Environmental RTDI Programme 2000–2006

Eutrophication from Agricultural Sources: The Impact of the Grazing Animal on Phosphorus, Nitrogen, Potassium and Suspended Solids Loss from Grazed Pastures – Field-Plot Study

(2000-LS-2.1.2-M2)

Final Report

Prepared for the Environmental Protection Agency

by

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DISCLAIMER

WATER QUALITY

The Water Quality Section of the Environmental RTDI programme addresses the need for research in Ireland to inform policy-makers and other stakeholders on a range of questions in this area. The reports in this series are intended as contributions to the necessary debate on water quality and the environment.

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Preface: Overview of LS-2 Projects – Eutrophication from Agricultural Sources

The objective of this large-scale integrated research project, commissioned in 2000, was to supply scientific data to underpin appropriate actions or measures that might be used in the implementation of national policy for reducing nutrient losses to waters from agricultural sources. The research, including desk, laboratory, field plot, farm and catchment studies, was conducted by teams in Teagasc, the National Universities of Dublin, Cork and Galway, Trinity College Dublin, University of Limerick and the University of Ulster at Coleraine.

The project was divided into three main sub-projects (Figure 1.1):

- ***LS-2.1: Pathways of Nutrient Loss to Water with Emphasis on Phosphorus Losses***, which aimed at quantifying and ranking the magnitude of phosphorus (P) loss from soil, grazed pastures and the application of slurry and fertiliser so as to identify effective mitigation strategies.
- ***LS-2.2: Models and Risk Assessment Schemes for Predicting Phosphorus Loss to Water***, which aimed at developing three modelling approaches that explored the sources of P and the hydrology that transports it from land to water.
- ***LS-2.3: Effects of Agricultural Practices on Nitrate Leaching***, which aimed at measuring nitrate leaching from an intensively managed dairy farm on a soil type typical of a nitrate vulnerable zone.

The main objectives of the project LS-2.1.2: Eutrophication from Agricultural Sources – Grazed Pastures were to provide an assessment of grazing on P losses under Irish conditions. This report synthesises the results and outputs from the project: LS-2.1.2 – Part A, which aimed at assessing losses of P from grassland under normally good grazing practice. Two separate sections, LS-2.1.2 – Part B and LS-2.1.2 – Part C, dealt respectively with small-plot studies and P balances and fluxes.

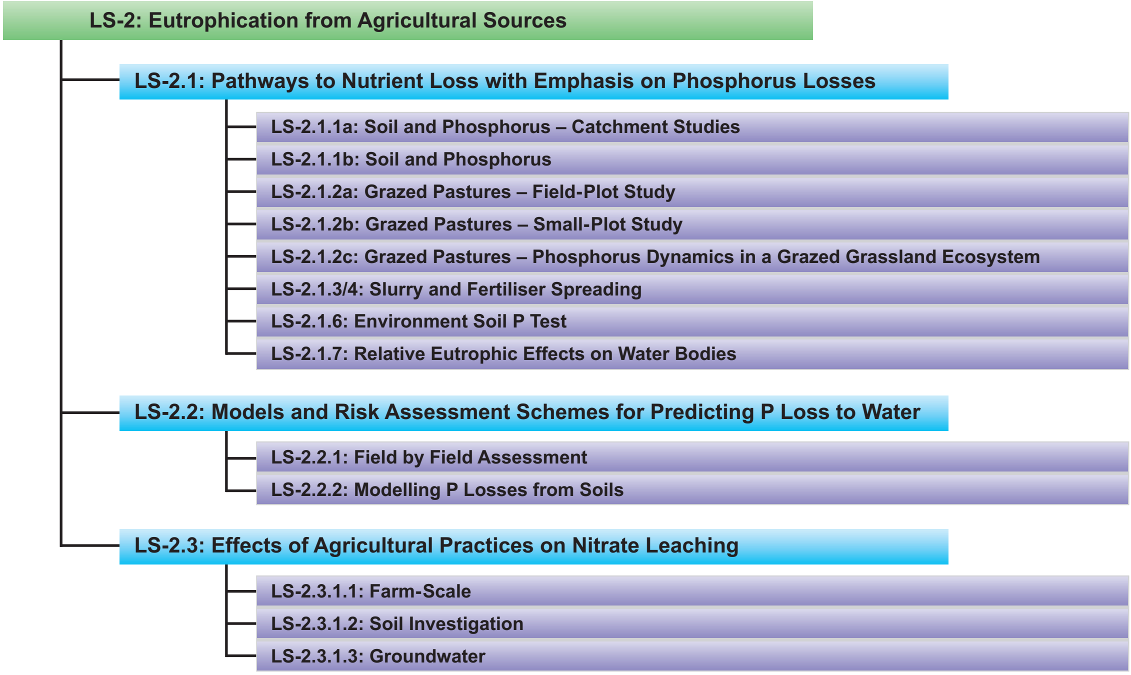

Figure 1: Overview of LS-2 projects

Integrated synthesis reports and individual reports from each subproject are available for download on the EPA website: www.epa.ie/downloads/pubs/research/water/.

Executive Summary

Ninety per cent of the 4.2 million ha of Irish farmland is grassland. In the past, phosphorus (P) deficiency limited grassland production in Ireland, and this was corrected by chemical fertiliser use in the 1960s and 1970s. This led to increased intensification of grassland with a doubling of grass yield and of grazing animal numbers – from approximately 3 million to over 6 million livestock units. There is little information available on the relative contribution of increased chemical fertiliser use compared to increased grazing animal numbers on P loss to water. The main objective of this study was to assess nutrient loss, particularly phosphorus, in overland flow from cut and grazed grassland plots with a range of soil test P levels.

Nutrient concentrations and loads from six grazed and cut field plots were studied between September 2000 and March 2004, at Teagasc, Johnstown Castle, Wexford. Overland flow volume and flow proportional overland flow samples were collected and analysed for P and nitrogen (N) fractions. A subset of samples was also analysed for potassium (K) and suspended solids (SS).

Overland flow water samples were analysed for total reactive phosphorus (TRP) in 2000–2001 and for dissolved reactive phosphorus (DRP), total dissolved phosphorus (TDP), and total phosphorus (TP) in 2002–2004. There were significant variations in P concentrations over the seasons and between the six field plots. Concentrations of DRP in overland flow varied from under 0.005 mg/l to over 3 mg/l. The estimated annual DRP loads in overland flow from the plots ranged from 0.1 to 1.2 kg/ha/year. There was a significant linear relationship between soil test P and mean annual DRP concentrations in overland flow. There was more than a ten-fold difference in mean annual DRP concentrations in overland flow between plots with the lowest and highest soil test P levels. This compared to a maximum of 66% increase in DRP concentrations between cut and grazed plots that may be attributable to the presence of the grazing animal.

A significant correlation was found between the three P fractions measured. TDP fractions represented 86% of total P. There was a significant correlation between total dissolved N (TDN) and total nitrogen (TN) concentrations and also between TP and TN concentrations in overland flow water; the latter was about five times higher than the former.

The highest P concentrations and loads occurred in autumn when overland flow started, after an extended summer dry period (autumn/winter wash-out effect). The difference in mean P concentrations in overland flow between cut and grazed plots, which was most evident on the high soil test P plots, were also generally highest in autumn/winter. In contrast, there was generally no difference between cut and grazed plots in January and February when concentrations were lowest and before the beginning of the grazing season.

Three factors influencing P concentrations in overland flow were identified in this work:

1. the highest concentrations were from plots with the highest soil test P and visa versa;
2. a seasonal P cycle with high P concentrations in autumn/winter when overland flow commenced after the summer and decreasing P concentrations over the following two months and the lowest levels of P concentrations at the start of the year;
3. a relatively small increase in P concentrations with grazing compared to cutting treatments on some occasions.

Whether cut or grazed, grassland can have an increased potential for P loss in overland flow compared to other land use. This is because of high surplus P inputs into intensive grassland systems in fertiliser and purchased feeds and the accumulation of the applied fertiliser and animal manure P at or near the soil surface. In contrast to what occurs with tillage soils, this can lead to very high soil P levels in the top few centimetres of grassland soils that are available for release to overland flow water. Therefore, special care is necessary in fertilising and managing grassland soils in order to minimise the risks of P loss to water.

The conclusion that the grazing animal has a limited impact on P losses compared to other factors is in broad agreement with US studies. A five-year study (Tunney et al., 2000) indicated that cattle grazing did not have a significant cumulative effect on P in runoff at the whole pasture scale.

The principal conclusion from this study is that while the grazing animal does influence P concentrations in overland flow, this impact is minor when compared to the other factors (such as soil P levels) which determine P loss from grassland under standard management regimes.

This study relates to good grazing practice and without further research cannot be applied to situations where animals are out-wintered in fields or are stocked at very high rates, particularly under wet conditions.

The main potential for mitigating P loss from grassland is to maintain soils at or near the lowest soil test P level compatible with good grassland production and to match P inputs with outputs in milk and meat.

1 Introduction and Aims

Over 90% of the 4.2 million ha of Irish farmland is under grass; most of this is grazed and in the region of 25% of this area is cut at least once per year, mostly for silage but also for hay. Results of an earlier EPA study (Tunney et al., 2000) found that there is relatively little information on the impact of the grazing animal on diffuse phosphorus (P) losses from grassland soils in Ireland under normal farming practices. The loss rates can be higher than required to maintain good water quality (Tunney, 2002).

It has been reported that grazing animals can be a significant contributor to nutrient and sediment loads in overland flow under conditions of very heavy grazing (Brooks et al., 1997; Thurow, 1991). A study in Montana, USA, on mixed grassland showed an increase in nutrient in runoff with grazing but this was small in comparison to the natural variation (Emmerich and Heitschmidt, 2002). A study in Alberta, Canada demonstrated increased nitrate loss but no consistent effect on P in runoff from grassland catchments with none, intensive and very intensive grazing (Mapfumo et al., 2002). The P concentrations in Lake Okeechobee, Florida, USA doubled from 0.05 to 0.10 mg P/l from the early 1970s to the 1990s and loss from intensively farmed grassland is considered to a be a significant contributor (Capece et al., 2007). In Florida, farmers have identified best-management practices for water-quality improvement, including fencing, drainage, feed/water location, fertilisation and changes in grazing practices that are expected to reduce P loss (FCA, 1999). High rates of P application and land use and other factors that contribute to P storage and erosion increase the potential of P loss into downstream ecosystems (McDowell et al., 2001; Sharpley et al., 1994).

The studies quoted above deal largely with data from North America and there is little information from Europe on how the grazing animal may affect P loss. A recent study in Finland on trampling of pasture by cattle showed that heavy compaction near a drinking site reduced infiltration to 10 to 20% of the rate in non-trampled pasture (Pietola et al., 2005). Excessive soil compaction by grazing animals (e.g. out-wintering or sacrifice paddocks) can lead to increased overland flow and thus a potential for increased nutrient and sediment loss; however, these extreme conditions were not intended to be studied in the current project.

The main objectives of this project (EPA LS-2.1.2 Grazed Pastures) were to provide an assessment of grazing on P losses under Irish conditions as follows:

1. Review existing available information on P loss from grazed grassland, including a simple model of P pools and fluxes.
2. Measure the P (and nitrogen [N]) loss from grazed and cut grassland on a number of soils.
3. Identify the most important factors influencing P loss from soil to water under grazed grassland conditions.
4. Investigate the interactions between physical, chemical and biological processes that affect P fluxes and loss to water.
5. Recommend possible remedial actions necessary to reduce P loss to water from grazed grassland and the projected cost, based on the results obtained and other available information.

Section A of the project, reported here, assesses losses of P from grassland under typical grazing practice and deals with aspects of Objectives 1, 2, 3 and 5 listed above. Two separate sections, B and C, deal respectively with small-plot studies and P balances and fluxes. Losses associated with overgrazing or out-wintering were not studied in this project.

This report (Section A) presents data from seven grassland field plots (of the order of 1 ha each) where the quantity and composition of overland flow were measured from September 2000 to March 2004, although most observations presented in this report relate to calendar years 2001, 2002 and 2003 on six of these plots. These six plots consisted of three pairs, normally one plot was grazed and the other cut in each pair: with a range of low to high soil test P levels.

2 Materials and Methods

This study was based on six existing (prior to 2000) hydrologically isolated plots (Plots 1 to 6) and one new plot (Plot 7) installed in 2001; these plots were (except Plots 1 and 2) accommodated within existing field experiments (Figure 2.1). The plots were not replicated as this would be prohibitively expensive.

The possibility of installing new plots was considered but it was decided that it would not be possible to obtain results in the three-year timeframe of this project. It was decided nonetheless that these seven plots could be used to give valuable information on P loss from grazed and cut grassland field plots.

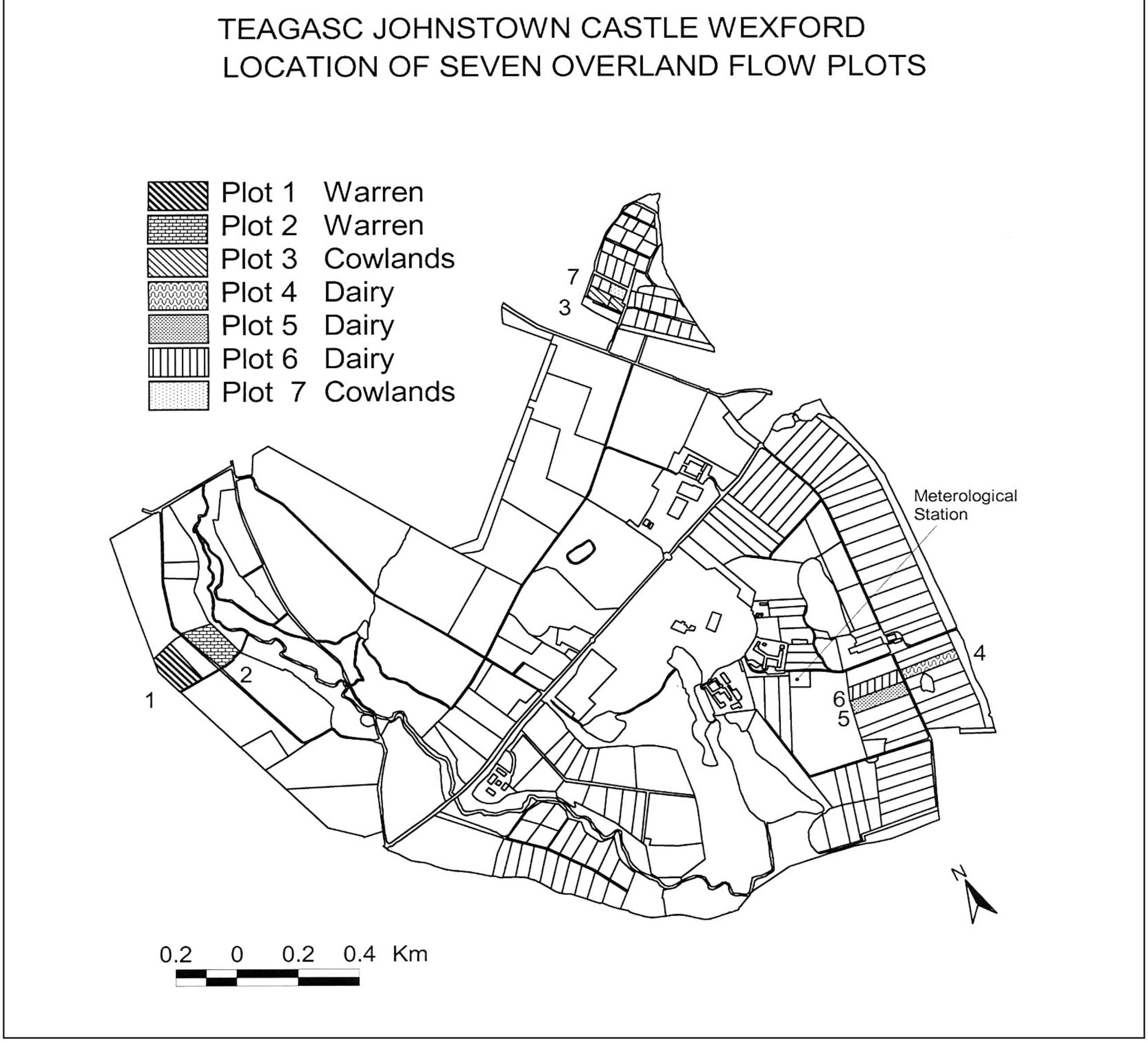

Figure 2.1: Layout of seven plots and meteorological station at Teagasc, Johnstown Castle

2.1 Water and Soil Sampling and Analyses

Overland flow water was channelled to the lowest point in each plot and then via a pipe to a tank with a V-notch. Flow was estimated based on the height of the water in the tank, and flow proportional samples were collected using American Sigma samplers. The flow proportional sampling was adjusted, based on experience with flow rates, so that the 24 sampling bottles in the Sigma samplers would be adequate to collect all the overland flow samples that were likely to be taken over a 24-hour period of very heavy rainfall (>30 mm). The flow proportional sampling provided one overland flow water sample from each 1 m^3 (Plot 3) to 10 m^3 (Plot 1) of flow depending on plot. These sampling patterns depended on the size of the plot and the proportion of rainfall that moved as overland flow.

From September 2003 to March 2004, when the study ended, sampling was halved to reduce the number of overland flow samples for laboratory analyses, because the large number of samples collected in 2002, a very wet year, was considered to be more than necessary. This was achieved by halving the above flow proportional sampling rates to every 2 m^3 (Plot 3) to every 20 m^3 (Plot 1) of overland flow, depending on plot. In practice, there was less than half the number of overland flow samples in this period compared to the same period in 2002/2003 because it was a relatively dry period with less rainfall and overland flow.

Overland flow water samples were normally collected and taken to the laboratory within 24 hours (48 hours at weekends) of the flow proportional sample being collected by the Sigma samplers.

Most samples were analysed on the day they arrived in the laboratory or within 24 hours after storing at 4°C. Some water samples were stored frozen before total P analyses. The 24 1-litre sample bottles in each of the seven Sigma samplers were acid washed at the start of each overland flow season (September) and from spring 2002 onwards the sample bottles were normally rinsed with distilled water on emptying after each overland flow event. The same set of 24 sample bottles was used for the same plot throughout the course of the study.

The soil and water analyses methods for nutrients and SS were in accordance with those used at the Teagasc Johnstown Castle Laboratory.

Overland flow samples were filtered through a 0.45 µm filter for soluble N and P fractions. The water analyses methods, including P fractions, N fractions, K and SS, were based on the Standard Methods for the Examination of Water and Wastewater (Greenberg et al., 1992). From 2002 to March 2004, dissolved reactive P (DRP) and total dissolved P (TDP) were measured on filtered (0.45 µm) samples; total reactive P (TRP) and total P (TP) were measured on unfiltered samples (Greenberg et al., 1992). TP and TDP were determined by oxidative persulphate digestion in an autoclave as described by Ebina et al. (1983). Water samples for TP were stored in a freezer while awaiting analysis.

In 2001, the overland runoff water samples were analysed for TRP (or molybdate reactive P, detection limit [DL] 0.005 mg/l), total oxidised N (TON, DL 0.3 mg/l) and ammonium N (NH_4-N, DL 0.1 mg/l). In 2002 the TRP analyses was stopped when the laboratory improved the suite of water analyses; samples were thereafter analysed for DRP (DL 0.005mg/l), TDP (DL 0.01 mg/l), TP (DL 0.01 mg/l), TON, NH_4-N, and total dissolved N (TDN, DL 0.15 mg/l). In 2003 the water samples were analysed for the same parameters as in 2002, plus total N (TN, DL 0.15 mg/l). In addition, overland flow water samples taken between October 2003 and March 2004 were analysed for SS (DL 1.0 mg/l). Particulate P (PP) is shown as the difference between TP and TDP. Values below the detection limit were recorded as zero. The P and N fractions were measured colorimetrically using a Kone Lab Discrete Analyser. Overland flow water was analysed for K using atomic absorption (AA) and the detection limit was 0.2 mg/l. Extractable P, K and magnesium (Mg) in soils were analysed using Morgan's soil extractant (Peech and English, 1944).

During data analyses it was found that some water samples had higher DRP values than the corresponding TRP and TP values. This was most evident in 2002 when the laboratory first introduced the autoclave digestion method.

To facilitate the comparison of grazing and cutting treatments, six field plots were paired (Plots 1 and 2, Plots 3 and 7, and Plots 5 and 6) at three locations on the Teagasc farm at Johnstown Castle, Wexford. Information on the field plots and their location on the farm is shown in Table 2.1 and Figure 2.1, respectively.

The plots had mean slopes of 3°. Results from an additional grazed plot (Plot 4) are also presented in the comparison of P and K concentrations in overland flow from September 2000 to April 2001. Flow and water sampling measurements on Plots 1 to 6, for this study, started in autumn 2000 and on Plot 7 in August 2001.

