Authors

H Tunney[1]*, I Kurz*[1]*, D Bourke*[1, 2]*, Colin O'Reilly*[1]*, D Jeffrey*[2]*, P Dowding*[2]*, B Foy*[3]*, D Kilpatrick*[3]*, P Haygarth*[4]*.*

[1]Teagasc, Johnstown Castle Research Centre, Wexford. [2]Trinity College Dublin. [3]DARDNI, Belfast , Northern Ireland. [4]Institute of Grassland and Environmental Research (IGER), North Wyke Research Station, Okehampton, Devon, EX20 2SB, England.

Teagasc wishes to acknowledge the support of the Environmental Research Technological Development and Innovation (ERTDI) Programme under the Productive Sector Operational Programme which was financed by the Irish Government under the National Development Plan 2000-2006. It was administered on behalf of the Department of the Environment, Heritage and Local Government by the Environmental Protection Agency which has the statutory function of coordinating and promoting environmental research.

June 2007

ISBN: 1-84095 –

AGRICULTURE AND FOOD DEVELOPMENT AUTHORITY

Teagasc Headquarters, Oak Park, Carlow

A. FIELD PLOT STUDY
THE IMPACT OF THE GRAZING ANIMAL ON PHOSPHORUS, NITROGEN, POTASSIUM AND SUSPENDED SOLIDS LOSS FROM GRAZED PASTURES

END OF PROJECT REPORT

RMIS 5022 – Section A

TABLE OF CONTENTS Page No.

Executive Summary

In Ireland 90% of the 4.2 million ha of farmland is grassland. Phosphorus deficiency limited grassland production in Ireland and this was corrected by chemical fertiliser use in the 1960s and 1970s. The increased inputs of fertilisers led to increased intensification of grassland with a doubling of grass yield and of grazing animal numbers, from about 3 million to over 6 million livestock units. There is little information on relative contribution of increased chemical fertiliser use compared to increased grazing animal numbers on phosphorus loss to water. The main objective of this study was to obtain information on nutrient loss, particularly phosphorus, in overland flow from cut and grazed grassland plots, with a range of soil test phosphorus levels over three years and implications.

The nutrient concentrations and loads from six grazed and cut field plots were studied in this experiment which started in September 2000 and finished in March 2004. Overland flow volume and samples were collected and analysed for phosphorus and nitrogen fractions, some samples were also analysed for potassium and suspended solids.

There were significant variations in phosphorus concentrations over the seasons and between the six field plots. Concentrations of phosphorus in overland flow varied form under 0.005 mg/l to over 3 mg/l. The estimated annual dissolved phosphorus 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 phosphorus and mean annual phosphorus concentrations in overland flow. There was more than a ten-fold difference in mean phosphorus concentrations in overland flow between plots with the lowest and highest soil test phosphorus levels. This compared to a maximum of 66% increase in phosphorus concentrations between cut and grazed plots that may be attributable to the presence of the grazing animal.

There was a significant correlation between the three phosphorus fractions measured; a mean of 86% of total phosphorus was dissolved phosphorus. There was a significant correlation between dissolved nitrogen and total nitrogen and also between total phosphorus and total nitrogen in overland flow water; the latter was about five times higher than the former.

The highest phosphorus concentrations and loads occurred in autumn when overland flow started, combining high flows and high phosphorus concentrations, after an extended summer dry period (autumn/winter wash-out effect). The difference in mean phosphorus concentrations in overland flow between cut and grazed plots, which was most evident on the high soil test phosphorus plots, were generally highest at this time of year (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 grazing season started.

Three factors influencing phosphorus concentrations in overland flow were identified in this work: a) the highest concentrations were from plots with the highest soil test phosphorus and visa versa, b) a seasonal phosphorus cycle with high phosphorus concentrations in autumn/winter when overland flow commenced after the summer and decreasing over the following two months and the lowest levels at the start of the year, c) relatively small increase in phosphorus concentrations with grazing compared to cutting treatments on some occasions.

Grassland, whether cut or grazed, can have an increased potential for P loss in overland flow compared to other land use. This is because of high surplus phosphorus inputs into intensive grassland systems in fertiliser and purchased feeds and the application and accumulation of fertiliser and animal manures phosphorus at or near the soil surface. This leads to the sometimes very high soil phosphorus levels in the top few centimetres of grassland soils that can be released it to overland flow water. Therefore, special care is necessary in fertilising and managing grassland soils in order to minimise the risks of phosphorus loss to water.

The conclusion that the grazing animal has a limited impact on phosphorus losses compared to other factors is in broad agreement with studies in the USA where it was concluded that cattle grazing did not have a significant cumulative effect on phosphorus in runoff at the whole pasture scale during a 5-year study.

The principal conclusion from this study is that while the grazing animal does influence P concentrations in overland flow, this impact is small compared to the other factors that determine P loss from grassland under standard management regime.

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

A1 INTRODUCTION AND AIMS

In Ireland, over 90% of the 4.2 million ha of 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 study (Tunney et al., 2000) and part of the more recent RTDI funded programme (LS2.1.1a, three catchments) found that 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 et al., 2000). It has been reported that grazing animals can be a significant contributor to nutrient and sediment load 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 showed increased nitrate but no consistent effect on P in runoff from grassland catchments with ungrazed, intensive and very intensive grazing (Mapfumo et al., 2002). The P concentrations and loads 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, if implemented (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). These references deal largely with data from North America and there is little information from Europe on how the grazing animal may impact on 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 the potential for increased nutrient and sediment loss; however, these extreme conditions were not studied in the current project.

The main objectives of this project (EPA LS2.1.2 Grazed Pasture, part funded by RTDI/EPA) 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 good or normal grazing practice and deals with aspects of objectives 1, 2, 3 and 5 listed above. Two separate sections (B and C) deal 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, grazed and cut, with a range of low to high soil test P (STP) levels.

A2 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. These plots were not ideal in terms of replications and matching sites for a comparison of the impact of grazing compared to cutting on nutrient loss in overland flow water. 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 time frame of this project. It was decided that these seven plots could be used to give valuable information on P loss from grazed and cut grassland field plots.

Overland flow water was channelled to the lowest point in each plot, via a pipe to a tank with a V notch where flow was measured, 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 twenty four sampling bottles in the Sigma samplers would be adequate to collect all the overland flow samples that were likely to occur over a 24 hour period of very heavy rainfall (>30mm). The flow proportional sampling collected one overland flow water sample from each 1 m^3 (plot 4) to 10 m^3 (plot 1) of flow depending on plot. This 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. This was achieved by taking a flow proportional sample after between 2 m^3 (Plot 4) to 20 m^3 (Plot 2) 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.

To facilitate the comparison of grazing and cutting treatments, six field plots were paired (1 & 2, 3 & 7, 5 & 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 A1 and Figure A1, respectively. 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 A1: Summary of site data for the filed plots.

Plot No.	Name	Area Ha	Grazing animal	Stocking rate*, LU/ha/year	Main soil type	Mean slope, degrees
1	Upper Warren	1.54	Beef	1.6	Gley	2
2	Lower Warren	1.09	Beef	1.6	Gley	4
3	Cowlands	0.46	Beef	2.5	Gley	3
4	Dairy 1	0.74	Dairy	2.5	Brown Earth	2
5	Dairy 2	0.73	Dairy	2.5	Brown Earth	3
6	Dairy 3	0.73	Dairy	2.5	Brown Earth	3
7	Cowlands cut	0.24	Beef	2.5	Gley	3

* When grazed.

Overland flow water samples were normally taken to the laboratory within 24 hours (could be over 48 hours at weekends) after the flow proportional samples were colleted by the Sigma samplers.

Most samples were analysed on the day they arrived in the laboratory or within 24 hours after storing at 4^{o} C. The 24, one 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 after 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 suspended solids were according to the methods 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 suspended solids (SS), were based on the Standard Methods for the Examination of Water and Wastewater (Greenberg et al., 1992). Analyses of total N and P concentration in water samples were based on the autoclave method described by Ebina et al., 1983. The soil analyses used the Morgan's soil extractant for P, K and magnesium

(Mg) (Peech and English, 1944).

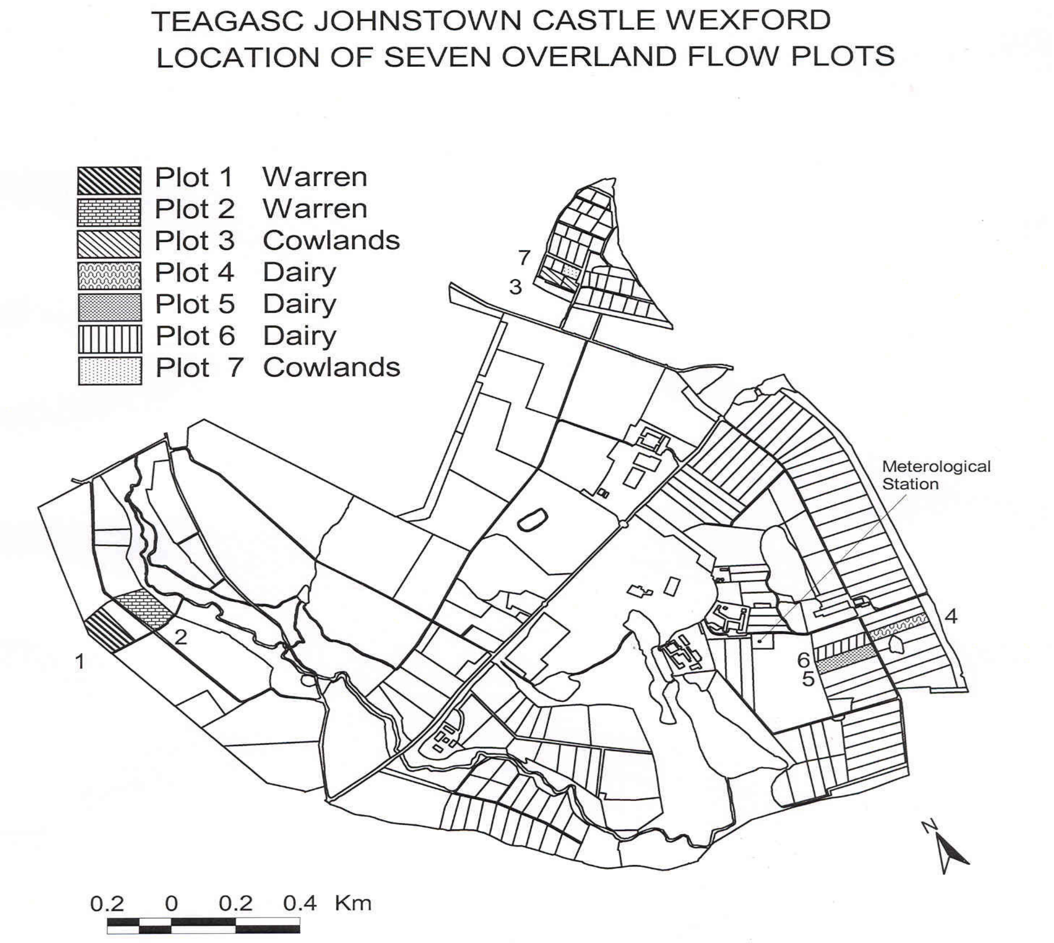

Figure A1. Layout of seven plots and meteorological station at Teagasc, Johnstown Castle.

In 2001, the overland runoff water samples were analysed for total reactive P (TRP, i.e. total or molybdenate 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 water samples were analysed for dissolved reactive P (DRP, DL 0.005mg/l), total dissolved P (TDP, DL 0.01 mg/l), total P (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, the overland flow water samples taken between October 2003 and March 2004 were analysed for suspended solids (SS, DL 1.0 mg/l). Values below the detection limit were show as zero.

