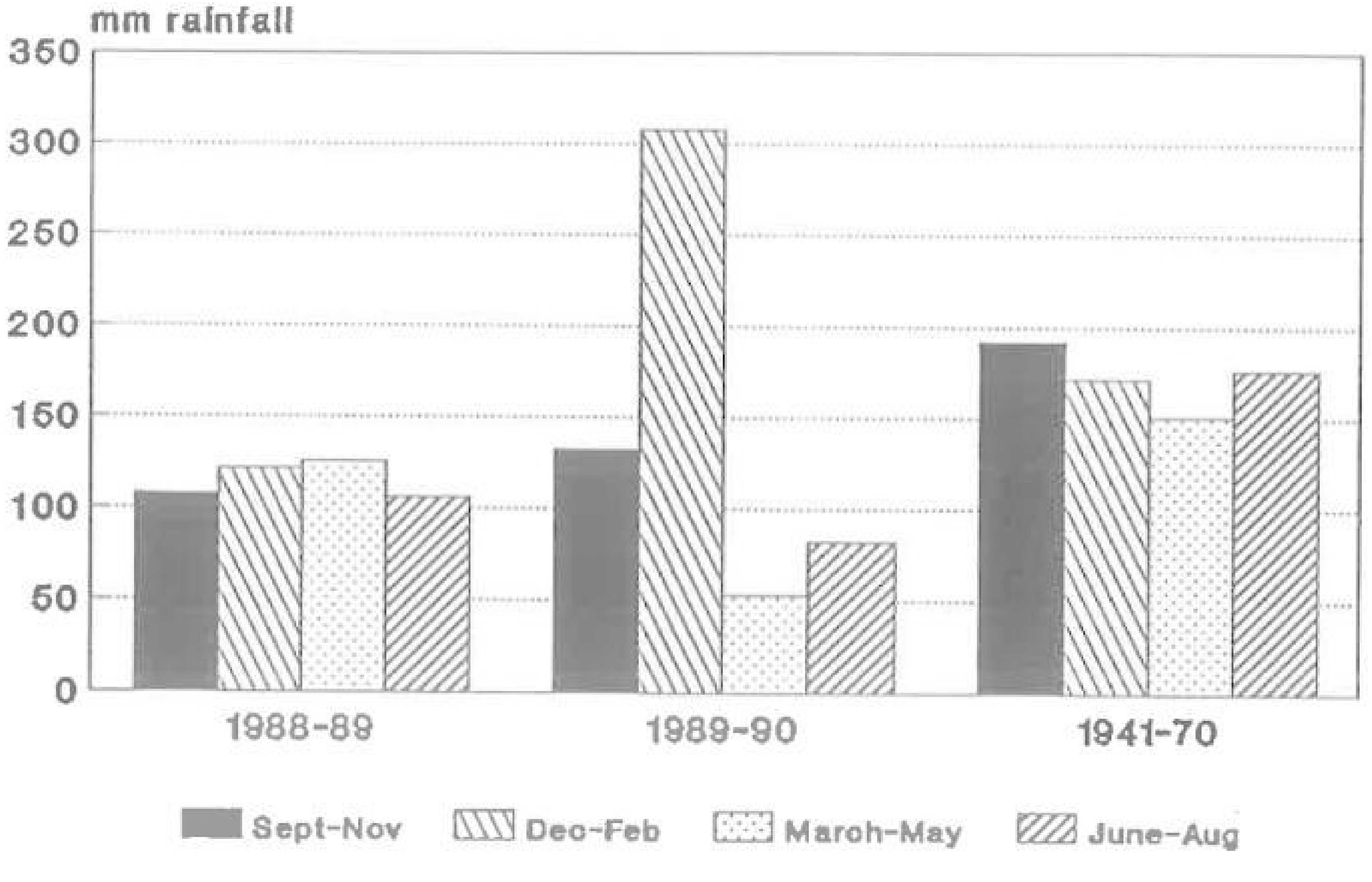


Fig.12. Seasonal rainfall (mm) 1988 - 90 and long term average 1941 - 70.

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), 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).

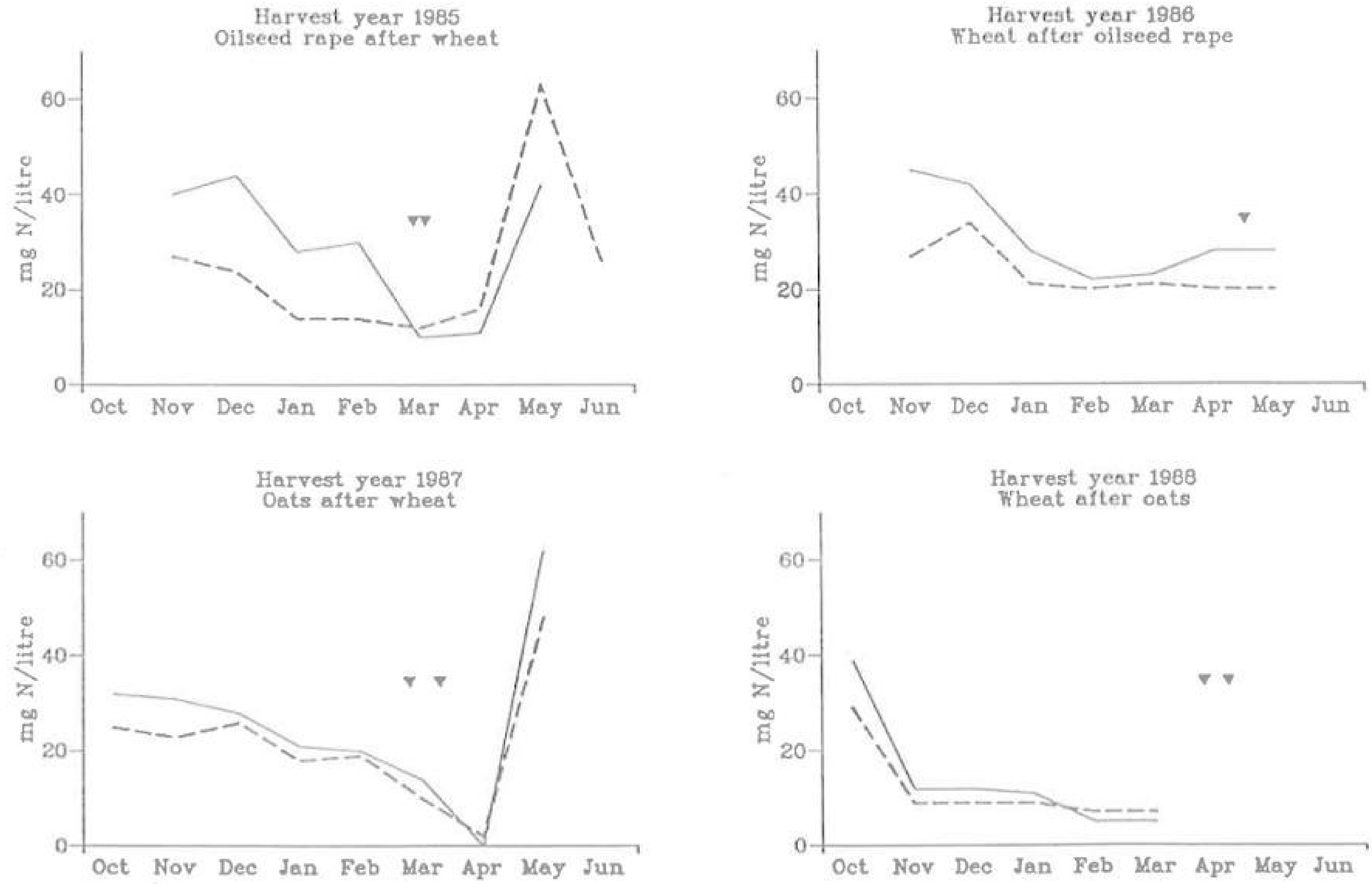


Fig. 13. Flow-weighted mean monthly concentrations of nitrate-N in drainwater, harvest years 1985-88. Arrows indicate date/s of spring top dressings, solid line - ploughed plots, dashed line - direct drilled plots.

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.