Table 2.1 Summary of site data for the field plots

Plot No.	Name	Area (ha)	Grazing animal	Stocking rate,* LU/ha/year	Main soil type	Soil drainage
1	Upper Warren	1.54	Beef	1.6	Gley	Very poor
2	Lower Warren	1.09	Beef	1.6	Gley	Very poor
3	Cowlands	0.46	Beef	2.5	Gley	Poor
4	Dairy 1	0.74	Dairy	2.5	Brown Earth	Fair/Good
5	Dairy 2	0.73	Dairy	2.5	Brown Earth	Fair/Good
6	Dairy 3	073	Dairy	2.5	Brown Earth	Fair/Good
7	Cowlands Cut	0.24	Beef	2.5	Gley	Poor

* When grazed

2.2 Site Management and Data Analyses

For this study, plots were grazed and cut according to existing practice for the stocking rate for beef and dairy animals, and N and K fertilisers were applied according to Teagasc recommendations (Coulter et al., 2002). Plots 3 and 7 received 30 kg chemical fertiliser P per ha per year from 1968 to 2000, in addition to N (300 kg/ha/year) and K (30 kg/ha/year) fertiliser. The cumulative effect of this treatment was high soil P concentrations. Plots 1 and 2 were on land reclaimed from scrub land in the 1970s and received very little chemical fertiliser or slurry in the interim, particularly Plot 1. The other plots (4, 5 and 6) were part of a dairy farm since the 1970s and received normal chemical fertiliser and slurry treatments for dairying systems (mean 300 N and 60 kg K per ha/year).

No chemical P fertiliser or slurry were applied to Plots 1, 2, 3 or 7 from 2001 to 2003. When grazed, Plots 1 and 2 had a set stocked grazing management (animals continually on the same area throughout the grazing season) while the other plots were grazed rotationally at approximately 21-day grazing intervals (animals moved on to a new paddock after approximately 3 days' grazing). Specific grazing and cutting treatments for each plot are summarised in Table 2.2. Details of grazing, cutting and fertiliser treatments for the field plots are summarised in Appendix 1.

The overland flow levels were recorded every 5 minutes and these data were stored together with the times of the overland flow sample collection in the Sigma Insight software. The combined data were later transferred to an MS Access database.

The nutrient concentrations in overland flow were linked to the flow data to allow calculation of nutrient loads. The daily mean flows and P concentrations were extracted by querying the MS Access database. The P concentrations in overland flow, daily flows and mean daily P loads and cumulative flows and P loads were calculated and graphed in MS Excel.

Statistical analysis was carried out on the P concentrations in overland flow water samples from the six plots with the help of MS Excel and GenStat 7.2 (Copyright 2004, Rothamsted Experimental Station, UK).

The P concentration data were averaged (as mean concentration) according to month of year and subjected to analysis of variance (ANOVA) using plots and months as factors. This analysis tested for the main effects of plot (i.e. averaged over months) and month (averaged over plots), and also the interactions between plot and month.

Table 2.2 Grazed and cut treatments on the field plots for 1999–2003. Plots 1 and 2, 3 and 7, 5 and 6 were paired (Figure 2.1)

Plot No.	1999	2000	2001	2002	2003
1	Cut	Cut	Grazed	Grazed	Cut
2	Cut	Cut	Cut	Grazed	Cut
3	Grazed	Grazed	Grazed	Grazed	Grazed
4	Grazed	Grazed	Grazed	Grazed	Grazed
5	Grazed	Grazed	Grazed	Grazed	Cut
6	Grazed	Grazed	Cut	Cut	Grazed
7	Grazed	Grazed	Cut	Cut	Cut

3 Results and Discussion

3.1 Soils Test Results

The soils in this study area were derived from Irish Sea drift glacial deposits. Plots 1 and 2 are predominantly clay soils and the other plots are predominantly loam. Plots 1 and 2 were poorly drained and fertiliser application and grazing started approximately 4 to 6 weeks later than the other plots, resulting in less intensive grazing. Plots 1 and 2 were the wettest; Plots 4, 5, and 6 were the driest and Plots 3 and 7 were intermediate. Soil test P varied more than four-fold between plots and this reflected the agronomic history of each plot (Table 3.1). There were smaller differences, less than two-fold, in soil K and Mg levels. The soil pH varied from 5.7 to 6.3.

3.2 Climatic Data

The meteorological station (shown in Figure 2.1) provided daily rainfall and air temperature. Daily rainfall and air temperatures from 2001 to 2003 are presented in Figure 3.1 and cumulative annual rainfall and evapo-transpiration are plotted in Figure 3.2. The 25-year (1980–2004) mean annual rainfall was 1037 mm. The 25-year (1980–2004) rainfall daily minimum, mean and maximum was 0, 2.84 and 63.6 mm, respectively. The corresponding air temperature minimum, mean and maximum was -3.7, 10.2 and 23.3 ^{0}C per day, respectively.

Table 3.1 Summary of soil test results for 7 plots sampled in January 2003. The P, K and Mg are in mg/l soil (Morgan’s extractant); lime requirement is in t/ha

Plot No.	Plot name	P mg/l	K mg/l	Mg mg/l	pH	Lime (t/ha)
1	Upper Warren	3.5	75	251	5.7	6.8
2	Lower Warren	4.8	73	272	6.1	5.5
3	Cowlands	17.9	92	374	6.1	5
4	Dairy 1	4.5	123	235	5.7	6.2
5	Dairy 2	7.0	131	324	6.0	4.5
6	Dairy 3	7.2	104	211	5.8	7.8
7	Cowlands	16.7	75	428	6.3	3.5

3.3 Overland Flow

Phosphorus export represents the product of concentrations in runoff multiplied by runoff volumes. It is of interest, therefore, to compare runoff rates between plots. For each set of paired plots it may be expected that runoff should be similar. If they are not, the difference may reflect the effect on runoff volumes of the experimental treatment of grazed compared to cut. However, the runoff measured in this study is overland flow (surface runoff) so that difference in runoff totals could also reflect differences in the permeability of each paired plot influencing runoff. Small differences in soil permeability could have resulted in a large difference in surface runoff.

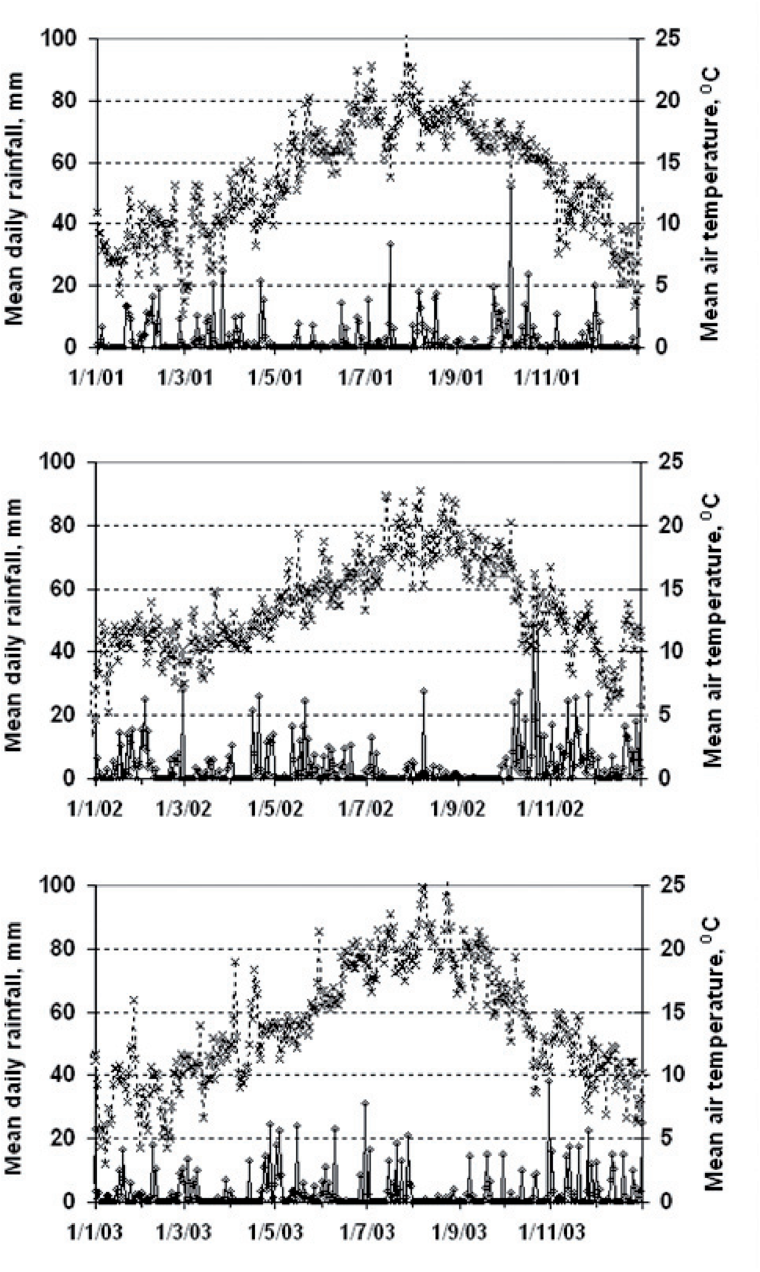

Figure 3.1: Summary of mean daily rainfall (line) (mm) and air temperature (x) (^{0}C) for 2001–2003

3.3.1 Overland Flow Volume

There were significant differences in cumulative annual overland runoff between the six plots and between years (Figure 3.3). The highest flows occurred in 2002 and the lowest flow in 2003. In 2001 the cumulative mean daily annual overland flow varied from under 100 mm on Plot 6 to over 250 mm on Plot 2. In 2002 the overland flow varied from just over 100 mm on Plot 6 to over 400 mm on Plots 1 and 2. Each of the other three plots had in the region of 250 mm overland flow.

The high overland flow in 2002 compared with the other two years was due to the higher rainfall in 2002 (Figure 3.2).

Plots 1 and 2 were on heavy, gley soil and therefore gave the highest runoff volumes and had the earliest start and the latest finish dates for overland flow. Plot 1 was grazed in both 2001 and 2002; however, there was a wide difference in overland flow between the two years owing to the difference in rainfall. Plot 2 was cut in 2001, grazed in 2002 and cut in 2003. In a parallel study (Kurz et al., 2006),

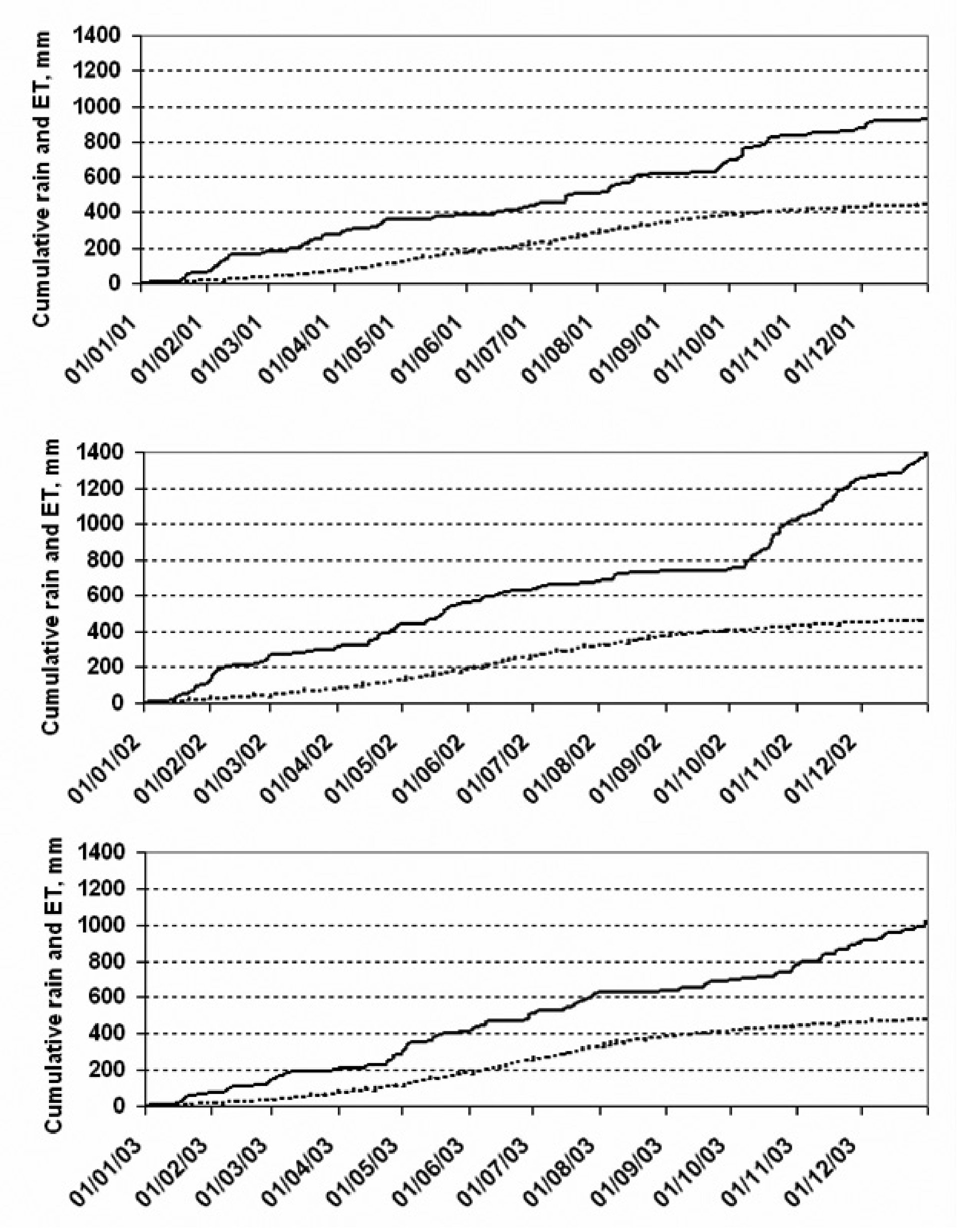

Figure 3.2: Cumulative mean daily annual rainfall and evapotranspiration (ET, dotted line) (mm) for 2001–2003

in small plots within some of these plots it was found that the grazing animal had significant effects ($P < 0.05$) on soil physical properties compared to plots without animals.

Plots 3 and 7 were paired on the highest STP treatments. Plot 3 was grazed and Plot 7 was cut in 2001, 2002 and 2003. Plot 3 had a cumulative overland flow of slightly over 100 mm in 2001, over 200 mm in 2002 and over 50 mm in 2003 (Figure 3.3). Plot 7 had almost 300 mm in 2002 and over 100 mm in 2003. The increased overland flow from Plot 7 compared to Plot 3 in 2002 and 2003 may be due partly to subsurface flow from the upslope plot appearing as overland flow in Plot 7 rather than a specific treatment effect.

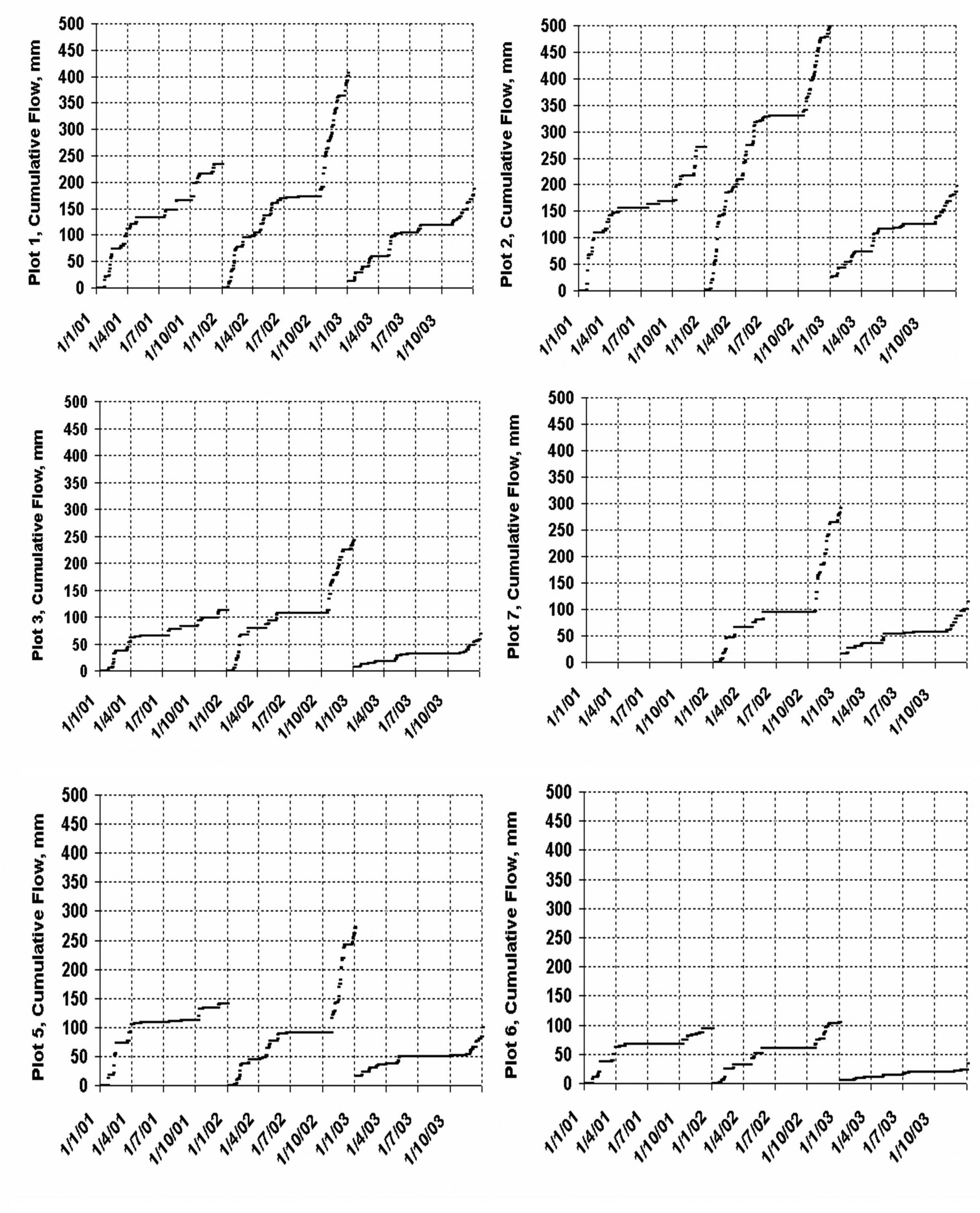

Figure 3.3: Cumulative overland flow water (mm) from the six plots in the three years 2001–2003

Plots 5 and 6 were the paired plots on the dairy farm but there were large differences in overland flow between the two with consistently higher runoff from Plot 5 (Figure 3.3). Plot 5 was grazed and Plot 6 was cut in 2001 and 2002. Plot 5 had higher overland flow than Plot 6 in each of the three years and it is likely that this was due to soil hydrology factors rather than the grazing and cutting treatments. At both these sites, the tanks were subject to flooding two or three times per year during the heaviest rainfall events. This flooding was not observed but was evident from the flow recorder; this recorded heights in excess of the V-notch heights which were the basis of flow recording by the Sigma 900 Max instruments. These high readings, which normally lasted for about 2 to 4 hours two or three times per year, were replaced with data from the highest flow events, where there was no evidence of flooding, in order to give an estimate of the true flow.

The main conclusion from the flow data is that there were significant differences ($P < 0.05$) in cumulative annual flow between the plots, but that these differences were due mainly to site characteristics and rainfall. Thus, the experiments were not sensitive enough to pick up the relatively small differences in flow generation because of the grazing and cutting treatments.

However, it is likely that the grazed plots would have more compaction than the cut plots and that they might therefore have higher overland flow. The effect of the grazing animals on soil compaction was confirmed in the small-plot study (Kurz et al., 2006).

3.3.2 Risks with Overland Flow Measurements

It is important to note that accurate measurement of overland flow under field plot conditions is difficult; at best, it gives an approximation. There are a number of reasons for this.

Under field plot conditions it is difficult to ensure that water from outside the area will not appear as overland flow from the plot being studied. This can occur when subsurface water from an area outside the plot appears as overland flow in the plot (‘return flow’), e.g. when there are springs in the plots as was the case in Plot 1 and possibly in other plots. It can also occur when overland flow water from outside the plot runs into the plot over the barriers (‘berms’) installed to prevent this or when flooding occurs and backs up onto the plot. This occurred on Plots 5 and 6 for a short period two or three times per year for 2 to 4 hours during very heavy rainfall. It also occurred on Plot 2 in 2001 before an improved drain was installed on one side of the plot to divert water from outside.

In addition, overland flow water from inside the plot may escape through a pathway other than the collection point installed at the lowest point in the plot to collect the flow. This can occur during very heavy rainfall when water may overflow the retaining berm or when overland flow water is held in pools behind the berm and some of it seeps out through the soil under the berm.

It is also necessary to consider the fate of overland flow water from edge-of-field plots as in this study. This overland flow may or may not enter a water course, e.g. it may infiltrate into the soil down slope. On the other hand, water that infiltrates in the plot under study may appear as overland flow down slope and subsequently enter a watercourse as overland flow.

The highest and most frequent overland flow occurred on Plots 1 and 2 and the highest overland flow, of the three years, occurred in 2002. On Plot 1, for example, there were 22 overland flow events over 35 days in 2002. Overland flow events sometimes occurred over two days, particularly during and after heavy rain when land was wet.

