Environmental RTDI Programme 2000–2006

EUTROPHICATION FROM AGRICULTURAL SOURCES – Small Plot Study on the Impact of Grazing Animals on Nutrient Losses to Water

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Final Report

Prepared for the Environmental Protection Agency

by

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WATER QUALITY

The Water Quality Section of the Environmental RTDI Programme addresses the need for research in Ireland to inform policymakers 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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1 Introduction

Grassland managed with the aim of supporting intensive animal husbandry can, under some circumstances, become a source of nutrients in waterbodies (Kurz *et al.*, 2005a). The influence that the presence of grazing animals as such may have on nutrient losses from pastures is unclear. Stock can impact on stream water quality directly by entering and excreting into the streams (Sharpley and Syers, 1979), and by trampling and eroding the stream banks (Line *et al.*, 2000). Grazing animals can furthermore alter the hydrology and the drainage pathways at a site. They can compact the topsoil, which is indicated by increased bulk density and decreased macroporosity (Singleton *et al.*, 2000). This can result in a decrease of the infiltration capacity of the soil (McColl *et al.*, 1985; Heathwaite *et al.*, 1990) and, consequently, in an increased occurrence of overland flow (Heathwaite *et al.*, 1990), which is considered to be an important nutrient loss pathway (McColl, 1979; McColl and Gibson, 1979). Finally, grazing animals can change the nutrient source aspects of grassland. They may alter the type and amount of nutrients that can be mobilised and lost to water by effecting a spatial and chemical re-distribution of nutrients (Bromfield and Jones, 1970) and, sometimes, by causing enough soil damage to reduce grass growth (Drewry and Paton, 2000a).

Generally, the impact of grazing animals on nutrient losses to water depends on site characteristics such as soil type and topography, on climate, season and weather, on management, on the type of grazing animal used and on the timing of run-off-producing rainfall events in relation to stock movement (Lambert *et al.*, 1985; Rowarth *et al.*, 1985; Drewry and Paton, 2000a; Drewry *et al.*, 2000). The effects of grazing animals on nutrient losses to water are reported to range from not measurable (Coltharp and Darling, 1975; Owens *et al.*, 1989) or small (Sharpley and Syers, 1976; Chichester *et al.*, 1979; Van Keuren *et al.*, 1979; Jawson *et al.*, 1982) to considerable (Turner *et al.*, 1979; Heathwaite and Johnes, 1996). This variation is probably due to the great number of variables involved in the nutrient loss process, and to the considerable effect the relative timing of management and weather factors can have on nutrient movement. Overall, grazing shortly before or during wet conditions was found to give rise to increased nutrient losses from land to water (Sharpley and Syers, 1976; Chichester *et al.*, 1979; McColl, 1979; McColl and Gibson, 1979; Jawson *et al.*, 1982; Jordan and Smith, 1985), but little is known about the impact of rotational summer grazing practices on nutrient losses to water.

1.1 Focus of the Project

Within the wide subject area of nutrient losses attributable to grazing animals, it was decided to focus this project on nutrient losses from pasture systems that are typical of Irish grassland. Such losses are greatly influenced by site characteristics, by meteorological variables, by management factors and by the interactions between these three elements (see above). The many sources of variation usually demand that studies on nutrient losses and grazing animals are restricted to examine a subset of circumstances. In this project, the following choices were made:

- The impact of the presence of the animals rather than the effect of stocking rate on nutrient losses was studied.
- Cattle were the type of grazing animal investigated and rotational grazing was the management system studied.
- The overall LS2 research programme emphasised phosphorus (P) rather than nitrogen (N) losses. This approach was also adopted in this study. As overland flow is a very efficient way of P export from grassland areas (Kurz *et al.*, 2005b), the main thrust of the study was to look at the impact of cattle on the occurrence of overland flow and on the P concentrations in overland flow. However, nitrogen (N), potassium (K), sulphur (S) and suspended solid (ss) concentrations were also measured in water samples.

1.2 Aims and Hypothesis

The null hypothesis to be tested was that the presence of cattle does not influence the quantity or quality of overland flow produced at a site.

The aims of the project were:

- To measure the impact of the presence of cattle on soil physical properties relevant to the hydrological characteristics of a site.
- To assess whether the presence of cattle is likely to influence the quality of the overland flow produced at a site.

1.3 Design of the Study

The design of the study therefore reduced the impact of all variables other than presence/absence of grazing animals on the measurements taken. This was achieved by using fields as study sites. Within these fields, replicated small plots (1.5 m × 15 m) to which the animals had access ('animals' (A) plots) and small plots from which the animals were excluded ('no animals' (N) plots) were set up. The small plot method thus offered a direct comparison of areas which were in the same place, had the same soil type, weather and management history. The treatment was the main difference between the two types of small plots, and the impact of environmental factors, site characteristics and management factors other than presence/absence of grazing animals on measurements was largely removed. The small plot studies were designed to yield data on the importance of the effect of cattle on overland flow quantity and quality at the specific sites used and under the weather patterns that occurred during the study period.

The small plot studies were carried out at four sites over 2 years (spring 2002 to spring 2004). Two of the study sites (Dairy Farm and Cowlands) were located at Johnstown Castle, Wexford and two at Grange, Co. Meath. Within each field site, 10 small plots were selected randomly. The Cowlands site at Johnstown Castle was split into a lower and an upper part because of a wetness gradient. In the upper part, three N and three A plots were randomly selected. In the lower part, two N and two A plots were randomly selected.

At each site, cattle had access to five of these plots and they were excluded from the other five. The N plots were fenced with electric wire (Fig. 1.1). The plots to which the animals had access (A) were marked with coloured stakes driven to ground level (Fig. 1.2). To ensure that no machinery drove through these plots, electric fencing posts were used to mark the A plots whenever the animals were not in the fields.

A pasture field at Grange was split into two parts. These parts formed the two experimental sites at Grange, and small plots were set up accordingly (see above). The two parts of the field were managed the same during the normal grazing season. Grazing was then continued on one part (Grange extra) for some extra days during the winter period (Table 1.1) when the other part (Grange normal) was closed.

The small-plot studies were set up on existing pasture swards. None of the four sites were re-seeded before the A and N areas were delineated. The A plots are therefore representative of established grazed grassland areas, and the N plots of established grazed grassland from which the animals were removed. Differences in measurements are thus always attributable to the combined effect of the recovery of the land in the N areas and the effect of cattle in the A areas.

Figure 1.1. Small plots at the Dairy Farm site at Johnstown Castle.

Figure 1.2. Coloured stake driven to ground level to mark the corner of an 'animals' plot.

Table 1.1. Management information.

	Grazing information			Fertiliser information		
	Start	End	No. of LU[a]	Dates	Type	Rates (kg element/ha)
Cowlands (Johnstown Castle)						
	19 Apr 02	22 Apr 02	11	27 Feb 02	K and urea	62 and 43
	17 May 02	19 May 02	13	3 May 02	Urea	57
	6 Jun 02	7 Jun 02	11	6 Jun 02	CAN[b]	50
	24 Jun 02	27 Jun 02	8	20 Jun 02	CAN	50
	11 Jul 02	13 Jul 02	8	19 Jul 02	CAN	33
	3 Aug 02	6 Aug 02	7	9 Aug 02	CAN	33
	23 Aug 02	26 Aug 02	6	5 Sep 02	CAN	33
	16 Sep 02	19 Sep 02	7			
	7 Oct 02	10 Oct 02	7			
	12 Apr 03	16 Apr 03	12	6 Mar 03	Urea	38
	4 May 03	8 May 03	12	20 Mar 03	K	62
	27 May 03	31 May 03	11	29 Apr 03	Urea	57
	21 Jun 03	24 Jun 03	10	21 May 03	CAN	50
	21 Jul 03	25 Jul 03	10	12 Jun 03	CAN	50
	18 Aug 03	21 Aug 03	11	4 Jul 03	CAN	33
	11 Sep 03	17 Sep 03	6	6 Aug 03	CAN	33
	2 Oct 03	5 Oct 03	6	17 Sep 03	CAN	33
Dairy Farm (Johnstown Castle)						
	30 Apr 02	6 May 02	20	20 Feb 02	Urea	37
	27 May 02	29 May 02	20	27 Feb 02	P/K	15 and 65
	16 Jun 02	17 Jun 02	20	9 May 02	CAN	35
	1 Jul 02	3 Jul 02	20	31 May 02	CAN	35
	23 Jul 02	25 Jul 02	20	20 Jun 02	CAN	35
	10 Aug 02	12 Aug 02	20	3 Jul 02	CAN	35
	30 Aug 02	1 Sep 02	20	26 Jul 02	CAN	35
	19 Sep 02	21 Sep 02	20	12 Aug 02	CAN	35
	12 Oct 02	14 Oct 02	20	9 Sep 02	CAN	35
	2 Nov 02	3 Nov 02	20			
	14 Apr 03	19 Apr 03	20	29 Jan 03	Urea	39
	14 May 03	17 May 03	20	18 Mar 03	P/K	17.5 and 75
	4 Jun 03	7 Jun 03	20	2 Apr 03	Urea	50
	21 Jun 03	23 Jun 03	20	27 Apr 03	CAN	50
	14 Jul 03	16 Jul 03	20	20 May 03	CAN	50
	3 Aug 03	5 Aug 03	20	12 Jun 03	CAN	50
	23 Aug 03	25 Aug 03	20	30 Jul 03	CAN	50
	21 Sep 03	23 Sep 03	20	3 Sep 03	CAN	50
	19 Oct 03	21 Oct 03	20			
	11 Nov 03	12 Nov 03	20			
	21 Apr 04	22 Apr 04	56	11 Feb 04	Urea	25
				13 Feb 04	P/K	37 and 74
				9 Mar 04	Urea	35
				22 Apr 04	Urea	57