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

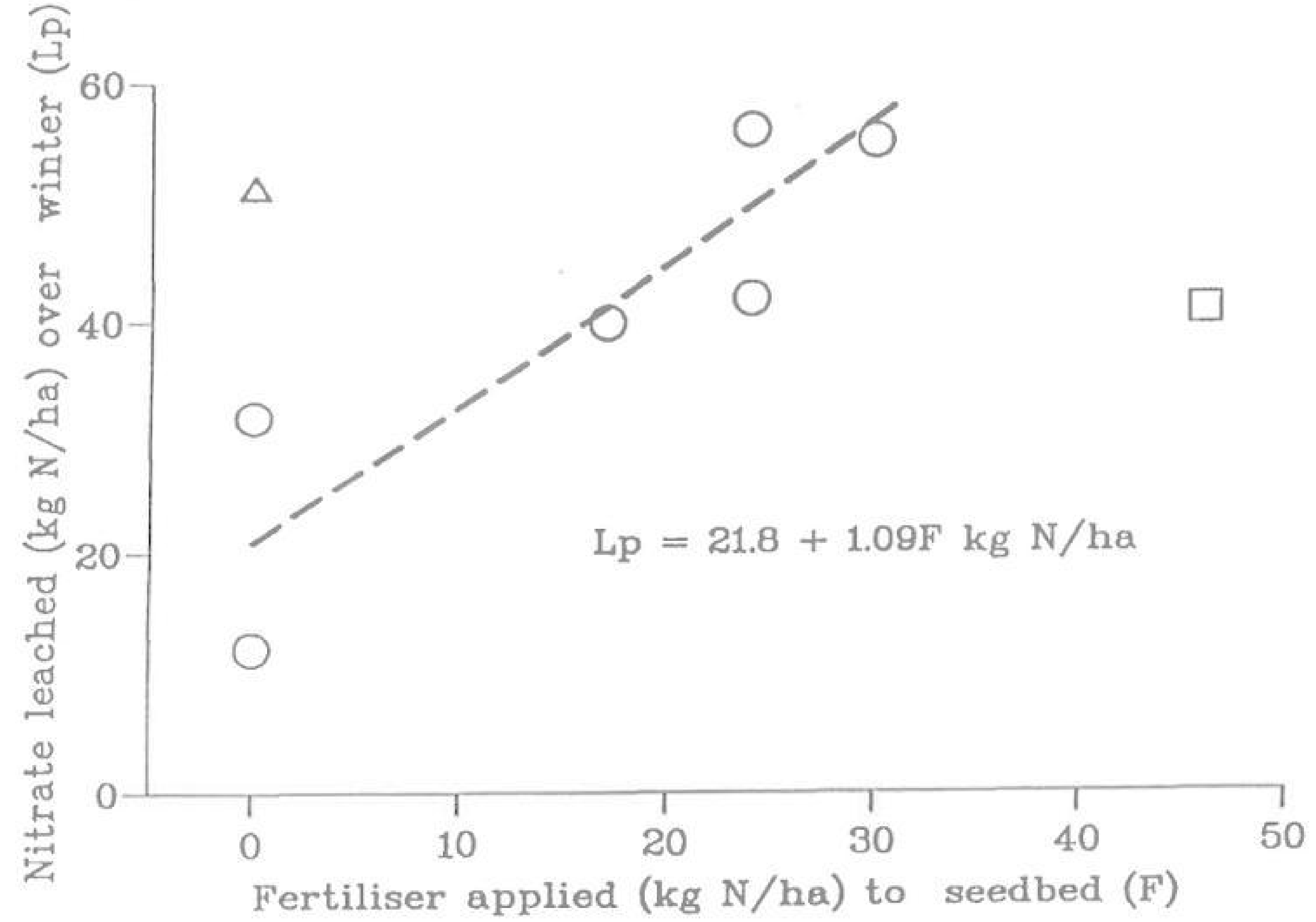


Fig. 13. Relationship between amount of autumn-applied fertiliser-N and nitrate leached over the winter period. The regression is fitted to results for cereals following wheat or barley on tilled plots (circles). Values for oilseed rape following wheat (square) and wheat following oilseed rape (triangle)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

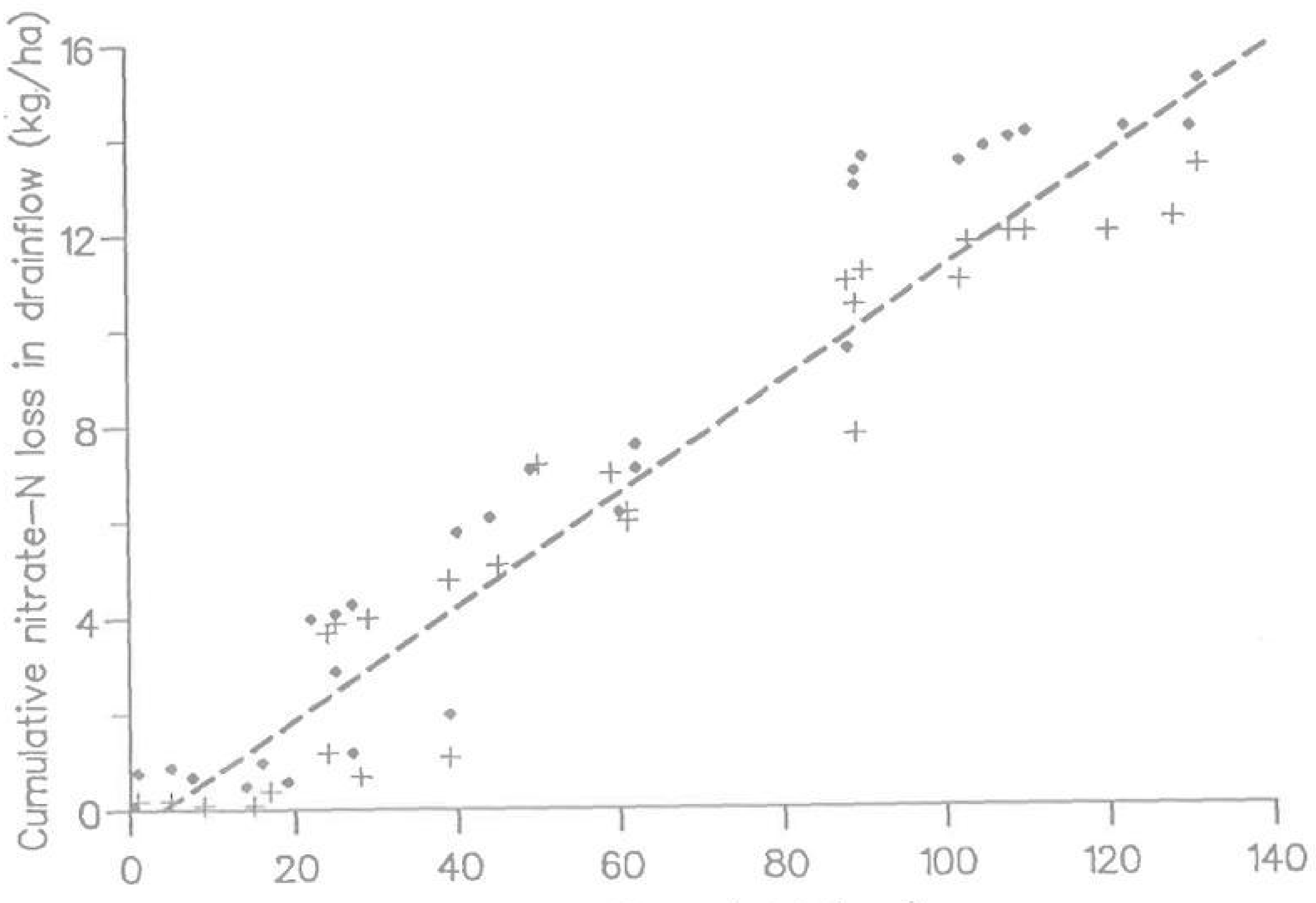


Fig. 14. Relationship between rainfall in the period after spring top-dressing 1983 and nitrate-N in drainflow (circles, direct drilled plots; crosses, ploughed plots).

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.

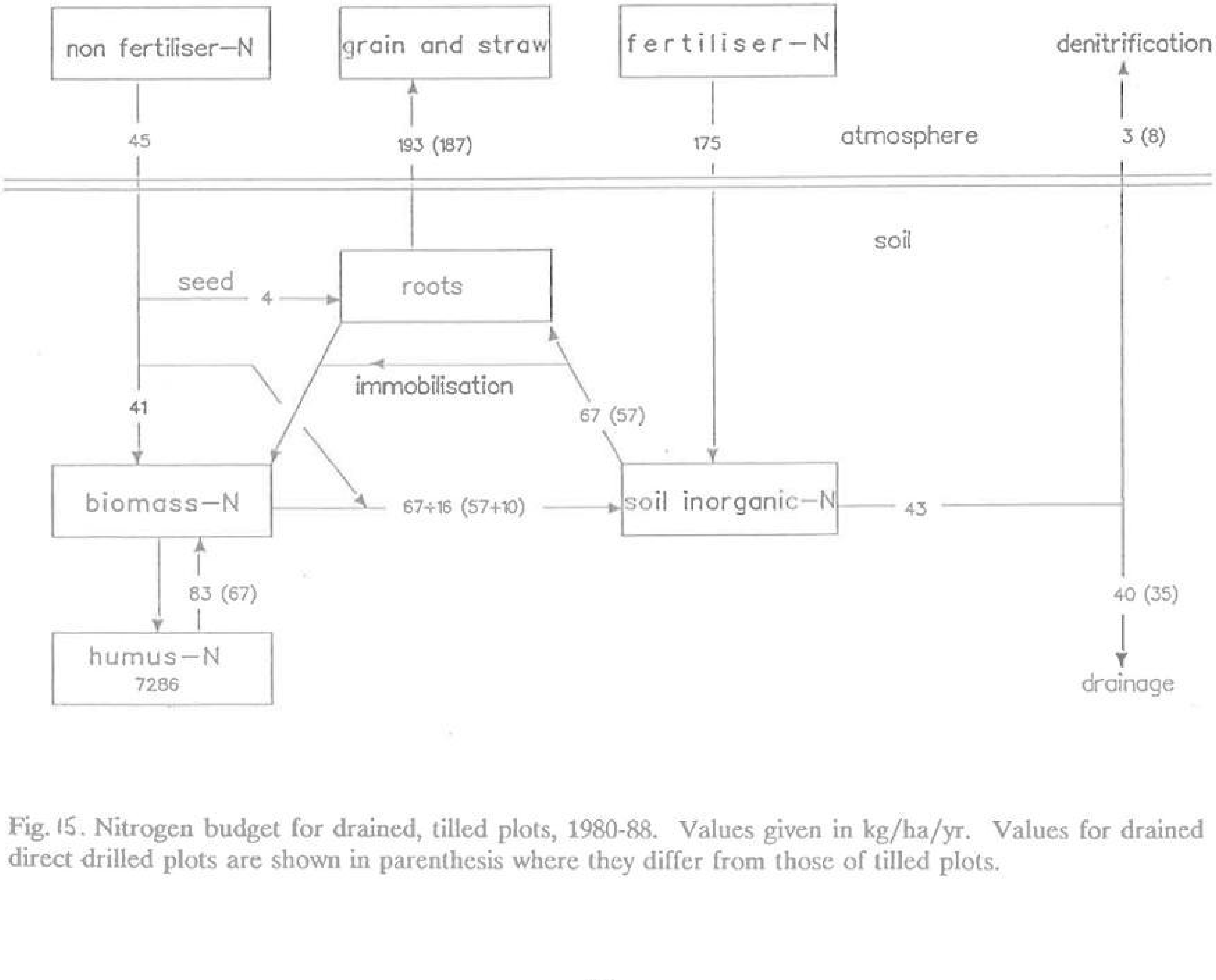


Fig. 15. Nitrogen budget for drained, tilled plots, 1980-88. Values given in kg/ha/yr. Values for drained direct drilled plots are shown in parenthesis where they differ from those of tilled plots.