For this study each plot was grazed and cut according to normal practice for the stocking rate for beef and dairy animals. Nitrogen and K fertilisers were applied to each plot according to Teagasc recommendations. 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 necessary for grazing.. The cumulative effect of this treatment was high soil P concentrations. Plots 1 and 2 were on land reclaimed from shrub land 30 years ago and received very little chemical fertiliser or slurry in the interim. The other plots were part of a dairy farm for the past 30 years and received normal chemical fertiliser and slurry treatments for dairying systems (average 300 N and 60 kg K per ha/year) . No chemical P fertiliser or slurry was applied to plots 1, 2, 3 or 7 from 2001 to 2003. When grazed, Plots 1 and 2 had a set stocked grazing management while the other plots were rotationally grazed at approximately 21 day grazing intervals. Specific grazing and cutting treatments for each plot are summarised in Table A3. Details of grazing, cutting and fertiliser treatments for the field plots are summarised in Appendix A1 at the end of this report.

The soils in this study area were derived from Irish Sea drift glacial deposits. The soils in plots 1, 2, 3 and 7 are predominantly poorly drained gleys and the soils in plots 4, 5 and 6 are predominantly moderately well drained brown earths. Plots 1 and 2 are predominantly clay soils and the other plots are predominantly loam soil. Plot 1 and 2 were poorly drained and fertiliser application and grazing started about four to six weeks later than the other plots, this resulted 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 A2). There were smaller differences, less than two-fold, in soil K and Mg levels. The soil pH varied from 5.7 to 6.3.

The overland runoff from each plot was channelled through a pipe to a tank with a V notch weir for height (and flow) measurement. Flow proportional water samples were collected from the pipe before it entered the tanks with the V notch. The meteorological station (location shown in Figure A1) provided daily rainfall and air temperature. Daily rainfall and air temperatures from 2001 to 2003 are presented in Figure A2 and cumulative annual rainfall and evapo-transpiration are plotted in Figure A3. The 25 year (1980-2004) average rainfall was 1037 mm per year. The 25 year (1980-2004) rainfall annual mean and maximum was 2.84 and 63.6mm per day, respectively. The corresponding air temperature minimum, mean and maximum was -3.7, 10.2 and 23.3 C^0 per day, respectively.

Table A2: 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

Table A3. Grazed and cut treatments on the field plots for the years 1999 to 2003. Plots 1 and 2, 3 and 7, 5 and 6 were paired (Figure A1).

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

The overland flow levels were recorded every 5 minutes and this was stored together with the time of the overland flow sample collection data in the Sigma Insight software. This data was later transferred to an Access database.

The nutrient concentrations in overland flow were linked to the flow data to allow calculation of nutrient loads. The daily average flows and P concentrations were extracted by querying the MS Access database. The average daily flows and loads and cumulative flows and loads were calculated and graphed in MS Excel. Statistical analyses and charts were made with the help of MS Excel and GenStat 7.2 (Copyright 2004, Rothamsted Experimental Station). For the purpose of statistical analysis, the data were averaged according to week of year and subject to Analysis of Variance 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 plot*month interactions (Appendix A2).

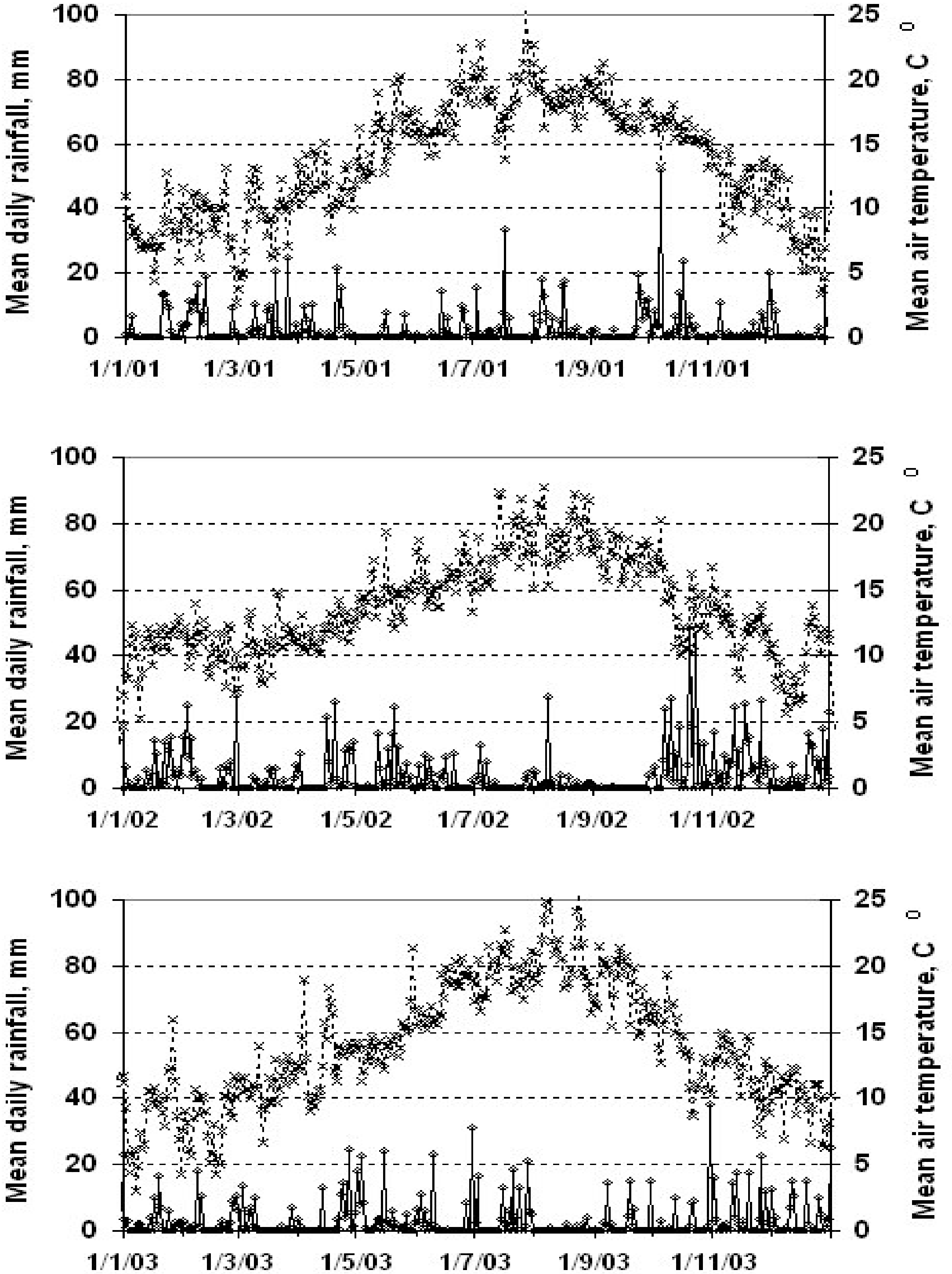

Figure A2. Summary of mean daily rainfall (line) and air temperature (x) for 2001 to 2003.

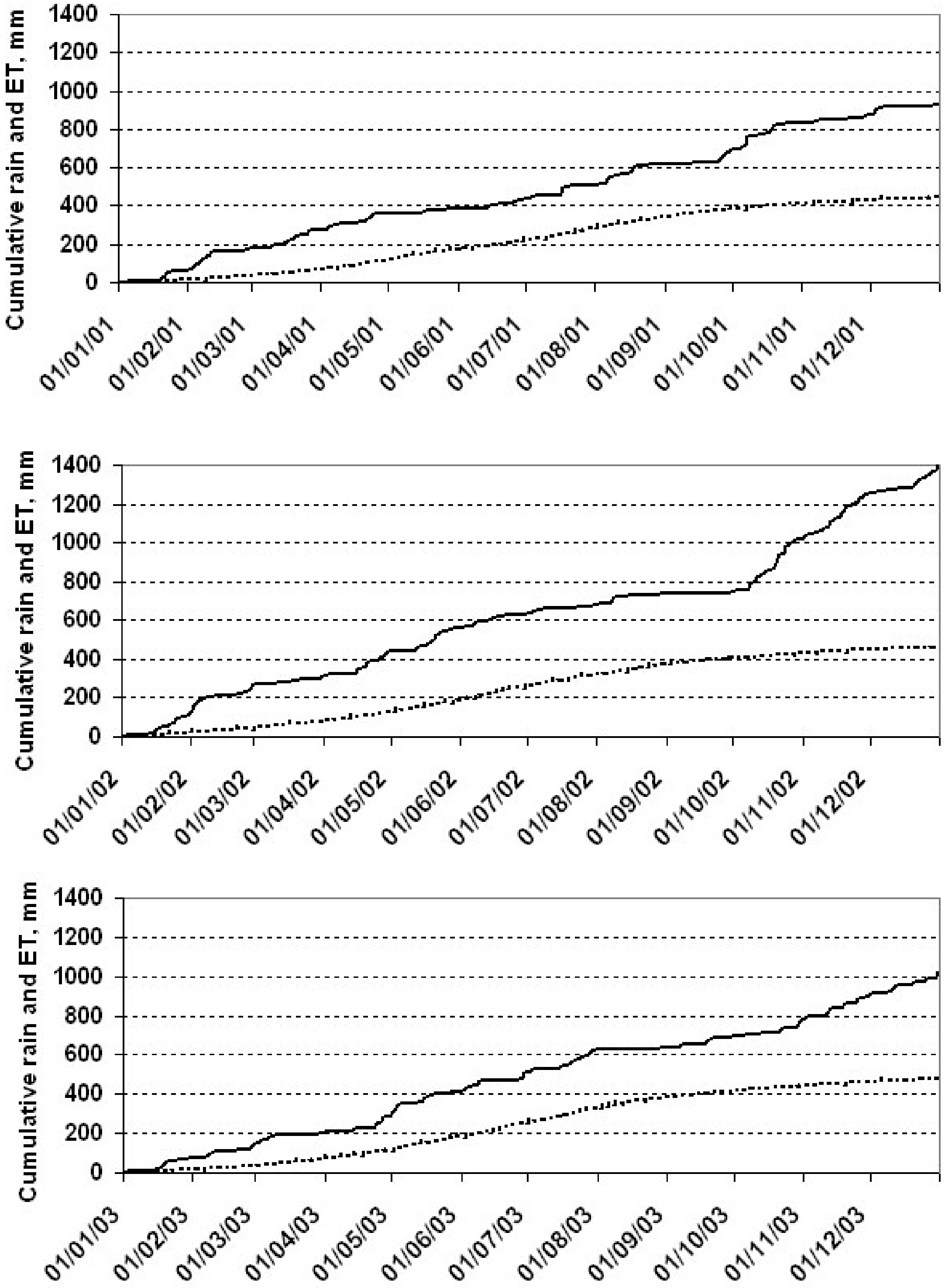

Figure A3. Cumulative average daily annual rainfall and evapotranspiration (ET, dotted line) for 2001 to 2003.

A3 RESULTS AND DISCUSSION

A3.1 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 summarized in Tables A4, A5 and A6 respectively.

Table A4. Summary of average, minimum, maximum and standard deviation (STDEV) for total reactive P (TRP), total oxidised nitrogen (TON) and ammonium nitrogen (NH_4-N) concentrations for the five plots studied in 2001. The second column shows the number of overland flow samples analysed.

			mg/l		
Plot Treatment	**No. Samples**		**TRP**	**TON**	**NH_4-N**
1 Grazed	288	Average	0.083	0.278	0.106
		Minimum	0.000	0.000	0.000
		Maximum	0.695	5.240	1.020
		STDEV	0.084	0.634	0.181
2 Cut	319	Average	0.090	0.197	0.067
		Minimum	0.028	0.000	0.000
		Maximum	0.400	5.050	0.630
		STDEV	0.052	0.477	0.110
3 Grazed	136*	Average	1.180	1.289	0.314
		Minimum	0.269	0.000	0.000
		Maximum	2.710	8.690	5.380
		STDEV	0.661	1.753	0.748
7 Cut		Started in autumn 2001			
5 Grazed	228	Average	0.485	0.467	0.139
		Minimum	0.000	0.000	0.000
		Maximum	3.250	3.000	0.990
		STDEV	0.589	0.530	0.244
6 Cut	206	Average	0.710	0.444	0.532
		Minimum	0.099	0.000	0.000
		Maximum	2.812	2.460	4.460
		STDEV	0.640	0.442	0.866
Overall Average (5 plots)			0.399	0.438	0.200
Overall STDEV (5 plots)			0.574	0.840	0.495

* There were100 flow proportional samples missed from plot 3 in spring 2001.