Table 1.1 *contd.*

	Grazing information			Fertiliser information		
	Start	End	No. of LU[a]/ha	Dates	Type	Rates (kg element/ha)
Grange normal (Grange)						
	Average information on summer 2002 grazing season:			Feb 02	P/K	19 and 37
	Middle of April	Late October	3.5	Feb 02	Urea	57
				22 Apr 02	Urea	43
				30 May 02	CAN	50
				21 Jun 02	Urea	57
				23 Jul 02	CAN	50
				30 Aug 02	CAN	50
	Average information on summer 2003 grazing season:			Feb 03	P/K	12 and 25
	Middle of April	Early November	3.4	18 Feb 03	Urea	57
				5 Jun 03	Urea	57
				3 Jul 03	Urea	57
				1 Aug 03	CAN	51
Grange extra (Grange)						
	Average information on summer 2002 grazing season:			Feb 02	P/K	19 and 37
	Middle of April	Late October	3.5	Feb 02	Urea	57
				22 Apr 02	Urea	43
	Winter 2002 grazing days:			30 May 02	CAN	50
	11 Dec 02	15 Dec 02	7	21 Jun 02	Urea	57
				23 Jul 02	CAN	50
				30 Aug 02	CAN	50
	Average information on summer 2003 grazing season:			Feb 03	P/K	12 and 25
	Middle of April	Early November	3.4	18 Feb 03	Urea	57
				5 Jun 03	Urea	57
				3 Jul 03	Urea	57
	Winter 2003 grazing days:			1 Aug 03	CAN	51
	25 Nov 03	28 Nov 03	4			
	12 Feb 04	14 Feb 04	6			

[a]LU, livestock units.

[b]CAN, Calcium Ammonium Nitrate.

2 Methods

2.1 Description of the Study Sites

The land use of the four sites in which small plot studies were set up was permanent pasture. The soils at the Dairy Farm site at Johnstown Castle and at the two sites at Grange are classified as brown earths, whereas the soil at the Cowlands site at Johnstown Castle is a gley (Gardiner, 1962; Culleton and Diamond, 2005). The Food and Agriculture Organisation of the United Nations (FAO) classes are humic gleysol at Cowlands, gleyic cambisol at Dairy Farm and orthic luvisol at the sites in Grange (FAO–UNESCO, 1974). The areas of the field sites are 0.46 ha for Cowlands, 0.74 ha for Dairy Farm and 0.26 ha for both sites at Grange.

2.2 Management of the Study Sites

At all sites the land was managed in rotational grazing systems at estimated stocking rates of 2 livestock units (LU)/ha. This means that the fields were grazed at intervals of approximately 3–4 weeks from April to October/November. In normal years, damage due to grazing pressure should not occur.

The cattle could reach and graze most of the fenced (N) plots by stretching their heads and necks underneath the wire. However, they could not walk or excrete on the N plots. Grass left in the middle of the plots was removed after every grazing cycle. If a lot of grass remained after grazing, a lawn mower was used to cut the middle of the fenced plots. Otherwise this operation was carried out with a strimmer. The N plots received additional nitrogen to allow for the nitrogen that would have been deposited by cattle had the plots been grazed. Additional P was not applied because the quantities available from deposited dung and urine were estimated to be small (4–5 kg/ha P per year) in comparison to the 20–40 kg/ha of P removal necessary to effect a change of 1 unit of Morgan's soil P (Culleton *et al.*, 1999).

The grazing information and details of fertiliser applications to the fields used as study sites are summarised in Table 1.1.

2.3 Soil Physical Measurements

2.3.1 *Choice of variables*

The soil physical variables measured in this study were bulk density (BD), macroporosity (MP), texture and particle density. Bulk density is the unit mass of the soil per unit volume. When this variable changes at a site, it usually implies a change in the porosity (percentage pores per unit volume) of the soil. Compaction by cattle was shown to have a particularly significant effect on pores larger than 30 µm equivalent diameter (Drewry *et al.* 2000). Such pores are called macropores. They are mainly drained by gravity (Germann, 1990) and are therefore responsible for the drainage of a soil down to field capacity (Radulovich *et al.*, 1992). Bulk density and MP are known to represent an important influence on the infiltration characteristics of soils (Free *et al.*, 1940; Sauer *et al.*, 2000), and they were found to be the most useful indicators of topsoil compaction caused by cattle (Drewry *et al.*, 2000).

The particle density of the soils at the study sites was measured in order to calculate the macroporosity. Particle size analysis was carried out because the textural classification of a soil holds information on its micropore network (Beven and Germann, 1982; Bouma, 1982).

Soil moisture (SM) and BD are the main parameters influencing resistance to penetration (RP) at sites of equal soil type (Vazquez *et al.*, 1991; Vaz and Hopmans, 2001). If SM is assessed alongside RP, repeated measurements of these variables during the year should indicate trends in BD with time. Resistance to penetration and SM surveys were therefore carried out several times in the small plots during the study period.

2.3.2 *Description of methods*

Bulk density and MP sampling and determination was carried out according to the methodology described by Drewry and Paton (2000b). Vegetation was removed from the soil surface. Each soil core for BD and MP determination was taken by pushing a bevelled stainless steel ring (inner diameter: 80 mm; depth: 50 mm) into the soil. The ring was excavated carefully, and a very sharp, thin knife was then used to trim the soil core flush with the two ends of the steel ring. For transport and storage, plastic caps were fitted onto both ends of the ring. Samples were stored in the cold room prior to processing in the laboratory.

In the laboratory, gypsum was used to peel the upper surface of the soil cores and thus eliminate smearing (Greenwood, 1989). Earthworms were removed by soaking the soil cores in potassium permanganate solution (Svendsen, 1955). The samples were then transferred to a sand tank (Stakman, 1980) and left to saturate for 2 weeks. Then, they were left to equilibrate at –10 kPa. Mass at equilibrium was recorded and the soil cores were oven dried at 105°C until a constant weight was achieved. Samples were sieved (2 mm) and the mass and volumes of stones were recorded. The volume of water at –10 kPa was calculated and the air-filled pore space at this tension, which corresponds to pores greater than 30 µm, was determined. Bulk density was calculated by dividing the mass of the oven-dried soil by the volume of the soil sample.

A cone penetrograph (Eijkelkamp) was used to measure the maximum RP at the soil surface. This instrument records RP as a function of depth. The resistance at the depth of interest can then be read off the chart. Whenever the rod clearly hit a stone, the readings were marked in the field and excluded from data analysis. Soil moisture was measured during or immediately after the resistance to penetration surveys. Soil moisture was determined using a Theta probe (Delta–T Devices).

Soil texture was analysed following a method based on the procedures described by Culleton (1972), Buurman *et al.* (1996) and MAFF (1986). The submersion method (Blake and Hartge, 1986) was used to estimate particle density.

2.3.3 Sampling depth and programme

The greatest effects of cattle on soil were measured at 0–100 mm depth (Singleton *et al.*, 2000). The plan was therefore to take soil cores at 0–50 and 50–100 mm. At the sites at Grange, there was a layer of gravel at 90 mm depth. A single core at a depth interval of 30–80 mm was therefore taken at these sites. At Dairy Farm and the two sites at Grange, two soil cores per depth interval were taken in each of the 10 plots per site. In 2002, the lower part of Cowlands, in which four of the plots were located, was too wet to be sampled. Sampling at this site was therefore restricted to the six plots in the upper part of the site. In 2002, these six plots were sampled at 0–50 and 50–100 mm and, in 2003, at 0–50 mm. Samples for BD and MP were taken after the grazing seasons in both years. Survey and sampling dates are listed in Table 2.1.