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.

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).

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.

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 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.

5. PESTICIDE LEACHING IN PHASE II

5.1 BACKGROUND

As sub-surface drainage and soil structure development influence the leaching of nitrate in the soil of Brimstone Farm, they may also influence losses of pesticide residues. Both surface flow and rapid water movement through soil cracks and other macropores may increase pesticide residue losses because of limited contact with the soil and therefore less opportunity for adsorption and/or degradation. Various crop management strategies, such as straw incorporation, and different types of soil drainage are also likely to affect losses of pesticides.

5.1.1 Objectives

5.1.1.1 To develop soil drainage and crop management strategies for minimizing leaching and runoff of pesticides.

5.1.1.2 To provide data for validating and improving models of pesticide movement.

5.2 EXPERIMENTAL DESIGN

The six pairs of plots with different drainage treatments and cropping systems utilized in Phase II had the following potential implications for leaching of pesticide residues:

a) Plots 1 and 15 (gravel-filled mole drains) indicated the effects of organic matter turnover on leaching of pesticide residues and the carry-over of pesticides applied in Phase I, as the grass leys on these plots in Phase II received no pesticides between autumn 1988 and autumn 1991.

b) Plots 4 and 18 (conventional mole drains) indicated the effects of straw burning in conjunction with tine cultivation on pesticide leaching in the first two years of Phase II. The incorporation of winter beans into the cropping cycle in 1990/91 then provided an opportunity to study losses of simazine.

c) Plots 6 and 19 (large expander mole drains) had crop residues incorporated and so offered a contrast to Plots 4 and 18. This is important now that burning of residues is restricted in UK. The large expander mole drains allow rapid water movement from topsoil to subsoil, which may accelerate pesticide leaching.

d) Plots 5 and 16 (closely spaced mole drains) and Plots 7 and 9 (closely spaced 35 mm diameter shallow pipes) had spring cropping programmes following winter cover crops and fallow in 1988/89 and 1990/91. Both drainage treatments encouraged rapid water movement through the soil profile, and the pipes minimized soil water contact time, which may be the worst situation for leaching of some pesticides in a clay soil.

Table 13. Applications of pesticides to Brimstone plots, Phase II.

Date	Trade name	Pesticide	Active Ingred. (g/ha)	Plots
(1988-89)				
08-02-89	Swipe 560EC	Ioxynil	280	4,6 10,14, 17,18,19,20
		Bromoxynil	280	
		Mecoprop	2240	
	New 5C Cycocel	Chlormequat Chloride	1612	
	Bayfidan	Triadimenol	125	
09-02-89	Cleansweep	Paraquat	300	5,7,9,16
		Diquat	300	
26-04-89	Cleansweep	Paraquat	5000	14 Only
		Diquat	500	
17-05-89	Mantrac	Manganese		4,6,10,17,18,19, 20,
22-5-89	Swipe 560EC	Ioxynil	224	5,7,9,16
		Bromoxynil	224	
		Mecoprop	1792	
	Bayfidan	Triadimenol	125	
04-07-89	Bayfidan	Triadimenol	125	5,7,9,16
19-07-89	Swipe 560EC	Mecoprop	1344	14 Only
		Ioxynil	168	
		Bromoxynil	168	
08-08-89	Roundup	Glyphosate	540	5,7,9,16
(1989-90)				
13-10-89	Grammoxone 100	Paraquat	800	14 Only
17-10-89	Avadex BW	Triallate	2160	All plots except 1,15
15-11-89	Decis	Deltamethrin	5	All Plots
	Arelon	Isoproturon	2488	
11-03-90	Cosmic FL	Carbendazim	160	All plots except 1,15
		Tridemorph	360	
		Maneb	1280	
	Musketeer	Isoproturon	1625	All plots except 1,15
		Ioxynil	325	
		Mecoprop	1170	
14-03-90	New 5C Cycocel	Chlormequat Chloride	1129	4,6,10,1418,19,20
09-04-90	Terpal	2-Chloroethyl-Phosphonic Acid	310	5,7,9,16,17
		Mepiquat-Chloride	610	
01-05-90	Mantrac	Manganese		
31-05-90	Tilt Turbo 375EC	Propiconazole	125	All plots except 1,15
(1990-91)				
		Tridemorph	250	
08-10-90	Grammoxone 100	Paraquat	300	6,7,9,10,14,17,19,20
	Arelon WDG	Isoproturon	2448	6,10,14,17,19,20
	Iso Cornox 57	Mecoprop	2394	6,10
16-10-90	Gesatop 500 FW	Simazine	1150	4,8,12,18
06-11-90	Decis	Deltamethrin	5	All Plots
16-01-91	Librel CMX	Iron	100	All Plots
		Copper	50	
		Manganese	100	

Table 13. Cont.

Date	Trade name	Pesticide	Active Ingred. (g/ha)	Plots
27-03-91	New 5C Cycocel	Chlormequat Chloride	1129	6,10,14,17,19,20
10-04-91	Musketeer	Isoproturon	1625	6,10,14,17,19,20
		Ioxynil	325	
		Mecoprop	1170	
	Sportak	Prochloraz	399	6,10,14,17,19,20
	Alpha	Carbendazim	150	
	Aventox SC	Simazine	216	5,7,9,16
		Triatezine	1509	
	Grammoxone 100	Paraquat	800	5,7,9,16
17-05-91	Decis	Deltamethrin	7.5	4,5,7,9,16,18
01-07-91	Bravocarb	Chlorothalonil	900	4,5,7,9,16,18
		Carbendazim	200	
10-07-91	Tilt Turbo 375EC	Propiconozole	125	6,10,14,19,20
		Tridemorph	250	
05-09-91	Grammoxone 100	Paraquat	800	1,15
(1991-92)				
09-10-91	Arelon WDG	Isoproturon	2448	All Plots
	Grammoxone 100	Paraquat	300	All Plots
	Iso Cornox	Mecoprop Salt	2394	
29-10-91	Iso Cornox 57	Mecoprop Salt	2394	Rest Of Plots
	Decis	Deltamethrin	5	All Plots
05-04-92	Musketeer	Isoproturon	625	All Plots
		Ioxinil Salt	325	
		Mecoprop Salt	1170	
	Sportak	Prochloraz	399	All Plots
	Alpha	Carbendazim	150	
29-04-92	Terpal	Mepiquat Chloride	610	All Plots
		2-Chloroethylphosph acid	310	
19-05-92	Tilt Turbo	Propiconazole	125	All Plots
		Tridemorph	285.7	
17-07-92	Roundup	Glyphosate	360	All Plots
	Ethokem	Polyethanoxy-alkyl amine		
(1992-93)				
05-09-92	Scythe	Paraquat	600	All Plots
19-03-93	Grammoxone 100	Paraquat	400	All Plots
	Agral	Dichloride Salt	360	All Plots
30-04-93	Starane2	Fluroxypyr	150	All Plots

e) Plots 10 and 20 (no-expander mole drains) grew continuous winter cereals, the burnt residues of which were incorporated by ploughing. As this type of mole channel was vulnerable to collapse in Phase I and offers slower movement of water than others, it may influence pesticide leaching by increasing the residence time in the soil.

An additional plot (14) was retained as an undrained control. This allowed the effect of increased flow in the surface (cultivated) layer on movement of pesticide residues to be measured. Table 13 gives the applications of pesticides to these plots in 1988-1991.

5.3 DATA COLLECTION

5.3.1 Water sampling

In the first year (1989/90) water samples were bulked from the small samples collected for nitrate analysis by the automatic vacuum water samplers (Fig. 5). This gave few data indicating variations within individual rainfall events, such as the initial response, the period near peak flow and the hydrograph recession. Monitoring was extended in the spring of 1990 and the second winter (1990/91) to give more intensive sampling over storm events. Two EPIC programmable samplers with flow-related trigger systems were added to the site facilities in autumn 1990, and a further five were installed in summer 1991 for work in the third winter. The programmable samplers delivered single samples of larger volume (1-2½ l) direct to darkened glass bottles through teflon tubing.

5.3.2 Analysis for pesticide residues

The work at Brimstone Farm in Phase II complements other UK research on leaching of pesticide residues. Those studied were the herbicides isoproturon, mecoprop and simazine, and the fungicides triadimenol, prochloraz and propiconazole, many of which have been found in surface water courses elsewhere.

Analyses were done by the MAFF CSL Pesticide Analysis Group. Water samples were stored in a cold room, the delay before extraction being < 14 days. One-litre samples were mixed with sodium chloride and hydrochloric acid, and pesticides were extracted with dichloromethane, which was then filtered through anhydrous sodium sulphate and evaporated to dryness under dry nitrogen. The residue of extracted pesticides was then dissolved in 1 ml methanol and divided into two 0.5 ml portions, which were stored at -18°C prior to analysis.

For determination of isoproturon, simazine, triadimenol, prochloraz and propiconazole the extract was used directly, but for determination of mecoprop a 0.5 ml portion was converted into a pentafluorotoluene derivative.