Table A5. Summary of average, minimum, maximum and standard deviation (STDEV) for dissolved reactive P (DRP), total dissolved P (TDP), total P (TP), total oxidised N (TON), ammonium N (NH_4-N) and total dissolved N (TDN) for the six plots in 2002.

Plot Treatment	No. Samples		mg/l					
			DRP	TDP	TP	TON	NH_4-N	TDN
1 Grazed	459	Average	0.047	0.063	0.150	0.369	0.231	2.089
		Minimum	0.000	0.000	0.003	0.000	0.000	0.060
		Maximum	0.515	0.470	0.878	26.020	6.870	40.040
		STDEV	0.053	0.055	0.084	2.432	0.426	3.545
2 Grazed	592	Average	0.085	0.099	0.181	0.343	0.314	2.484
		Minimum	0.000	0.000	0.000	0.000	0.000	0.000
		Maximum	1.550	1.590	1.409	30.380	12.170	60.730
		STDEV	0.130	0.155	0.165	2.771	1.068	6.973
3 Grazed	672	Average	0.574	0.599	0.764	0.388	0.931	4.296
		Minimum	0.136	0.150	0.212	0.000	0.000	0.500
		Maximum	1.759	1.650	3.626	9.160	17.250	45.400
		STDEV	0.271	0.316	0.409	0.806	2.413	7.636
7 Cut	450	Average	0.585	0.624	0.715	0.138	0.566	3.598
		Minimum	0.149	0.220	0.156	0.000	0.000	0.530
		Maximum	1.995	1.740	2.080	1.670	12.510	41.030
		STDEV	0.300	0.272	0.321	0.295	1.717	7.142
5 Grazed	386	Average	0.514	0.606	0.727	0.554	0.828	3.618
		Minimum	0.090	0.090	0.091	0.000	0.000	0.480
		Maximum	3.312	3.530	3.612	7.940	20.190	34.160
		STDEV	0.453	0.465	0.432	0.917	2.313	3.902
6 Cut	227	Average	0.431	0.485	0.763	0.644	1.004	3.558
		Minimum	0.102	0.140	0.206	0.000	0.000	0.500
		Maximum	1.196	1.300	1.810	20.860	26.210	46.970
		STDEV	0.261	0.312	0.357	2.018	2.604	4.966
Overall Average (6 plots)			0.361	0.405	0.525	0.379	0.615	3.288
Overall STDEV (6 plots)			0.354	0.378	0.422	1.805	1.875	6.233

The TRP concentrations in the overland flow water samples from the paired plots 1, 2 and 5, 6 for 2001 are summarized in Figure A4. The DRP concentrations in overland flow from the six plots for 2002 and 2003 are summarized in Figure A5 and A6, respectively. The TDP concentrations in overland flow water samples from the six plots for 2003 are summarized in Figure A7. The TP concentrations in overland flow water samples from the six plots for 2003 are summarized in Figure A8.

Table A6. Summary of average, minimum, maximum and standard deviation (STDEV) for dissolved reactive P (DRP), total dissolved P (TDP), total P (TP), total oxidised N (TON), ammonium N (NH_4-N), total dissolved N (TDN) and total N (TN) for the six plots in 2003.

			mg/l						
Plot Treatment	**No. Samples**		**DRP**	**TDP**	**TP**	**TON**	**NH_4-N**	**TDN**	**TN**
1 Cut	130	Average	0.029	0.079	0.166	0.224	0.215	2.088	3.149
		Minimum	0.006	0.010	0.065	0.000	0.000	0.520	1.290
		Maximum	0.100	0.200	1.140	1.510	1.499	5.850	18.400
		STDEV	0.019	0.040	0.113	0.392	0.324	1.314	1.910
2 Cut	170	Average	0.092	0.142	0.199	0.126	0.148	2.016	2.573
		Minimum	0.016	0.030	0.043	0.000	0.000	0.360	0.960
		Maximum	1.290	2.260	2.460	7.379	1.733	13.570	13.930
		STDEV	0.115	0.187	0.200	0.590	0.274	1.411	1.376
3 Grazed	135	Average	0.723	0.835	1.010	1.295	0.266	4.180	5.429
		Minimum	0.195	0.200	0.315	0.000	0.000	0.860	0.720
		Maximum	2.390	2.500	3.200	14.220	2.751	15.760	27.010
		STDEV	0.441	0.493	0.540	1.385	0.377	2.835	3.636
7 Cut	90	Average	0.483	0.534	0.631	0.498	0.161	1.737	2.478
		Minimum	0.193	0.260	0.287	0.000	0.000	0.660	0.520
		Maximum	1.987	2.190	2.300	3.140	1.755	5.070	7.140
		STDEV	0.298	0.273	0.312	0.537	0.230	0.987	1.373
5 Cut	93	Average	0.434	0.498	0.735	2.100	1.087	5.171	6.797
		Minimum	0.139	0.160	0.213	0.000	0.000	1.310	2.150
		Maximum	3.010	1.400	3.500	15.499	28.590	28.760	41.480
		STDEV	0.455	0.229	0.523	3.860	3.586	5.585	7.133
6 Grazed	43	Average	0.455	0.571	0.699	1.107	0.585	2.549	3.753
		Minimum	0.087	0.110	0.131	0.000	0.000	0.700	0.930
		Maximum	1.320	1.420	1.790	4.626	3.740	6.880	12.260
		STDEV	0.284	0.348	0.416	1.028	0.827	1.557	2.345
Overall Average (6 plots)			0.333	0.403	0.525	0.776	0.348	2.914	3.930
Overall STDEV (6 plots)			0.398	0.407	0.495	1.783	1.419	2.951	3.754

The TDN and TN concentrations in overland flow water samples from the six plots for 2003 are summarized in Figure A9 and A10, respectively. A small number of individual high values (e.g. maximum values in Tables A4 to A6) are above the scale (y axis) in Figures A6 to A10. 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 heavy rain when land was wet.

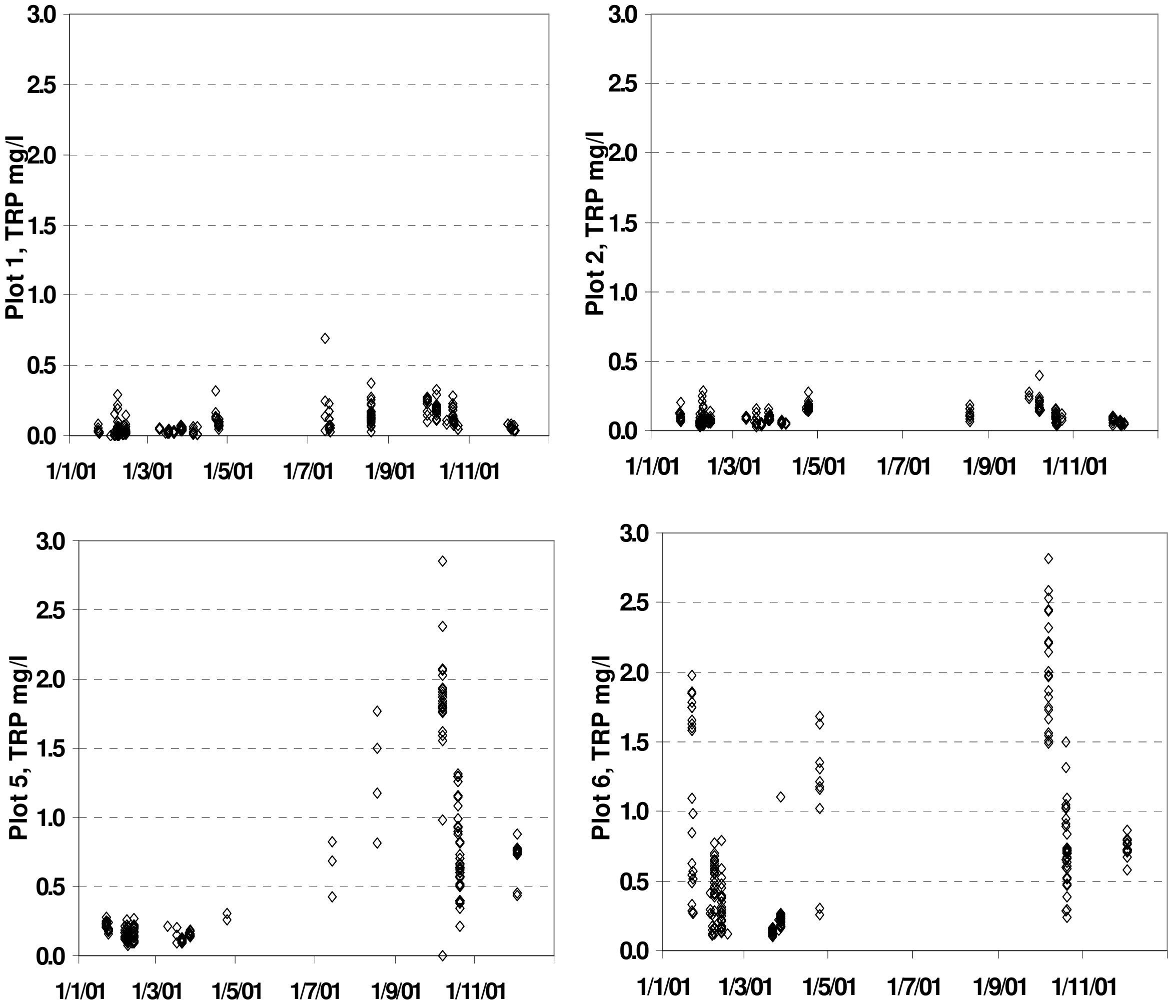

Figure A4. Total reactive P (TRP) concentrations in overland flow water samples from plots 1 and 5 (grazed) and plots 2 and 6 (cut) in 2001. Each vertical series of data points indicates single or adjacent storm events over a short time frame of normally one or two days.