In accordance with the sampling depth, maximum RP was determined between 0 and 100 mm below the ground surface at the Dairy Farm and the Cowlands sites and between 0 and 80 mm below the ground surface at the sites at Grange.

Table 2.1. Resistance to penetration/soil moisture survey dates and MP/BD sampling dates.

Site	RP/SM surveys	MP/BD sampling
Cowlands	31-Mar-03 15-Oct-03	November 2002 October 2003
Dairy	11-Dec-02 02-Apr-03 10-Nov-03	November 2002 October 2003
Grange	09-Dec-02 23-Jan-03 14-Mar-03 03-Dec-03 16-Feb-04	November 2002 December 2003
Grange extra	23-Jan-03 14-Mar-03 16-Feb-04	January 2003 February 2004

2.4 Nutrient Status of Soils

At the end of the second year of applying different treatments (presence/absence of cattle) in the two types of plots, soil was sampled for nutrient analysis. The soil samples were taken to a depth of 100 mm, which is common practice in Ireland (Culleton *et al.*, 1996). Each soil sample was made up of 20 soil cores taken over the five plots of either the A or the N treatment at a study site. These cores were combined and mixed to form a single soil sample per treatment and site. Morgan's P and K levels in soils were measured using an automated version of the procedure described by Peech and English (1944).

2.5 Rainfall Simulation

Rainfall has been simulated by a wide range of systems. The choice of simulator is generally governed by the requirements of each specific experiment (Bowyer-Bower and Burt, 1989). The main criteria for this study were that (1) the set-up allowed a direct comparison between the two treatments and (2) that one person, with some help when erecting and dismantling the simulators, was able to carry out the simulations.

In their comparison of a spray-type and a drip-type rainfall simulator, Bowyer-Bower and Burt (1989) recommended the use of the Amsterdam simulator, which is a drip-type model, for comparative studies. The rainfall produced by this simulator was shown to replicate well at different sites, and the labour requirements for running the Amsterdam simulator are such that one person can look after two simulators running simultaneously on plots that are in close proximity. Other advantages of the Amsterdam model were economy of water use and ease of protection of simulator and plot from wind and natural rainfall. The main disadvantage of the Amsterdam simulator is that it is not able to reproduce the characteristics of natural rainfall. However, the most important aspect of this study was to compare two treatments (A and N). Reproducing the same rainfall conditions on areas of different treatment was therefore more important than accurately reflecting natural rainfall. One of the simulators used in this study is depicted in Fig. 2.1.

Figure 2.1. Rainfall simulator.

Preliminary rainfall simulation trials were carried out in autumn 2003, and the bulk of the simulations took place in late March to early May 2004. One rainfall simulation trial usually consisted of two simulators running more or less simultaneously on one N and one A plot. Start times of rainfall and overland flow were recorded. The rainfall simulations were continued until 1 h after the onset of overland flow, unless extra amounts of sample were needed for a related project (see Bourke *et al.*, 2006). All overland flow was collected as series of time-composite samples. Each sample was the overland flow produced during a 10-min (less if more than 970 ml of flow occurred in 10 min) interval at one site. Flow per 10 min was calculated unless malfunctions of the simulators occurred. The time-composite samples were analysed for the water quality parameters described below. Rainfall simulation was only undertaken at the Dairy Farm site at Johnstown Castle due to time constraints. Five parallel simulations (Runs 1 to 5) were carried out before the start of the grazing season and four parallel simulations (Runs 6 to 9) after the first grazing (cutting) cycle. Note that after the first grazing/cutting cycle, urea was applied to all plots (see Table 1.1).

During all the simulations after the grazing cycle, some dung was contained within the overland flow production area on the A plot. The amount of dung varied between about 10% and 20%. This coverage was chosen because it is a generous estimate of the area covered by dung under an intensive grazing regime. The dung pat areas and frequencies quoted by Whitehead (2000) were used in conjunction with the management figures from the Dairy Farm site (Table 1.1) to estimate the area covered by dung each year. This area amounts to about 10% of the plot and, according to Castle and MacDaid (1972), up to 40% of the area of the site could be rejected by cattle.

A high rainfall intensity was chosen in order to ensure that overland flow occurred within a reasonable time interval. The simulators were set to rain at 20 mm/h – a storm event which has a return period of about 5 years in Ireland (Logue, 1995). When conditions were either known to be dry (last run) or when overland flow had not started by mid-afternoon (second-last run on N plot), rainfall was simulated at a higher intensity of 25 mm/h. In Ireland, such high rainfall rates sometimes occur in connection with thunderstorms (Logue, 1995).

To set the simulators to rain at desired rainfall intensities, a relationship between the manometer board readings of the simulators and the rainfall intensities needed to be developed (Bowyer-Bower and Burt, 1989). Both simulators were therefore calibrated in autumn 2003. After the second run in March 2004, it became obvious that the two simulators no longer rained at comparable rates. When the hourly rainfall rate of both simulators was gauged, one of them was found to be wrong and this one was re-calibrated. The performance of the other simulator was adequate. To ensure that no bias attributable to the two machines was introduced, the simulators were alternated between the two treatments. For example, if, during Simulation 1, Simulator 1 was used on a plot of the A treatment while Simulator 2 was raining on an N plot, Simulator 1 was used on an N and Simulator 2 on an A plot during Simulation 2.

The simulators were designed to rain on an area of 0.5 m^2. Within this area, the zone from which overland flow was to be collected was demarked by pushing a stainless steel frame about 50 mm into the soil. The grass on the areas within the frames was clipped before starting the simulations. The frames used were 900 mm long (excluding collection drain), 400 mm wide and 100 mm deep (Fig. 2.2). At the lower end of each frame, a roofed drain to collect overland flow ran along the shorter axes of the frames. This drain was located at 50 mm from the top of the frame and was about 50 mm deep. When the frame was installed (i.e. pushed 50 mm into the soil), the top of the collection drain was level with the soil surface. The simulators and frames were set up so that the longer axis ran approximately in the direction of the main slope of the land. Each frame was installed in such a way that the lowest point within the frame coincided with one of the downslope corners. At this corner, overland flow flowed from the collection drain through a spout and into 1-l bottles used for overland flow collection (Fig. 2.3).

To accommodate the collector frame and the sampling bottles, it was necessary to excavate a trench along the downslope end of the frames. All-weather sealant (Panabound™) was applied generously to seal any crevices along the inside walls of the frames. Particular care was taken to create a good joint between the soil and the collector drain. However, preliminary simulation runs in autumn 2003 showed that the soil adjacent to the collector drain was a source of suspended solids (ss) in overland flow. A length of metal was therefore pushed into the soil at an angle to the collector drain. The triangle made by this extra piece of metal and the frame was roofed (Fig. 2.4). The interface between the soil and the collector drain was thus reduced to 20–40 mm and any exposed soil within this small area was covered with sealant. The exact area from which overland flow was collected was recorded for each trial. The measures described above successfully eliminated sources of ss due to the set-up rather than the experimental treatment.

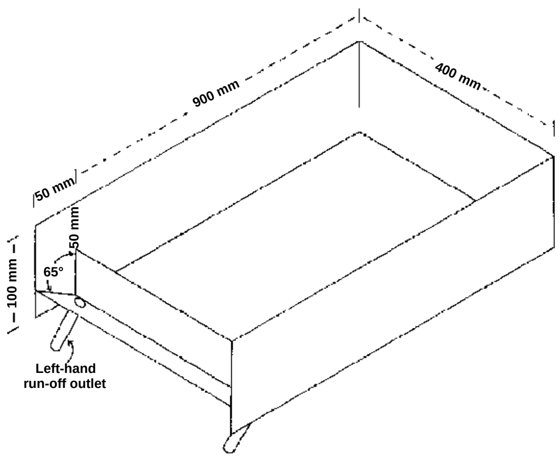

Figure 2.2. Overland flow collection frame.

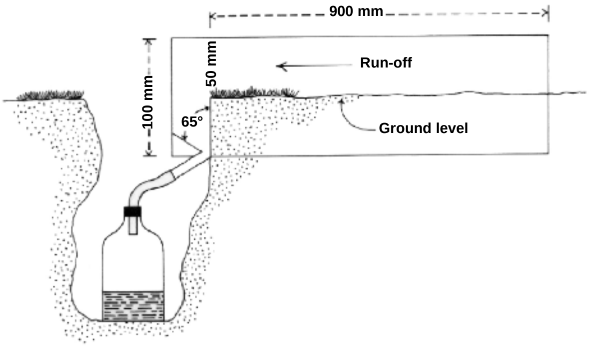

Figure 2.3. Overland flow collection frame installed.