In the three years (2001–2003) most of the overland flow occurred between the months of October and April. There was a total of 1177 (112), 2786 (239) and 661 (40) overland flow samples collected from the six plots in 2001, 2002 and 2003 respectively. The numbers collected in the May to September (inclusive) period are shown in brackets and were less than 10% of the annual total. Figure 3.3 shows that the cumulative annual overland flows (mm) were: Plot 1 – 234, 406, 187; Plot 2 – 271, 509, 197; Plot 3 – 112, 242, 68; Plot 5 – 140, 273, 99; Plot 6 – 95, 105, 34 in 2001 (TRP), 2002 (DRP) and 2003 (DRP), respectively. The corresponding values for Plot 7 were 292 and 115 mm in 2002 and 2003, respectively (Figure 3.3).

3.4 Mean Annual P and N Concentrations in Overland Flow

The results of the P and N fractions in overland flow from the six paired plots in the three years 2001, 2002, and 2003 are summarised in Tables 3.2, 3.3, 3.4 and 3.5 respectively.

The TRP concentrations in the overland flow water samples from the paired Plots 1, 2 and 5, 6 for 2001 are summarised in Figure 3.4. The DRP concentrations in overland flow from the six plots for 2002 and 2003 are summarised in Figures 3.5 and 3.6, respectively. The TDP concentrations in overland flow water samples from the six plots for 2003 are summarised in Figure 3.7. The TP concentrations in overland flow water samples from the six plots for 2003 are summarised in Figure 3.8.

The TDN and TN concentrations in overland flow water samples from the six plots for 2003 are summarised in Figures 3.8 and 3.9, respectively.

Table 3.2 Mean, minimum, maximum and STDEV for TRP, TON and NH_4-N concentrations (mg/l) in runoff from the five plots studied in 2001. The second column shows the number of overland flow samples collected and analysed

			mg/l		
Plot Treatment	**No. Samples**		**TRP**	**TON**	**NH_4-N**
1 Grazed	288	Mean	0.08	0.3	0.1
		Minimum	0.00	0.0	0.0
		Maximum	0.70	5.2	1.0
		STDEV	0.08	0.6	0.2
2 Cut	319	Mean	0.09	0.2	0.1
		Minimum	0.03	0.0	0.0
		Maximum	0.40	5.1	0.6
		STDEV	0.05	0.5	0.1
3 Grazed	136*	Mean	1.18	1.3	0.3
		Minimum	0.27	0.0	0.0
		Maximum	2.71	8.7	5.4
		STDEV	0.66	1.75	0.8
5 Grazed	228	Mean	0.49	0.5	0.1
		Minimum	0.00	0.0	0.0
		Maximum	3.25	3.0	1.0
		STDEV	0.59	0.5	0.2
6 Cut	206	Mean	0.71	0.4	0.5
		Minimum	0.01	0.0	0.0
		Maximum	2.81	2.5	4.5
		STDEV	0.64	0.4	0.9
	Overall Mean (5 plots)		0.40	0.4	0.2
	Overall STDEV (5 plots)		0.57	0.8	0.5

* Sampling problems resulted in 100 water samples being missed from Plot 3 in spring 2001.

Table 3.3 Mean, minimum, maximum and standard deviation (STDEV) for DRP, TDP, TP, TON, NH_4-N and TDN concentrations (mg/l) in runoff from the six plots studied in 2002. The second column shows the number of overland flow samples collected and analysed

			mg/l					
Plot Treatment	**No. Samples**		**DRP**	**TOP**	**TP**	**TON**	**NH_4-N**	**TDN**
1 Grazed	459	Mean	0.05	0.06	0.15	0.4	0.2	2.09
		Minimum	0.00	0.00	0.00	0.0	0.0	0.06
		Maximum	0.52	0.47	0.88	26.0	6.9	40.04
		STDEV	0.05	0.06	0.08	2.4	0.4	3.55
2 Grazed	592	Mean	0.09	0.10	0.18	0.3	0.3	2.48
		Minimum	0.00	0.00	0.00	0.0	0.0	0.00
		Maximum	1.55	1.59	1.41	30.4	12.2	60.73
		STDEV	0.13	0.16	0.17	2.8	1.1	6.97
3 Grazed	672	Mean	0.57	0.60	0.76	0.4	0.9	4.30
		Minimum	0.14	0.15	0.21	0.0	0.0	0.50
		Maximum	1.76	1.65	3.63	9.2	17.3	45.40
		STDEV	0.27	0.32	0.41	0.8	2.4	7.64
7 Cut	450	Mean	0.59	0.62	0.72	0.1	0.6	3.60
		Minimum	0.15	0.22	0.16	0.0	0.0	0.53
		Maximum	2.00	1.74	2.08	1.7	12.5	41.03
		STDEV	0.30	0.27	0.32	0.3	1.7	7.14
5 Grazed	386	Mean	0.51	0.61	0.73	0.6	0.8	3.62
		Minimum	0.09	0.09	0.09	0.0	0.0	0.48
		Maximum	3.31	3.53	3.61	7.9	20.2	34.16
		STDEV	0.45	0.47	0.43	0.9	2.3	3.90
6 Cut	227	Mean	0.43	0.49	0.76	0.6	1.0	3.56
		Minimum	0.10	0.14	0.21	0.0	0.0	0.50
		Maximum	1.20	1.30	1.81	20.9	26.2	46.97
		STDEV	0.26	0.31	0.36	2.0	2.6	4.97
Overall Mean (6 plots)			0.36	0.41	0.53	0.4	0.6	3.29
Overall STDEV (6 plots)			0.35	0.38	0.42	1.8	1.9	6.23

Table 3.4 Mean, minimum, maximum and standard deviation (STDEV) for DRP, TDP, TP, TON, NH_4-N, TDN and TN concentrations (mg/l) in runoff from the six plots studied in 2003. The second column shows the number of overland flow samples collected and analysed

			mg/l						
Plot Treatment	**No. Samples**		**DRP**	**TOP**	**TP**	**TON**	**NH_4-N**	**TDN**	**TN**
1 Cut	130	Mean	0.03	0.08	0.17	0.2	0.2	2.09	3.15
		Minimum	0.01	0.01	0.07	0.0	0.0	0.52	1.29
		Maximum	0.10	0.20	1.14	1.5	1.5	5.85	18.40
		STDEV	0.02	0.04	0.11	0.4	0.3	1.31	1.91
2 Cut	170	Mean	0.09	0.14	0.20	0.1	0.1	2.02	2.57
		Minimum	0.02	0.03	0.04	0.0	0.0	0.36	0.96
		Maximum	1.29	2.26	2.46	7.4	1.7	13.57	13.93
		STDEV	0.12	0.19	0.20	0.6	0.3	1.41	1.38
3 Grazed	135	Mean	0.72	0.84	1.01	1.3	0.3	4.18	5.43
		Minimum	0.20	0.20	0.32	0.0	0.0	0.86	0.72
		Maximum	2.39	2.50	3.20	14.2	2.8	15.76	27.01
		STDEV	0.44	0.49	0.54	1.4	0.4	2.84	3.64
7 Cut	90	Mean	0.48	0.53	0.63	0.5	0.2	1.74	2.48
		Minimum	0.19	0.26	0.29	0.0	0.0	0.66	0.52
		Maximum	1.99	2.19	2.30	3.1	1.8	5.07	7.14
		STDEV	0.30	0.27	0.31	0.5	0.2	0.99	1.37
5 Cut	93	Mean	0.43	0.50	0.74	2.1	1.1	5.17	6.80
		Minimum	0.14	0.16	0.21	0.0	0.0	1.31	2.15
		Maximum	3.01	1.40	3.50	15.5	28.6	28.76	41.48
		STDEV	0.46	0.23	0.52	3.9	3.6	5.59	7.13
6 Grazed	43	Mean	0.46	0.57	0.70	1.1	0.6	2.55	3.75
		Minimum	0.09	0.11	0.13	0.0	0.0	0.70	0.93
		Maximum	1.32	1.42	1.79	4.6	3.7	6.88	12.26
		STDEV	0.28	0.35	0.42	1.0	0.8	1.56	2.35
Overall Mean (6 plots)			0.33	0.40	0.53	0.8	0.3	2.91	3.93
Overall STDEV (6 plots)			0.40	0.41	0.50	1.8	1.4	2.95	3.75

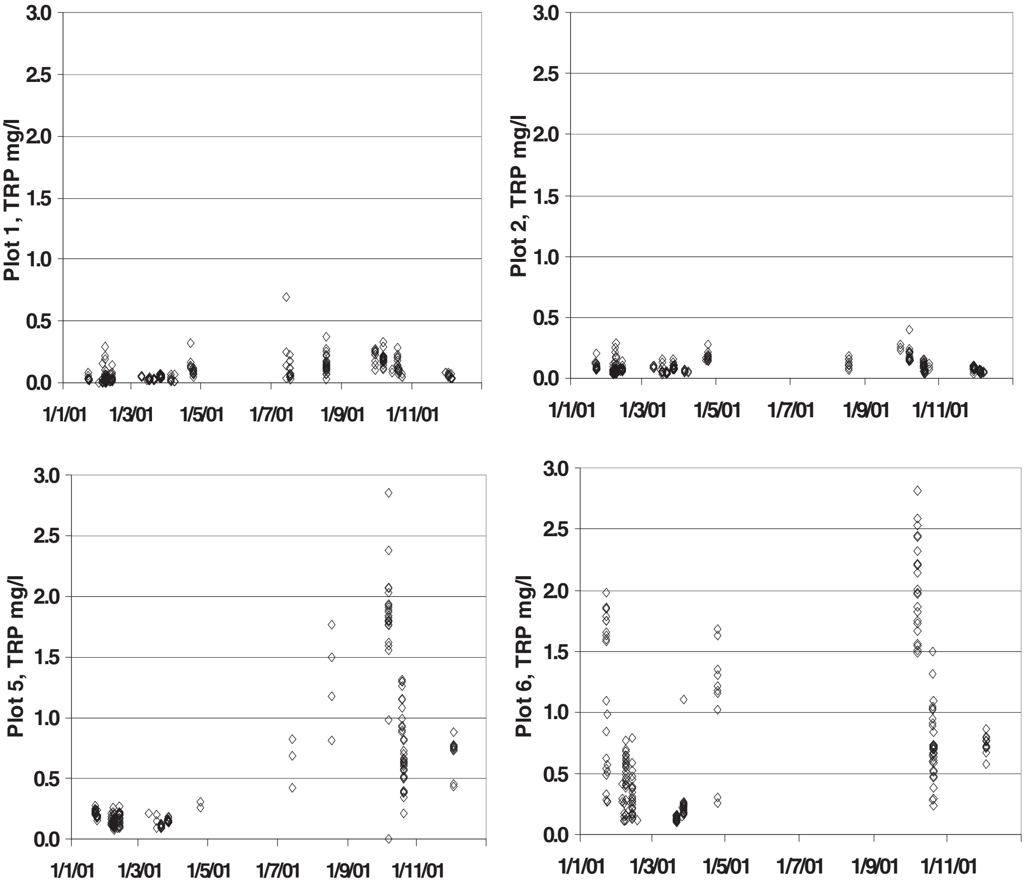

Figure 3.4: A TRP concentration (mg/l) in overland flow water samples from Plots 1 and 5 (grazed) and Plots 2 and 6 (cut) in 2001. Each vertical series of data points indicates single or adjacent storm events over a short time frame of normally one or two days

3.4.1 P Concentrations in Overland Flow

Table 3.2 shows that there was not a wide variation in the mean TRP concentrations between the paired Plots 1 (mean 0.08 mg/l P) and 2 (mean 0.09 mg/l P) and between the paired Plots 5 (mean 0.49 mg/l P) and 6 (mean 0.71 mg/l P) in 2001. The largest difference in TRP was between Plot 1 (mean 0.08 mg/l P) and Plot 3 (mean 1.18 mg/l P), both of which were grazed in 2001. Tables 3.3 and 3.4 indicate a broadly similar position for 2002 and 2003.

In 2002, the mean DRP concentrations for the paired Plot 3 (grazed, mean 0.57 mg/l) and Plot 7 (cut, mean 0.59 mg/l) were similar as were those for Plots 5 (grazed, mean 0.51 mg/l) and 6 (cut, mean 0.43 mg/l) (Table 3.3). However, the mean DRP concentration was higher for the April/May period on Plot 3 (grazed, 0.57) compared to Plot 7 (cut, 0.59).

Because of the practical difficulties of having separate cut and grazed treatments at the Warren which is far from the farmyard, Plots 1 and 2 were both grazed in 2002 and both cut in 2003. There was a larger difference in the mean DRP concentration between Plots 1 and 2 in 2002 (Table 3.3) compared to the mean TRP differences between these Plots in 2001 (Table 3.2). The relatively small difference in TRP concentration between Plot 1 (0.08 mg/l) and Plot 2 (0.09 mg/l) in 2001 compared to the DRP concentrations in 2002 (Plot 1, 0.047; Plot 2, 0.09 mg/l) may have been partly due to the presence of the grazing animals on Plot 1 in 2001. The highest mean P concentrations in overland flow were on Plots 3 and 7 and the lowest were on Plots 1 and 2. There was more than a 10-fold difference in annual mean soluble P (TRP, DRP and TDP) concentrations in overland flow between Plot 1 and Plot 3; and a 25-fold difference for DRP between these plots in 2003 (Tables 3.2, 3.3 and 3.4).

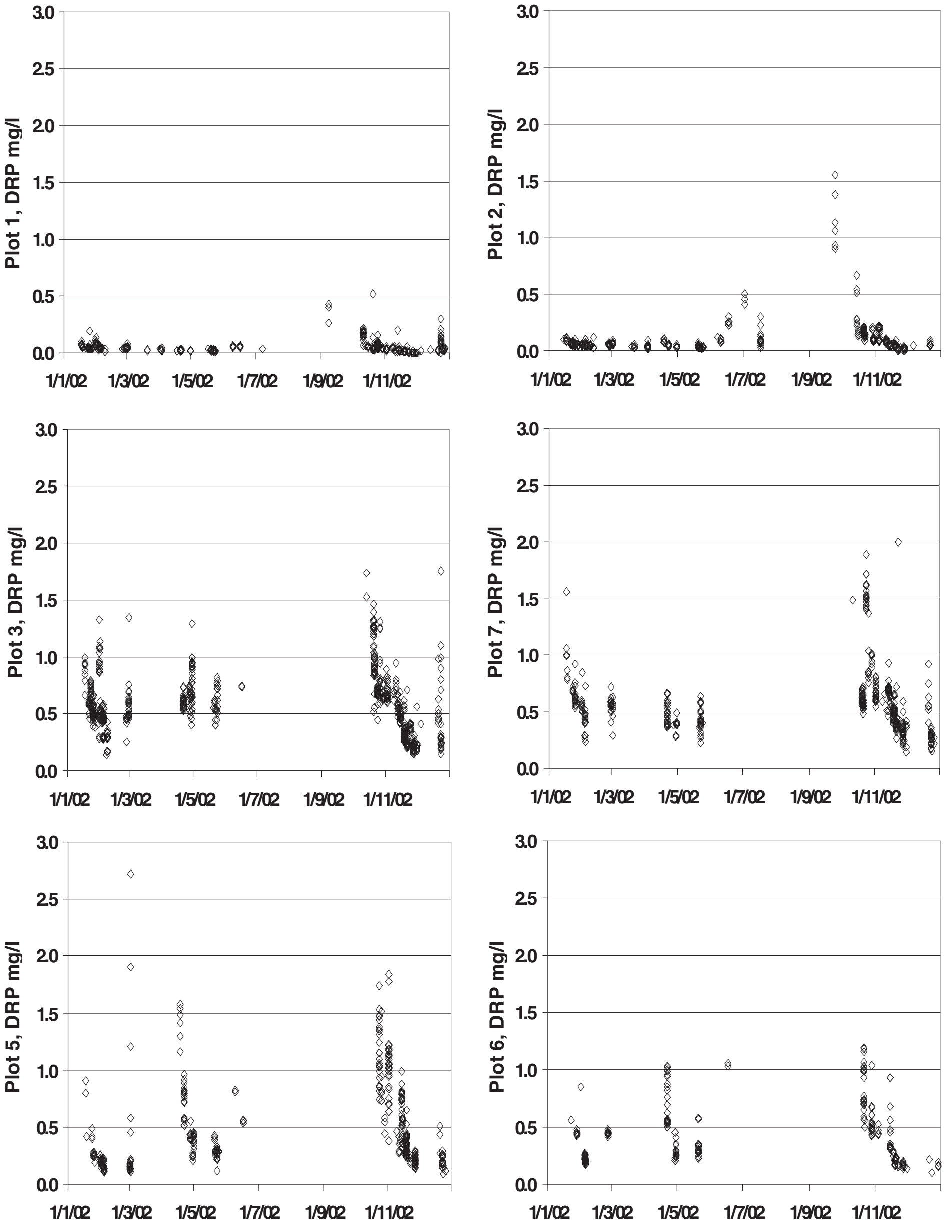

Figure 3.5: DRP concentrations (mg/l) in overland flow water samples from Plots 1, 2, 3 and 5 (grazed) and Plots 6 and 7 (cut) in 2002

Table 3.4 shows that the mean DRP concentration in overland flow water (0.029 mg/l) from Plot 1 in 2003 when the plot was cut, was lower than in 2002 (0.047 mg/l) when the plot was grazed. However, there was only a small difference in mean DRP concentration between Plot 2 in 2003 (0.092 mg/l, cut) compared to 2002 (0.085 mg/l, grazed). In 2003 the mean DRP concentration for Plot 3 (0.72 mg/l, grazed) was higher than for Plot 7 (0.48 mg/l, cut) indicating that the grazing may have contributed to increased P concentrations in overland flow. The difference was due mainly to the higher DRP concentration in November/December 2003 on Plot 3 compared to Plot 7 (Figure 3.6). However; there was no evidence of difference in DRP concentrations in the first three months of the year. In 2002, the mean DRP concentrations were almost the same for Plot 3 (grazed) and Plot 7 (cut). However, there was still over a ten-fold difference in mean DRP concentrations between Plot 1 and Plot 3 in both 2002 (0.047 versus 0.574 mg/l P) and 2003 (0.029 versus 0.723 mg/l P), indicating that soil factors, rather than the

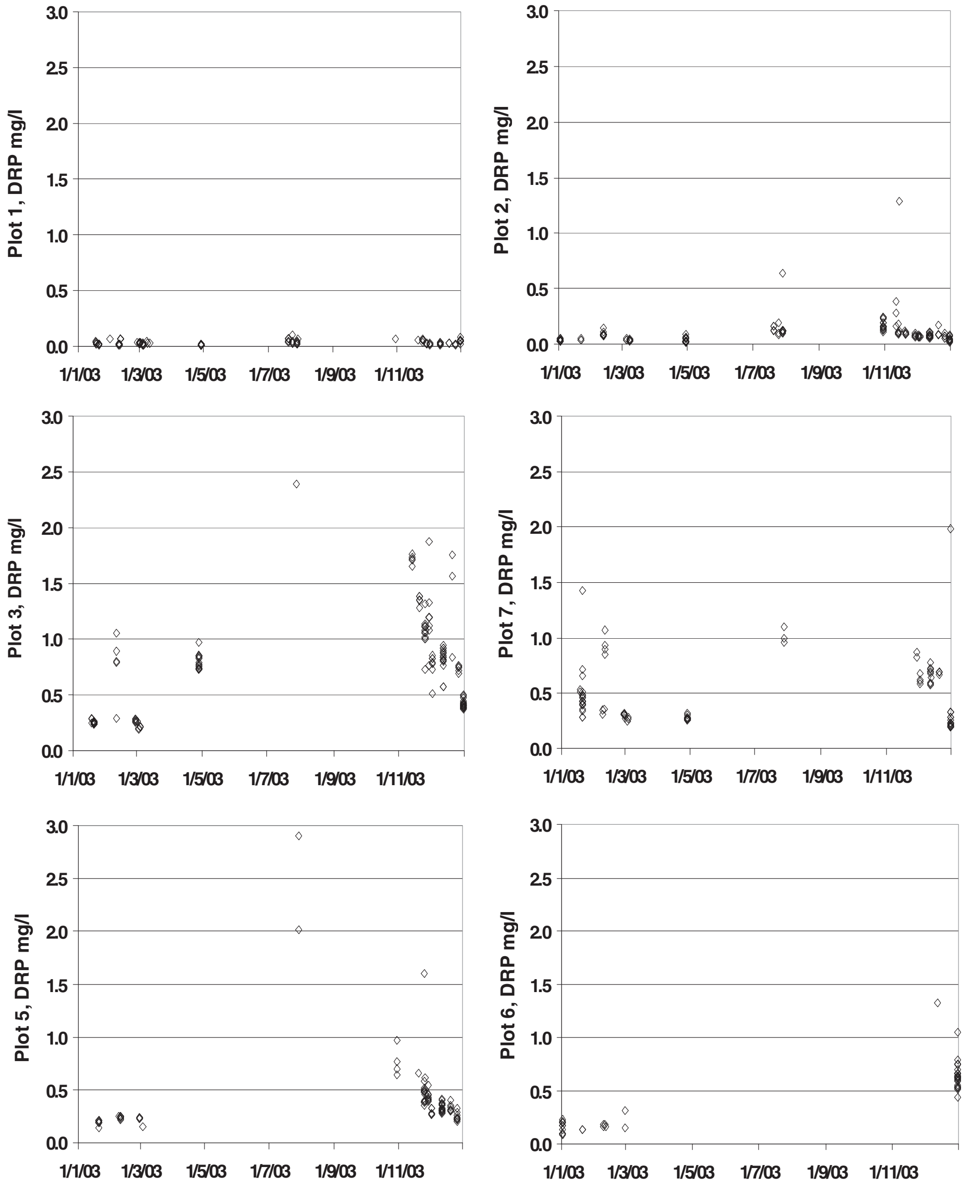

Figure 3.6: DRP concentrations (mg/l) in overland flow water samples from Plots 3 and 6 (grazed) and Plots 1, 2, 5 and 7 (cut) in 2003

cutting or grazing treatments, were the main source of variation in P concentration in overland flow water under the conditions of this experiment.