Concentrations of isoproturon and simazine were determined by reverse phase high performance liquid chromatography (hplc) using a photodiode array detector. Concentrations of fungicides were determined by gas chromatography (gc) using a nitrogen-phosphorus detector. The mecoprop derivative was determined by gas chromatography-mass spectrometry (gc-ms). The limits of detection were less than the EC maximum permitted concentration (0.1 μg/l) for a single pesticide in drinking water

(Anon. 1980), but greater than this for mecoprop. The identity of any pesticide found in drinking water by hplc using the photodiode array detector was confirmed by comparing ultraviolet spectra with those of known standards; those determined by gc were confirmed by gc-ms or by reanalysis using a column of different polarity.

5.4 WEATHER PATTERNS AND DRAINAGE

Because the weather was unusually dry from November 1988 to January 1989, the typical winter water table position (above the drains) was not reached until mid-March 1989 on some plots. Drainflow was intermittent in these conditions and was influenced by the different secondary drainage treatments. However, in February 1989 the rainfall was 150% of the long-term mean for the month; this resulted in considerable variation in drainflow, though with little difference in peak flow rates between the drainage treatments except that the no-expander mole drains gave lower peak flows and longer drainflow recessions.

Heavy rainfall early in the second winter (1989/90) produced drainflow on all plots by mid-December, but the water table again did not rise above the drains until mid-March. As in 1988/89, mid-winter responses were dominated by crack flow. Peak flows occurred approximately 2 hr after peak rainfall, but there was a gradual decrease in the peakiness of some hydrographs because of deterioration of the mole channels. The most responsive systems were the gravel-filled and large expander mole drains, which gave hydrograph peaks greater than those of the no-expander mole drains and closely spaced pipes.

By the third winter (1990/91) further deterioration of the no-expander mole drains resulted in slow runoff so that the closely spaced pipe system then became the most responsive (Fig. 16). However, the bare fallow may have increased the runoff from the plots with closely spaced pipes (7 and 9).

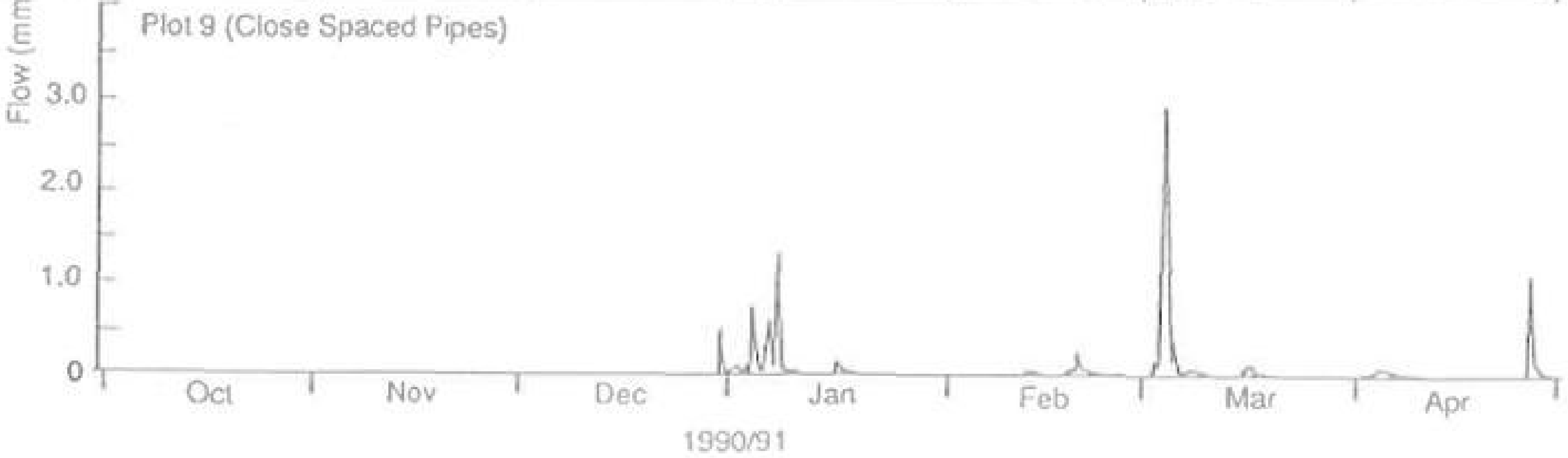


Fig. 16 Comparison of drainflow (mm/hr) between no-expander, large expander and close spaced drainage treatments, winter 1990/91. Arrows show major rainfall events

5.4.1 Deterioration of secondary drainage treatments

In March 1989 all the mole drains had decreased in cross sectional area by about 40%, which was a slightly greater first year deterioration than was seen in Phase I. By July 1990 they were partly infilled with topsoil as a result of deep cracking during the dry summers of 1989 and 1990. However, the gravel-filled channels and closely spaced pipes were still in good condition.

5.5 RESULTS

5.5.1 Winter 1989/90

Approximately 120 samples over this winter drainage season were analysed for the three fungicides and for isoproturon but not for mecoprop because of initial difficulties in detecting this herbicide. None of the samples contained any of the fungicides in amounts greater than the detection limit. Isoproturon occurred in concentrations > 50 μg/l in the first drainflows after autumn application, and then declined to give typical winter concentrations of about 3 μg/l in most treatments. After several days of rain in mid-January (total 15 mm) a further 2 mm event increased peak drainflow to 0.2 mm/hr and increased isoproturon concentrations to 2-7 μg/l.

After spring applications of herbicide, much greater isoproturon concentrations up to 600 μg/l occurred in a similar small drainflow event following 13 mm rain (Table 14).

Table 14. Concentrations of isoproturon (μg/l), 1989/90 from slow, medium and fast runoff responses through the drainage system.

Drainage treatment	Response type	Autumn flush	January event	Residual loss	Spring event
Large expander/ annual mole drainage	(Fast)	10-35	2-7	3	550
Close spaced pipes	(Medium)	35-50	4-7	3-6	600
No-expander mole drainage	(Slow)	3	3	<0.1	550

Winter loadings of isoproturon losses in runoff, obtained by integrating flow totals for each bulk sampling period with the concentrations for that period, were equivalent to 11-22 g/ha, or 0.5-1.0% of the herbicide applied in autumn. The largest loading was from the closely spaced pipe treatment, suggesting that the limited soil-water contact time associated with this treatment increases losses.

5.5.2 Winter 1990/91

The first drainflow event in this winter occurred between December 25 and January 10, and resulted from rapid water movement through macropores, as water tables did not rise above mole drain level until March 1991. Isoproturon concentrations were high at the start of drainage, but declined rapidly over a few days. Isoproturon could not be detected in the soil below a depth of 20 cm, indicating the role of macropore flow in the isoproturon reaching the mole drains at 55 cm depth. In Plot 9 where the last applications had been in the previous winter, concentrations were almost as high as on plots where isoproturon was applied in autumn. Neither mecoprop nor the target fungicides were above the detection limit in this period.

Comparison of drainflow hydrographs and isoproturon chemographs often showed a dilution effect after the first leaching event; the concentrations on all plots decreased over periods of rapid water flow through the macropores, but increased in the hydrograph recession periods when more of the flow was through smaller soil pores. However, no dilution effect was seen in the single chemograph obtained for simazine. The dilution effect for isoproturon is similar to than for nitrate at Brimstone Farm (Fig. 17). This suggests that the two are leached in similar ways when macropore flow dominates the drainflow, so that models for nitrate movement may be applicable to leaching of isoproturon.

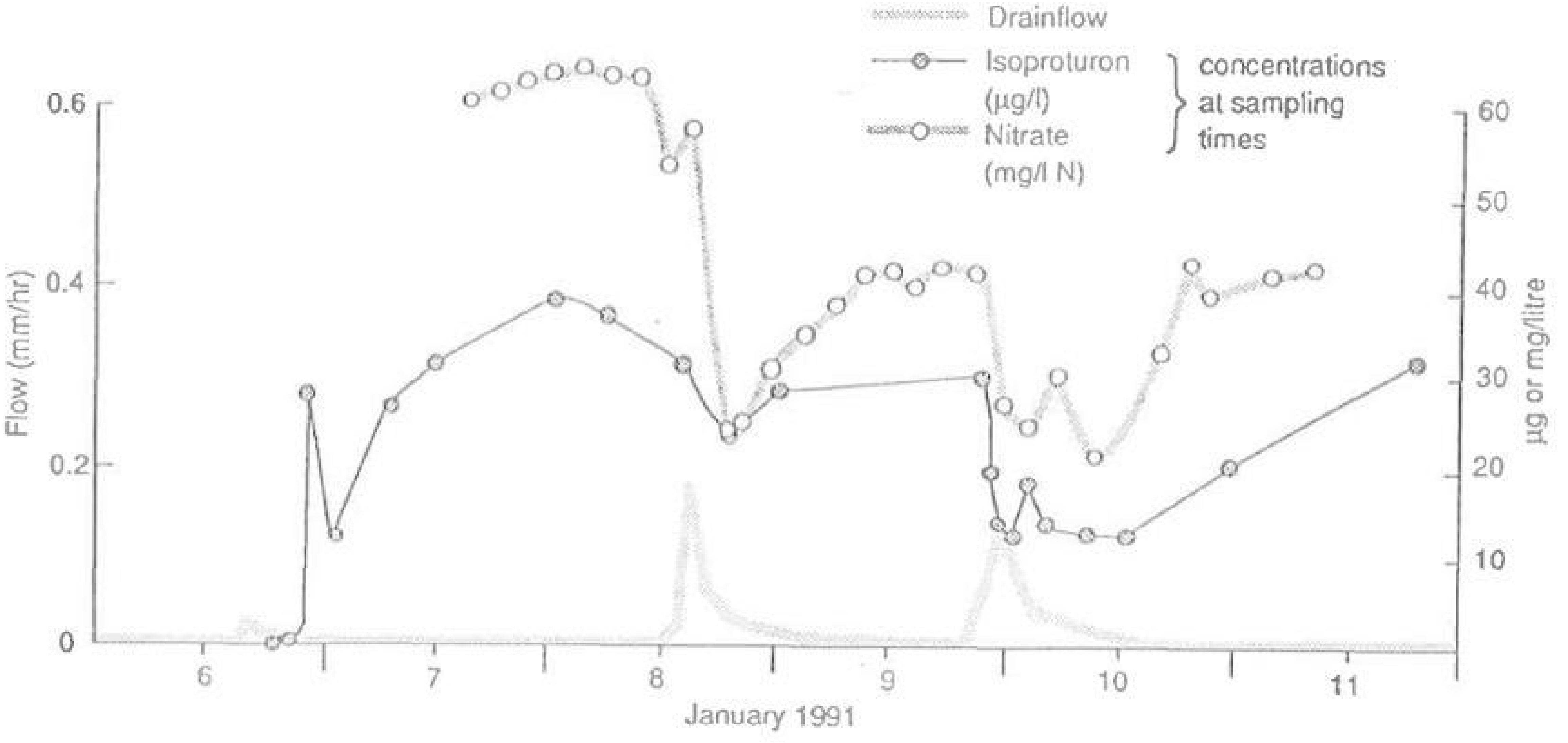


Fig.17. Drainflow (mm/hr), losses of isoproturon (μg/l) and nitrate (mg/l), early January 1991, Plot 10 (no-expander mole drainage treatment).