The rate of rainfall minus the rate of overland flow equals the rate of infiltration into the soil. When set in relation to the rate of rainfall, the amount of overland flow produced during simulation runs can provide an indication of the rate of infiltration at a site. This is, however, only the case if it is possible to seal the frames well enough to avoid preferential flow along the plot boundaries (sides of the frames). The sealing was done with great care in order to obtain an estimate of the rate of infiltration.

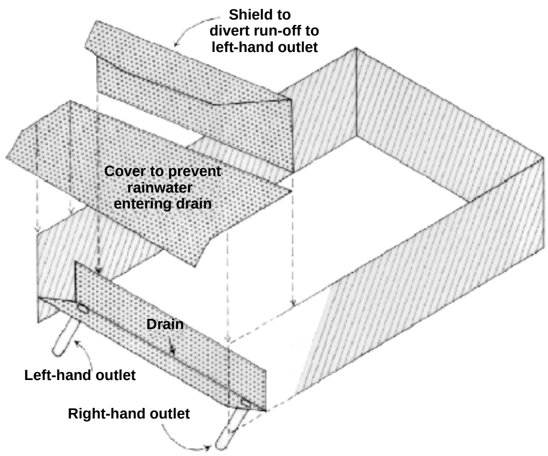

Figure 2.4. Overland flow collection tray with system to eliminate set-up-related sources of suspended material.

2.6 Water Quality Analysis

The following measurements were carried out on most raw and filtered (0.45 µm) samples: reactive P, total oxidised N (TON), total ammonia (TA), total P (TP), total N (TN), sulphur (S) and potassium (K). Suspended solid (ss) concentrations were estimated from one bulk sample, which contained subsamples of the individual samples, for each treatment and run.

Filtration (0.45 µm) separated the dissolved from the particulate fractions. Samples for TP and TN determination were digested and analysed according to an autoclave method described by Ebina *et al.* (1983). An automated version of the ascorbic acid reduction method described by Murphy and Riley (1962) was used to measure reactive P levels. Total ammonia was measured by a method based on the reaction of ammonia with salicylate and dichloroisocyanurate in alkaline solution (Krom, 1980). An automated hydrazine reduction method was employed for TON determination. This method uses hydrazine sulphate to reduce nitrate to nitrite, and the thus produced nitrite, together with nitrite present in the raw sample, is determined colorimetrically (Kamphake *et al.*, 1967). Sulphate was measured by a turbidimetric method (Rossum and Villarruz, 1961). Potassium levels were determined by flame atomic absorption spectrometry (Ediger, 1973), and ss concentrations according to Wyckoff (1964). Reactive P, TON and TA analyses were usually carried out within 24 h of sampling. Dissolved reactive P (DRP) results are missing for the first rainfall simulation trial because the filtered samples could not be analysed within this time limit. All sampling bottles were scrubbed and washed with P-free detergent (Decon 90). The materials used (sealant and bottles in field, vials and filters in laboratory) were tested to determine whether they represented sources of contamination. No contamination was found. Rain falling from the simulators was collected in washed sample bottles during three of the nine simulation trials. The samples were filtered and treated like all other samples in the laboratory. All of these blanks were clear of contamination.

To continuously assess the accuracy of analysis, the Johnstown Castle laboratory takes part in an intercalibration scheme set up and run by the Irish Environmental Protection Agency. The limits of detection and precision values of the measured parameters are listed in Table 2.2. The measured and calculated parameters for which data are presented in this report are summarised in Table 2.3.

Table 2.2. Method limits of detection and precision values (mg/l) for P, N, S and K analyses at the Johnstown Castle laboratory.

Parameter	Method limit of detection	Precision
Reactive P (DRP/TRP)	0.005	0.008
Total P (TDP/TP)	0.009	0.003
TN (TN/TDN)	0.12	0.040
TA	0.1	0.12
TON	0.3	0.2
S	1	0.51
K	0.1	0.8

Dissolved reactive P (DRP) estimates the minimum amount of P that is immediately available to aquatic life (Ekholm, 1998). Particulate P (PP) can be reactive or unreactive. Similar to DRP, particulate reactive P is assumed to be immediately available to algae and macrophytes. The term unreactive P refers to all the forms of P which do not react during the direct colorimetric test. These include unreactive particulate P and dissolved organic and condensed forms of P. These P fractions are less readily available than reactive P (Stevens and Stewart, 1982; Ekholm, 1998). The concentration of these forms of P is nonetheless important, because they can become available through transformation processes in waterbodies (Ball and Hooper, 1963; Lean, 1973).

2.7 Data Analysis

Analysis of variance was carried out on the soil physical and soil chemical data sets. Each site was analysed separately. The results of the different RP and SM surveys (dates) were analysed individually and combined in a repeated measures analysis. This analysis of variance takes account of correlation. This means that the RP or SM in a plot measured on one date influences (or is influenced by) the RP or SM found on a different date.

A Spearman's Rank Correlation was carried out to relate soil moisture deficit and flow data collected during rainfall simulations.

Table 2.3. List of water quality parameters presented in this study.

Parameter	Abbreviation	Measured/calculated	Comments
Dissolved reactive P	DRP	Measured	Dissolved P and colloidal P (colloids <0.45 µm) that reacted with the reagents to form molybdenum blue during direct (no pretreatment of sample other than filtration) colorimetric analysis. DRP is mainly made up of orthophosphate (dissolved and colloidal (colloids <0.45 mm)), but condensed and organic forms of P (dissolved and colloidal (colloids <0.45 µm)) may also contribute (Stevens, 1980)
Dissolved unreactive P	DUP	DUP = TDP – DRP	Dissolved P and colloidal P (colloids <0.45 µm) that did not react with the reagents to form molybdenum blue during direct (no pretreatment of sample other than filtration) colorimetric analysis. This P fraction mainly contains dissolved organic and condensed P and organic and condensed forms of P associated with colloids <0.45 µm
Total particulate P	PP	PP = TP – TDP	All forms of P associated with solids
Total oxidised nitrogen	TON	Measured	Sum of nitrate and nitrite N
Total ammonia	TA	Measured	Sum of ionised and unionised ammonia
Total dissolved N	TDN	Measured	Total nitrogen in filtered sample
Total particulate N	TPN	Total N in unfiltered sample - TDN	Total N associated with suspended solids
Dissolved S	DS	Measured	S in filtered sample
Particulate S	PS	S in unfiltered sample - DS	S associated with suspended solids
Potassium	K	Measured	

3 Results

3.1 Soil Texture and Nutrient Levels

The sites at Johnstown Castle have a sandy loam topsoil and the sites at Grange a clay loam topsoil.

The means and levels of significance for cases in which there was a statistically significant treatment (A or N) effect on soil nutrient levels are listed in Table 3.1. At the end of the experiments, the potassium concentrations were significantly higher in plots to which the animals had access (A) than in plots from which the animals were excluded (N) at all study sites. There was no statistically significant effect of treatment (presence/absence of cattle) on soil P levels at the Dairy Farm site at Johnstown Castle and at the two sites at Grange. At the Cowlands site at Johnstown Castle, the soil P levels were significantly higher in A than in N areas.

3.2 Resistance to Penetration and Soil Moisture

The repeated measures analyses of the RP data show date-by-treatment interactions for each site except the extra grazing site in Grange. This suggests that, at most sites, the difference between the treatments was not constant over time. Therefore, effects of treatments over time cannot be averaged and the data for each date need to be analysed separately. At the extra grazing site in Grange, the repeated measures analysis shows no date-by-treatment interaction. This means that the difference between the treatments, which is statistically significant, is the same for all surveys, i.e. there is no statistically significant difference between the treatment effect at different dates. The analyses of variance of the single dates are compiled in Table 3.2. For each sampling date,

Table 3.1. Soil nutrient levels where there were significant treatment effects recorded between plots to which cattle had access (A) and plots from which cattle were excluded (N).

Site	Nutrient (mg/l)	Mean N (mg/l)	Mean A (mg/l)	Difference (mg/l)	p
Dairy Farm	K	104	179	75	0.041
Cowlands	P	15	19	4	0.035
Cowlands	K	62	130	68	0.038
Grange normal	K	107	210	103	0.008
Grange extra	K	66	223	157	0.026

Table 3.2. Analyses of variance of resistance to penetration (RP) measurements in plots to which cattle had access (A) and plots from which cattle were excluded (N).