Figure 3.4 shows large differences in TRP concentrations on Plots 1 and 2 compared to those on Plots 5 and 6 in 2001. However, these data show little evidence of a major impact of the grazing animal on TRP concentrations in overland flow water when the grazed plots are compared to the cut plots. For instance, higher TRP concentrations were recorded for Plot 6 (cut) compared to Plot 5 (grazed) from January to April 2001. Figures 3.5 (2002) and 3.6 (2003) show lower DRP concentrations in overland flow from Plot 1 and Plot 2 compared to the other plots. Differences in annual mean DRP concentrations in overland flow between Plot 1 and Plot 2 or between Plot 3 and Plot 7 were minor when compared to the difference between Plots 1 and 3. It is likely that this difference in the lowest and highest DRP concentrations can be attributed to the higher soil P as reflected in the STP levels (Table 2.2).

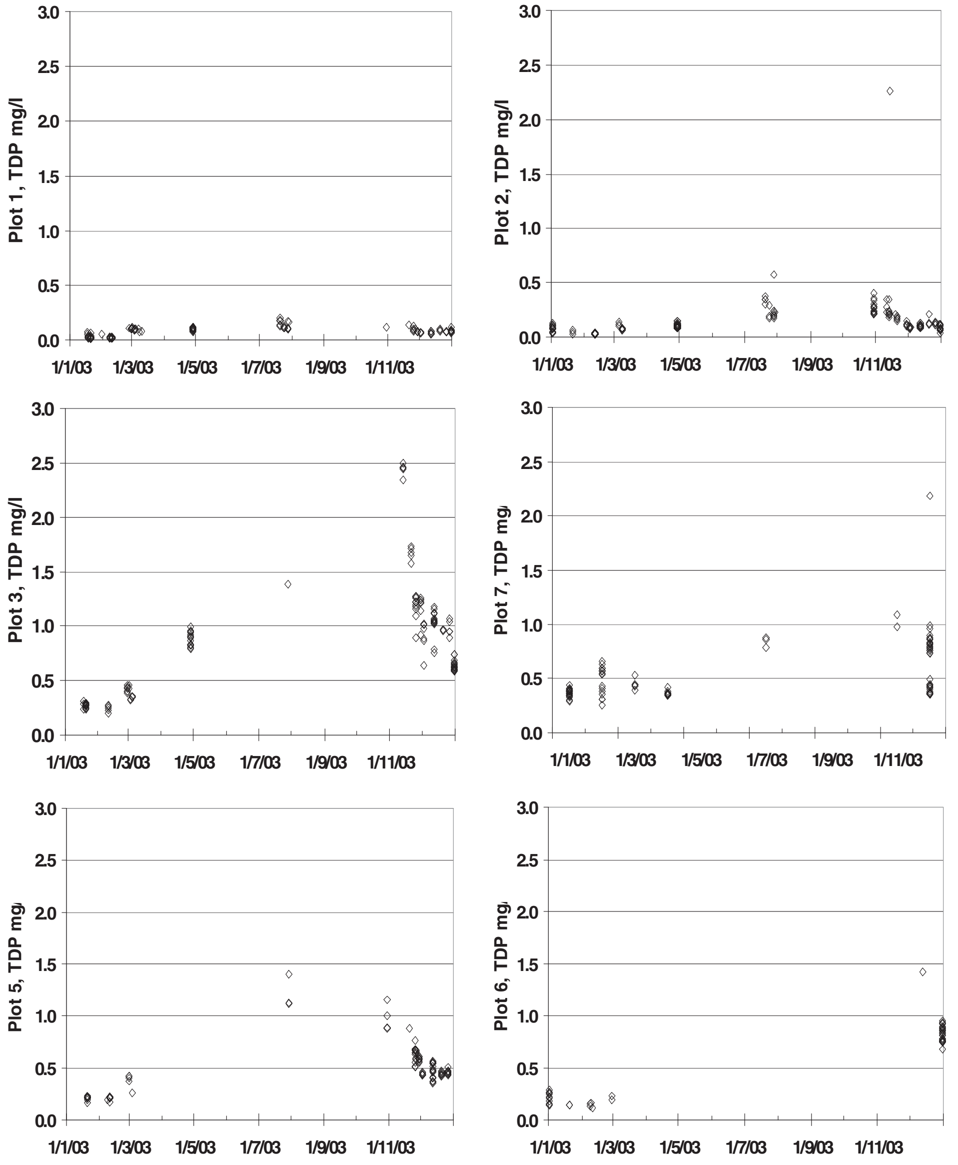

Figure 3.7: Summary of TDP concentrations (mg/l) in overland flow water samples from Plots 3 and 6 (grazed) and Plot 1, 2, 5 and 7 (cut) in 2003

The trends in TDP and TP concentrations for 2003 shown in Figures 3.7 and 3.8, respectively, indicate broadly similar trends to the DRP concentrations shown in Figure 3.6. In 2002, there were a number of anomalies (about 25% of samples) where DRP concentrations were a little higher than the TDP or TP values and where TDP concentrations were higher than TP. These occurred when the laboratory began analysing water samples for TDP and TP using autoclave digestion and the figures shown in Table 3.3 for these parameters should therefore be interpreted with caution as they may have been underestimated in 2002.

3.4.2 N Concentrations in Overland Flow

Most of the high NH_4-N and TON concentrations occurred in the wet year 2002 (Tunney et al., 2003). Table 3.3 shows some high maximum TON, NH_4-N and TDN concentrations in 2002. Some of these high levels were associated with overland flow occurring after the application of urea or calcium ammonium nitrate fertiliser. Examples of high NH_4-N concentrations were observed on three plots (3, 5 and 7) in overland flow after heavy rainfall (28 mm) on 28 February to 1 March 2002. Urea was spread at 43, 37 and 80 kg/ha N (27 February on Plots 3 and 7 and 20 February on Plot

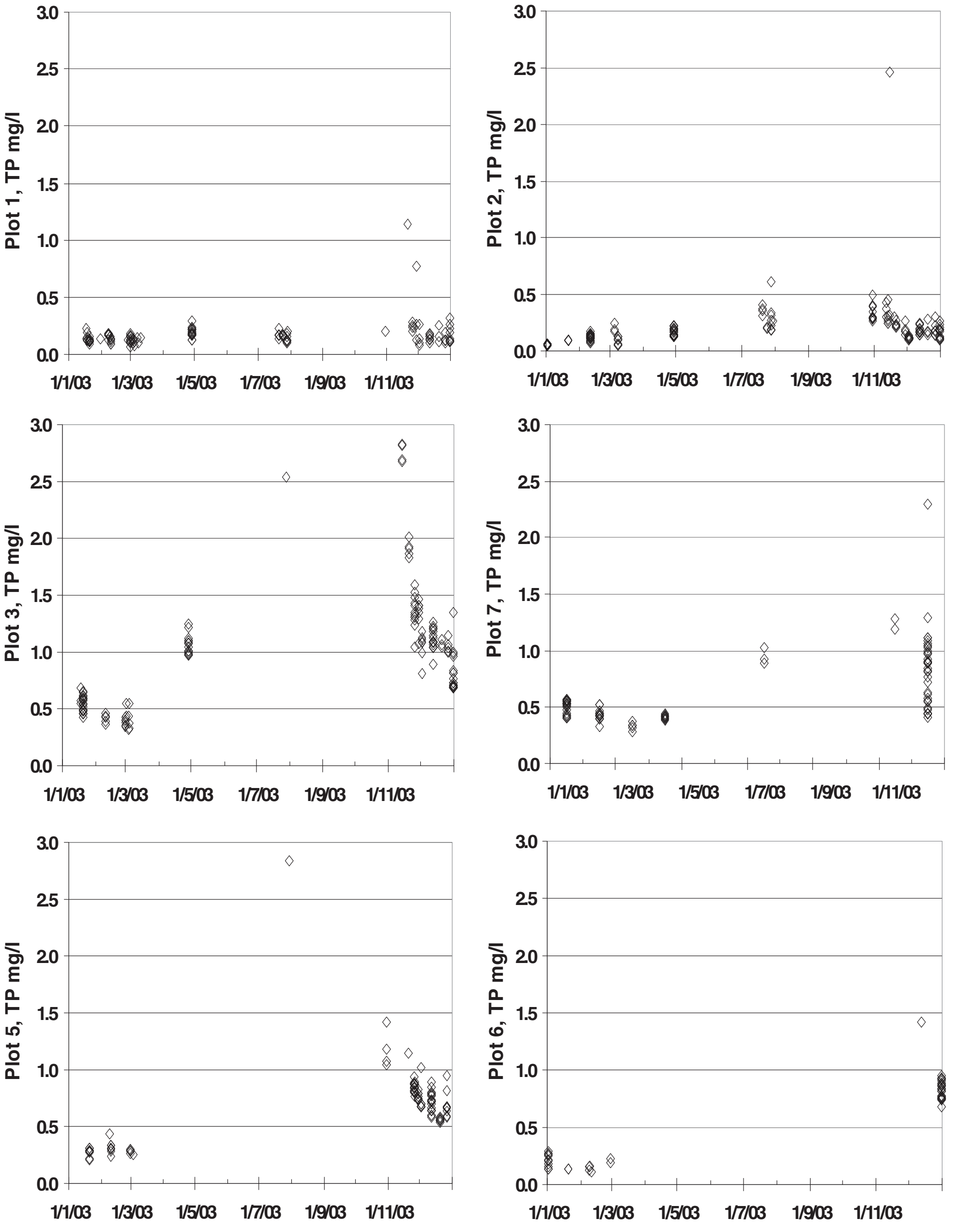

Figure 3.8: Summary of TP concentrations (mg/l) in overland flow water samples from Plots 3 and 6 (grazed) and Plots 1, 2, 5 and 7 (cut) in 2003

6) on Plots 3, 6 and 7 respectively. Over a two-and-a-half hour period on 28 February to 1 March 2002, the mean NH_4-N concentrations were 12 (5 samples, between 22:30 and 23:30h), 5 (5 samples, between 00:00 and 01:00 h) and 8 (8 samples, between 22:45 and 00:30 h) mg/l for Plots 3, 6 and 7, respectively.

The N concentrations in overland flow also tended to be high when overland flow started in the autumn and then decreased. In 2003 there were some high individual TON, NH_4-N, TDN and TN (Figures 3.9 and 3.10) concentrations in overland flow water, particularly on Plot 3 and Plot 5.

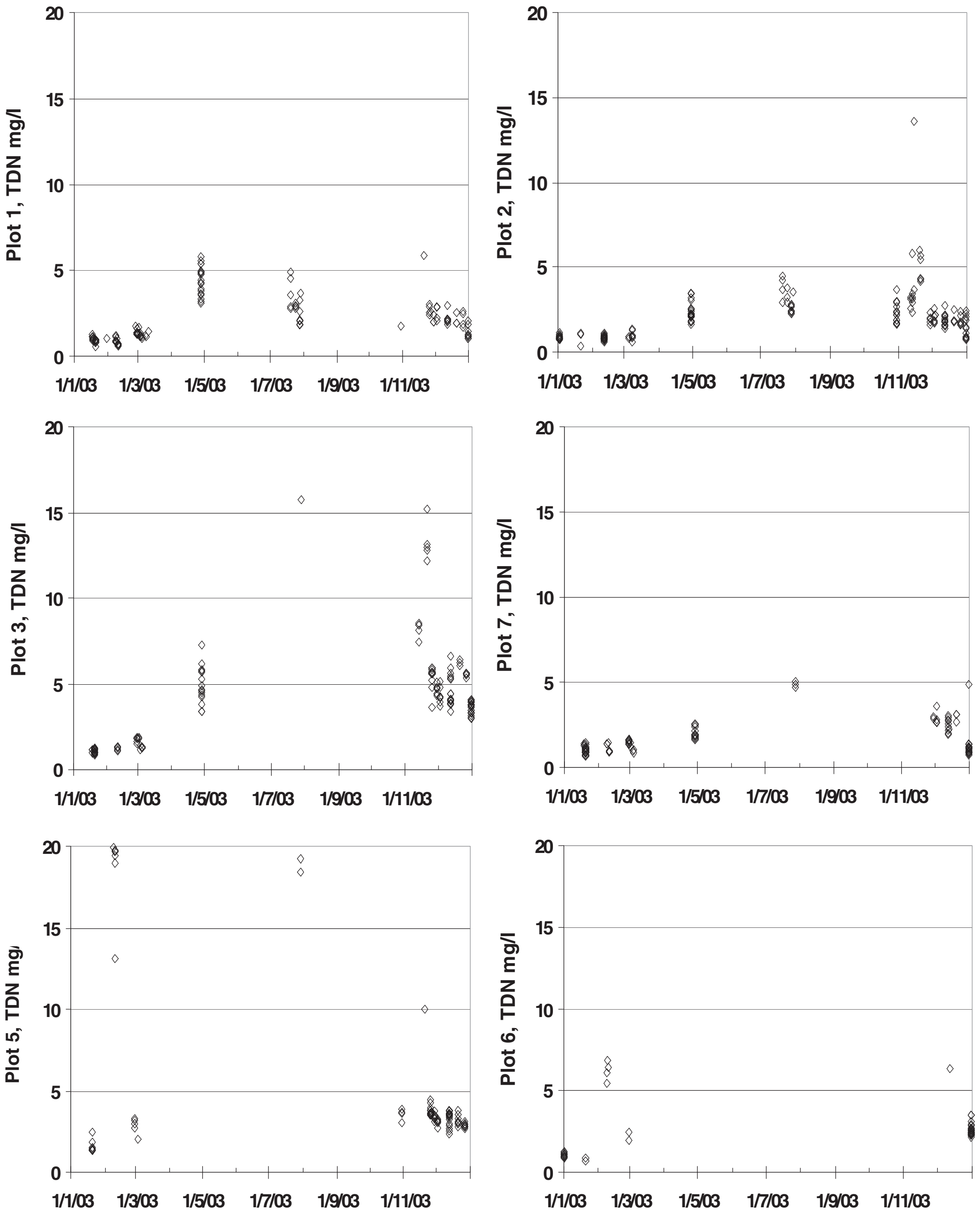

Figure 3.9: Summary of TDN concentrations (mg/l) in overland flow water samples from Plots 3 and 6 (grazed) and Plots 1, 2, 5 and 7 (cut) in 2003

The mean TDN concentrations were broadly similar in 2002 and 2003. The high maximum N levels that occurred for short periods merit further investigation.

It appears that the TDN and TN concentrations for 2003, shown in Figures 3.9 and 3.10, respectively, were somewhat lower on Plot 7 (cut) compared to Plot 3 (grazed). However, the data indicate that the opposite was the case on Plot 5 (cut) and Plot 6 (grazed) in 2003.

There is evidence from recent work in New Zealand (Menneer et al., 2005) that the grazing animal can lead to changes in N transformations in soil. Animal treading increased denitrification (from 52 g/ha/day N_2O-N [nitrous oxide] after severe treading compared to 2.3 g/ha/day with no treading) in grass clover swards.

3.5 Statistical Analysis of Mean Monthly Concentrations of P and N Fractions in Overland Flow

A summary of the statistical analyses of the mean monthly and annual concentrations of P and N fractions in flow proportional overland flow samples is shown in Appendix 2 for 2001, 2002 and 2003. It should be noted that the annual plot and overall means in Appendix 2 are calculated from the monthly means and therefore differ from the annual plot and overall means shown in Tables 3.2, 3.3 and 3.4, which are arithmetic means of all samples.

In 2001 neither the mean annual or mean monthly TRP concentrations were significantly ($P < 0.05$) different between Plot 1 (grazed) and Plot 2 (cut). The mean annual TRP concentrations as well as the monthly means for January and April from Plot 5 (grazed) were significantly ($P < 0.05$) lower than those from Plot 6 (cut). Plot 3 (grazed) had a significantly ($P < 0.05$) higher annual mean TRP concentration than the other four plots; it also had higher monthly means than the other plots with the exceptions of Plot 6 in January and Plots 5 and 6 in December.

In 2002 the mean annual DRP concentration was significantly ($P < 0.05$) lower for Plot 1 than Plot 2 (both grazed) and this was also the case for the monthly means in June, July, September and October. The mean annual DRP concentration was not significantly different between Plot 3 (grazed) and Plot 7 (cut), but the monthly means for the former were significantly ($P < 0.05$) lower in January and higher in April. The mean annual DRP concentration from Plot 5 (grazed) was significantly ($P < 0.05$) higher than that from Plot 6 (cut) but the monthly means were lower than those from the latter in February and June and higher in October, November and December.

In 2003 the mean annual DRP concentration was not significantly different between Plot 1 and 2 (both cut). The mean annual DRP concentration was significantly ($P < 0.05$) higher on Plot 3 (cut) than Plot 7 (grazed) and the monthly means were also higher in April, July, November and December but lower in January. In contrast, the annual DRP concentration was not significantly different between Plot 5 (cut) and Plot 6 (grazed), although, the December mean for the latter was significantly ($P < 0.05$) higher.

Owing to the statistically significant correlation between the three P fractions measured, the mean annual and mean monthly TDP and TP concentrations for 2002 and 2003 (Appendix 2) were broadly similar to that described for the DRP concentrations.

The overall mean annual DRP concentration was 0.49 mg/l for both 2002 and 2003 compared to the TRP concentration of 0.62 mg/l in 2001. The mean annual TDP concentrations were 0.52 and 0.50 mg/l and the mean annual TP concentrations were 0.60 and 0.70 mg/l in 2002 and 2003, respectively.

In general, there was a tendency for significantly ($P < 0.05$) higher mean DRP concentrations to occur in summer months (on the few occasions when overland flow occurred) and when overland flow started in the autumn, compared to December and January.

The mean annual and monthly DRP concentrations were significantly ($P < 0.05$) higher on Plots 3 and 7 (both with high STP) than on Plots 1 and 2 (both with low to medium STP) in both 2002 and 2003 and for all months where samples were taken. This is one of the most significant results of this study: other differences were lower in magnitude and less consistent.

There were significant differences ($P < 0.05$) in the mean annual and monthly concentrations of the N fractions studied between plots (Appendix 2). There were some high mean monthly concentrations for TON, NH_4-N, TDN and TN. Many of these occurred in months when N fertiliser was spread and when overland flow started in the autumn. The mean annual TON, NH_4-N and TDN concentrations appeared to be higher in the wet year 2002 than the other two years. However, this may have been partly influenced by the high estimated values for the N fractions for Plot 6 in June and for Plots 3, 5, 6 and 7 in July and August 2002, which were based on a small number of observations and should be interpreted with caution.