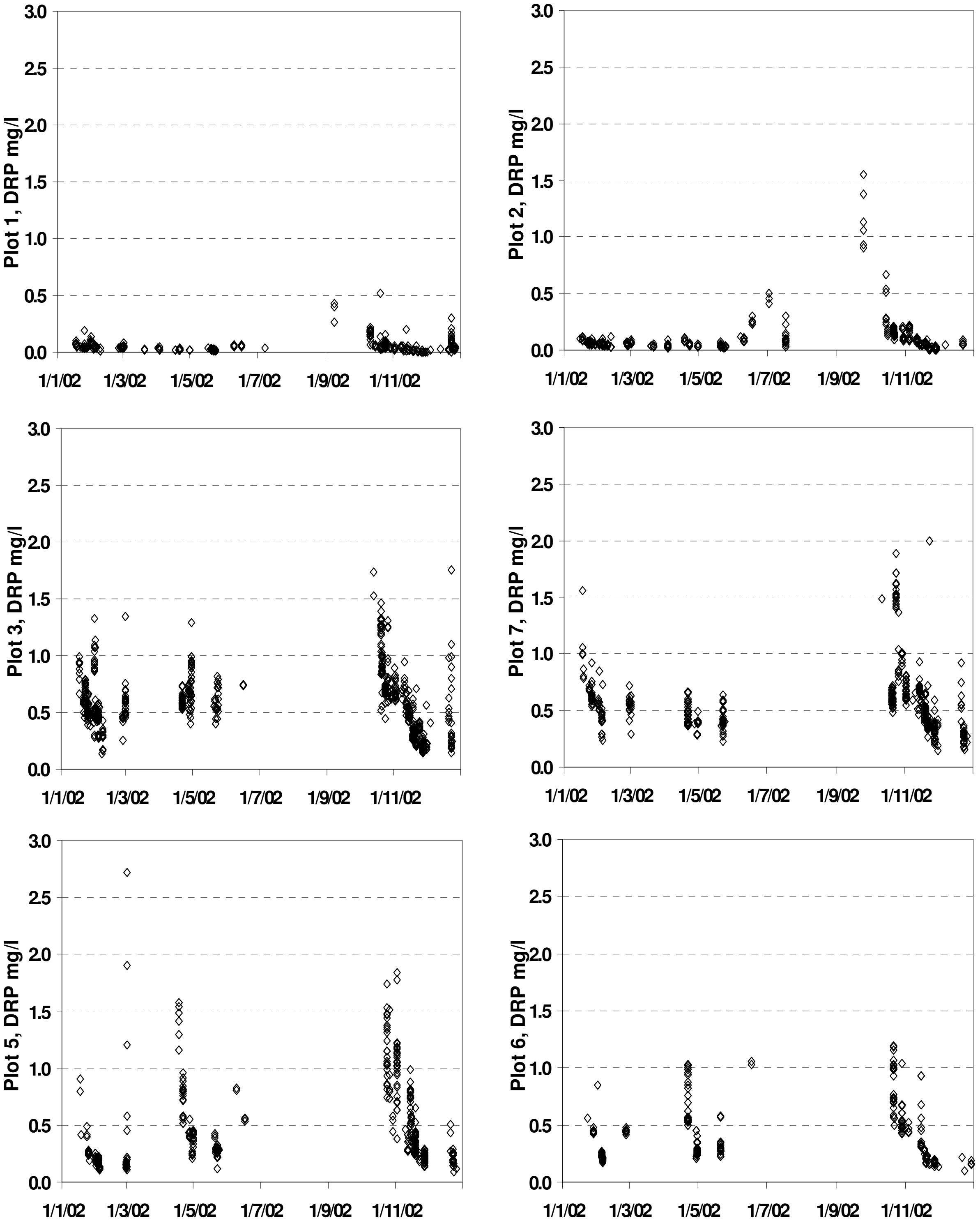

Figure A5. Dissolved reactive P (DRP) concentrations in overland flow water samples from plots 1, 2, 3 and 5 (grazed) and plots 6 and 7 (cut) in 2002.

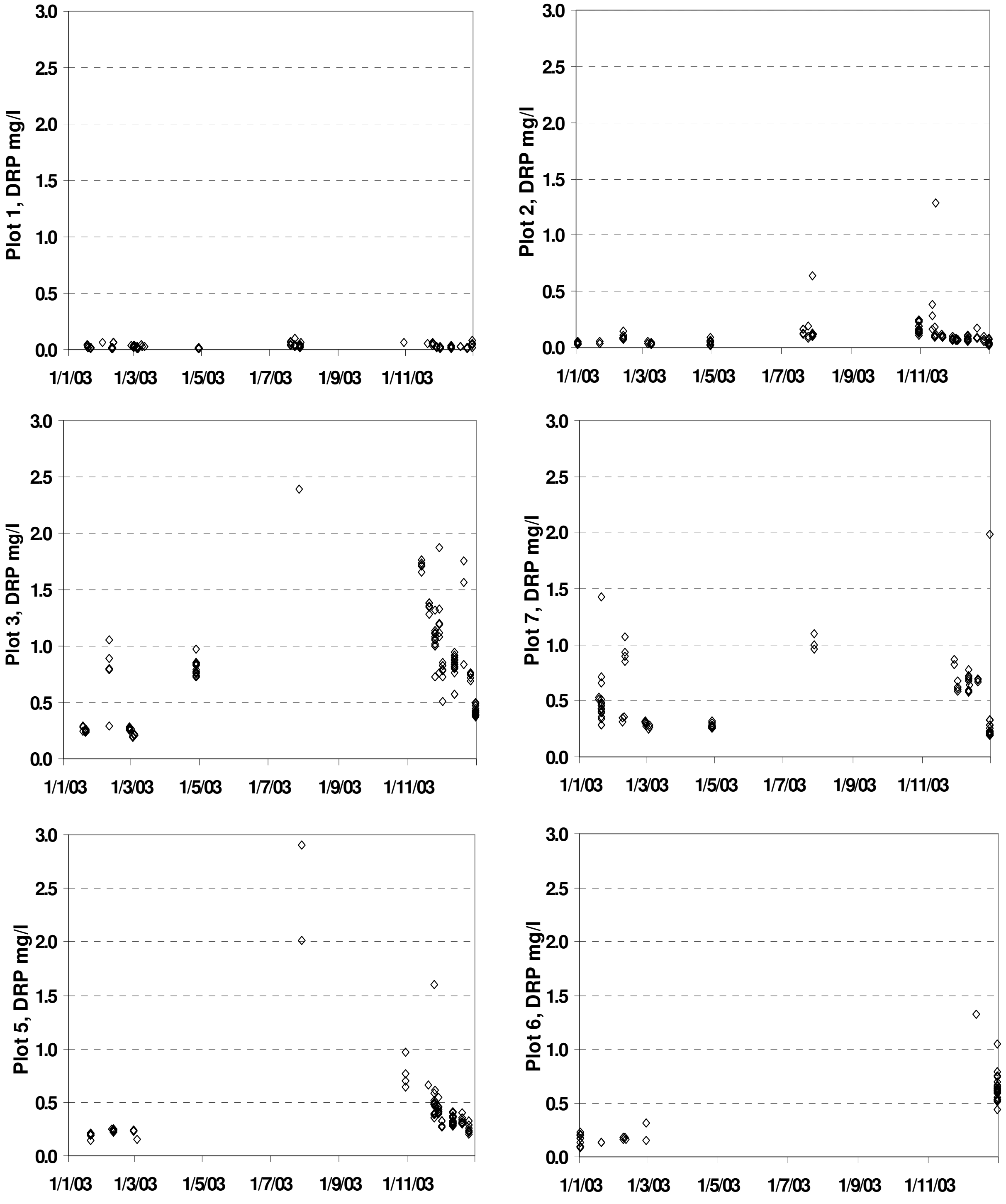

Figure A6. Dissolved reactive P (DRP) concentrations in overland flow water samples from plots 3 and 6 (grazed) and plot 1, 2, 5 and 7 (cut) in 2003.

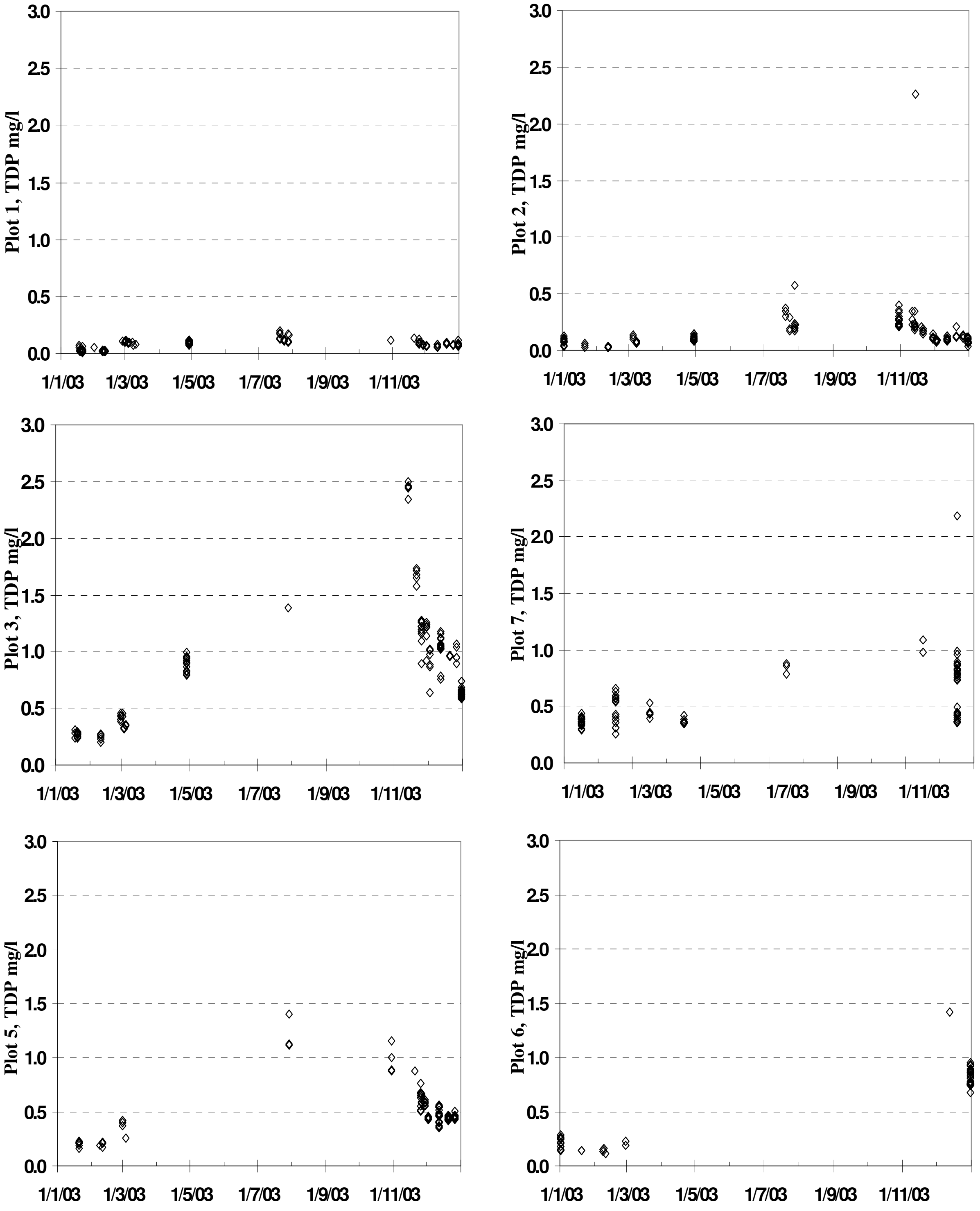

Figure A7. Summary of total dissolved P (TDP) concentrations in overland flow water samples from plots 3 and 6 (grazed) and plot 1, 2, 5 and 7 (cut) in 2003.