Little surface layer flow occurred in Phase II, so few samples were analysed. However, results for isoproturon losses show that very high concentrations can occur. Work by Water Research Centre, Medmenham, on samples of surface layer flow from the undrained Plot 14 collected over the period between application on November 15, 1989 and cessation of flow on March 1, 1990, indicated a total loading of about 13% of the amount applied.

5.6 DISCUSSION OF RESULTS

The first two years' results of Phase II showed that the leaching losses of some pesticides in clay soils can be modified by the type of secondary drainage system used. Winter isoproturon loadings from the closely spaced pipes treatment, which decreases soil-water contact time, were nearly twice those of other drainage types, and rapid surface layer flow or macropore water movement also seemed to increase isoproturon leaching.

The decreased autumn rainfall in 1989 and 1990 resulted in delays of nearly two months between the autumn application of herbicides and the first leaching losses in drainflow. This probably accounts for the absence of mecoprop in the drainflow; although this is more mobile than isoproturon on the basis of its octanol-water partition coefficient (Worthing and Hance 1991), confirmed by sorption measurements, it is degraded more rapidly. Isoproturon persists not only through this two month period but also from year to year in sufficient amounts to produce runoff containing many times the EC drinking water limit. The measured concentrations in runoff do not take into account the opportunities for further degradation in the transport of pesticides to surface waters or the impact of dilution from other water sources containing less pesticide residues. However, the clay plot lysimeters of Brimstone Farm do allow the effects of soil structure and different secondary drainage treatments on pesticide leaching to be evaluated in a way that is realistic to the commercial farmer. They also provide data to develop and evaluate predictive models of pesticide leaching based upon soil physical and physico-chemical properties.

6. PHOSPHORUS LEACHING IN PHASE II

6.1 BACKGROUND

Early work on the composition of drainage waters from arable soils at Rothamsted and elsewhere had shown that they contain very little phosphate, because most of the P applied in fertilizer but not taken up by crops is effectively fixed by most soils. For many years the eutrophication of surface waters was consequently attributed to P from sewage outfalls, which often contained the residues of P-rich detergents. However, minimizing P inputs from sewage in the late 1980s and early 1990s did not eliminate the problem of eutrophication, and the possibility remains that low levels of diffuse agricultural P contamination of surface waters is at least partly responsible for the continuing increase in eutrophication.

Measurements of soluble (molybdate reactive) and total (perchloric-nitric acid extractable) P in water samples from the mole and pipe drain system and cultivated layer flow of Brimstone plots were begun in February 1990. Initially losses in selected flow events were monitored, but since November 1993 soluble P has been determined on all water samples simultaneously with nitrate, nitrite and chloride using a SHENA multichannel flow injection analyser.

6.2. RESULTS

6.2.1 Drainflow

Amounts of soluble P in drainflow are fairly constant (0.03-0.15 mg P/l), and like nitrate often show a dilution effect with increasing flow rate. In contrast, total P is more variable (0.06-1.31 mg/l), the concentration depending strongly on flow rate, presumably because much of it is in particulate form and water samples collected during storm conditions are often turbid.

Losses in the cultivated layer flow (0.05-0.72 mg soluble P/l; 0.07-3.13 mg total P/l) are usually greater than in drainflow.

Concentrations of soluble P and total P in both drainflow and cultivated layer flow show few differences between runoff events at different times after P fertilizer applications. For example, the concentrations in drainflow in November 1991, one month after an application of 56 kg P/ha, were 0.05-0.10 mg soluble P/l and 0.07-0.23 mg total P/l, whereas the ranges for winter 1993/94, more than 2 years after this fertilizer application, were 0.03-0.15 mg soluble P/l and 0.06-0.75 mg total P/l. This suggests that the losses of P are controlled by processes in the soil not directly related to fertilizer applications. Nevertheless they are usually greater than the minimum concentrations (0.02-0.035 mg P/l) thought to cause eutrophication (OECD 1982).

7. PHASE III

7.1 BACKGROUND

The results for pesticide and nitrate leaching in earlier phases of the experiment suggested that both might be influenced beneficially by restricting drainflow. By preventing rapid flow through the mole and pipe drainage system, degradation and sorption of pesticides should be increased by prolonged contact with the soil. In addition, raising the water table in the plot should cause the clay soil to swell, thereby closing the desiccation cracks and other macropores responsible for rapid transfer of pesticides to the drains. It should also decrease losses of nitrate by encouraging denitrification and possibly by limiting the rate of mineralization of organic matter. Decreasing the rate of water flow through macropores and mole drains should also limit losses of phosphorus in particulate material.

7.1.2 Phase III objectives

7.1.2.1 To investigate the effects of temporary restriction of drainflow in autumn on leaching of pesticides, nitrate, nitrite and phosphorus.

7.1.2.2 To assess the effect of decreased application rates on leaching and degradation of pesticide residues.

7.1.2.3 To study the effect of late summer cover crops, sown before harvest of the preceding main crop, on turnover of organic matter and leaching of nitrate.

7.1.2.4 To assess the effect of a reduced P fertilizer rate on P losses.

7.1.2.5 To study the effects of a finer surface tilth and subsoil (30-45 cm depth) loosening on macropore water movement and leaching of pesticides, nitrate and phosphorus.

7.1.2.6 To utilize the various databases in parallel collaborative modelling exercises, to develop models which accurately predict the losses of nutrients and pesticides from cracking clay soils.

7.2 SITE CHANGES FOR PHASE III

In winter 1992/93 rotatable U-bends (Fig. 18) were installed in the pipework leading from the main collector drain to the weir box and flow recorder on twelve of the drained plots. The number of programmable EPIC water samplers was increased to 17 at the same time, and Plots 5, 6, 10, 19 and 20 were re-moled to maintain effective drainage systems. Plot 14 remained undrained to provide a control linked to the previous phases of the experiment.

The EPIC samplers were linked to an upgraded data logging and telemetry system, allowing flow proportional water sampling, which takes samples more frequently as flow

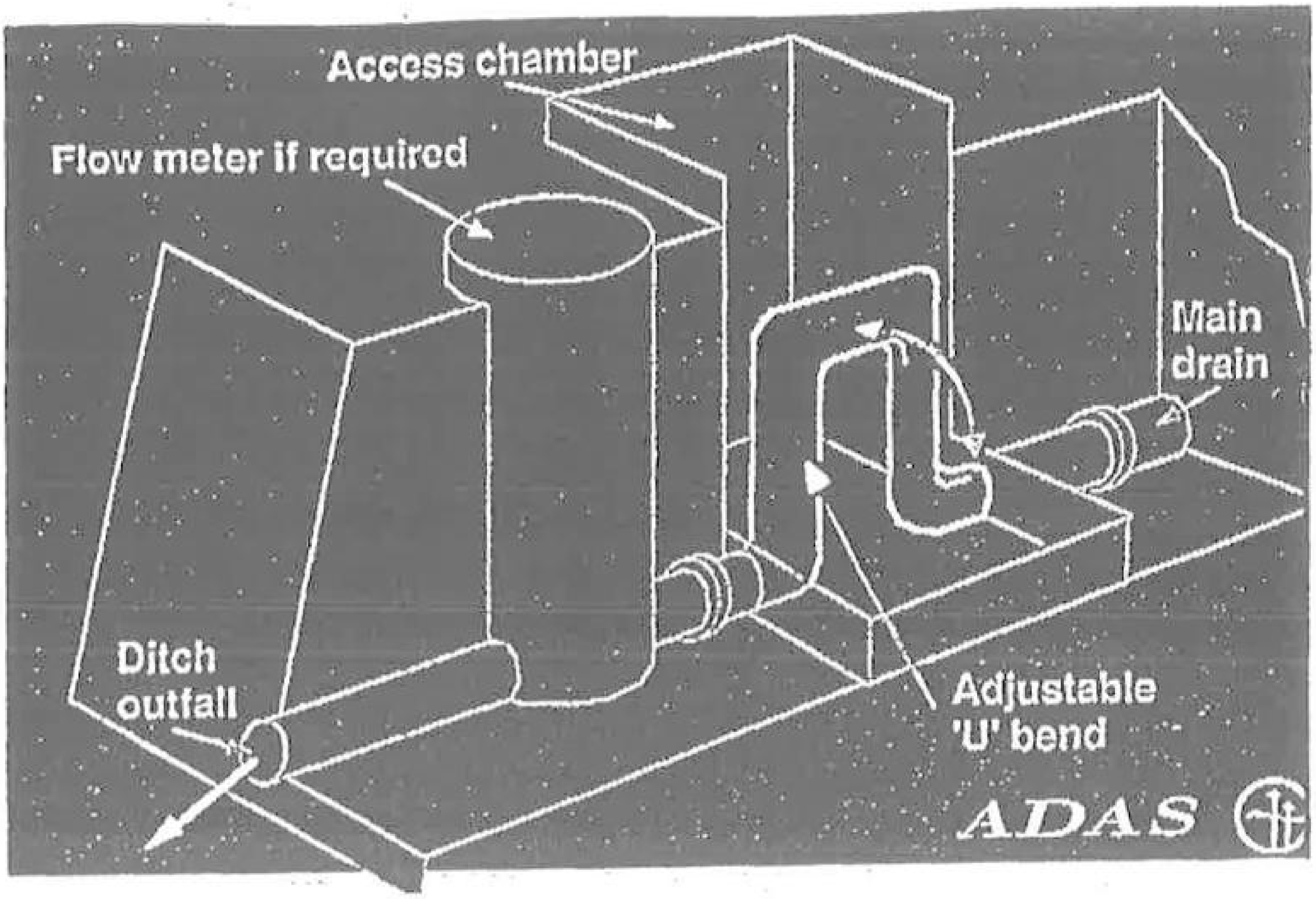


Fig. 18A. Drainage valve installation in upright position - drainage restricted.