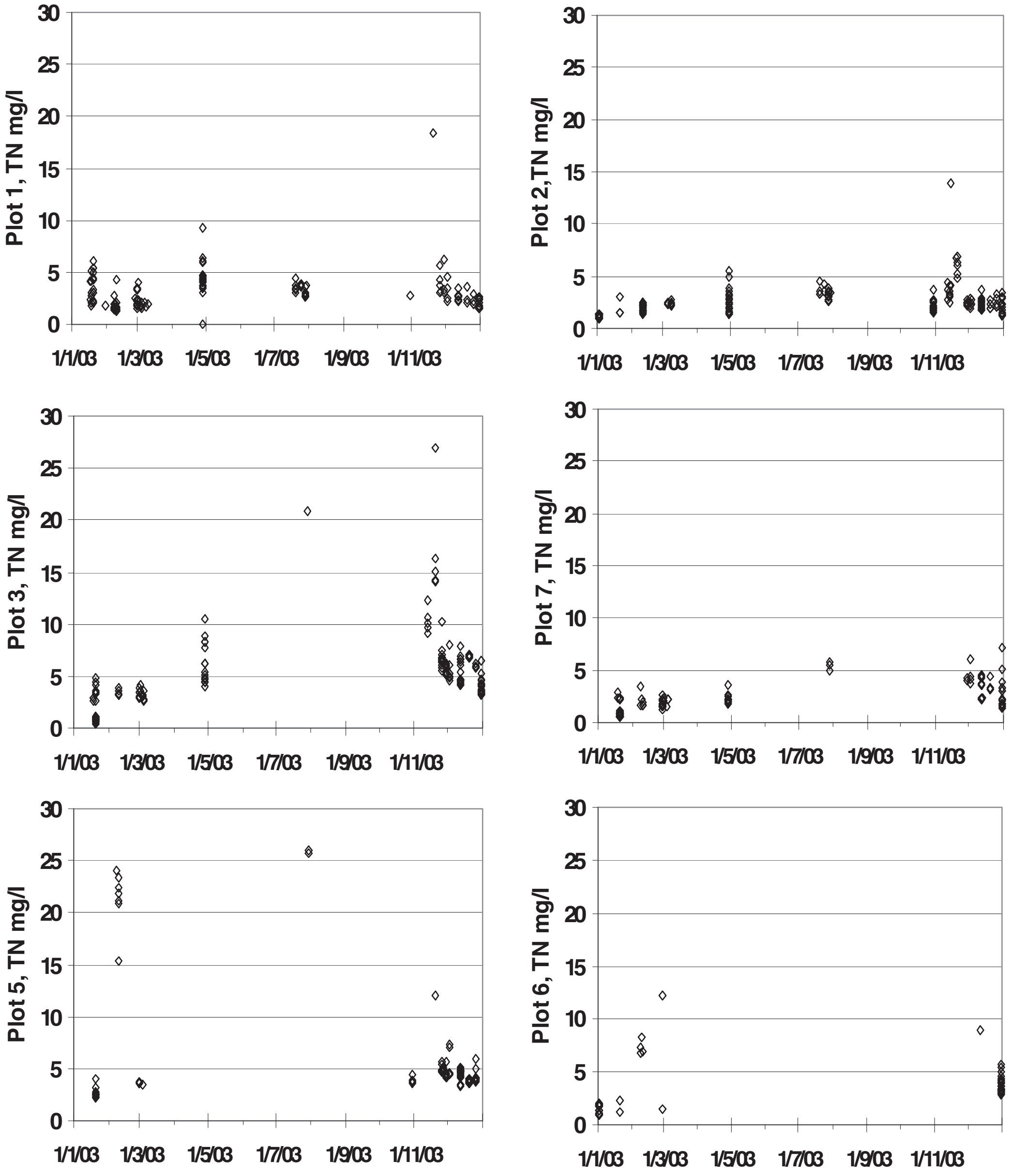

Figure 3.10: Summary of TN concentrations (mg/l) in overland flow water samples from Plots 3 and 6 (grazed) and Plots 1, 2, 5 and 7 (cut) in 2003

3.6 Relationships between N Concentrations in Overland Flow Water Samples

3.6.1 P and N

There was an overall significant relationship between TP and TDP concentrations over the two years (2002 and 2003) for the six plots (TDP = 0.79TP - 0.018, R^2 = 0.84, P <0.001), between TDP and DRP concentrations (DRP = 0.87TDP + 0.0084, R^2 = 0.81, P <0.001) and between TP and DRP concentrations (DRP = 0.72TP - 0.019, R^2 = 0.73, P <0.001). There was also a strong relationship between TN and TDN concentrations (TDN = 0.74TN + 0.012, R^2 = 0.88, P <0.001). There were weak relationships between TN and either TON or NH_4-N concentrations. A scatter plot of the TON and NH_4-N concentration in overland flow from the six plots for the three years is shown in Figure 3.11. This shows that a significant relationship does not exist between the two parameters; however, Figure 3.11 does illustrate that, in general, when ammonium concentrations were high, TON (mostly nitrate N) was low and visa versa. There were two samples where both parameters were high.

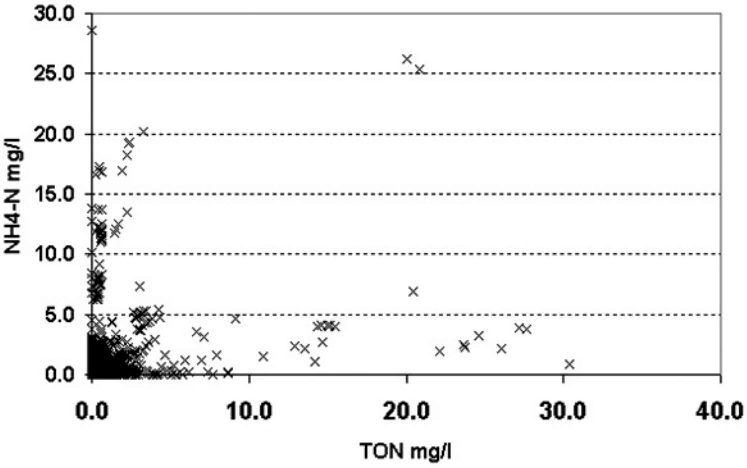

Figure 3.11: Scatter plot of TON and NH_4-N concentrations (mg/l) in overland flow water from six plots over three years (2001–2003)

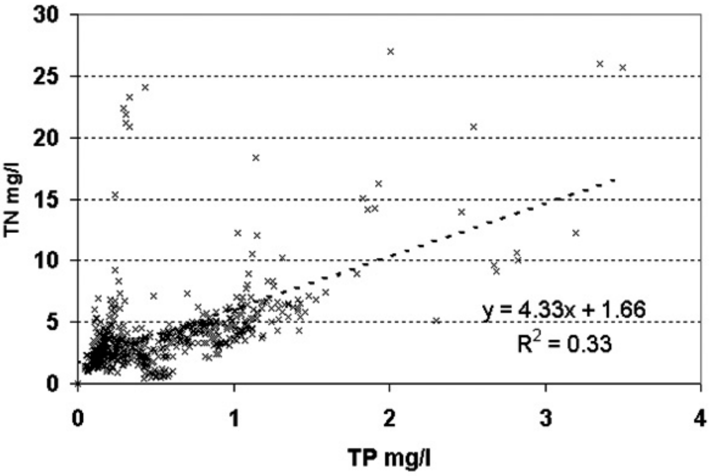

Figure 3.12: Relationship between TP and TN concentrations (mg/l) in overland flow water samples from the six plots in 2003

Twenty-four samples had TON concentrations (mostly nitrate N) over 10 mg/l and 75 samples had NH_4-N concentrations over 5 mg/l.

There was an overall statistically significant ($P < 0.001$) relationship between TP and total TN concentrations in overland flow water. This relationship is illustrated in Figure 3.12 and indicates that on average there were 4 to 5 times higher TN than TP concentrations in overland flow water.

The relationship was best on Plots 1, 2, 3 and 7 (individual plot data sets with $R^2 > 0.5$) and weak on Plots 5 and 6 ($R^2 < 0.2$). There was also a significant relationship between TP and TDN concentrations ($R^2 = 0.32$, $P < 0.001$) and between TDP and TDN concentrations ($R^2 = 0.24$, $P < 0.001$).

The relationships between TP and TDP and also between TN and TDN concentrations for the six plots from November 2003 to March 2004 are summarised in Figure 3.13. It is clear that most of the TN and TP concentrations in overland flow from these grassland plots were in soluble form; this is similar to results of other work (Haygarth et al., 1998).

There was also a statistically significant relationship between TP and DRP concentrations for the same period ($DRP = 0.77TP - 0.112$, $R^2 = 0.77$, $P < 0.001$). These results for this period, when the methodology was well established in the laboratory, are broadly in agreement with the results for 2002 to 2003, given at the start of this section (3.6.1).

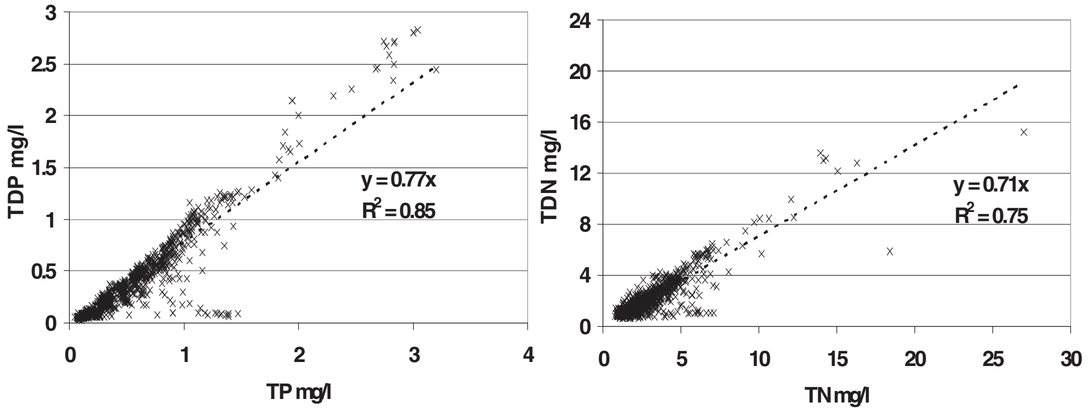

Figure 3.13: Relationships between TP and TDP concentrations (mg/l) and between TN and TDN concentrations (mg/l) for the six paired plots, November 2003–March 2004

There was a statistically significant relationship between soluble P and N concentrations in overland flow water; in 2003 the relationship was as follows; TDN = 3.80TDP + 1.42, $R^2 = 0.26$, $P < 0.001$.

3.6.2 P and K

This section describes the total reactive P (TRP) and K concentrations in overland flow water from six plots (Plots 1 to 6, including Plot 4), from September 2000 to April 2001.

A total of 2467 flow proportional water samples were collected during this study period (520, 499, 382, 250, 415 and 401 from Plots 1 to 6 respectively). There was a statistically significant relationship ($P < 0.01$) between TRP and K for all six plots combined and for Plots 2 to 6 individually. The relationship was not significant for Plot 1, which had the lowest TRP levels. There was not a statistically significant correlation between soil test P and soil test K for the six plots; however, there are only six data points. The mean concentrations of TRP and K in overland flow for the six plots are summarised in Table 3.5. Relationships between the mean concentrations of TRP and K in overland flow for the six plots (1 to 6) are plotted in Figure 3.14.

The K concentrations in overland flow water were generally of the order of 5 to 10 times higher than the TRP concentrations.There were significant correlations ($P < 0.05$) between TRP and K loss in overland flow from five of the six plots. The best relationship, of the six plots, was on Plots 3 and 6. These plots also had the highest TRP and K concentrations in overland flow water and the highest soil STP of the six plots monitored at that time.

Figure 3.15 indicates that there were similar temporal trends for both K and TRP concentrations in overland flow, with the highest concentration occurring when overland flow started in the autumn followed by a steady decline.

The highest TRP concentrations for this period were in autumn 2000 when overland flow started after the summer (see Plot 3, Figure 3.15). The relationship between TRP and K exists despite the wide variations in TRP and K concentrations.

An important factor influencing the relationship between P and N concentrations and P and K concentrations is the tendency for all these nutrients to be high as overland flow starts in the autumn (autumn wash-out) and for them to decrease together over the following months to reach lower concentrations in December and January.

3.6.3 Suspended Solids

SS were analysed on the overland flow samples from the six paired plots from November 2003 (when overland flow started after the summer) to March 2004 only. The trends in SS in overland flow water from the six plots from November 2003 to March 2004 are summarised in Table 3.6 and in Figure 3.16.

The overall mean was 45 mg/l SS for the six plots in this overland flow period and Plots 5 and 6 had the lowest level

Table 3.5 Mean TRP and K concentrations (mg/l) in overland flow water and correlation coefficient between TRP and K (R^2) for the six plots (1 to 6) from September 2000 to April 2001. The last row shows the number of overland flow samples per plot

Plot No.	**1**	**2**	**3**	**4**	**5**	**6**
TRP mg/l	0.06	0.11	1.23	0.27	0.39	0.68
K mg/l	1.34	0.82	8.07	6.68	7.02	9.37
*TRP v K, R^2	0.004	0.29	0.61	0.39	0.54	0.72
Significance	ns	$P<0.001$	$P<0.001$	$P<0.001$	$P<0.01$	$P<0.01$
No. samples	520	499	382	250	415	401

*Statistical significance differences shown in title of Figure 3.13, which is a chart of the data.

of SS. Plot 2 had the highest SS and this was due to very high SS levels during two events (06:23–07:14 h on 8 January and 08:16–13:00 h on 4 February 2004). Plot 1, the pair of Plot 2, also had high SS in two overland flow samples in November 2003. On neither of these occasions were grazing animals present on theplots as they were not grazed after October 2002.

The high SS levels, particularly on Plots 1 and 2 were unusual and may have been because of channel erosion with soil entering overland runoff water (e.g. on 3 and 4 February 2004, see Plot 2 on top-right of Figure 3.16).

Examples of trends in flow and SS, TP and TDP concentrations for 3 and 4 February 2004 for Plots 3 and 7 are shown in Figure 3.17.

The concentration of SS is linked closely to flow as is TP. The concentration of TDP is less closely linked.

There was a significant relationship ($P <0.05$) between SS and PP on all six plots. The highest correlation was on Plots 1 and 7 (R^2 of 0.9 and 0.8 respectively). The mean %PP in the SS was 0.41, 0.64, 0.91, 0.73, 0.73 and 0.62 for Plots 1, 2, 3, 7, 5, and 6 respectively.

3.6.4 SS Load

For Plots 2, 3, 7 and 5, in the region of 50% of the total SS load to the overland flow water measured between November 2003 and March 2004, occurred in two days, namely on 3 and 4 February 2004.

An estimate of the SS load that could be lost from these soils can be made as follows. Assuming an annual overland flow of 100 mm (1000 m^3 per ha) per annum (the overland flow on these plots was generally between 50 and 250 mm per annum in 2003, see Figure 3.3) and a mean concentration of 45 mg SS per litre, then the SS load lost to overland flow would be 45 kg SS per ha. With 200 mm overland flow the load would be 90 kg SS per ha per annum. These levels of SS loss are low compared to losses of several tonnes per ha that can occur with severe soil erosion under tillage conditions (Morgan et al., 1998).

The data indicate that presence or absence of grazing animals in the previous grazing season was not the major factor influencing the concentration of SS in overland flow water between November 2003 and March 2004 on the six plots (see Plots 3, 7, 5 and 6 in Figure 3.16). The low loss of SS from these grazed grassland plots is likely to be true for most grazing situations under conditions of good farming practice in Ireland. However, it is possible that there could be significantly greater SS loss in situations where soil poaching occurs due to animals grazing on wet soils or on sacrifice paddocks.

The concentrations of SS in overland flow water in this field plot study were lower than the values measured in the Oona Water, Co. Tyrone but higher than those measured in the Dripsey, in Co. Cork as part of the Three Catchment Study (Project LS-2.1.1a). It is possible that some of the SS present in these edge-of-plot overland flow water samples would be trapped and deposited before reaching the nearest natural watercourse.

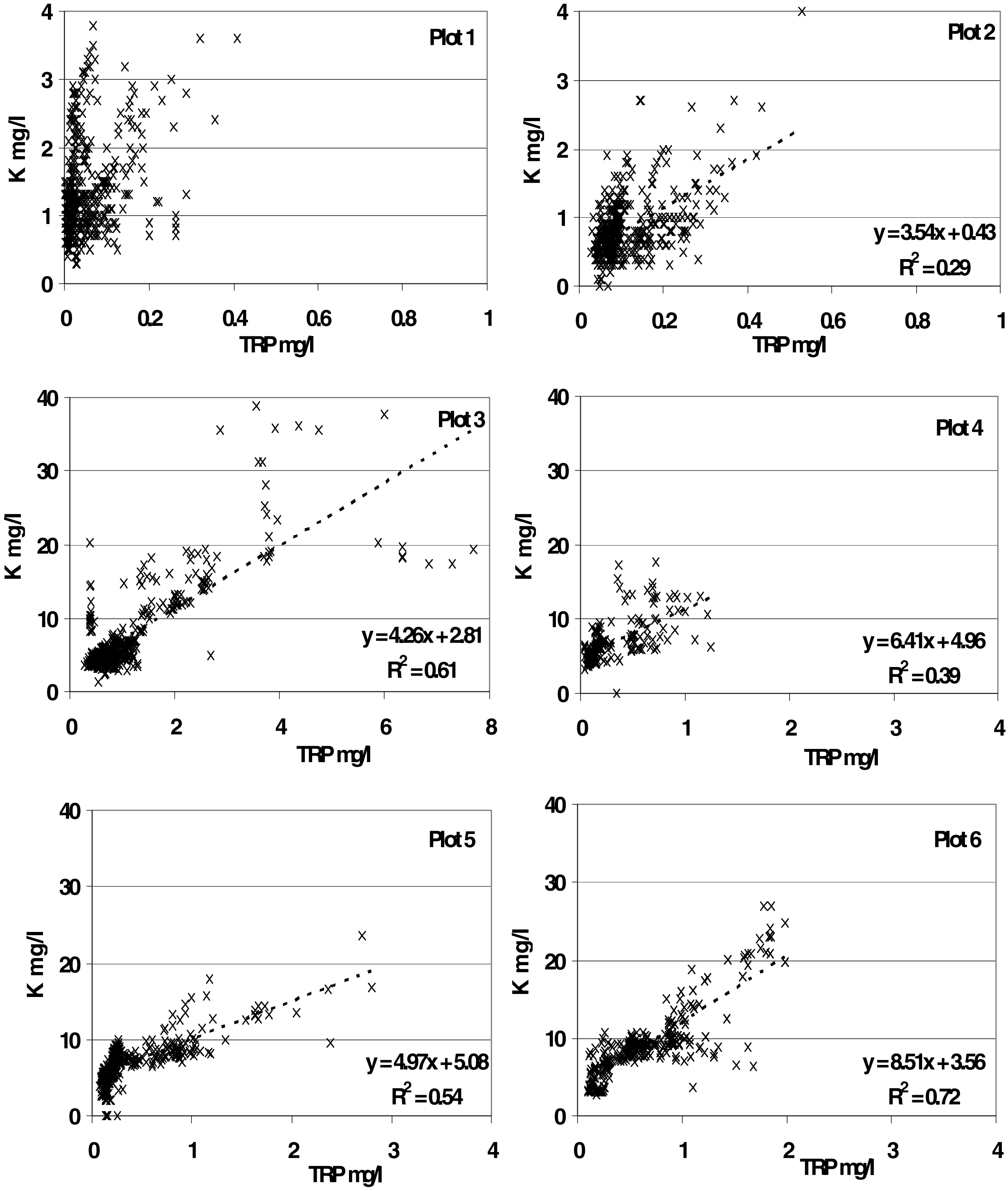

Figure 3.14: Relationship between TRP and K concentrations (mg/l) in overland flow from six plots, Sept. 2000–April 2001 (Plot 1, not significant; 2, P<0.001; 3, P<0.001; 4, P<0.001; 5, P<0.01; 6, P<0.01)

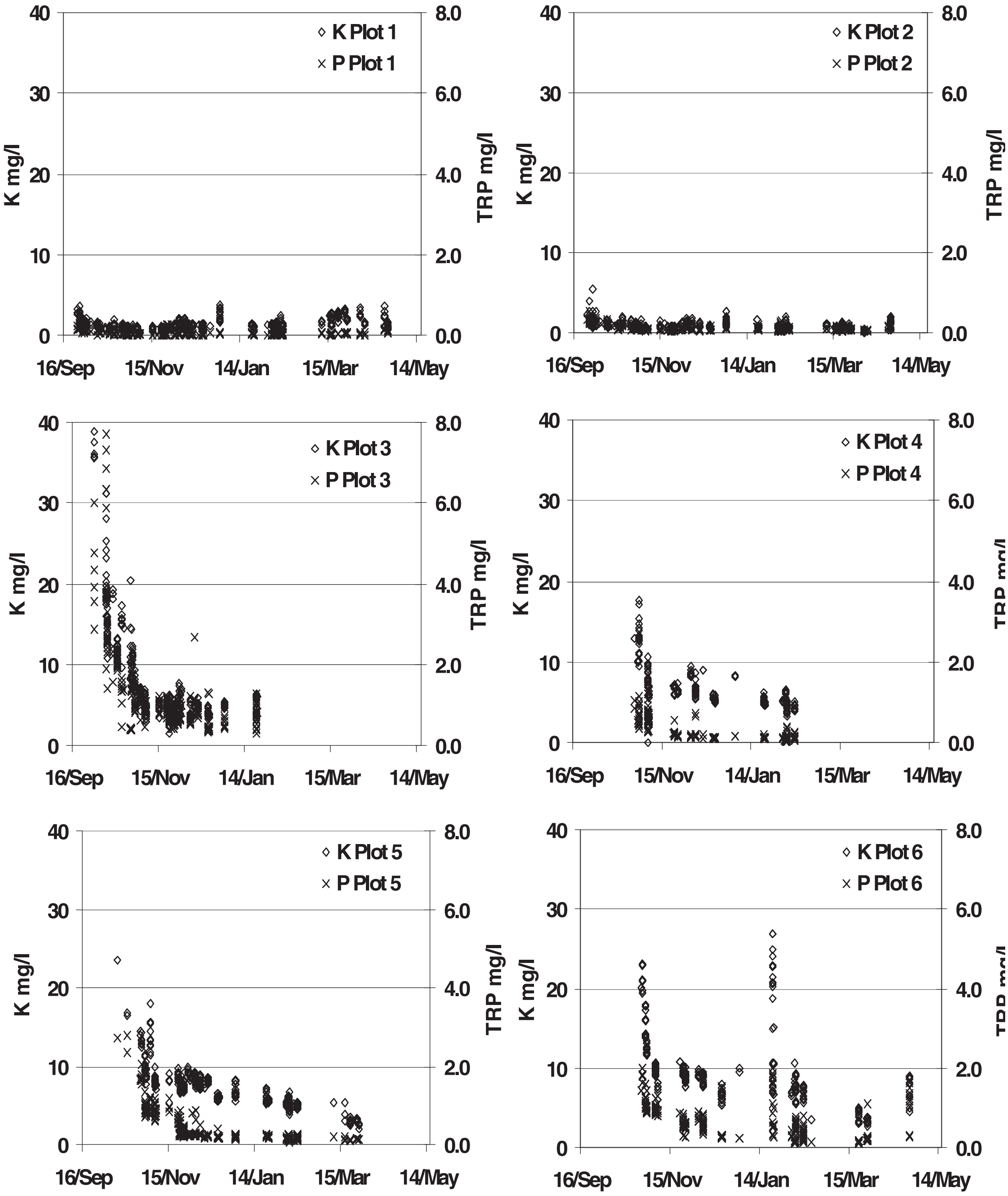

Figure 3.15: Temporal trends in K and TRP concentrations (mg/l) in overland flow water from six plots, Sept. 2000–April 2001