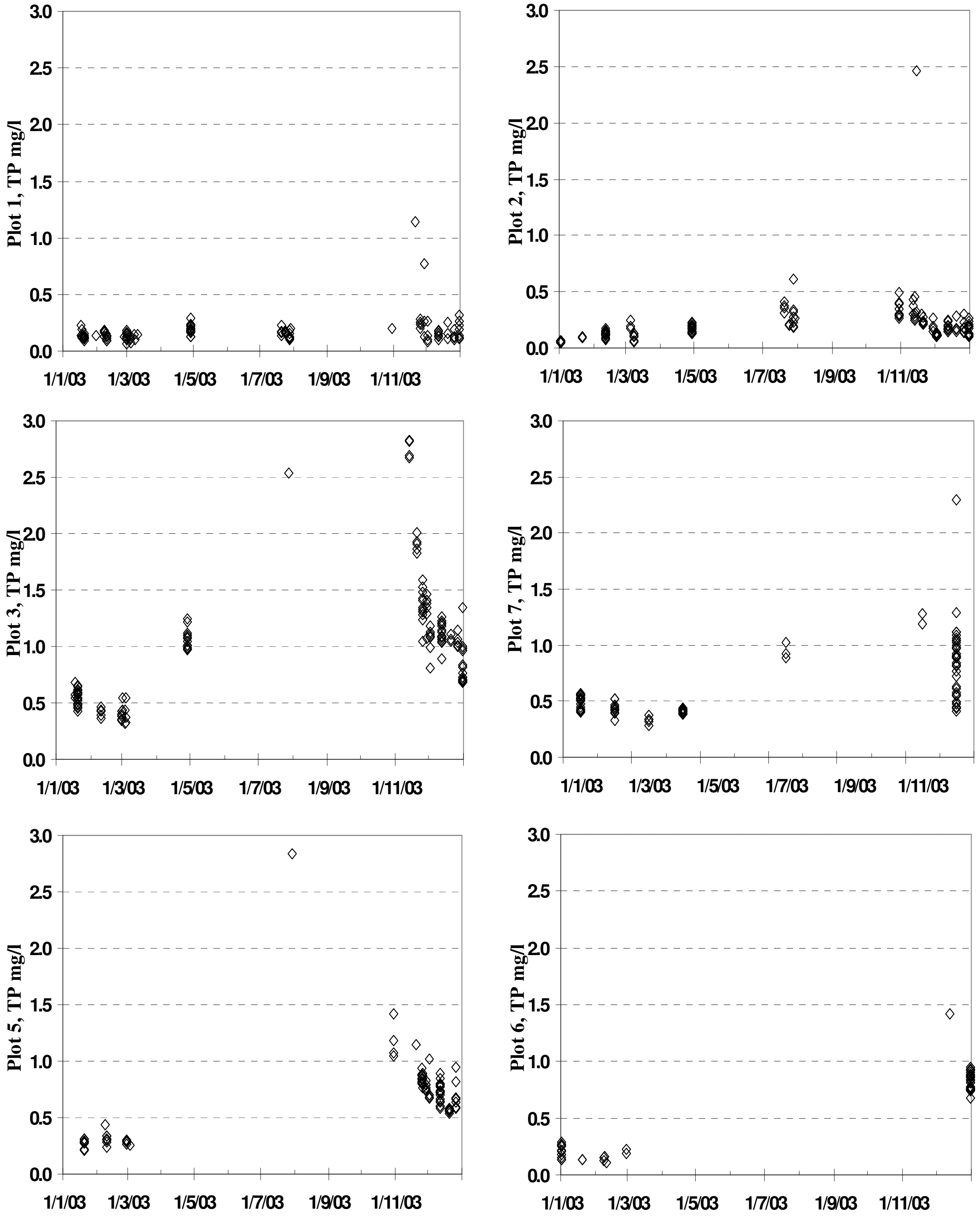

Figure A8. Summary of total P (TP) concentrations in overland flow water samples from plots 3 and 6 (grazed) and plot 1, 2, 5 and 7 (cut) in 2003.

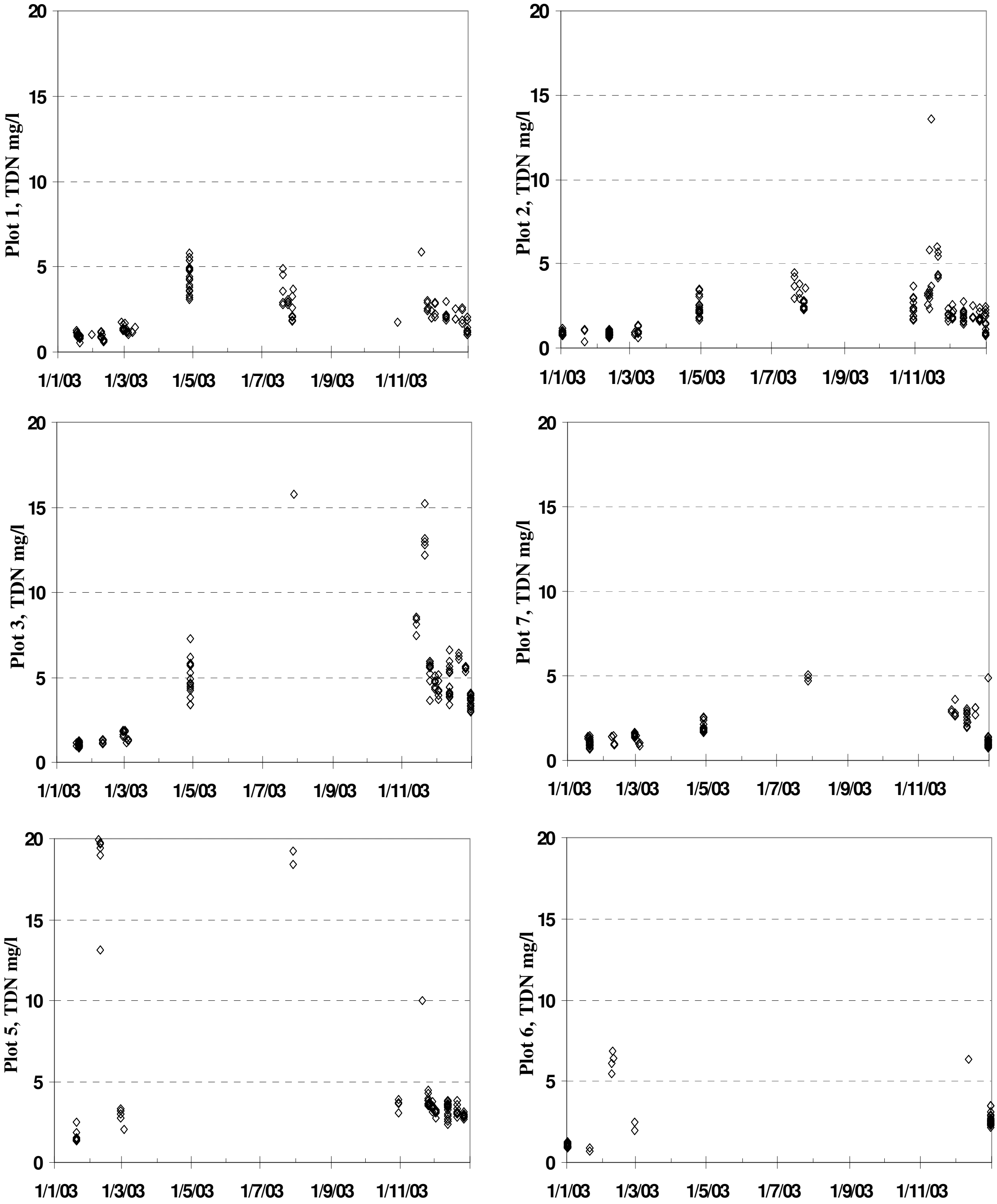

Figure A9. Summary of total dissolved N (TDN) concentrations in overland flow water samples from plots 3 and 6 (grazed) and plot 1, 2, 5 and 7 (cut) in 2003.

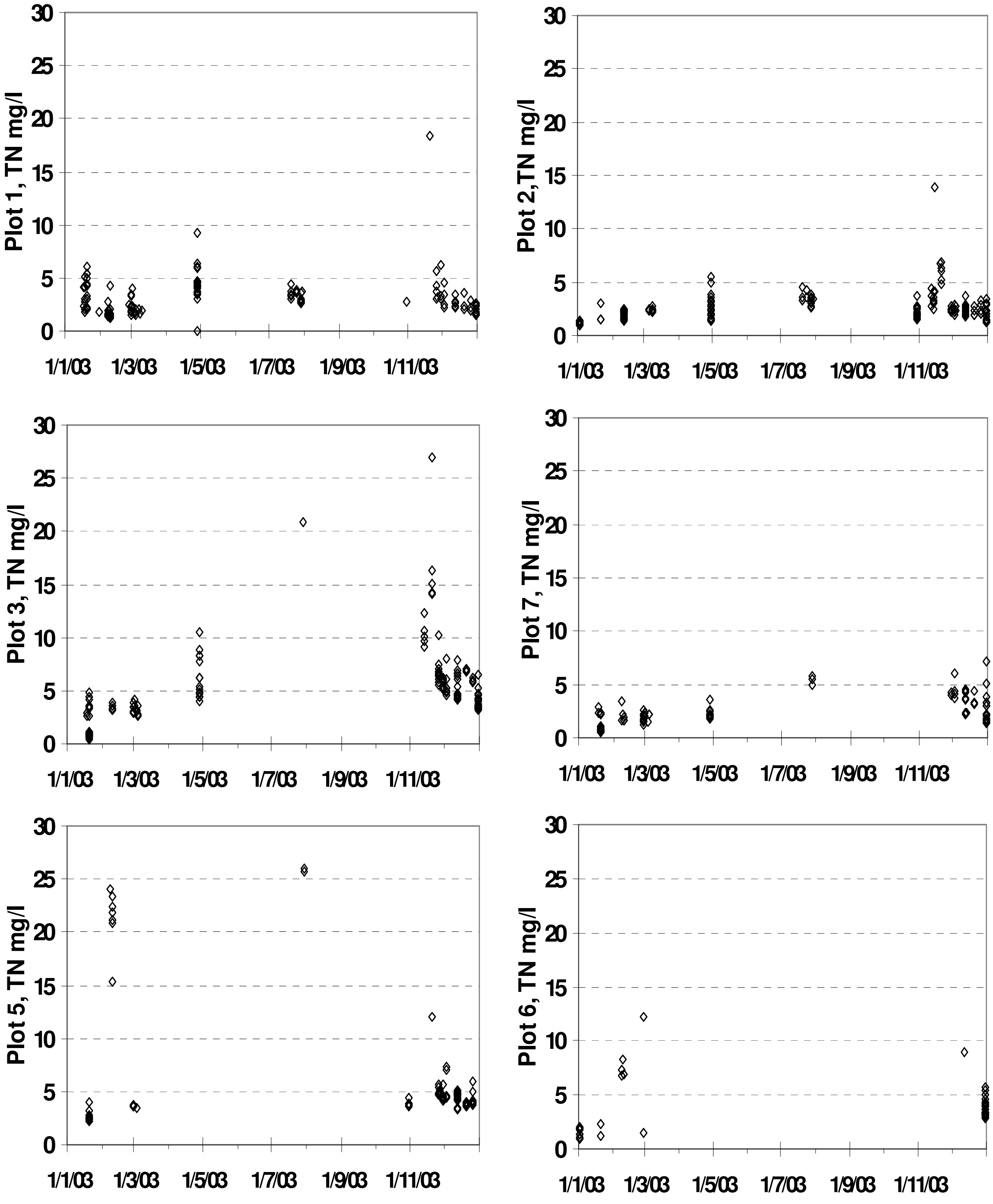

Figure A10. Summary of total N (TN) concentrations in overland flow water samples from plots 3 and 6 (grazed) and plot 1, 2, 5 and 7 (cut) in 2003.

Table A4 and Figure A4 show that there was not a wide variation in the average TRP concentrations between the paired plots 1 (mean 0.083 mg/l P) and 2 (mean 0.090 mg/l P) and between the paired Plots 5 and 6 in 2001. The largest difference in TRP was between plot 1 (mean 0.083 mg/l P) and plot 3 (mean 1.18 mg/l P) both of which were grazed in 2001.

Tables A5 and A6 show broadly similar trends for 2002 and 2003. Total reactive P was the only P fraction analysed in 2001 compared to DRP, TDP and TP in 2002 and 2003 (Tables A4, A5 and A6). In 2002, the average DRP concentrations between the paired plot 3 (grazed, mean 0.57 mg/l) and plot 7 (cut, mean 0.59 mg/l) or between 5 (grazed) and 6 (cut) (Table A5 and Figure A5) were similar. However, the average DRP concentration was higher for the April/May period on plot 3 compared to plot 7 (Figure A5). For operational reasons plots 1 and 2 were both grazed in 2002 and both cut in 2003. There was a larger difference in the average DRP concentration between plots 1 and 2 in 2002 (Table A5) compared to the average TRP differences in 2001 (Table A4). The relatively high average TRP concentration from plot 1 relative to plot 2 in 2001 compared to the relatively small differences in DRP concentrations in 2002 may have been partly due to the presence of the grazing animals on plot 1 in 2001. The highest average P concentrations in overland flow were on plots 3 and 7 and the lowest were on plots 1 and 2. There was of the order of a ten-fold difference in annual average soluble P (TRP, DRP and TDP) concentrations in overland flow between plot 1 and plot 3 (Tables A4, A5 and A6).