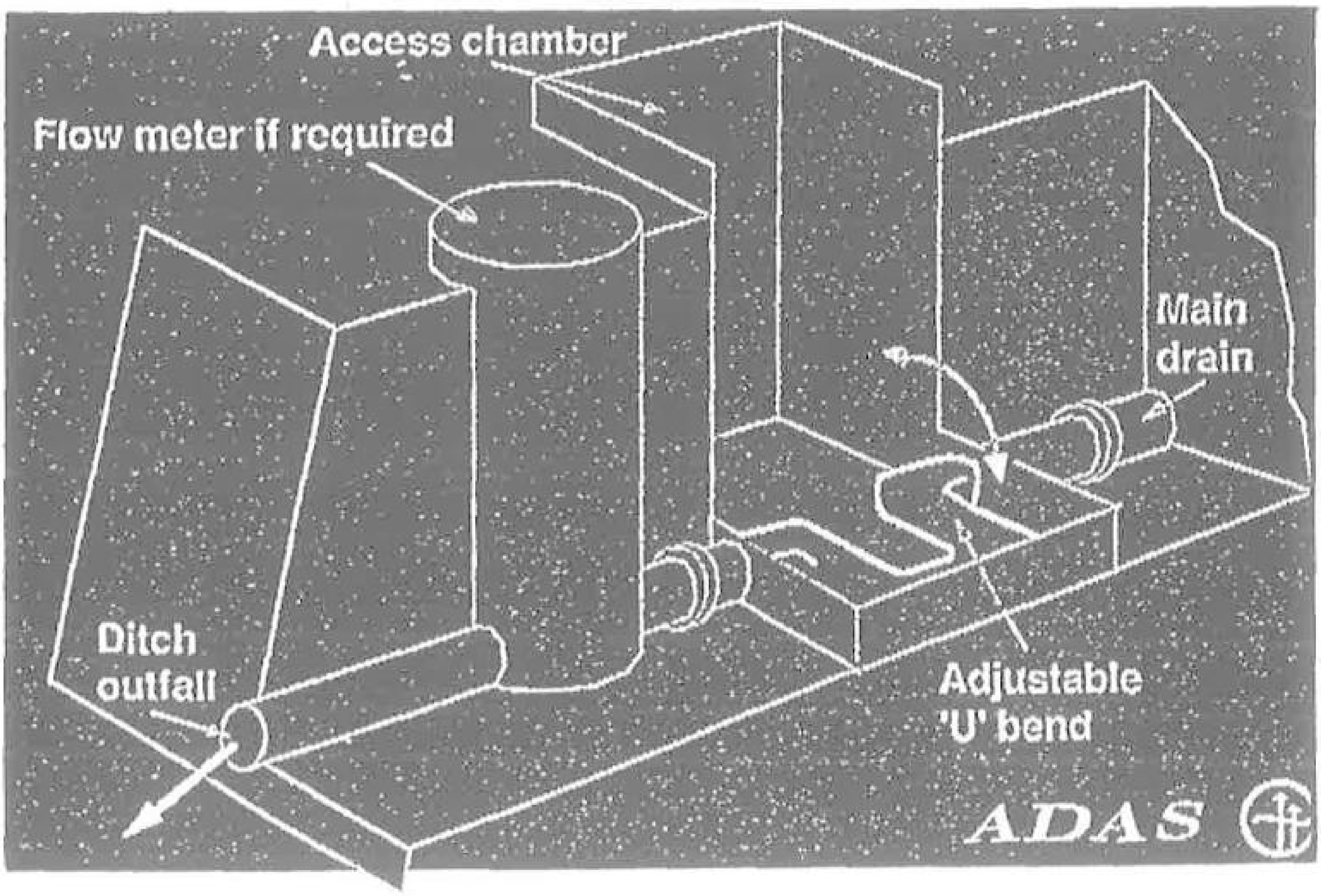


Fig. 18B. Drainage valve in lowered position - free drainage.

increases. Sample size is 1 litre, and the programme provides for an automatic flushing routine before sampling. A flagging system is used to initiate sampling remotely from ADAS Cambridge at the start of major autumn/winter flow events. Alternatively daily sampling can be initiated remotely until 16 bottles are filled out of the 24 available on each EPIC; thereafter samples are taken every 48 hr. A manual override is also available, for example in the event of a system failure.

7.3 SITE UNIFORMITY

The final crop of Phase II (unfertilized spring oats following a winter fallow) was chosen to assist removal of the variable amounts of pesticide and nitrate in the soil following the different treatments of Phase II. Water samples for nitrate analysis were taken throughout the winter of 1992/93 and samples for pesticide analysis in late March and early April 1993.

The peak nitrate concentrations for runoff events in the autumn and early winter were much greater on some plots than on others (e.g. 30-120 mg NO_3-N/l in September and October). However, the variation decreased over the winter, and in a runoff event in early April the range was only 26-39 mg/l; the N loadings for April for the different plots ranged from 0.07 to 1.63 kg N/ha, whereas those for the early winter (August - January incl.) were much more variable (1.84-14.55 kg N/ha). The pesticide concentrations in March/April 1993 were also uniformly small; isoproturon (last applied April 1992) ranged from < 0.1 to 0.3 μg/l, and pendimethalin (not applied in the previous 5 years (Table 13), and possibly derived by spray drift from adjacent fields) ranged from < 0.1 to 0.4 μg/l. These data suggested that the site had almost returned to a uniform condition by spring 1993. Nevertheless, the growth of spring oats in 1993 was very variable, though this would have further decreased the variability of soil mineral N.

7.4 CROPPING IN PHASE III

Winter wheat has been grown in every year of Phase III, except that winter oats were grown as a break crop in 1995/96 to avoid disease problems. This provided an opportunity to test a wider range of pesticides.

7.5 EFFECTS OF DRAINFLOW RESTRICTORS

7.5.1 Water table

Brief tests of the U-bend restrictors or valves in January 1993 showed that they are effective at ponding water in the plots, though there was considerable variation between plots in depth to the raised water table. A further test between April 2 and 22, 1993 again showed some variation in depth to the water table and in persistence of the raised water table level after a dry period of weather began in mid-April. The most problematic plots were those known to be affected by a lystric periglacial slip surface in the deep subsoil, which probably allowed loss of water beneath the peripheral polythene barriers and gravel-filled trenches containing the plot drains.

7.5.2 Pesticide losses

In the winter of 1993/94 the restrictors were raised on November 3 on four plots: 1 (gravel-filled moles), 6 and 10 (conventional moles) and 7 (close-spaced perforated plastic pipes). The remaining 8 plots fitted with U-bends had unrestricted drainflow, and were divided between full-rate (label instructions) applications of the pesticides isoproturon and pendimethalin (Plots 15 - gravel-filled moles, 5 and 20 - conventional moles and 9 - plastic pipes) and half rate applications (Plots 4, 16, 18 and 19 - all conventional moles). The pesticides were applied on November 2.

The first major flow event on November 13/14 produced flow from all plots, though this was delayed on the four plots with restricted drainflow by a maximum of 4 hr compared with the plots with unrestricted drainflow. Subsequent rainfall and flow events occurred on December 7-8, December 18-19 and January 5.

The peak concentrations of isoproturon in November 1993 were typically 200-500 μg/l, several times those found in drainflow in Phase II. Although drainflow was held up for no more than 4 hr in the first event on the plots with restricted drainflow, the isoproturon (full rate) concentrations in this event were decreased from a mean of 465 μg/l on plots without restriction to a mean of 190 μg/l on plots with restriction. In subsequent drainflow events the mean concentrations of isoproturon decreased progressively to 130 μg/l (unrestricted) and 115 μg/l (restricted). Over the four main events in 1993/94 total losses of isoproturon were approximately 20 g from unrestricted plots, 15 g from restricted plots (4% and 3% of the amounts applied, respectively).

Application of isoproturon at half rate (unrestricted drainflow) decreased the concentrations for the same flow events to 140-30 μg/l, i.e. there was a greater than 50% decrease in the drainflow concentrations. In the cultivated layer flow of Plot 14 the peak concentration of isoproturon was nearly four times greater than in the drainflow (unrestricted) in the first event, but it decreased very rapidly to < 100 μm/l in subsequent events.

Concentrations of pendimethalin were much less than for isoproturon under all conditions. Losses from the half rate treatment were especially small. Laboratory studies showed that pendimethalin is quite stable in the Brimstone soil; more than half of an application can be recovered after 32 weeks for incubations at 15°C or less. However, the sorption coefficient (K_d) for pendimethalin (87.7 l/kg) in Brimstone topsoil is much greater than that of isoproturon (2.9 l/kg), and this may account for the much lower concentrations in the drainwaters.