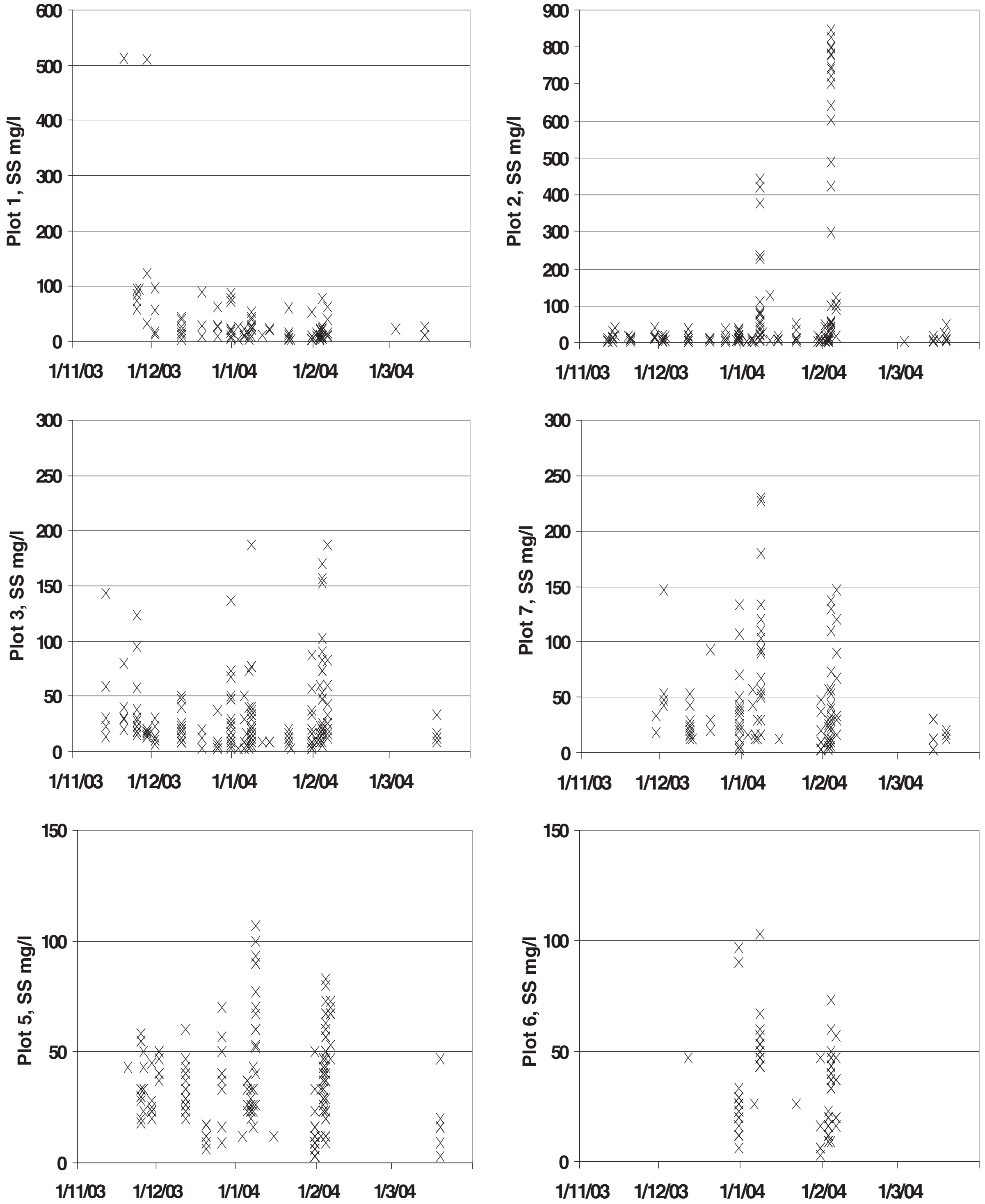

Figure 3.16: Trends in SS concentrations (mg/l) for six plots in the overland flow, November 2003–March 2004. Plots 3 and 6 were grazed the other plots were cut in 2003

Table 3.6 The mean, maximum and standard deviation (STDEV) of SS in mg/l in overland flow water samples from the six plots between November 2003 and March 2004. The last row shows the number of overland flow samples per plot

	Plot 1	Plot 2	Plot 3	Plot 7	Plot 5	Plot 6
Mean	36.3	83.7	30.5	41.9	34.2	34.3
Maximum	513.0	847.0	187.0	230.0	107.0	103.0
STDEV	73.2	193.8	34.6	45.9	20.7	19.4
No. Samples	100	183	183	122	194	106

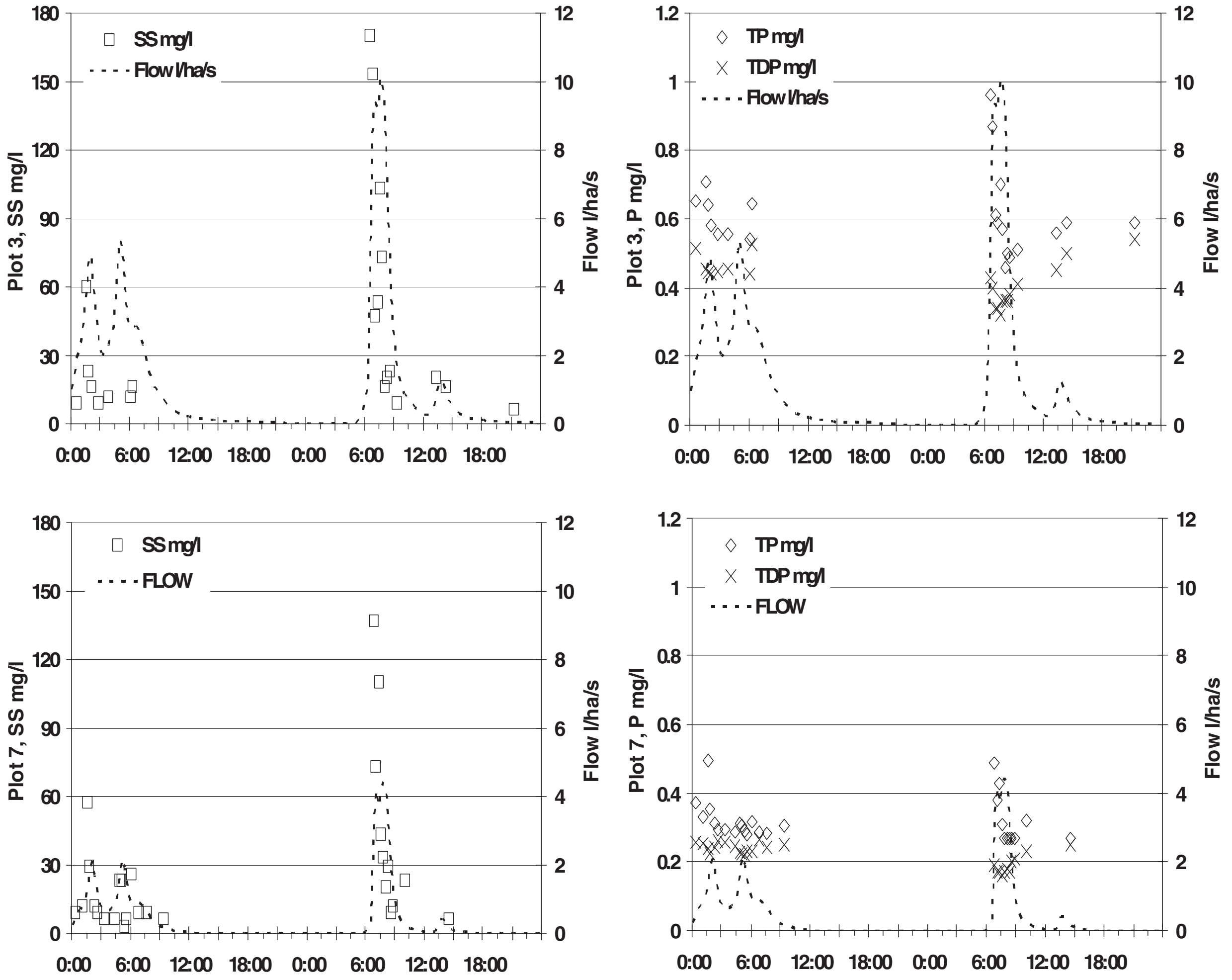

Figure 3.17: Trends in flow (l/ha/s), SS, TP and TDP concentrations (mg/l) for Plot 3 (grazed to October 2003) and Plot 7 (cut in 2003) on 3 and 4 February 2004

3.7 Examples of N and P Concentrations from Grazed and Cut Grassland during Single Overland Flow Events

This section deals with a number of individual overland flow events and gives details of flow (in litres per second per ha) and the concentrations of the P and N fractions in overland flow sampled during these events.

3.7.1 April 2002

An extreme example of the difference between cut and grazed areas was observed on Plots 3 and 7 on 21 April 2002. Plate 3.1 shows the two plots after the rainfall. The poaching due to grazing during the heavy rainstorm is not representative of good farming practice. Nonetheless, it is an example of what can occur in practice on a farm. During this event, there was more colour in the water from Plot 3 compared to Plot 7 (Plate 3.2). This colour may have been because of increased soil organic matter and/or fine soil particles due to poaching by the grazing animals.

Plate 3.1: Plot 3 on left (grazed) and Plot 7 on right (cut) photographed on 21 April 2002. Grazing animals poached Plot 3 during the heavy rainfall on the morning of 21 April

Plate 3.2: Overland flow water collected from Plot 3 (grazed, left) and Plot 7 (cut, right) on 21 April 2002 after the heavy rainfall when the animals were grazing Plot 3.

Flow measurements and P concentrations in overland flow water from the two plots are shown in Figure 3.18 while flow and NH_4-N and TDN concentrations are summarised in Figure 3.19. Figure 3.18 indicates that while DRP concentrations were broadly similar from each plot, TP concentrations from the grazed plot were almost double those from the cut or ungrazed plot. This suggests that the poaching by grazing animals increased sediment loss and hence increased TP concentration. TDN was greatest at the start of storm flow and then decreased with time (Figure 3.19). This contrasts with DRP which increased with time as flow increased (Figure 3.18). TDN was lower for the grazed plot compared to the cut but the opposite was found for NH_4-N which was higher in runoff from the grazed plot (Figure 3.19).

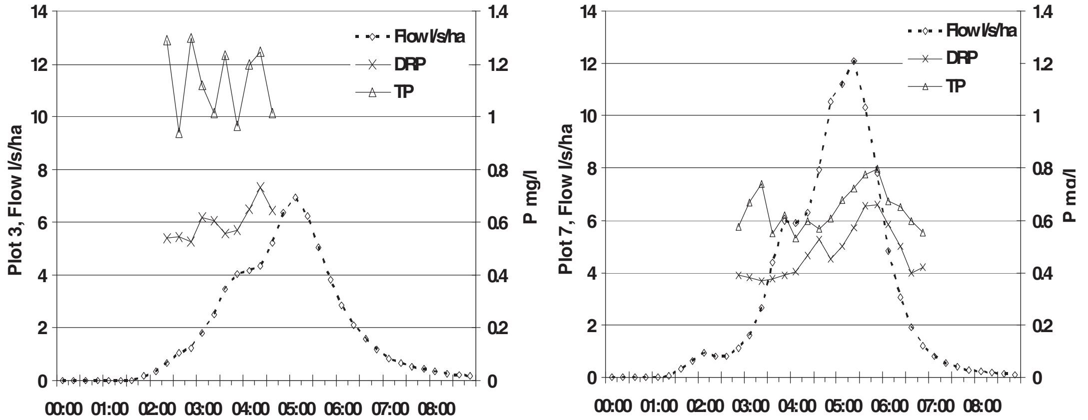

Figure 3.18: Overland flow (l/s/ha) and DRP and TP concentrations (mg/l) in overland flow from Plot 3 (left, grazed) and Plot 7 (right, cut) sampled on 21 April 2002 after heavy rainfall

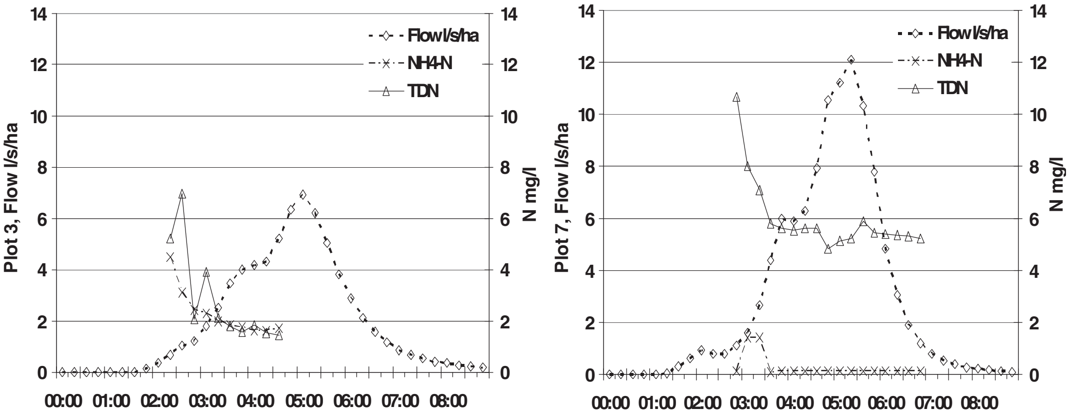

Figure 3.19: Overland flow (l/s/ha) and NH_4-N and TDN concentrations (mg/l) in overland flow from Plot 3 (left, grazed) and Plot 7 (right, cut) on 21 April 2002 after heavy rainfall

3.7.2 October 2002

Concentrations of the P fractions in overland flow from Plots 3 and 7 on 20 and 21 October 2002 show evidence of higher P concentrations from the grazed plot (Plot 3) than from the cut plot (Plot 7, Figure 3.20). Overland flow samples were missed from the peak of the event at about 22:00 h on 20 October because all the bottles in the Sigma sampler were full. The grazed plot had higher TP for the flow peak from 12:00 to 18:00 h on 21 October.

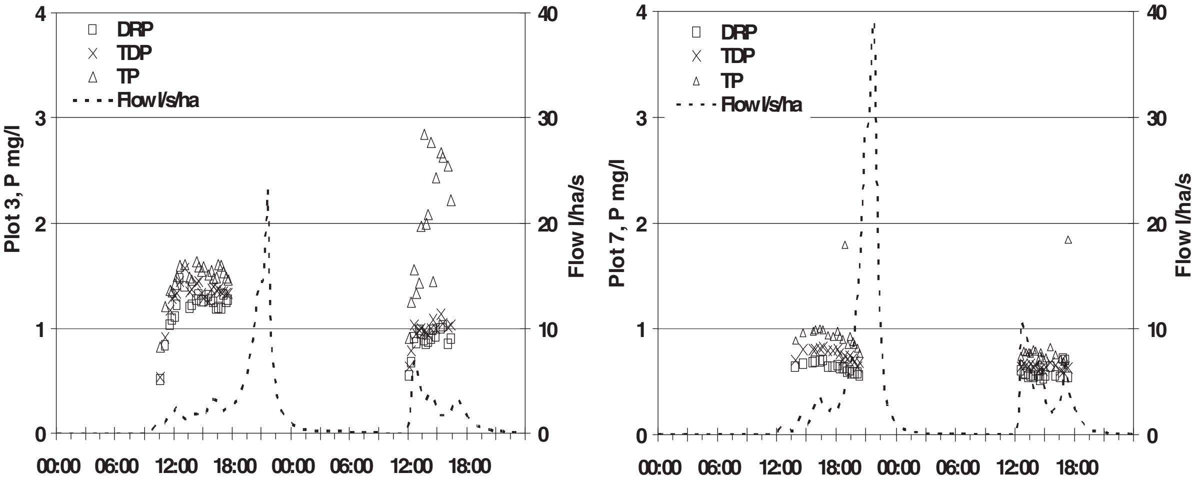

Figure 3.20: Overland flow (l/s/ha) and P concentrations (mg/l) in overland flow from Plot 3 (left, grazed) and Plot 7 (cut) on 20–21 October 2002

3.7.3 November 2002

For the storm event of 18 and 19 November 2002 (Figure 3.21) there was no clear evidence of a difference in the concentrations of the P fractions between the grazed and cut plots. The data in the figure also indicate that, in the case of the grazed pair, Plot 1 had lower concentrations of DRP and TDP than Plot 2, which had higher STP (Table 2.2). As with P, there was not a large difference in N concentrations (Figure 3.22) between the grazed and cut plots, as also noted for the storm of 21 April 2002. However, the TDN concentrations declined through the event, in contrast to the P concentrations (Figure 3.21). The TDN concentrations were low (<3 mg/l) and the TON and NH_4-N concentrations were very low. The TDN was lower on Plot 2 than on the other plots – the reason for this is not clear (Figure 3.22).

3.7.4 February 2004

The concentrations of P in overland flow from the grazed plots (3 and 6) on 3 February 2004 were higher than from the corresponding cut plots (5 and 7) (Figure 3.23). Plot 3 was last grazed in October 2003 (Appendix 1). Most of the TN was present as TDN and the concentrations of TON and NH_4-N were generally low (Figure 3.24).

The results in this section (3.7) show differences in the concentrations of P fractions between cut and grazed plots for some overland flow events. However, the differences were generally small compared to the overall difference between the six plots.

3.8 P Load

The cumulative mean daily TRP and DRP loads via overland flow are summarised in Figure 3.25. Plots 1 and 2 had the lowest cumulative TRP load in 2001 and DRP loads in 2002 and 2003. Although they had the highest overland flow they had low P loads, because of the low P concentration in the flow. Plots 3, 7 and 5 had the highest loads.

Figure 3.25 shows that the highest P loss (load) to water generally occurred between October and December and this is particularly evident for 2002. This is due to the high P concentrations and high flows during the autumn. The loads of the other P and N fractions had trends similar to those shown in Figure 3.25.

As already indicated in the discussion on flow (Section 3.3) there are limitations in using nutrient load to shown differences between plots in this study, because the major influence on flow was plot related and this largely masked any possible effects of the grazing compared to the cutting treatments under these experimental conditions. However, the results of the load estimations show that the loss was generally in the range of 0.2 to 1.4 kg DRP per ha per year.