Site	Date	RP N (N/cm^2)	RP A (N/cm^2)	P of diff*	RP diff (A–N) (N/cm^2)	Diff (%)
Cowlands	31 Mar 03	52	71	0.0432	19	27
Cowlands	15 Oct 03	59	103	<0.0001	44	43
Dairy Farm	11 Dec 02	65	96	0.0021	31	32
Dairy Farm	2 Apr 03	71	107	0.0037	36	34
Dairy Farm	10 Nov 03	52	104	<0.0001	52	50
Grange normal	9 Dec 02	68	97	0.0005	29	29
Grange normal	23 Jan 03	66	102	<0.0001	36	35
Grange normal	14 Mar 03	70	99	0.0032	29	29
Grange normal	3 Dec 03	78	125	<0.0001	47	38
Grange normal	16 Feb 04	49	84	<0.0001	35	42
Grange extra	23 Jan 03	72	103	0.0024	31	30
Grange extra	14 Mar 03	59	94	<0.0001	35	37
Grange extra	16 Feb 04	44	82	<0.0001	38	46

*Probability (P) of a significant difference (diff).

at all sites, the RP was statistically significantly greater in the A than in the N plots. At Cowlands, Dairy Farm and the normal grazing site at Grange, the treatment effect was greatest after the second grazing season. The data do not indicate a recovery of the Dairy Farm, Grange normal and Grange extra A plots during the winter following the 2002 grazing season. The RP data are displayed in Fig. 3.1.

The repeated measure analyses show that for the study period as a whole, the SM in the A plots was statistically significantly higher than that in the N plots at Cowlands and Dairy Farm. At Grange normal and extra, there was no overall significant treatment effect. However, SM was significantly higher in N than in A plots for one date (14 March 2003) at Grange normal, and the opposite was the case for one date (16 February 2004) at Grange extra. The analyses of variance of the single dates are compiled in Table 3.3.

Figure 3.2 shows that there is no obvious pattern in the relationship between RP and SM, and a least square regression did not reveal any statistically significant trends. It is therefore unlikely that, at the high SM values prevalent in this study, SM had a considerable effect on the RP measurement.

Figure 3.3 displays a scatterplot of the RP data against BD values. The figure suggests the existence of a site-specific linear relationship between these two parameters. The scatterplot also shows that the relationships for the Grange sites resemble each other

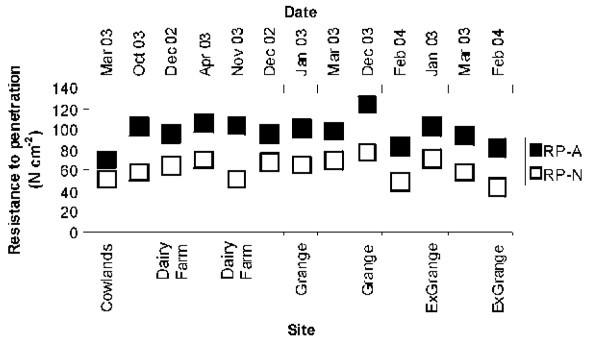

Figure 3.1. Resistance to penetration (N/cm^2) in 'animals' (A) and 'no animals' (N) plots at the sites at Johnstown Castle (Cowlands and Dairy Farm) and Grange (Grange normal and Grange extra (ExGrange)).

and that the same is true for the two sites at Johnstown Castle.

3.3 Bulk Density and Macroporosity

The statistical analyses of the BD and MP data are summarised in Tables 3.4 and 3.5. At all sites and sampling dates, BD was statistically significantly higher and MP lower in plots to which the animals had access (A) than in plots from which the animals were excluded (N). The magnitude of the treatment effects varied between 8% and 17% for BD and between 57% and 83% for MP.

At the Cowlands site, there were no interactions between measurements of different treatments and years. There

Table 3.3. Analyses of variance of soil moisture (SM) measurements in 'animals' (A) and 'no animals' (N) plots.

Site	Date	SM N (m^3/m)	SM A (m^3/m)	P of diff*	SM diff (A–N) (m^3/m)	Diff (%)
Cowlands	31 Mar 03	0.464	0.501	0.055	0.037	7
Cowlands	15 Oct 03	0.397	0.448	0.0142	0.051	11
Dairy Farm	11 Dec 02	0.454	0.493	0.0027	0.039	8
Dairy Farm	2 Apr 03	0.429	0.448	0.2966	0.019	4
Dairy Farm	10 Nov 03	0.404	0.429	0.0772	0.026	6
Grange normal	9 Dec 02	0.519	0.544	0.211	0.025	5
Grange normal	23 Jan 03	0.586	0.591	0.271	0.005	1
Grange normal	14 Mar 03	0.608	0.562	0.0101	–0.046	–8
Grange normal	3 Dec 03	0.522	0.528	0.6852	0.007	1
Grange normal	16 Feb 04	0.537	0.553	0.4838	0.017	3
Grange extra	23 Jan 03	0.577	0.568	0.5755	–0.009	–2
Grange extra	14 Mar 03	0.601	0.576	0.2552	–0.026	–4
Grange extra	16 Feb 04	0.542	0.582	0.0225	0.039	7

*Probability (P) of a significant difference (diff).

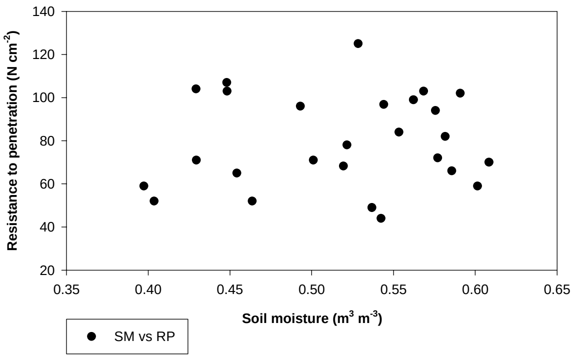

Figure 3.2. Soil moisture (SM) plotted against resistance to penetration (RP).

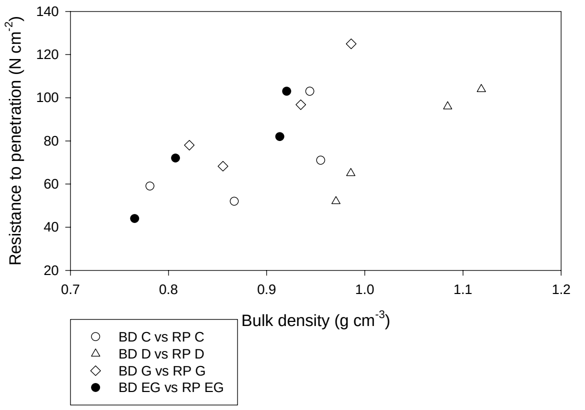

Figure 3.3. Scatterplot between bulk density and the resistance to penetrations at Cowlands (C), the Dairy Farm (D), Grange normal (G) and Grange extra (EG).

was no statistically significant difference between the effect cattle had on BD and MP measured after the first grazing season and values determined after the second grazing season.

At the Dairy Farm site, there were no interactions between the treatment, the year and the sampling depth. The effect that the presence of cattle had on BD and MP was therefore of comparable magnitude at 0–50 mm and 50–100 mm depth, and in November 2002 and October 2003.

At the normal grazing site at Grange, there were significant interactions between treatment and year. This indicates that the treatment effect was different in the two study years. Tables 3.4 and 3.5 illustrate that the BD and MP variations resulting from the presence/absence of cattle were greater in 2003 than in 2002. More detailed information can be gained when studying the factors contributing to the overall variations between the treatments. In the N plots, BD was lower and MP greater after the 2003 than after the 2002 grazing season. The reverse trend was true for the A plots, where BD was higher and MP lower in 2003 than in 2002.

At the Grange extra site, there were no interactions between measurements of different treatments and years in the case of BD, but significant interactions became apparent in the MP data. Thus, there was no statistically significant difference between the treatment effect on BD measurements taken after the first grazing season and values determined after the second grazing season. The differences in MP between the A and N plots were, however, significantly greater after the first than after the second grazing season monitored.

The BD was also shown to be statistically significantly higher and the MP lower at 5–100 mm when compared to samples taken at 0–50 mm (Dairy Farm site). The difference between the BD and MP values associated with the two treatments was, however, comparable at the two depths.

3.4 Rainfall Simulation

3.4.1 Amount of overland flow

The main purpose of the rainfall simulation was to obtain samples to determine the nutrient concentrations in

Table 3.4. Analyses of variance of bulk density (BD) measurements in 'animals' (A) and 'no animals' (N) plots.

Site	Date	Depth (cm)	BD N (g/cm^3)	BD A (g/cm^3)	P of diff*	Diff (A–N) (g/cm^3)	Diff (%)
Cowlands	November 2002, October 2003	0–5	0.824	0.950	0.005	0.126	13
Dairy Farm	November 2002, October 2003	0–5, 5–10	0.978	1.102	<0.001	0.123	11
Grange normal	November 2002	3–8	0.856	0.935	<0.001	0.079	8
Grange normal	December 2003	3–8	0.821	0.986	<0.001	0.165	17
Grange extra	January 2003, February 2004	3–8	0.786	0.917	<0.001	0.131	14

*Probability (P) of a significant difference (diff).