Table A6 shows that the average 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 average DRP concentration between plot 2 in 2003 (0.085 mg/l, cut) compared to 2002 (0.092 mg/l, grazed). In 2003 the average 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. This was due mainly to the higher DRP concentration in November/December 2003 on plot 3 compared to plot 7 (Figure A6), however, there was no evidence of difference in DRP concentrations in the first three months of the year. The annual average DRP concentrations were of the same order for plot 3 (grazed, 0.57 and 0.72 mg L^{-1} in 2002 and 2003, respectively, Tables 5 and 6) and plot 7 (cut, 0.59 and 0.48 mg L^{-1} in 2002 and 2003, respectively).

However, there was still over a ten-fold difference in average 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 cutting or grazing treatments, were the main source of variation in P concentration in overland flow water under the conditions of this experiment.

Figure A4 shows large differences in TRP concentrations between plot 1 and 2 compared to plot 5 and plot 6 in 2001. This data show little evidence of a major impact of the grazing animal on TRP concentrations in overland flow water compared to the cut plots. There is evidence of higher TRP on plot 6 (cut) compared to plot 5 (grazed) from January to April 2001 (Figure A4). Figures A5 (2002) and A6 (2003) show lower average DRP concentrations in overland flow from plot 1 and plot 2 compared to the other plots. Differences in DRP concentrations in overland flow between plots 1 and 2 or between plots 3 and 7 were small compared to the difference between plots 1 and 3, for example. This is in agreement with work in the USA, where the affect of grazing on P and suspended solids (SS) loss to water was considered small in comparison to natural variation (Emmerich and Heitschmidt, 2002).

The trends in TDP and TP concentrations for 2003 shown in Figures A7 and A8, respectively, indicate broadly similar trends to the DRP concentrations shown in Figure A6. 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 started analysing water samples for TDP and TP using autoclave digestion and should be interpreted with caution as they may have been underestimated in 2002.

Most of the high NH_4-N and TON concentrations occurred in the wet year 2002. Table A5 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 urea or calcium ammonium nitrate fertiliser application. An example of high NH_4-N concentrations was observed on three plots (3, 5 and 7) in overland flow after heavy rainfall (28 mm) on the 28th February to the 1st March 2002. Urea was spread at 43, 37 and 80 kg/ha N (27th February on plots 3 and 7 and 20th February on plot 6) on plots 3, 6 and 7 respectively. The average NH_4-N concentrations were 12 (5 samples, between 22:30-23:30 h), 5 (5 samples, between 00:00-01:00 h) and 8 (8 samples, between 22:45-00:30 h) mg/l for plots 3, 6 and 7, respectively, over a two and a half hour period on the 28th February to 1st March 2002. Recent work in New Zealand showed that animal treading increased denitrification (52 g/ha/day N_2O-N after severe treading compared to 2.3 g/day with no treading) in grass clover swards (Menneer et al., 2005).

Similar to P 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 (Figure A10) concentrations in overland flow water, particularly on plot 3 and plot 5. The average 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 A9 and A10, respectively, were somewhat lower on plot 7 (cut) compared to plot 3 (grazed). However, it could be interpreted that the opposite was the case on plots 5 (cut) and 6 (grazed) in 2003.

A3.2 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 A2 (at end of this report) for 2001, 2002 and 2003. It should be noted that the annual plot and overall means in Appendix A2 are calculated from the monthly means and therefore differ from the annual plot and overall means show in Tables A4, A5 and A6 which are arithmetic means of all samples. In the following description a statistical significance level of 5% ($P<0.05$) is used.

In 2001 the mean annual or mean monthly TRP concentrations were not significantly different between plots 1 (grazed) and 2 (cut). The mean annual TRP concentration from plot 5 (grazed) was significantly lower than from plot 6 (cut) and was also significantly lower in January and April. Plot 3 (grazed) had a significantly higher annual mean TRP concentration than the other four plots and higher than plots 1 and 2 in all months but lower than plots 6 (cut) in January.

In 2002 the mean annual DRP concentration was significantly lower for plot 1 than plot 2 (both grazed) and also in June, July, September and October. The mean annual DRP concentration was not significantly different between plots 3 (grazed) and 7 (cut), but the former was significantly lower in January and higher in April. The mean annual DRP concentration from plot 5 (grazed) was significantly higher than from plot 6 (cut) but lower in February and April and higher in October, November and December.

In 2003 the mean annual DRP concentration was not significantly different between plots 1 and 2 (both cut). The mean annual DRP concentration was significantly higher on plot 3 (grazed) than plot 7 (cut) and also higher in April, July, November and December but lower in January. In contrast, the annual DRP concentration was not significantly different between plots 5 (cut) and 6 (grazed), however, in December the latter was significantly higher.

The overall mean annual DRP concentration was 0.49 mg/l for both 2002 and 2003 compared to the TRP concentration of 0.63 mg/l in 2001. The mean annual TDP concentration was 0.52 and 0.50 mg/l while the mean annual TP concentration was 0.60 and 0.70 mg/l in 2002 and 2003, respectively.

In general, there was a tendency for significantly higher mean DRP concentrations 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 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 in all months where there were samples. This is one of the most significant results of this study; other differences were lower in magnitude and less consistent.

The trends in mean annual and mean monthly TDP and TP concentrations for 2002 and 2003 (Appendix A2) were broadly similar to the DRP concentrations discussed above.

There were significant differences in the mean annual and monthly concentrations of the N fractions studied, between plots (Appendix A2). There were some high mean monthly concentrations for TON, NH4-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, NH4-N and TDN concentrations were 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.

A3.3 Relationships between Nutrient Concentrations in Overland Flow Water Samples

A3.3.1 Phosphorus and nitrogen

There was a significant relationship between TP and TDP 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 (DRP = 0.87TDP + 0.0084, R^2 = 0.81, $P<0.001$) and between TP and DRP (DRP = 0.72TP - 0.019, R^2 = 0.73, $P<0.001$).

There was also a strong relationship between TN and TDN (TDN = 0.74TN + 0.012, R^2 = 0.88, $P<0.001$). A scatter plot of the TON and an NH_4-N concentration in overland flow from the six plots for the three years is shown in Figure A11. This shows that there was not a significant relationship between the two parameters, however, Figure A11 illustrates that, in general when ammonium concentrations were high total oxidised N (mostly nitrate N) concentrations were low and visa versa. There were two samples where both parameters were high (Figure A11). Twenty four samples (total samples analysed 4581) had TON (mostly nitrate N) over 10 mg/l and 75 samples (total samples analysed 4566) had NH_4-N over 5 mg/l (Figure A11).

There was an overall statistically significant ($P<0.001$) relationship between TP and total TN in overland flow water. This relationship is illustrated in Figure A12 and indicates that on average there was 4 to 5 times higher TN than TP concentrations in overland flow water. The relationship was best on plots 1, 2, 3 and 7 ($R^2>0.5$) and weak on plots 5 and 6 ($R^2<0.2$). There was also a significant relationship between TP and TDN (R^2 = 0.32, $P<0.001$) and between TDP and TDN (R^2 = 0.24, $P<0.001$).

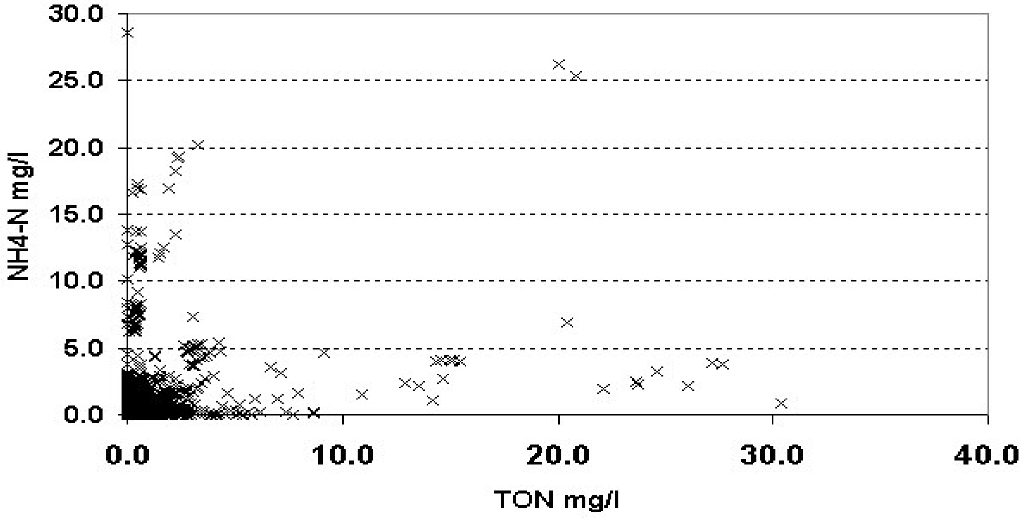

Figure A11. Scatter plot of total oxidised nitrogen and ammonium nitrogen concentrations in overland flow water from six plots over three years (2001 to 2003).

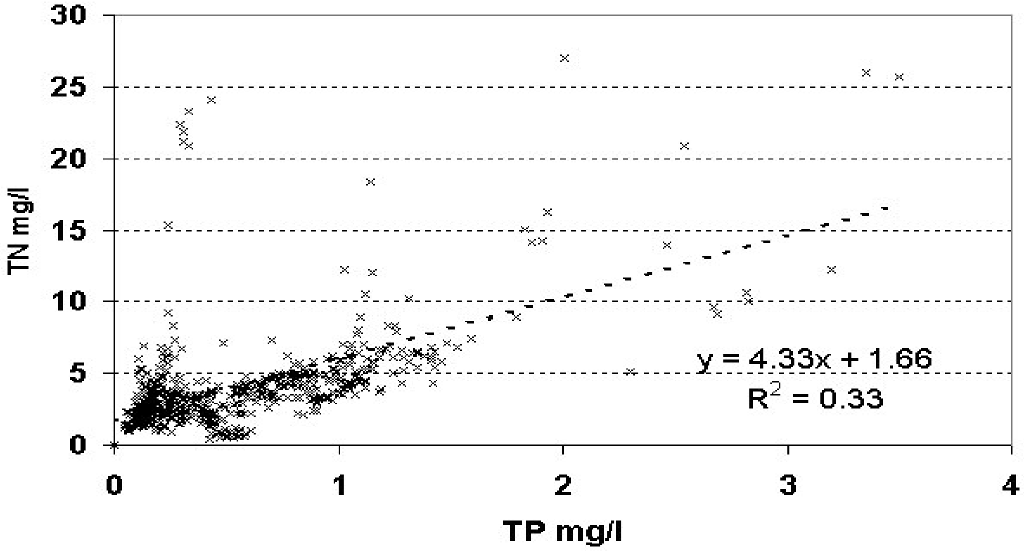

Figure A12. Relationship between total phosphorus and total nitrogen in overland flow water samples from the six plots in 2003.

The relationships between TP and TDP and also between TN and TDN for the six plots from November 2003 to March 2004 are summarised in Figure A13. It is clear that most of the TN and TP 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 for the same period (DRP = 0.77TP - 0.112, R^2 = 0.77, P<0.001). These results for this period are broadly in agreement with the results for 2001 to 2003, shown at the start of this section (A3.3.1).

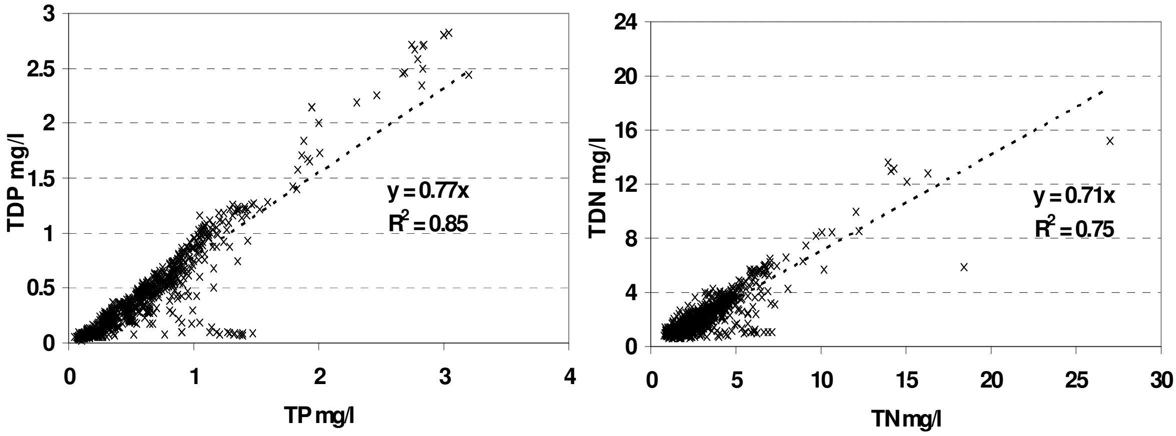

Figure A13. Relationship between total P (TP) and total dissolved P (TDP) and total N (TN) and total dissolved N (TDN) for the six plots from November 2003 to March 2004.