In the winter of 1994/95 the concentrations and loadings of isoproturon were much less than in 1993/94, and were similar to those measured in Phase II. Peak concentrations in the first drainflows (in early December) were 53 μg/l on unrestricted plots and 36 μg/l with restricted drainage. Restriction decreased the winter loading by 33%, from 1.2 g to 0.8 g.

In 1995/96, when oats were grown, isoproturon was applied at 10% rate to minimize potential damage to the crop. Drainflow began much later than in 1994/95, and isoproturon was consistently detected in only the first drainflow event (19-23 December). Peak concentrations adjusted to account for the reduced application rate were 100 μg/l on unrestricted plots, 11 μg/l on restricted, and loadings were 0.04 g (unrestricted) and 0.03 g (restricted), equivalent to < 0.1% of applied.

Over the three winters of Phase III the losses of isoproturon (g/ha), standardised to unit volume of drainflow (100 mm) to eliminate the effects of variable drainflow between plots and seasons, were decreased by 19% by drainflow restriction. In 1994/95 and 1995/96 triasulfuron was applied as the second target pesticide instead of pendimethalin, and the losses of these two over the three winters (again expressed per unit volume of drainflow) were 20% less with restricted drainflow than with unrestricted.

7.5.3 Nitrate

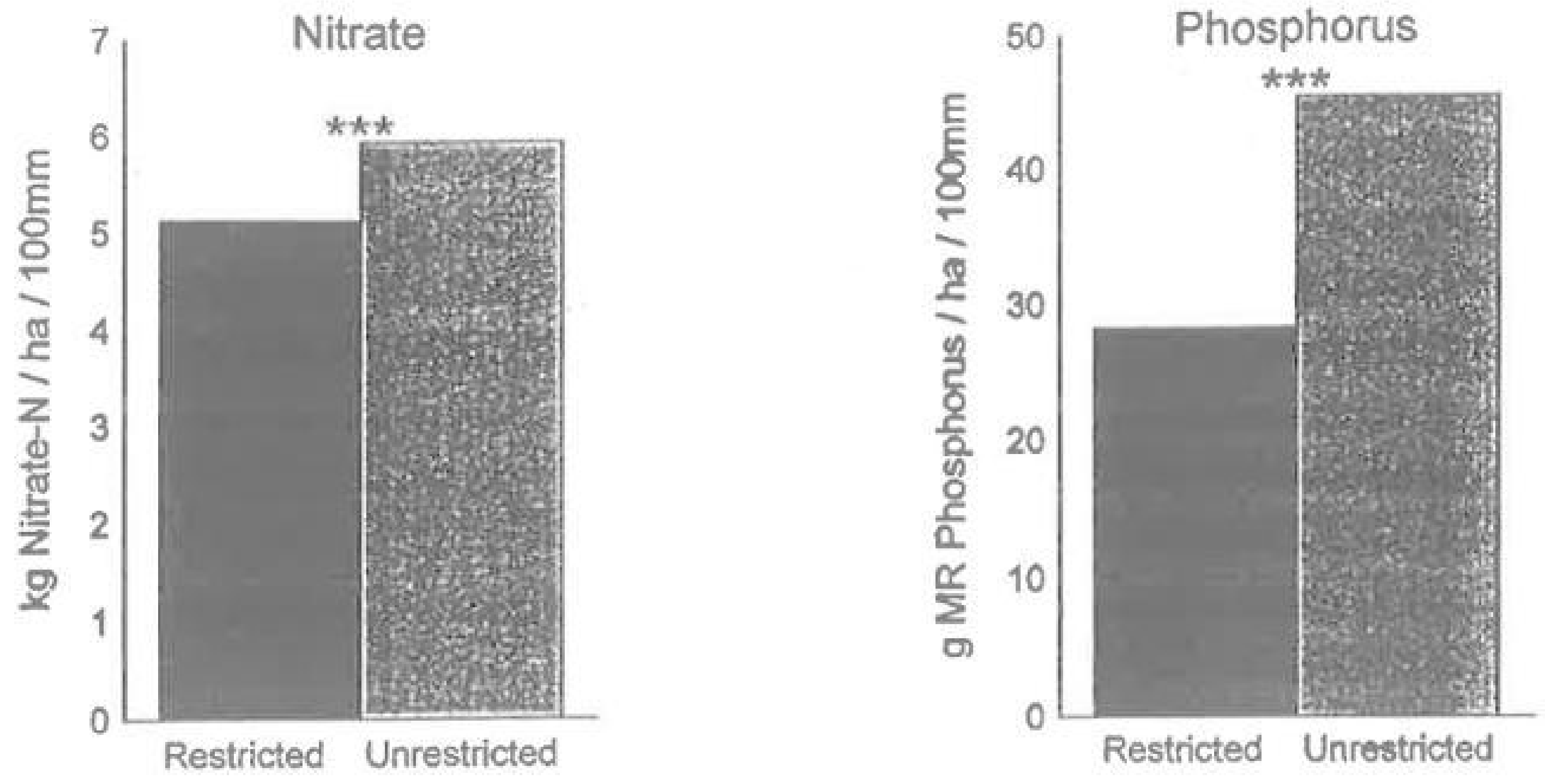
In the three winters of Phase III drainflow restriction has decreased mean annual nitrate concentrations by 1-21%, mean nitrate loadings by 7-69% and losses per unit volume of drainflow by 11-27%. The smallest decreases were in 1995/96 when the rainfall was close to the long term mean but the soil was often drier than usual following the very dry summer of 1995 and several dry periods during the winter. As drainflow restriction probably decreases nitrate by increasing the period of winter waterlogging and thus enhancing denitrification, the weak effect in 1995/96 can be attributed to the unusually dry soil conditions. Evidence for increased denitrification with restricted drainage is provided by increases with restriction in nitrite concentrations (26-54%), loadings (44-143%) and losses per unit volume of drainflow (9%). However the actual as opposed to percentage increases in nitrite loadings (usually in the range 10-22 g/ha/yr) are much too small to account for the actual decreases in nitrate loadings (5-11 kg/ha/yr).

Figure 19 shows the overall effect of drainflow restriction on nitrate loadings per unit volume of drainflow for the three year period 1993/94 to 1995/96. The decrease attributable to restriction is 14%. Figure 20 shows that drainflow restriction has not affected crop yields in any year of Phase III.

7.5.4 Phosphorus

Phosphorus losses in Phase III are determined as either soluble (molybdate reactive) P or total P (i.e. including particulate P). MRP has been measured in all three years of Phase III, but to date TP has been determined only in samples taken in 1994/95. Both are assessed in drainflow and cultivated layer flow, but at present MRP and TP data are available only for 1994/95.

Over the three winters of Phase III (1993/94 to 1995/96) drainflow restriction has decreased mean annual MRP concentrations by 25-73%, annual loads of MRP by 25-50% and annual losses per unit volume of drainflow by 24-52%. Mean concentrations have ranged from 0.003 to 0.158 mg P/l, and annual loads from 0.004 to 0.26 kg/ha/yr. The lowest values were in the winter of 1995/96 when the soil was unusually dry for much of the season. Figure 19 shows the effect of drainflow restriction on MRP losses per unit volume of drainflow averaged over the three years of Phase III.



Significant difference *(P<0.05) **(P<0.01) ***(P<0.001)

Fig. 19. Effect of drainflow restriction on losses of nitrate and soluble (molybdate reactive) phosphorus at Brimstone Farm 1993/94 - 1995/96.