Table 3.5. Analyses of variance of macroporosity (MP) measurements in 'animals' (A) and 'no animals' (N) plots.

Site	Date	Depth (cm)	MP N (%)	MP A (%)	P of diff*	Diff (N–A) (%)	Diff (%)
Cowlands	November 2002, October 2003	0–5	17.3	5.6	<0.001	11.7	68
Dairy Farm	November 2002, October 2003	0–5, 5–10	13.6	5.3	<0.001	8.2	61
Grange normal	November 2002	3–8	9.6	3.0	<0.001	6.6	69
Grange normal	December 2003	3–8	12.4	2.1	<0.001	10.4	83
Grange extra	January 2003	3–8	10.0	4.3	<0.001	5.7	57
Grange extra	February 2004	3–8	15.6	6.2	<0.001	9.3	60

*Probability (P) of a significant difference (diff).

overland flow. Because of the possible interactions between flow and nutrient concentrations in overland flow, data on the amounts of overland flow produced during rainfall simulations were also collected. The simulators were set to rain at equal rates on the A and N plots. This was not always achieved because the calibration curve of one of the simulators had changed since its development. There were also some malfunctions (e.g. air leaks). However, the fact that the machines were swapped between the treatments after each run (see Section 2.5) ensured that no overall bias was introduced. Rainfall rates actually achieved, the time to the onset of overland flow and the maximum flow rate recorded per treatment and event are presented in Table 3.6 and in Figs 3.4 and 3.5. Only overland flow figures of periods when the simulators were functioning satisfactorily were included. The maximum rate of overland flow per unit of rain was calculated to allow for the fact that the rates of rainfall were not always equal on the N and A plots. This ratio cannot be used to estimate the steady-state infiltrability because the simulations were not continued long enough to reach steady-state conditions. However, the ratio between maximum rate of overland flow and rainfall can provide some indication of trends in the rate of infiltration because the flow maxima often occurred towards the end of the overland flow monitoring interval of 1 h.

There is a large amount of scatter in the data (Figs 3.4 and 3.5) but some general trends are recognisable. The time to overland flow was always longer in N than in A plots (Fig. 3.4). This was even the case when the rainfall intensity during the entire (Runs 1 and 5) or a part (Run 8) of the experimental run was greater on the N than the A plot. The maximum amount of overland flow produced per mm of rain was generally (apart from Run 1) greater on N than on A plots. This tendency increased after the site had been grazed (between Runs 5 and 6) (Fig. 3.5). The increase is, however, not simply attributable to the grazing cycle because the increasing SMD (soil moisture deficit calculated according to Schulte *et al.*, 2006) from Run 5 to Run 9 is another factor which is likely to have influenced the drainage pattern of the soil (Fig. 3.5). The rate of overland flow to rate of rainfall ratio tends towards a stable value in the A plots but seems to follow a broadly downward trend from Run 5 onwards in the N plots. The scatterplots of the overland flow to rainfall ratios against

Table 3.6. Information on rainfall and overland flow (OF) during rainfall simulation.

Date	N plots			A plots		
	Rain (mm/h)	OF (mm/h)	Time to OF (min)	Rain (mm/h)	OF (mm/h)	Time to OF (min)
26 Mar 04	25	13	32	20	9	28
1 Apr 04	20	7	62	25	15	24
7 Apr 04	19	14	39	20	15	26
14 Apr 04	20			19	4	62
20 Apr 04	20	14	35	19	15	21
27 Apr 04	20	7	49	20	16	5
30 Apr 04	20	12	27	20	15	10
4 May 04	24	3	208	20	17	7
6 May 04	25	8	49	25	21	14

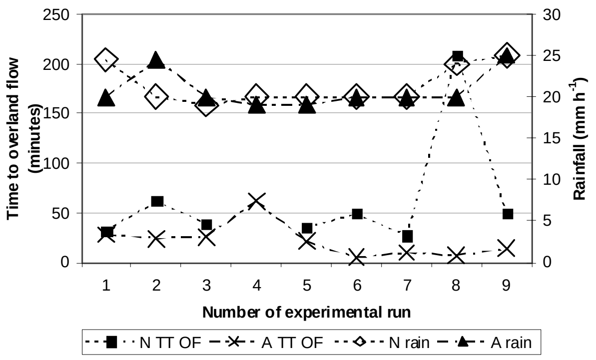

Figure 3.4. Rainfall rates (rain) and time to overland flow (TT OF) in ‘no animals’ (N) and ‘animals’ (A) plots at the site at the Dairy Farm.

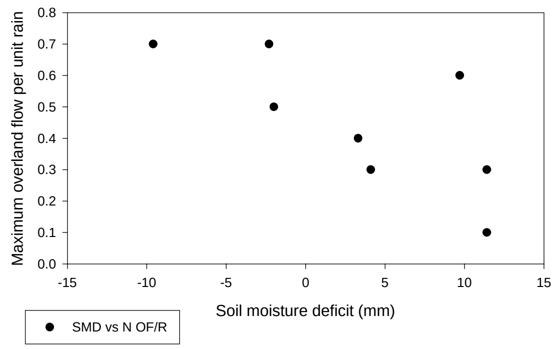

Figure 3.6. Ratio of the maximum overland flow rate (OF) and the rainfall rate (R) in ‘no animals’ (N) plots graphed against soil moisture deficit (SMD).

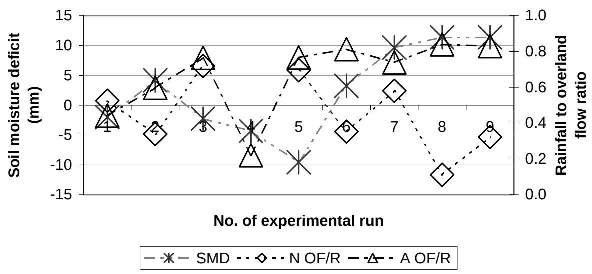

Figure 3.5. Ratio of the maximum overland flow rate (OF) and the rainfall rate (R), and soil moisture deficits (SMD) for the rainfall simulations in the ‘no animals’ (N) and ‘animals’ (A) plots at the Dairy Farm.

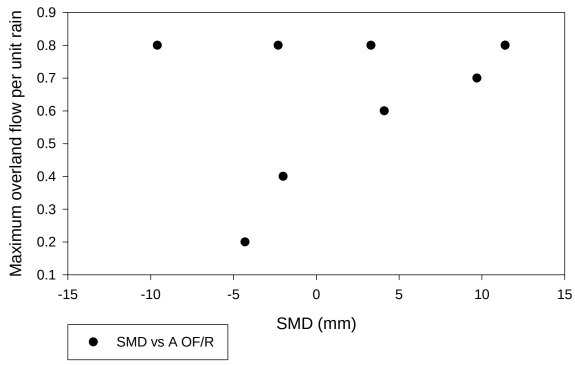

Figure 3.7. Ratio of the maximum overland flow rate (OF) and the rainfall rate (R) in ‘animals’ (A) plots graphed against soil moisture deficit (SMD).

the SMD suggest the existence of an inverse linear relationship between SMD and the maximum amount of flow per unit rain in the N plots (Fig. 3.6) but not in the A plots (Fig. 3.7). The Spearman’s rank correlation assigned statistical significance ($P < 0.013$) to the trend described for the N plots.

3.4.2 Overland flow quality

There were no consistent differences between TA, TON, K and reactive P results of filtered and unfiltered samples. Unless unavailable, the results for the analyses of filtered samples are presented.

The minimum, maximum and mean DRP, DUP, PP, TON, TA, TDN, TPN, DS, PS, and K concentrations and the ss levels are summarised in Table 3.7 and in Figs 3.8–3.29. The wide ranges of minimum, maximum and mean concentrations achieved by the water quality parameters for each treatment (N and A) indicate how variable the nutrient concentrations were across the nine simulations. The substantial difference between the minimum and maximum values measured for each water quality parameter during a single run shows that the concentrations of the nutrients varied greatly during the course of one run.

The main features of interest are (1) a comparison between overland flow quality of plots of the different treatments and (2) a comparison of the overland flow quality before the management operations (grazing/cutting, urea application) (Runs 1–5) to the overland flow quality after the management operations (Runs 6–9).

No clear patterns are obvious in the DRP data (Figs 3.8 and 3.9). For Runs 3–7, mean DRP concentrations were

Table 3.7. Summary statistics of water quality measurements in overland flow from 'no animals' (N) and 'animals' (A) plots at the Dairy Farm site.