A3.3.2 Phosphorus and potassium

This section describes the total reactive P (TRP) and K concentrations in overland flow water from the six plots (plots 1 to 6, note plot 4 was included here) from September 2000 to April 2001. Information on P and N concentrations in overland flow water from these grassland plots was reported previously (Tunney et al., 2000; Tunney et al., 2002; Tunney et al., 2003).

A total of 2467 flow proportional water samples were collected during the 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. Relationships between the mean concentrations of TRP and K in overland flow for the six plots (1 to 6) are plotted in Figure A14.

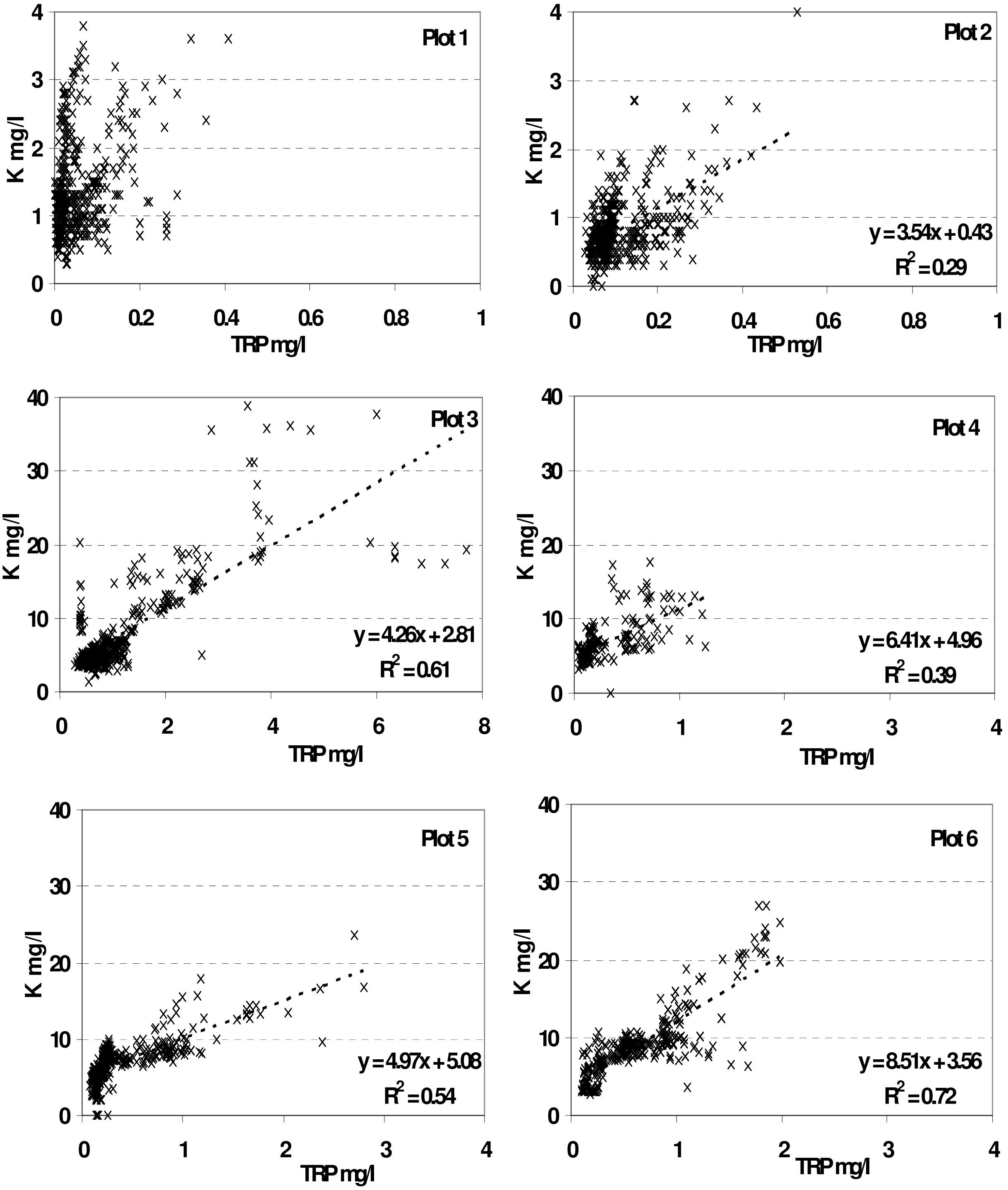

Figure A14. Relationship between TRP and K in overland flow from six plots, Sept. 2000 to April 2001 (plot 1 not significant; 2, P<0.001; 3, P<0.001; 4, P<0.001; 5, P<0.01; 6, P<0.01).

There was not a statistically significant correlation between soil test P and soil test K for the six plots. The mean concentrations of TRP and K in overland flow for the six plots are summarised in Table A7.

Table A7. Mean TRP and K in overland flow water and correlation coefficient between TRP and K (R^2) for the six plots from September 2000 to April 2001.

Plot	**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

*statistical significance differences shown in title of Figure A14, which is a chart of the data.

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 between TRP and K loss in overland flow at 5 of the 6 plots. The best relationship, of the six plots, was on Plot 3 and 6; they also had the highest TRP and K concentration in overland flow water and the highest soil STP of the six plots monitored at that time. The relationship between TRP and K in overland flow water for all six plots is summarised in Figure A15.

Figure A16 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 values in autumn 2000, were when overland flow started after the summer (see Plot 3, Figure A16). The relationship between TRP and K exists despite the wide variations in TRP and K concentrations.

There was also a statistically significant relationship between P and N in overland flow water. In 2003 the relationship was as follows: TDN = 3.80TDP + 1.42, $R^2 = 0.26$, $P<0.001$. An important factor influencing the relationship between P and N and P and K is the trend 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.

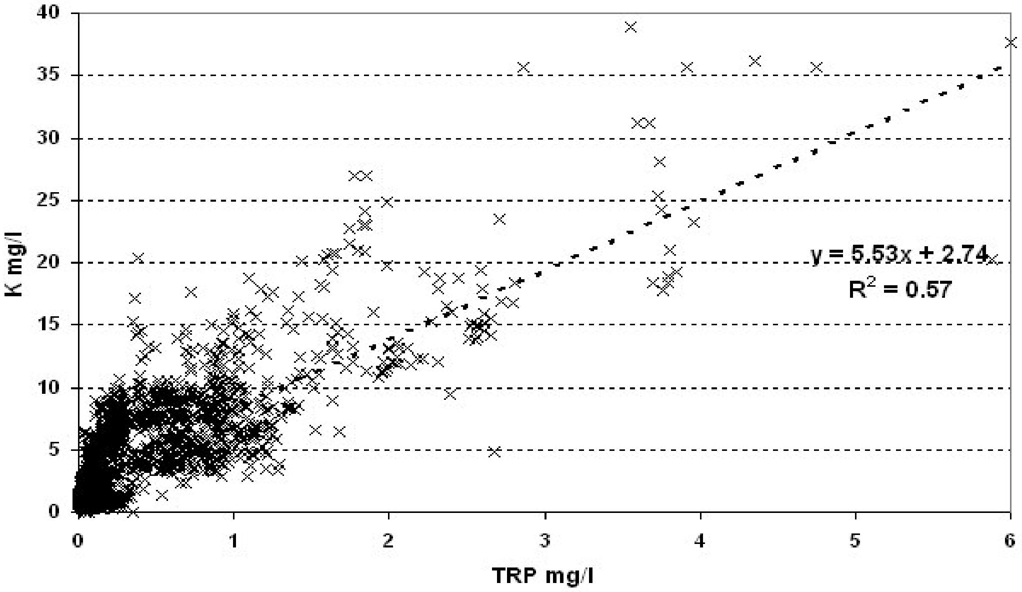

Figure A15. Relationship between TRP and K concentrations in overland flow water from all the six plots (P<0.01) for the period September 2000 to May 2001.

A3.3.3 Suspended Solids

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 A8 and in Figure A17.

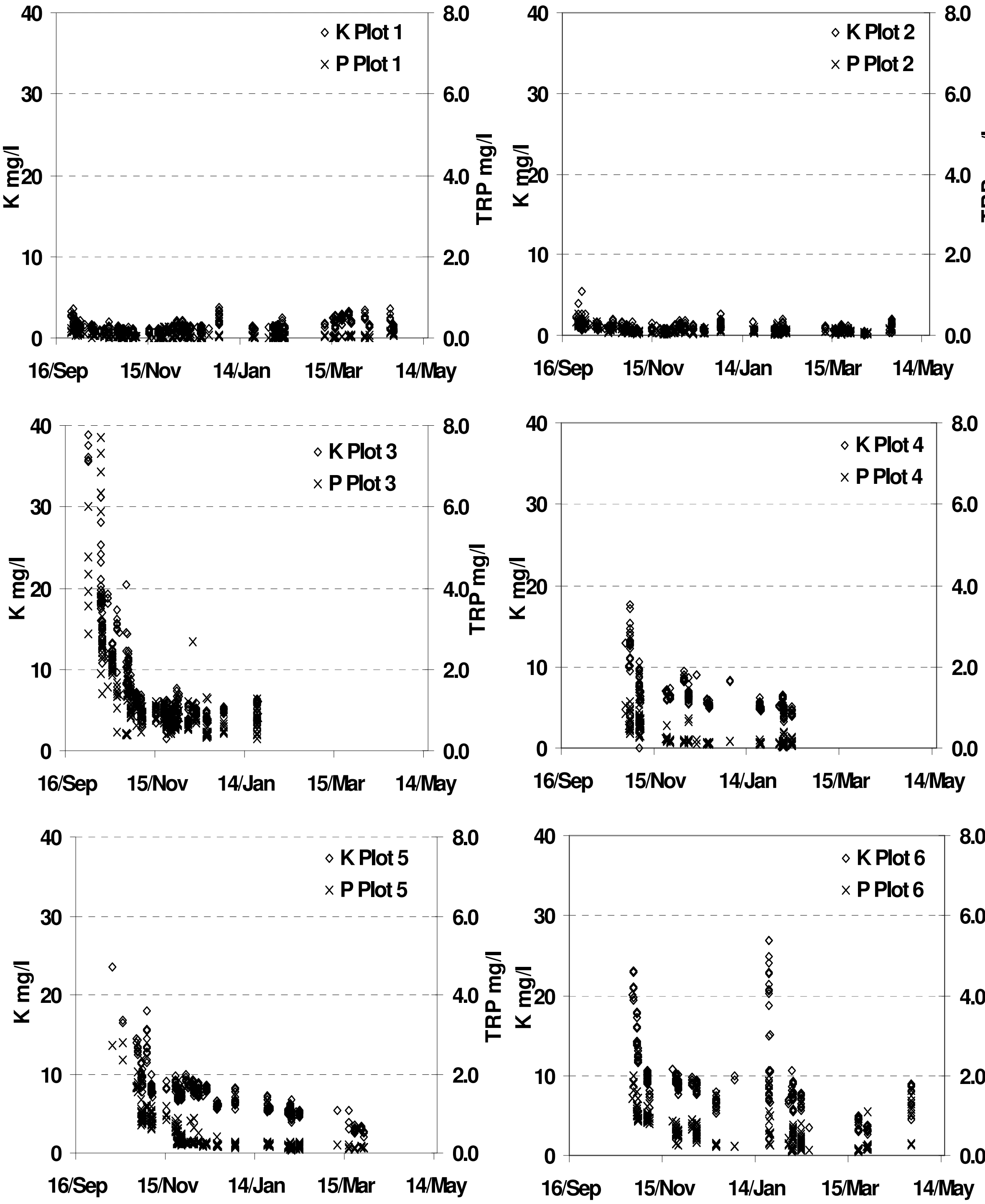

Figure A16. Temporal trends in K and TRP (P) concentrations in overland flow water from six plots, Sept. 2000 to April 2001.