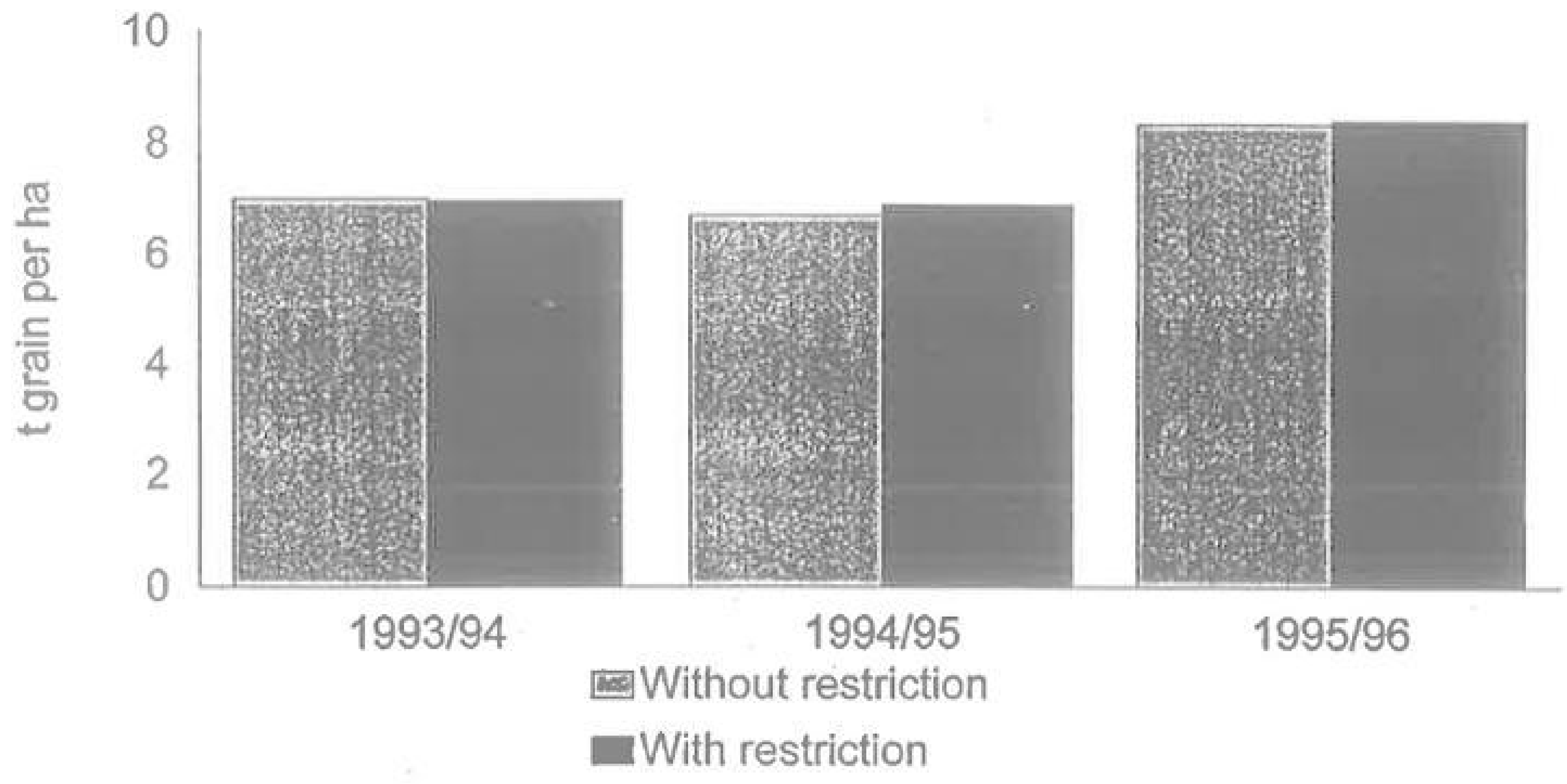


Fig. 20. Effect of drainflow restriction on crop yields at Brimstone Farm, 1993/94 - 1995/96.

In 1994/95 drainflow restriction decreased mean annual TP concentration by 26% (from 0.382 to 0.284 mg P/l), annual TP loading by 26% (from 0.503 to 0.370 kg P/ha) and TP loss per unit volume of drainflow by 29%. In the same year the concentrations of MRP were increased in cultivated layer flow by 63% and the loading of MRP was increased by 323%. Similarly the mean concentration of TP in cultivated layer flow was increased by 153% (from 0.980 to 2.483 mg P/l) and the TP loading was increased by 880% (from 0.048 to 0.470 kg P/ha. The increased loading was largely attributable to increased cultivated layer flow on the plots with restricted drainage, but even after allowing for this by standardising to unit volume of flow, the TP loss was 124% greater with drainage restriction. So, although drainage restriction decreases MRP and TP losses in drainflow, it can increase the volume of cultivated layer flow and also increase the concentrations of MRP and TP in it, so that loadings of MRP and TP in cultivated layer flow are greatly increased.

7.5.5 Effect of P fertilizer rate on P losses

Because of wet soil conditions, the first application of P fertilizer (at rates equivalent to 32 and 16 kg P/ha) in Phase III was not made until early December 1994, shortly before the first winter drainflow event. For approximately four weeks the concentrations of MRP in drainflow were greatly increased, but by early January they had returned to the levels measured during other periods. The effect was much greater at the higher P application rate, with the result that over the winter of 1994/95 as a whole the mean annual MRP concentration in drainflow was 290% greater at the higher application rate, and the annual MRP loading was 73% greater. However there was almost no effect on TP, the concentrations of which were slightly less in drainflow from the plots given the higher P fertilizer rate, and the loadings were increased by only 3%. However, drainage restriction was quite effective in decreasing the MRP concentration in drainflow from the high P plots; it decreased the mean annual MRP concentration by 82% on the high P plots, but by only 16% on the low P plots. The results for 1994/95 show that P fertilizer applications should be made in spring, summer or autumn to a dry soil, and that applications in excess of crop requirements do increase P losses to surface waters.

In 1995 the P fertilizer was applied at the same two rates in late summer between harvest and ploughing. It had no effect on concentrations in the first drainflows in late December, but over the 1995/96 winter as a whole MRP concentrations in drainflow were 70% greater and MRP loadings 73% greater at the higher P rate.

7.6 LATE SUMMER COVER CROPS

Forage rape was broadcast on four plots on 15 August 1995 after harvest of winter wheat and shallow power harrowing to prevent the seed falling down the wide desiccation cracks that had formed during the dry summer. Germination and growth were very slow in the dry conditions, and together with volunteer wheat plants gave total dry weights on September 27 (just before autumn ploughing) of only 105-157 kg/ha. The amounts of N taken up were very small (4-6 kg/ha). In the winter of 1995/96 the mean concentration of nitrate in drainwater from the plots that had grown the cover crop was 4% less than where no cover crop was sown; the daily loading of nitrate was 2% greater; the loss per unit volume of drainflow was 11% more. The yield of oats at harvest 1996 was 10% greater where cover crops had been grown and the N uptake over the season was 11% greater. These results suggest that summer cover crops have little or no effect on nitrate leaching in the subsequent winter, but may increase the yield of subsequent winter crops slightly. However, a second summer cover crop (again forage rape) was planted in 1996 and grew better; its effects are still being assessed.

7.7 FINE TILTH

This was tested in 1994/95, but was difficult to create because the soil was too wet, and numerous passes with a power harrow were required. Its effect on nitrate losses was small; mean annual nitrate concentration was decreased by 15%, loading by 23% and loading per unit volume of drainflow by 8%. The effect on nitrite losses was even less.

However, fine tilth decreased MRP concentrations by 74%, MRP loading by 24% and MRP loss per unit volume of drainflow by 29%, presumably because the slower water flow allowed more time for sorption of soluble P on soil mineral particles. In contrast, TP was increased; mean concentration was increased by 37%, loading by 81% and loss per unit volume of drainflow by 57%. The increase in TP can probably be attributed to the large energy input in repeated harrowing, which would have dispersed fine soil particles that were subsequently transported to the mole drains during periods of heavy rain and more rapid, turbulent water flow through the soil profile. Probably for the same reason, the loss of TP in cultivated layer flow was also increased by the fine tilth treatment: mean annual TP concentration was increased by 330%, annual TP loading by 1044% and loss per unit volume of drainflow by 289%.

7.8 SUBSOIL LOOSENING

This was tested on three plots (8, 11 and 12) in 1995/96. It increased mean annual concentration of nitrate by 56%, loading by 44% and loss per unit volume of drainflow by 50%. It also increased nitrite by 42%, 38% and 71% for the same three factors. The slower water movement through the profile to the mole drains on plots with loosened subsoil probably allowed greater uptake of the nitrate formed during the autumn and winter by mineralisation of organic matter, and may also have created more anaerobic zones for production of nitrite by denitrification, though this was insufficient to compensate for the increased nitrate.

7.9 WIDELY SPACED MOLE DRAINS

A treatment with widely spaced (4 m) mole drains was tested on four plots (4, 16, 18 and 19) in 1995/96 as a simple alternative method of restricting drainflow. However, it had little effect on nitrate losses in drainflow, yet increased nitrite by 45% (mean annual concentration), 38% (loading) and 71% (loss per unit volume of drainflow), probably by slightly increasing sites for denitrification. It also increased MRP losses by 171% (concentration), 43% (loading) and 53% (loss per unit volume of drainflow), especially on plots given the higher rate of P fertilizer (240% concentration, 52% loading, 98% loss per unit volume of drainflow). Therefore it does not seem to be a useful technique for reducing nutrient losses.

7.10 ABSORBENT MATERIALS IN MOLE DRAINS

A carbonaceous material (Jimsorb), which sorbs pesticides more effectively than the Brimstone subsoil, was tested in selected mole drains of two pilot plots in the winter of 1995/96. It proved successful in removing almost all the pesticides from drainwater, but increased the mean annual concentration of nitrate by 40%, the loading of nitrate by 35% and the loss of nitrate per unit volume of drainflow by 64%. The increased nitrate losses could have resulted from partial mineralization of the Jimsorb or from increased mineralization of soil organic matter through the greater disturbance of the soil during insertion of the Jimsorb into the mole drain channels.

Although the Jimsorb was softened slightly by immersion in the mole channels over winter, it recovered its hardness and structure in the summer of 1996 and is being retested in 1996/97. Likewise, an ironstone gravel is being tested in 1996/97 for sorption of soluble P from the drains.

7.11 DISCUSSION OF PHASE III RESULTS

Of the various strategies for limiting pesticide and nutrient losses from the Brimstone soil tested in Phase III, the most consistently successful has been drainflow restriction by the use of rotatable u-bends in the collector drains. By raising the watertable in the plot and increasing contact time with the subsoil, this has had a beneficial effect on nitrate, MRP, TP and pesticide losses without adversely affecting crop growth and yield. It has increased denitrification and this is partly reflected in the increased amounts of nitrite in drainage water, though concentrations of nitrite are rarely enough to cause problems with fish stocks in surface waters. The extent to which enhanced denitrification is also increasing emissions of nitrous oxide (a greenhouse gas) to the atmosphere is currently being addressed by a new programme monitoring gaseous emissions from selected Brimstone plots, which began in 1996. A further adverse effect is the increase in cultivated layer flow with drainage restriction and the large increases in MRP and TP losses by this route, though these are usually less in absolute terms than the decreased MRP and TP losses in drainflow. Nevertheless, the enhanced movement of water and pollutants on or just below the surface in winter is a matter of concern, and will be addressed in future work at Brimstone.

The contrasting influence of the natural carbonaceous material Jimsorb on pesticide and nitrate losses, together with the above considerations relating to drainflow restriction, emphasize the need for an holistic approach to diffuse pollution of surface waters by agriculture. Treatments that decrease one pollutant may increase another in the water or cause greater pollution of the atmosphere. The correct balance for sustainable agriculture can only be achieved by carefully integrated studies on a fully instrumented site such as Brimstone Farm.

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