Parameter		Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9
		26 Mar 04	1 Apr 04	7 Apr 04	14 Apr 04	20 Apr 04	27 Apr 04	30 Apr 04	4 May 04	6 May 04
No animals										
DRP-P	**Min**	0.363	0.470	1.895	0.745	0.503	1.076	0.911	0.325	0.538
(mg/l)	**Max**	0.487	0.902	2.947	0.944	1.242	2.815	3.307	0.380	0.803
	Mean	0.402	0.600	2.276	0.872	0.701	1.571	1.567	0.347	0.631
	No. obs.	6	6	7	6	6	6	6	6	7
TA-N	**Min**	<0.10	<0.10	0.15	0.16	0.15	3.83	3.64	0.19	0.36
(mg/l)	**Max**	<0.10	0.12	0.62	0.25	0.59	7.14	5.98	0.44	1.11
	Mean	<0.10	<0.10	0.31	0.19	0.27	4.96	4.66	0.30	0.59
	No. obs.	6	6	8.00	6	6	6	6	6	7
TON-N	**Min**	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	0.3	<0.3	<0.3
(mg/l)	**Max**	<0.3	<0.3	<0.3	<0.3	<0.3	0.5	0.8	<0.3	<0.3
	Mean	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	0.6	<0.3	<0.3
	No. obs.	6	6	8	6	6	6	6	6	7
K	**Min**	2.4	<0.1	9.9	3.3	3.5	9.0	11.7	4.3	3.8
(mg/l)	**Max**	4.5	4.6	21.0	4.5	10.3	18.6	40.4	5.9	6.8
	Mean	3.1	2.0	13.7	3.8	5.5	13.1	20.1	4.9	4.9
	No. obs.	6	6	8.0	6	6	6	6	6	7
DS-S	**Min**	4.3	4.5	7.6	4.9	<1.0	<1.0	<1.0	<1.0	<1.0
(mg/l)	**Max**	42.2	7.0	19.2	7.1	<1.0	11.8	1.4	<1.0	<1.0
	Mean	19.1	5.7	13.0	6.0	<1.0	4.1	<1.0	<1.0	<1.0
	No. obs.	6	6	8	6	6	6	6	6	7
PS-S	**Min**		1.8	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
(mg/l)	**Max**		6.3	1.6	2.2	10.7	1.3	<1.0	<1.0	<1.0
	Mean		3.7	1.1	1.8	5.3	<1.0	<1.0	<1.0	<1.0
	No. obs.	6	6	8	6	6	6	6	6	7
PP	**Min**	0.26	0.12	<0.01	0.01	<0.01	0.05	0.37	0.18	0.12
(mg/l)	**Max**	0.39	0.44	<0.01	0.18	0.11	0.27	0.64	0.31	0.22
	Mean	0.31	0.24	<0.01	0.09	0.06	0.19	0.54	0.21	0.19
	No. obs.	6	6	8	6	6	6	6	6	7
TDN-N	**Min**	0.18	3.59	1.19	1.57	1.26	10.88	8.81	1.19	1.41
(mg/l)	**Max**	1.11	5.87	3.18	2.22	3.34	19.01	15.08	2.89	3.33
	Mean	0.67	4.26	2.03	1.88	1.88	13.79	12.44	1.79	2.09
	No. obs.	6	6	8	6	6	6	6	6	7
TPN-N	**Min**	1.20	3.49	<0.12	0.35	0.87	<0.12	0.62	<0.12	0.84
(mg/l)	**Max**	2.45	10.07	1.35	1.44	1.29	1.51	2.13	0.98	1.15
	Mean	1.57	6.06	0.83	0.71	1.12	0.79	1.41	0.65	1.00
	No. obs.	6	6	8	6	6	6	6	6	7
DUP-P	**Min**	<0.01	<0.01	<0.01	0.09	0.09	0.38	0.27	0.06	0.13
(mg/l)	**Max**	0.03	0.04	0.01	0.15	0.11	0.55	0.45	0.11	0.17
	Mean	<0.01	0.02	<0.01	0.12	0.10	0.43	0.33	0.09	0.15
	No. obs.	6	6	8	6	6	6	6	6	7
ss (mg/l)	**Bulk**	98	160	28	18	38	26	20	40	16

Table 3.7 *contd.*

Parameter		Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9
		26 Mar 04	1 Apr 04	7 Apr 04	14 Apr 04	20 Apr 04	27 Apr 04	30 Apr 04	4 May 04	6 May 04
Animals										
DRP-P	**Min**	1.277	1.196	0.562	0.402	0.237	0.941	0.759	0.443	0.807
(mg/l)	**Max**	1.902	1.899	0.912	0.558	0.306	1.530	1.158	0.812	1.430
	Mean	1.448	1.420	0.691	0.443	0.272	1.307	0.865	0.718	1.192
	No. obs.	6	6	8	6	6	7	6	6	9
TA-N	**Min**	<0.10	<0.10	<0.10	<0.10	<0.10	4.33	2.91	0.51	0.40
(mg/l)	**Max**	<0.10	0.58	<0.10	0.23	0.16	7.75	4.35	1.22	0.99
	Mean	<0.10	0.16	<0.10	0.11	<0.10	5.76	3.49	0.68	0.87
	No. obs.	6	6	8	6	6	7	6	6	9
TON-N	**Min**	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	0.5	<0.3	0.3
(mg/l)	**Max**	<0.3	0.4	<0.3	0.8	<0.3	<0.3	1.5	0.3	0.8
	Mean	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	1.0	<0.3	0.6
	No. obs.	6	6	8	6	6	7	6	6	9
K	**Min**	3.3	7.7	2.6	2.9	2.9	16.4	14.4	11.0	15.0
(mg/l)	**Max**	4.3	19.2	7.3	5.6	4.5	28.5	22.1	22.7	19.6
	Mean	3.9	11.4	4.2	3.8	3.6	20.4	18.0	14.1	17.0
	No. obs.	6	6	8	6	6	7	6	6	9
DS-S	**Min**	8.8	4.2	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	3.8
(mg/l)	**Max**	56.8	9.1	6.9	<1.0	<1.0	<1.0	<1.0	3.7	8.1
	Mean	19.9	5.7	2.5	<1.0	<1.0	<1.0	<1.0	<1.0	6.0
	No. obs.	6	6	8	6	6	7	6	6	9
PS-S	**Min**		1.8	1.2	<1.0	<1.0	2.4	<1.0	<1.0	<1.0
(mg/l)	**Max**		4.5	1.9	1.4	<1.0	3.8	<1.0	<1.0	1.5
	Mean		2.9	1.4	<1.0	<1.0	3.0	<1.0	<1.0	1.1
	No. obs.	6	6	8	6	6	7	6	6	9
PP	**Min**	0.03	0.19	<0.01	0.07	0.08	1.41	0.42	0.29	0.52
(mg/l)	**Max**	0.25	0.57	0.02	0.16	0.13	1.66	0.70	0.39	1.24
	Mean	0.20	0.28	0.01	0.10	0.11	1.54	0.58	0.33	0.78
	No. obs.	6	6	8	6	6	7	6	6	9
TDN-N	**Min**	0.55	4.03	0.87	1.28	0.69	14.18	8.69	2.96	6.11
(mg/l)	**Max**	0.95	7.34	1.41	1.70	1.28	26.39	14.39	5.10	8.97
	Mean	0.69	5.08	1.11	1.43	0.94	18.37	11.10	3.73	7.37
	No. obs.	6	6	8	6	6	7	6	6	9
TPN-N	**Min**	1.11	3.61	<0.12	0.49	1.20	4.80	1.22	0.86	2.98
(mg/l)	**Max**	1.61	9.05	0.55	1.04	1.50	7.33	2.74	2.00	4.72
	Mean	1.30	5.41	0.12	0.69	1.36	6.63	1.96	1.44	3.46
	No. obs.	6	6	8	6	6	7	6	6	9
DUP-P	**Min**	<0.01	<0.01	<0.01	0.05	0.03	0.78	0.27	0.16	0.49
(mg/l)	**Max**	<0.01	0.09	0.08	0.13	0.09	1.06	0.51	0.22	0.79
	Mean	<0.01	0.03	0.04	0.08	0.05	0.97	0.44	0.19	0.69
	No. obs.	6	6	8	6	6	7	6	6	9
ss (mg/l)	**Bulk**	58	78	26	46	28	97	44	26	32