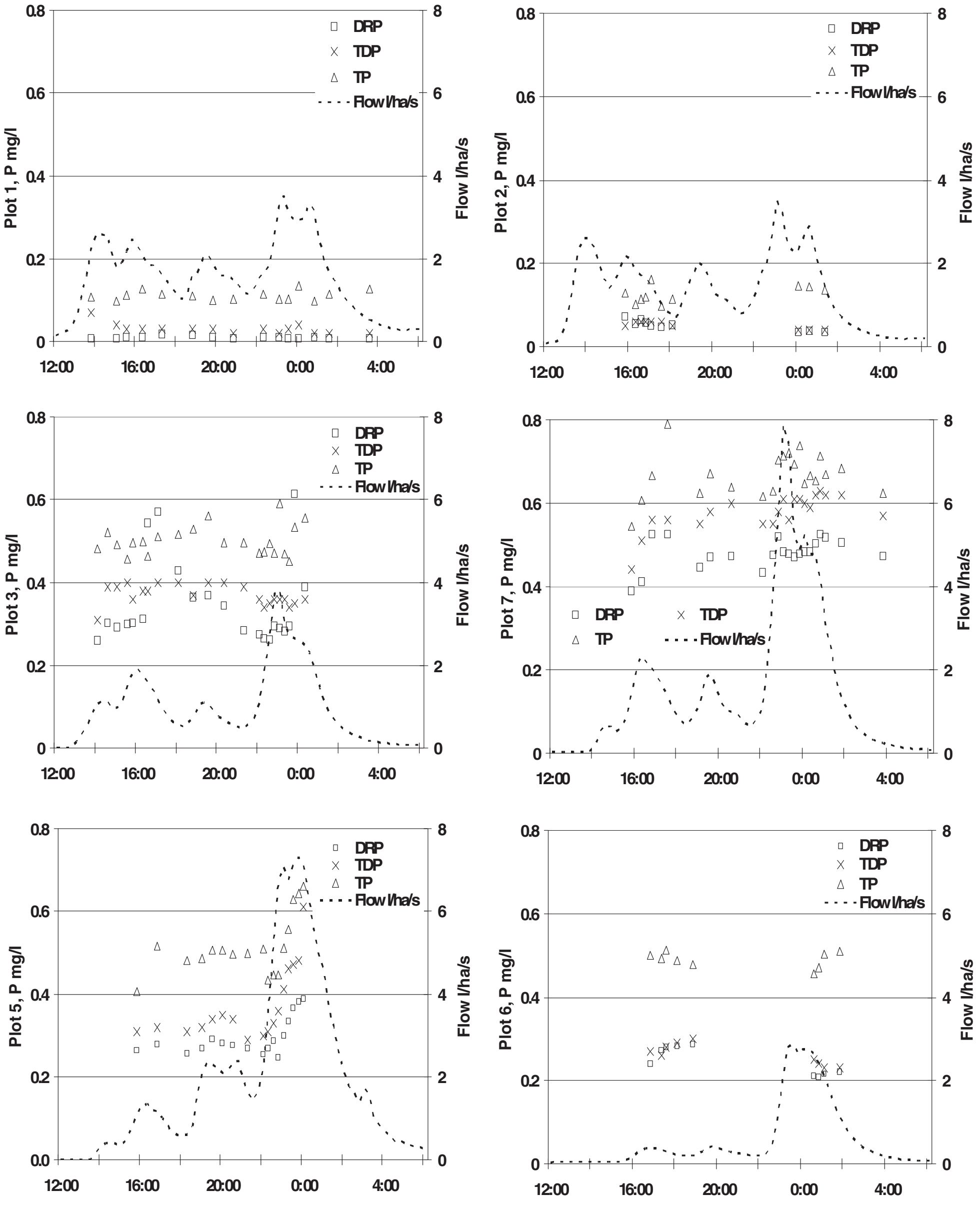

Figure 3.21: Overland flow (l/s/ha) and P concentrations (mg/l) in overland flow from six plots on 18–19 November 2002 (Plots 1, 2, 3 and 5 were grazed and Plots 6 and 7 were cut in 2002)

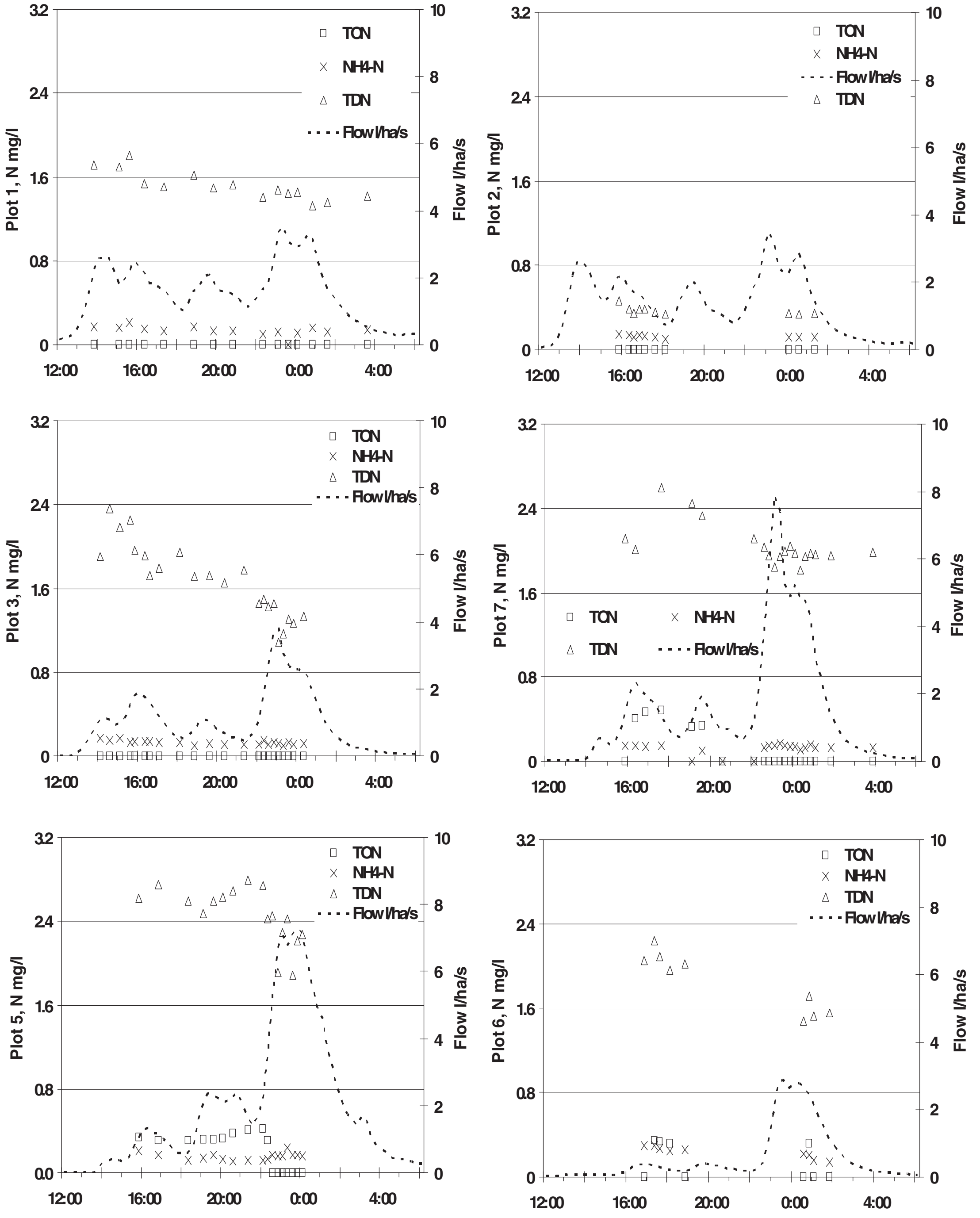

Figure 3.22: Overland flow (l/s/ha) and N concentrations (mg/l) in overland flow from six plots on 18–19 November 2002 (Plots 1, 2, 3 and 5 were grazed and Plots 6 and 7 were cut in 2002)

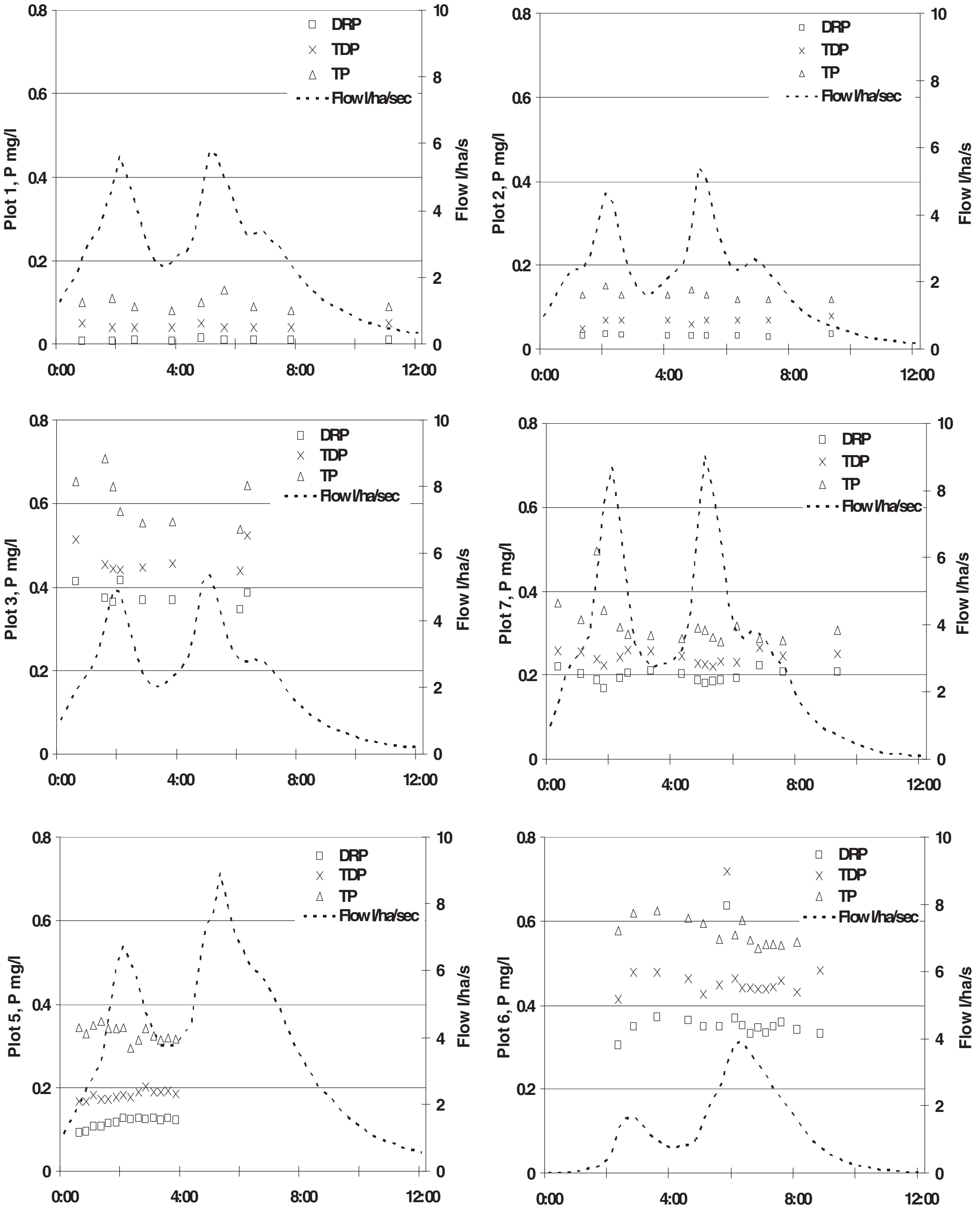

Figure 3.23: Overland flow (l/s/ha) and P concentrations (mg/l) in overland flow from six plots on 3 February 2004 (Plots 3 and 6 were grazed and Plots 1, 2, 5 and 7 were cut in 2003)

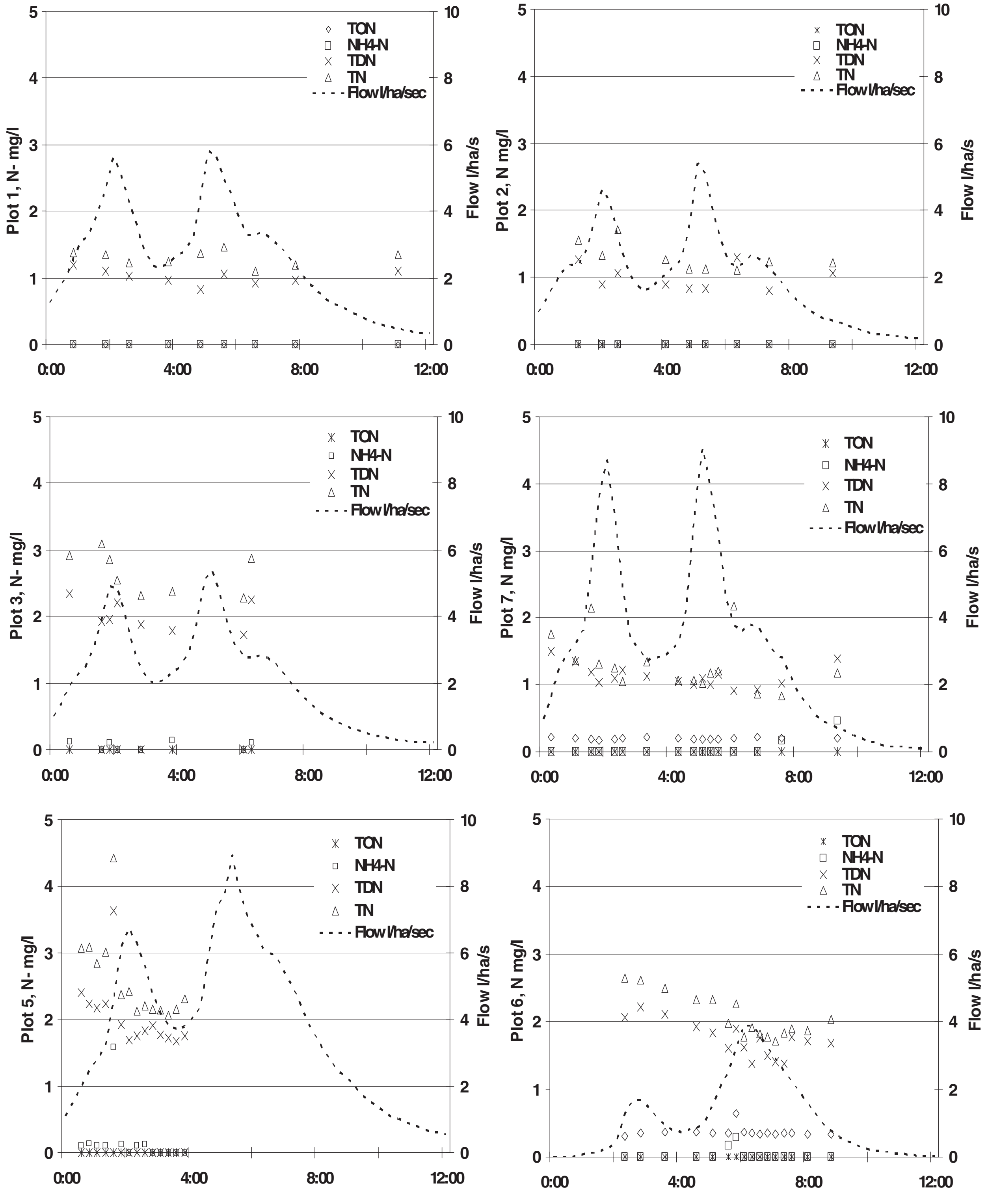

Figure 3.24: Overland flow (l/s/ha) and N concentrations (mg/l) in overland flow from six plots on 3 February 2004 (Plots 3 and 6 were grazed and Plots 1, 2, 5 and 7 were cut in 2003)

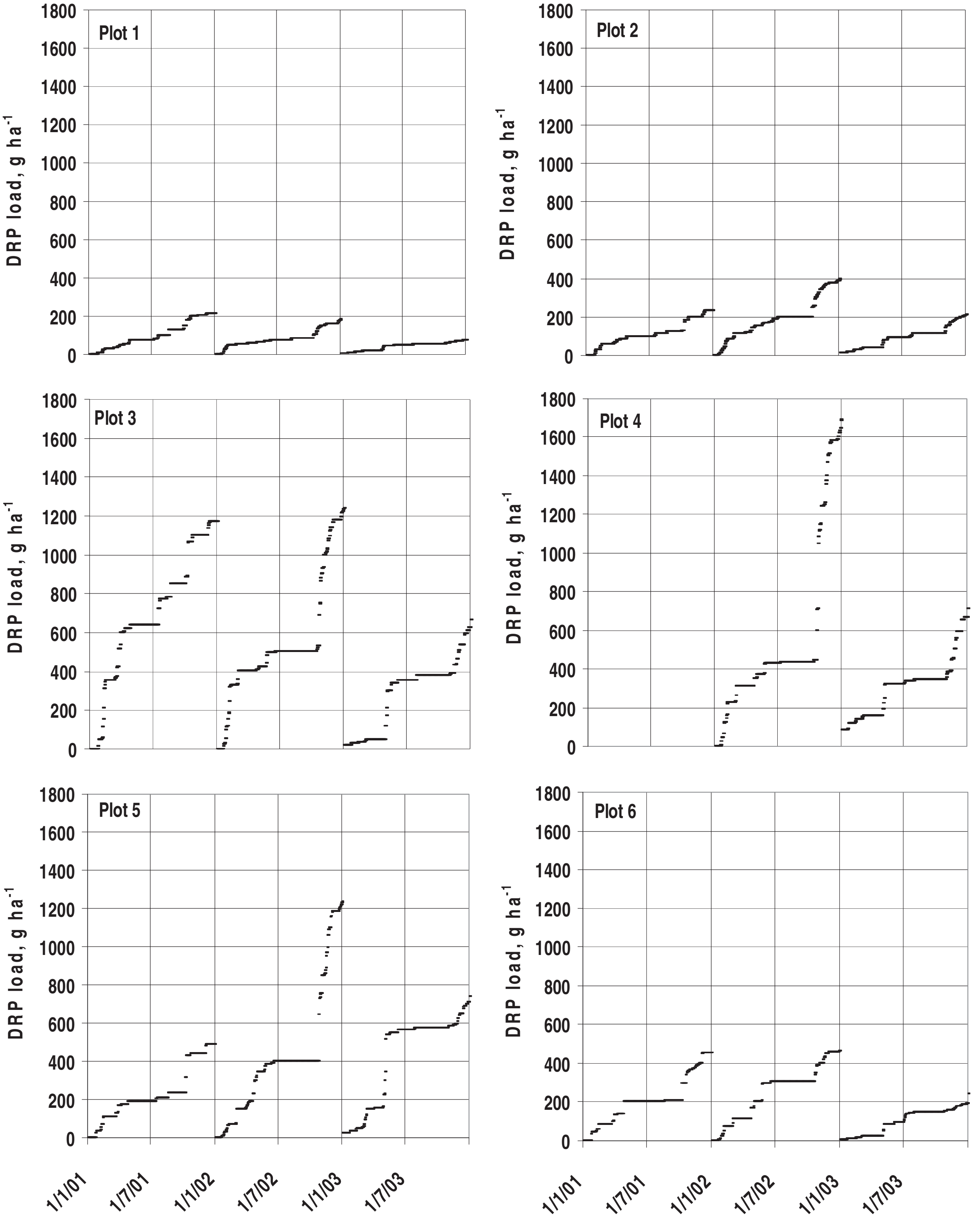

Figure 3.25: Cumulative P (TRP in 2001 and DRP in 2002 and 2003) loads in overland water (g/ha) from the six paired field plots in the three years 2001–2003

4 Conclusions and Recommendations

The principal conclusion from this part of the LS-2.1.2 project is that while the grazing animal does influence P concentrations in overland flow, this impact is minor when compared to the other factors that determine P loss from grassland under standard management regimes.

The wide variation of P concentrations in surface runoff between plots appeared to be related predominantly to factors other than the presence or absence of grazing animals. The accumulated surplus applied P, resulting in increased STP, is a more important factor than grazing in influencing the P concentration in overland flow water. This is in agreement with work in North America indicating that a variety of factors control P release from soils to surface runoff and that there is often a strong relationship between soil test P and runoff P although the relationship varies for different soils (Sharpley et al., 1994; McDowell et al., 2001; Torbert et al., 2002). Further, larger studies with more replications would be necessary to obtain greater confidence on the apparently relatively small impact of the grazing animal on nutrient and sediment loss in overland flow water under a range of Irish grasslands conditions.

4.1 Other Studies

The conclusion that the grazing animal has a limited impact on P losses compared to other factors is also in broad agreement with a recent study from Florida, USA, where it was concluded that cattle grazing did not have a significant cumulative effect on nutrients in runoff at the whole pasture scale during a five-year period (Capece et al., 2007). In the Florida study the main difference in P loss was between summer- and winter-grazed pastures. The former was fertilised more intensively and had significantly ($P < 0.05$) higher P losses than the latter, which had low soil test P levels. In that study (conducted from 1998–2003), the improved summer pasture discharged a mean of 1.7 kg TP (mean TP conc. 0.63 mg/l) per ha per year. The semi-improved winter pasture discharged a mean of 0.25 kg TP (mean TP conc. 0.15 mg/l) per ha per year. These differences in runoff nutrients were attributed to soil-nutrient test results from the top 5 cm of pasture soils due to earlier fertiliser practices. There was no significant difference between P runoff from lands with four stocking rates (control, low, medium and high) (Capece et al., 2007).

4.2 Risk of High P Loss from Grassland

While the grazing animal *per se* was not found to be the main factor influencing P concentration in overland flow from grassland plots under these experimental conditions, it is important to note that grassland, whether cut or grazed, can have an increased potential for P loss in overland flow compared to other land use. There are a number of reasons for this, including: normally high surplus P inputs into intensive grassland systems in fertiliser and purchased feeds and the application and accumulation of applied P in fertiliser and animal manures at or near the soil surface, thus making it more available for interaction with overland flow water. In addition, worm casts and decaying biomass, both flora and fauna, that often have high P contents, also tend to accumulate at or near the soil surface and release P on mineralisation. This leads to the sometimes very high soil P levels in the top few centimetres of grassland soils. On tillage soils and other forms of land use, the accumulation of P at the soil surface is less pronounced. For this reason, special care is necessary in fertilising and managing grassland soils in order to minimise the risks of P loss to water.

The concentrations of P and N fractions in overland flow from the individual plots did not vary greatly between the three years of this study. This consistency increases confidence in the results.

There were significantly ($P < 0.05$) higher TP concentrations (up to double, but not for DRP) from grazed compared to cut plots for some individual overland flow events but not for others. The differences were minor in comparison to the differences between the six plots. TDP concentrations tended to increase and TDN tended to decrease with the rising limb of the overland flow hydrograph. The concentration of P in overland flow was highest in field plots with highest STP and visa versa.