The overall average was 45 mg/l SS for the six plots in this overland flow period and plots 5 and 6 had the lowest level of SS (Figure A17). Plot 2 had the highest SS and this was due to very high SS levels during two events (06:23 to 07:14 h on the 8th January and 08:16 to 13:00 h on the 4th February 2004). Plot 1, the pair of plot 2, also had high SS in two overland flow samples in November 2003 (Figure A17). On neither of these occasions were gazing animals present on the plots, these two plots were not grazed after October 2002.

Table A8. The average, maximum and standard deviation (STDEV) of suspended solids (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
Average	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

The high SS levels, particularly on Plot 1 and 2 were unusual and may have been due to channel erosion with soil entering overland runoff water (e.g. 3rd and 4th of February 2004, see Plot 2 on top right of Figure A17).

An example of trends in flow and SS, TP and TDP concentrations for the 3rd and 4th February 2004 for Plots 3 and 7 is shown in Figure A18. The concentrations of SS is closely linked to flow as is TP, the concentration of TDP is less closely linked.

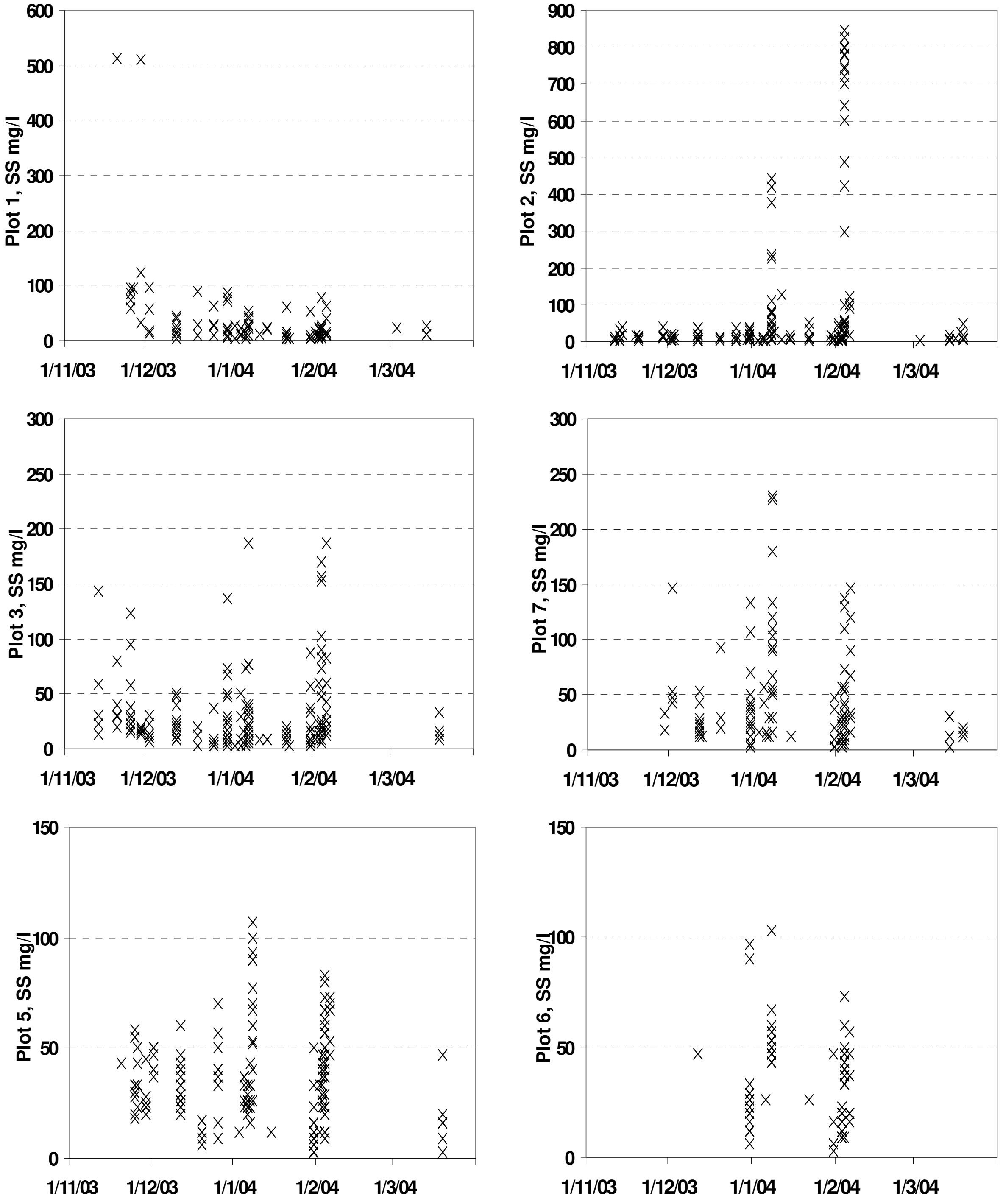

Figure A17. Trends in suspended solids (SS) concentrations for six plots in the overland flow, November 2003 to March 2004. Plots 3 and 6 were grazed the other plots were cut in 2003.

There was a significant relationship between SS and particulate (PP) on all six plots, the highest correlation was on plots 1 and 7 (R^2 of 0.9 and 0.8 respectively). The average %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.

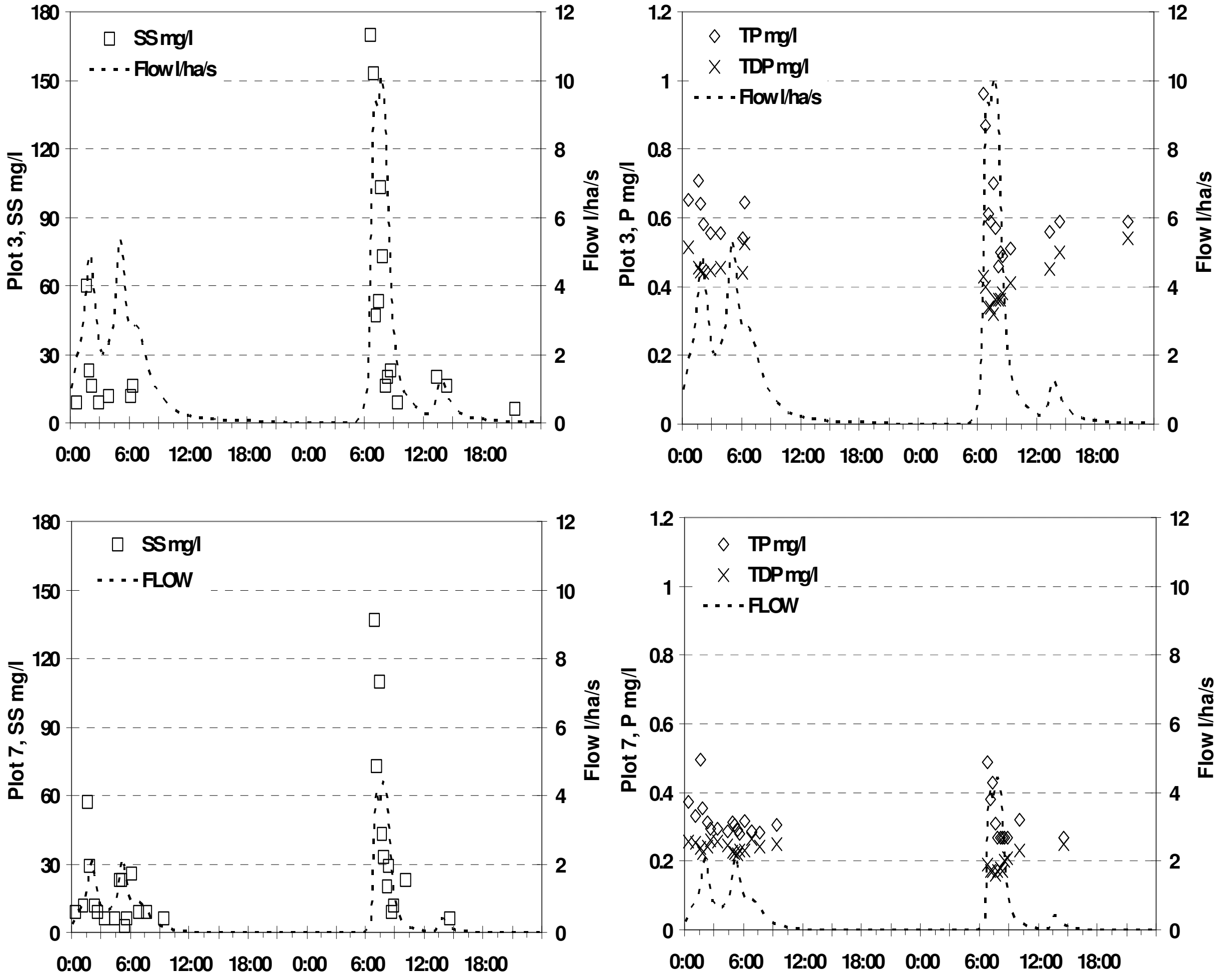

Figure A18. Trends in flow, SS, TP and TDP for Plot 3 (grazed to October 2003) and 7 (cut in 2003) on the 3rd and 4th of February 2004.

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 the 3rd and 4th of February 2004. An estimate of the SS load that could be lost from these soils can be estimated as follows. Assuming an annual overland flow of 100mm (1000 m^3 per ha) per annum and an average concentration of 45 mg SS per litre, then the load would be 45 kg/ha SS. With 200mm overland flow the load would be 90 kg SS per ha per annum (the overland flow on these plots was generally between 50 and 250mm per annum, see later section). 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.

The 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 (Figure A17). The low loss of SS from grazed grassland 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 significant SS loss in situations where soil poaching occurs, for example, when animals are grazed 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 found in measurements of river water in the Oona Water, Co. Tyrone but higher than in the Dripsey, in Co. Cork, which was part of the three catchment study (EPA Project LS2-2.1.1a). It is possible that some of the SS present in these edge of plot overland flow water samples would be trapped and deposited before it reached the nearest watercourse.

A3.4 Examples of P and N Concentrations from Grazed and Cut Grassland During Individual Overland Flow Events

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

A3.4.1 April 2002

An extreme example of a comparison between cut and grazed areas was observed on plots 3 and 7 on the 21st April 2002; Plate 1 shows the two plots after the rainfall event. The poaching due to the heavy rainstorm, that was unexpected, is not representative of good farming practice; nonetheless, it is an example of what can occur in practical farming. During this event overland flow water from Plot 7 (cut) was clearer than from Plot 3 (grazed, Plate 2). This colour may have been due to increased soil organic matter and/or fine soil particles due to poaching by the grazing animals.

Figure A19 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 un-grazed plot. This suggests that the poaching by grazing animals increased sediment loss and hence increased TP concentration. Total dissolved N was greatest at the start of storm flow and then decreased with time (Figure A20), this contrasts with DRP which increased with time as flow increased (Figure A19). Total dissolved N was lower for the grazed plot compared to the cut but this was reversed for NH_4-N which was higher in runoff from the grazed plot (Figure A20).

Plate 1. Plot 3 on left (grazed) and plot 7 on right (cut) photographed on the 21st April 2002. Grazing animals poached plot 3 during the heavy rainfall on the morning of the 21st April.


SCHOTT
DURAN
2000 ml
West Germany

```
ERROR: stackunderflow
OFFENDING COMMAND: ~

STACK:
```