There were high P concentrations (mean TP 0.72 mg/l in 2002 and 0.63 in 2003) in overland flow from the high STP Plot 7 that received no P fertiliser or slurry post-2000 and on which the grass was cut and removed during 2001–2003. This was significantly ($P < 0.05$) higher than the concentration from the lowest STP grazed Plot 1 (mean TP 0.15 mg/l in 2002). The estimated annual dissolved P loads in overland flow ranged from under 0.2 to over 1.0 kg/ha P and these are broadly in line with values from other studies (Capece et al., 2007).

4.3 Autumn Nutrient Wash-Out Effect

There was a wash-out effect on P, N and K concentrations in overland flow when this started in the autumn (normally September/October but November in 2003) after the extended period of no flow during the summer. This autumn wash-out effect was first observed in the autumn of 2000 (Tunney and O'Donnell, 2002). The concentrations decreased and stabilised over the succeeding 1 to 2 months. The highest concentrations and loads were associated with high overland flows in autumn and early winter, similar to the results found in the three-catchments study (2.1.1a). This temporal trend in nutrient concentration contributed to the correlation between nutrients in overland flow as illustrated in Section 3.6.2. Other studies show temporal trends in P loss (Puustinen et al., 2007).

SS concentrations measured from November 2003 to March 2004 averaged 45 mg/l for all plots. Only a small number of samples were over 100 mg/l and most of these were associated with a storm event in spring 2004, the highest being on plots that were not grazed in 2003.

There was a highly significant correlation between the concentrations of the three P fractions measured (on average DRP made up more than 80% of TDP and over 70% of TP). There was also a significant correlation between TDN and TN concentrations: TDN made up over 70% of TN on average. There was also a significant correlation between TP and TN concentrations: the latter was about five times higher than the former.

4.4 Main Conclusions

The main points from this part (A) of the LS-2.1.2 project are:

- The grazing animal was not the major risk factor in P loss in overland flow from grassland under these experimental conditions.
- The results of this study indicate that the major risk factor for P loss on these grassland soils is probably the accumulation of excess P near the soil surface and this was reflected in the soil test P.
- The risk of P loss to water is likely to be highest where there is a rapid transfer of water from soil to water courses, either in overland flow or in drainage (Haygarth et al., 2004).
- This study relates to good grazing practice and without further research cannot be applied to situations where animals are out-wintered in fields or are stocked at very high rates, particularly under wet conditions. Further studies will be necessary to quantify the P loss to water and its sources under these conditions.

4.5 Main Recommendations

Minimum soil test P for optimum grassland production (Index 2/3; Tunney, 2002) is advised. This is in line with recommendations of a previous EPA study on P desorption (Tunney et al., 2000) and with the results of the three-catchments study (LS-2.1.1a) and international studies (Sharpley and Tunney, 2000). In addition to the increased risk of P loss from high STP soils, such soils also contribute to high P in the herbage. This in turn gives high P in the dung and increases the risk of P loss to water.

There is need for research to establish if management practices such as ploughing down the P-enriched surface layer on high STP soils or other approaches (such as adding alum to the soil) can be used in the medium term to reduce the P loss in overland flow water from P-enriched soils.

Occasionally, high N levels, including high ammonium and nitrate concentrations, were found in overland flow water from the field plots. Some of these were associated with overland flow following fertiliser spreading. It is recommended that this is studied further.

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Acronyms

ANOVA	analyses of variance
AA	atomic absorption
DL	detection limit
DRP	dissolved reactive phosphorus
K	potassium
Mg	magnesium
N	nitrogen
NH_4-N	ammonium nitrogen
P	phosphorus
PP	particulate phosphorus
SE	standard error
SS	suspended solids
STDEV	standard deviation
TDN	total dissolved nitrogen
TN	total nitrogen
TON	total oxidised nitrogen
TP	total phosphorus
TRP	total reactive phosphorus

Appendix 1

Table A.1 Grazing, cutting and fertiliser treatments for Plots 1, 2, 3, 7, 5 and 6, 2001–2004

Plot 1, Upper Warren				**Plot 2, Lower Warren**			
Grazing and Cutting		**Fertiliser**		**Grazing and Cutting**		**Fertiliser**	
	Dates	**Type**	**N,P,K kg/ha**		**Dates**	**Type**	**N,P,K kg/ha**
2001 Grazed				**2001 Grazed**			
	April	Urea	120		April	Urea	120
Grazed May - Sep				Cut June	April	K	123
	June	CAN	100	Cut Sep	June	CAN	100
2002 Grazed				**2002 Grazed**			
	April	Urea	120		April	Urea	120
Grazed May - Sep				Grazed May - Sep			
	June	CAN	100		June	CAN	100
2003 Silage				**2003 Silage**			
	April	Urea	120		April	Urea	120
Cut June	April	K	123	Cut June	April	K	123
Cut Sep	June	CAN	100	Cut Sep	June	CAN	100
2004 to end of Mar				**2004 to end of Mar**			
No treatments to Mar		No treatments to Mar		No treatments to Mar		No treatments to Mar	

…continued overleaf

Table A.1 (continued). Grazing, cutting and fertiliser treatments for Plots 1, 2, 3, 7, 5 and 6, 2001–2004

Plot 3, Cowlands					**Plot 7, Cowlands**				
Grazing and Cutting		**Fertiliser**			**Grazing and Cutting**		**Fertiliser**		
Start	**End**	**Dates**	**Type**	**N,P,K kg/ha**	**Start**	**End**	**Dates**	**Type**	**N,P,K kg/ha**
2001 Grazed					**2001 Silage**				
14-May	18-May	30-Jan	K	62			30-Jan	K	62
05-Jun	08-Jun	20-Feb	Urea	57			04-Apr	Urea	120
28-Jun	01-Jul	16-May	CAN	50	Cut Jun				
25-Jul	28-Jul	20-Jun	CAN	50			20-Jun	CAN	100
18-Aug	21-Aug	18-Jul	CAN	50	Cut Sep				
16-Sep	19-Sep	17-Aug	CAN	34		02-Oct-02			
2002 Grazed					**2002 Silage**				
19-Apr	22-Apr	27-Feb	Urea	43			27-Feb	K	62
17-May	19-May	27-Feb	K	62			27-Feb	Urea	80
06-Jun	07-Jun	03-May	Urea	57					
24-Jun	27-Jun	06-Jun	CAN	50	Cut Jun				
11-Jul	13-Jul	20-Jun	CAN	50			June	CAN	100
03-Aug	06-Aug	19-Jul	CAN	33					
23-Aug	26-Aug	09-Aug	CAN	33	Cut Sep				
16-Sep	19-Sep	05-Sep	CAN	33					
07-Oct	10-Oct								
2003 Grazed					**2003 Silage**				
12-Apr	16-Apr	06-Mar	Urea	38			18-Mar	Urea	114
04-May	08-May	20-Mar	K	62			20-Mar	K	123
27-May	31-May	29-Apr	Urea	57					
21-Jun	24-Jun	21-May	CAN	50	Cut Jun				
21-Jul	25-Jul	12-Jun	CAN	50			June	CAN	100
18-Aug	21-Aug	04-Jul	CAN	33					
11-Sep	17-Sep	06-Aug	CAN	33					
02-Oct	05-Oct	17-Sep	CAN	33	Cut Sep				
2004 to end of Mar					**2004 to end of Mar**				
		01-Mar	K	62			01-Mar	K	62

*Urea = 46%N; CAN = calcium ammonium nitrate, 27.5% N; K = muriate of potash, 50%K; 0-7-30 = 0%N-7%P-30%K

Table A.1 (continued). Grazing, cutting and fertiliser treatments for Plots 1, 2, 3, 7, 5 and 6, 2001–2004

Plot 5, Dairy					**Plot 6, Dairy**				
Grazing and Cutting		**Fertiliser**			**Grazing and Cutting**		**Fertiliser**		
Start	**End**	**Dates**	**Type**	**N,P,K kg/ha**	**Start**	**End**	**Dates**	**Type***	**N,P,K kg/ha**
2001 Grazed		14-Feb	Urea	50	**2001 Silage**				
		18-Apr	Urea	50			14-Feb	Urea	50
		15-May	CAN	50			02-Apr	Urea	74
Dates not available but broadly similar to 2002		13-Jun	CAN	50	Cut 1	30-May	06-Jun	CAN	100
		03-Jul	CAN	34	Cut 2	30-Jul			
		08-Aug	CAN	34	Sep-01	2 days	08-Aug	CAN	50
		06-Sep	CAN	34	Oct-01	2 days	06-Sep	CAN	34
2002 Grazed					**2002 Silage**				
07-Apr	12-Apr	20-Feb	Urea	37			20-Feb	Urea	37
12-May	16-May	28-Feb	0-7-30	15P, 65K			28-Feb	0-7-30	25, 107
01-Jun	04-Jun	12-Apr	Urea	38			03-Apr	Urea	110
22-Jun	24-Jun	16-May	CAN	35	Cut 1	11-Jun	13-Jun	CAN	100
11-Jul	13-Jul	04-Jun	CAN	35	Cut 2	19-Aug			
02-Aug	05-Aug	30-Jun	CAN	35			22-Aug	CAN	70
21-Aug	23-Aug	15-Jul	CAN	35	14-Oct	19-Oct			
12-Sep	14-Sep	07-Aug	CAN	35					
04-Oct	06-Oct	11-Sep	CAN	35					
28-Oct	29-Oct								
2003 Grazed					**2003 Silage**				
		27-Jan	Urea	39	10-Apr	16-Apr	29-Jan	Urea	39
		06-Feb	0-7-30	17P, 74K	18-May	22-May	18-Mar	0-7-30	17P, 4K
		11-Mar	Urea	100	11-Jun	15-Jun	02-Apr	Urea	50
Cut 1	27-May	29-May	CAN	100	06-Jul	08-Jul	27-Apr	CAN	50
Cut 2	05-Aug	14-Aug	CAN	34	27-Jul	29-Jul	27-May	CAN	50
08-Sep	10-Sep	03-Sep	CAN	34	15-Aug	17-Aug	17-Jun	CAN	50
12-Oct	14-Oct				15-Sep	17-Sep	30-Jul	CAN	34
					07-Oct	10-Oct	03-Sep	CAN	34
					04-Nov	05-Nov			
					27-Nov				
2004 to end of Mar					**2004 to end of Mar**				
		11-Feb	Urea	25					
Grazed		13-Feb	0-7-30	37P, 74K	Grazed				
01-Apr	02-Apr	09-Mar	Urea	35	01-Apr	02-Apr			

*Urea = 46%N; CAN = calcium ammonium nitrate, 27.5% N; K = muriate of potash, 50%K; 0-7-30 = 0%N-7%P-30%K

Appendix 2

Table A.2 Summary of statistical analyses of the mean monthly concentrations of the P and N fractions in overland flow samples, 2001–2003[1, 2]

TP	**2002**				SEMs	Plot=0.031***		Month=0.040***		Plot/Month=0.099***			
Plot	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ave**
1	0.184	0.087	0.125	0.135	0.151	0.221	0.404			0.230	0.127	0.100	0.176
2	0.168	0.107	0.120	0.136	0.072	0.526	0.634			0.316	0.179	0.128	0.239
3	0.581	0.426	*0.812*	1.101	0.885	1.047	*1.163*			*1.346*	0.661	0.508	0.853
5	0.564	0.283	1.247	1.006	0.836	1.008	*1.136*			*1.093*	0.769	0.325	0.827
6	0.482	0.603	*0.739*	1.021	0.705	1.295	*1.090*			*1.012*	0.581	0.275	0.780
7	0.679	0.379	0.286	0.573	0.563	*0.942*	*1.008*			*1.206*	0.698	0.648	0.698
Ave	0.443	0.314	0.555	0.662	0.535	0.840	0.906			0.867	0.502	0.331	0.596
TP	**2003**				SEMs	Plot=0.045***		Month=0.052***		Plot/Month=0.126***			
Plot	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ave**
1	0.134	0.134	0.123	0.185			0.160			0.200	0.718	0.156	0.226
2	0.075	0.124	0.148	0.165			0.322			0.329	0.317	0.167	0.206
3	0.552	0.400	0.426	1.062			2.539			*1.265*	2.034	1.025	1.163
5	0.274	0.301	0.254	*0.850*			3.228			1.180	0.985	0.677	0.969
6	0.240	0.407	*0.539*	*0.816*			*1.720*			*1.037*	*1.340*	1.380	0.935
7	0.507	0.437	0.333	0.410			0.943			*0.802*	1.235	0.929	0.699
Ave	0.297	0.300	0.304	0.581			1.485			0.802	1.105	0.722	0.700
TON	**2001**				SEMs	Plot=0.079***		Month=0.112***		Plot/Month=0.251***			
Plot	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ave**
1	0.022	0.111	0.169	0.436			0.924	0.659	0.045	0.283	0.001	0.001	0.265
2	0.198	0.190	0.100	0.418			*0.880*	0.244	0.184	0.149	0.041	0.019	0.242
3	0.314	*1.519*	*1.560*	*2.084*			1.828	4.784	3.800	1.179	*1.671*	0.300	1.904
5	0.178	0.176	0.233	0.695			2.162	1.067	*1.369*	1.004	*0.598*	0.829	0.831
6	0.323	0.210	0.346	1.397			*1.524*	*1.764*	*1.424*	0.684	*0.653*	0.534	0.886
Ave	0.207	0.441	0.481	1.006			1.464	1.704	1.364	0.660	0.593	0.337	0.826
TON	**2002**				SEMs	Plot=0.138***		Month=0.187***		Plot/Month=0.458***			
Plot	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ave**
1	0.029	0.045	0.000	0.826	0.022	0.000	20.444		23.932	0.375	0.000	0.007	4.153
2	0.028	0.035	0.037	0.214	0.040	0.000	0.398		27.326	0.176	0.017	0.000	2.570
3	0.244	0.173	*1.558*	0.447	0.062	8.133	*11.870*		*27.063*	2.987	0.085	0.601	4.838
5	0.344	0.991	1.788	1.263	0.166	3.927	*11.459*		*26.652*	0.400	0.292	1.418	4.427
6	0.188	1.516	*3.030*	0.251	0.029	20.448	*13.342*		*28.535*	0.975	0.540	0.565	6.311
7	0.732	0.191	0.450	0.100	0.016	6.276	*11.268*		*26.461*	0.095	0.059	0.955	4.237
Ave	0.261	0.492	1.144	0.517	0.056	6.464	11.463		26.662	0.835	0.165	0.591	4.423
TON	**2003**				SEMs	Plot=0.305***		Month=0.353***		Plot/Month=0.864***			
Plot	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ave**
1	0.08	0.04	0.05	0.98			0.54			0.00	0.00	0.02	0.21
2	0.02	0.00	0.00	0.29			0.38			0.00	0.24	0.04	0.12
3	0.51	0.10	0.10	1.02			14.20			*2.42*	2.08	1.81	2.78
5	0.78	7.77	0.30	*1.30*			0.00			0.86	1.04	0.90	1.62
6	0.31	2.05	*0.61*	*1.20*			*3.97*			*1.16*	*1.26*	1.62	1.52
7	0.57	0.24	0.46	0.26			2.61			*0.37*	0.81	0.56	0.74
Ave	0.38	1.70	0.25	0.84			3.62			0.80	0.91	0.82	1.17

[1] The model used estimated means for plot/month combinations without samples; these are shown underlined in italics. This model compares the plot means averaged over all months with samples. The Standard Errors of Means (SEM) are shown with significances of differences (all significant, ***=P<0.001) between plots, months and the plot*month interaction. Least Significant Differences (LSD) can be calculated to compare individual means; LSDs are approximately three times the SEM.

[2] The estimated means for Plots 3, 5, 6 and 7 in July and September 2002 are based on a small number of samples; therefore, caution is required when interpreting these data points.

Table A.2 Summary of statistical analyses of the mean monthly concentrations of the P and N fractions in overland flow samples, 2001–2003[1, 2]

NH4	**2001**				SEMs	Plot=0.043***		Month=0.061***		Plot/Month=0.136***			
Plot	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ave**
1	0.019	0.028	0.026	0.068			0.045	0.167	0.714	0.175	0.045	0.035	0.132
2	0.034	0.028	0.031	0.068			*0.000*	0.143	0.440	0.163	0.039	0.029	0.064
3	0.058	*0.549*	*0.556*	*0.809*			0.011	0.092	4.787	0.304	*0.749*	0.140	0.805
5	0.040	0.024	0.064	0.415			0.015	0.088	*1.987*	0.446	*0.285*	0.051	0.341
6	0.733	0.124	0.112	0.692			*0.288*	*0.477*	*2.336*	1.496	*0.634*	0.015	0.691
Ave	0.177	0.151	0.158	0.410			0.004	0.193	2.053	0.517	0.350	0.054	0.407
NH4	**2002**				SEMs	Plot=0.214***		Month=0.290***		Plot/Month=0.710***			
Plot	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ave**
1	0.161	0.162	0.126	0.340	0.124	0.220	6.866		2.182	0.335	0.108	0.147	0.979
2	0.087	0.092	0.065	2.071	0.083	1.030	0.952		2.459	0.405	0.072	0.080	0.672
3	0.166	3.345	*2.945*	1.550	1.158	3.908	*5.189*		*3.604*	1.125	0.200	0.156	2.122
5	0.188	0.556	1.089	3.304	0.849	1.464	*4.497*		*2.913*	0.354	0.352	0.171	1.431
6	0.186	2.601	*5.419*	1.070	0.189	*25.766*	*7.662*		*6.078*	1.008	0.381	0.205	4.597
7	1.147	3.662	7.921	0.190	0.125	7.334	*5.885*		*4.301*	0.147	0.171	0.127	2.819
Ave	0.322	1.736	2.927	1.421	0.421	6.620	5.175		3.589	0.562	0.214	0.148	2.103
NH4	**2003**				SEMs	Plot=0.078***		Month=0.090***		Plot/Month=0.221***			
Plot	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ave**
1	0.007	0.044	0.000	0.867			0.307			0.136	0.173	0.098	0.204
2	0.056	0.019	0.000	0.046			0.591			0.214	0.140	0.080	0.143
3	0.029	0.000	0.000	0.723			1.100			*0.000*	0.312	0.237	0.225
5	0.132	2.007	0.100	*3.428*			18.361			0.669	0.330	0.214	3.155
6	0.174	2.231	*0.721*	*1.730*			*4.864*			*0.629*	*0.959*	0.345	1.457
7	0.028	0.054	0.026	0.106			0.483			*0.000*	0.362	0.298	0.075
Ave	0.071	0.726	0.141	1.150			4.284			0.049	0.379	0.212	0.877
TDN	**2002**				SEMs	Plot=1.039***		Month=1.407***		Plot/Month=3.448***			
Plot	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ave**
1	1.30	1.05	1.19	3.15	2.15	2.61	39.98		29.32	2.60	1.45	1.09	7.81
2	0.69	0.95	0.90	20.02	1.42	3.57	4.72		32.44	2.09	1.23	0.94	6.27
3	1.30	11.44	*10.87*	2.99	4.03	16.31	*25.90*		*34.39*	7.69	1.82	1.88	10.78
5	1.53	2.91	4.79	8.74	4.04	10.01	*23.86*		*32.35*	2.85	2.70	2.35	8.74
6	1.28	7.11	*13.62*	4.66	2.74	*46.53*	*28.66*		*37.14*	3.51	2.20	1.48	13.54
7	1.32	17.22	29.48	3.71	2.70	19.48	*28.24*		*36.72*	1.86	1.67	1.88	13.12
Ave	1.24	6.78	10.14	7.21	2.85	16.42	25.23		33.73	3.43	1.84	1.60	10.04
TDN	**2003**				SEMs	Plot=0.441***		Month=0.509***		Plot/Month=1.248***			
Plot	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ave**
1	0.97	1.12	1.28	4.39			3.16			1.77	4.16	2.11	2.37
2	0.85	0.84	0.93	2.32			3.33			2.28	3.73	1.88	2.02
3	1.07	1.49	1.45	4.92			15.75			*3.94*	8.86	4.81	5.29
5	1.57	10.97	2.07	*7.72*			22.11			3.55	6.82	3.13	7.24
6	0.91	4.21	*2.19*	*5.09*			*10.66*			*3.27*	*6.12*	4.46	4.62
7	1.02	1.33	1.13	2.02			4.88			*0.71*	2.91	2.42	2.05
Ave	1.07	3.33	1.51	4.41			9.98			2.59	5.44	3.13	3.93
TN	**2003**				SEMs	Plot=0.606***		Month=0.700***		Plot/Month=1.714***			
Plot	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Ave**
1	2.66	2.10	1.91	4.51			3.45			2.75	11.23	2.64	3.91
2	1.63	2.03	2.40	2.61			3.51			2.28	4.29	2.30	2.63
3	2.04	3.35	3.27	6.23			20.85			*4.80*	11.36	5.61	7.19
5	2.71	13.12	3.44	*9.39*			31.01			3.89	8.42	4.50	9.56
6	1.62	7.11	*4.22*	*6.60*			*14.44*			*4.39*	*9.49*	6.37	6.78
7	1.20	1.93	2.06	2.29			5.40			*0.21*	4.13	3.59	2.60
Ave	1.98	4.94	2.88	5.27			13.11			3.05	8.15	4.17	5.45