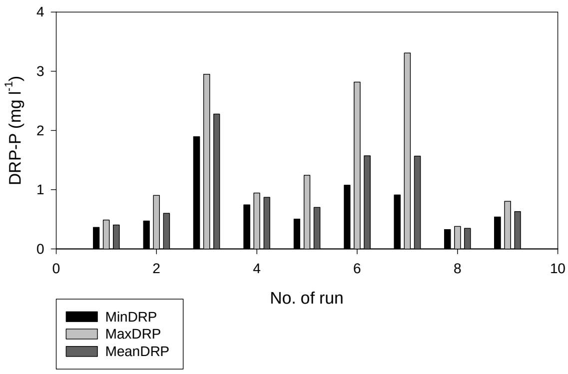

Figure 3.8. Minimum, maximum and mean DRP concentrations in overland flow from 'no animals' (N) plots during the rainfall simulations at the Dairy

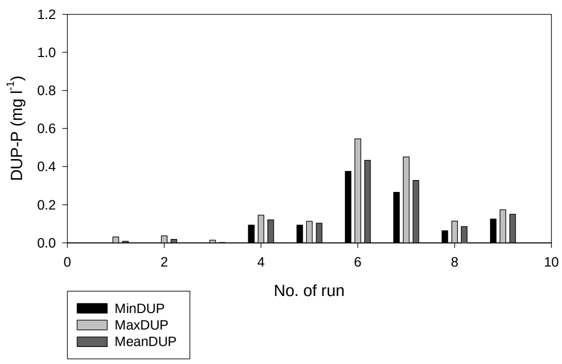

Figure 3.10. Minimum, maximum and mean DUP concentrations in overland flow from 'no animals' (N) plots during the rainfall simulations at the Dairy Farm.

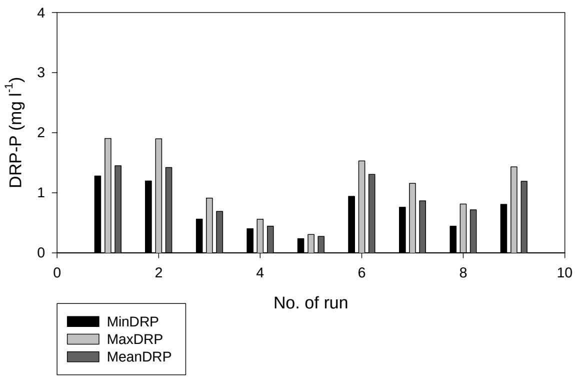

Figure 3.9. Minimum, maximum and mean DRP concentrations in overland flow from 'animals' (A) plots during the rainfall simulations at the Dairy Farm.

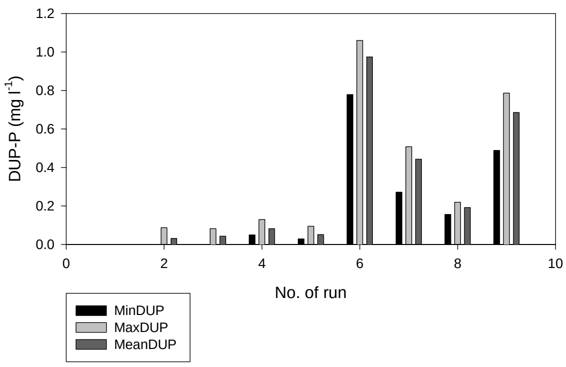

Figure 3.11. Minimum, maximum and mean DUP concentrations in overland flow from 'animals' (A) plots during the rainfall simulations at the Dairy Farm.

higher in the N plots than in the A plots, and the reverse was the case for Simulations 1, 2, 8 and 9. In the A plots, DRP concentrations decreased from Runs 1 to 5 and they recovered during the management operations. The difference between DUP in overland flow from the N and the A plots was relatively small during Runs 1–5 but it increased significantly after the management operations (Runs 6–9) in the N as well as in the A plots (Figs 3.10 and 3.11). However, the effect of the management factors on the DUP levels was much greater in the A than in the N plots. The PP concentrations were of comparable magnitude in the two types of plots during Runs 1–5 (Figs 3.12 and 3.13). From Run 6 onwards, PP was much higher in overland flow from the A than from the N plots.

In the N plots, there was no clear increase in PP after the management operations.

The TDN concentrations were similar in overland flow from A and N plots (Figs 3.14 and 3.15). In both types of plots, a substantial increase in TDN occurred after the management operations. The TPN concentrations were high during Run 2 in overland flow from the N and the A plot, and also during Runs 6 and 9 in overland flow from the 'animals' (A) plots (Figs 3.16 and 3.17). The difference between the mean TPN levels in overland flow from the A and N plots increased after the management operations. Total oxidised nitrogen and TA levels in overland flow were often below the limits of detection (Figs 3.18–3.21). In N as well as in A plots, there was a slight increase in

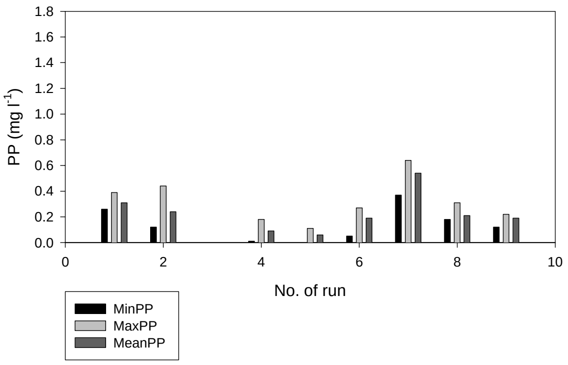

Figure 3.12. Minimum, maximum and mean PP concentrations in overland flow from 'no animals' (N) plots during the rainfall simulations at the Dairy Farm.

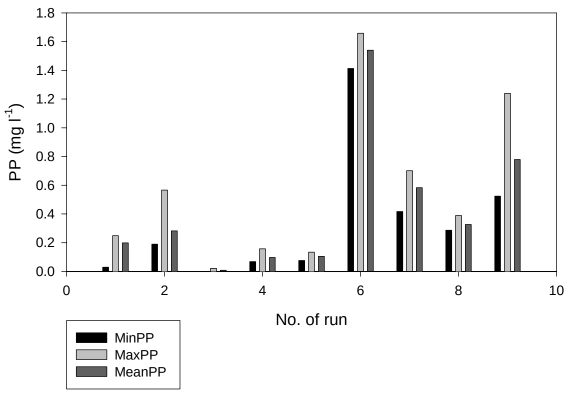

Figure 3.13. Minimum, maximum and mean PP concentrations in overland flow from 'animals' (A) plots during the rainfall simulations at the Dairy Farm.

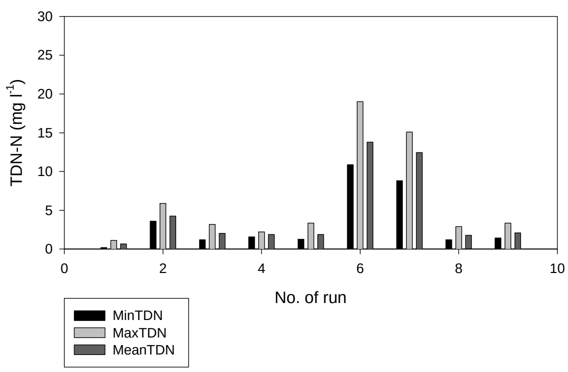

Figure 3.14. Minimum, maximum and mean TDN concentrations in overland flow from 'no animals' (N) plots during the rainfall simulations at the Dairy Farm.

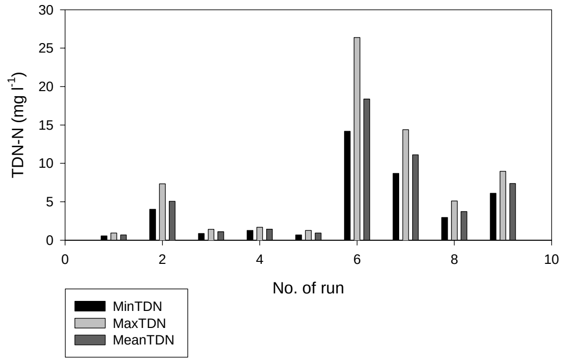

Figure 3.15. Minimum, maximum and mean TDN concentrations in overland flow from 'animals' (A) plots during the rainfall simulations at the Dairy Farm.

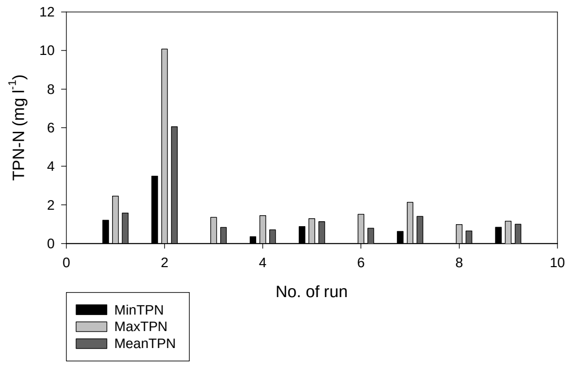

Figure 3.16. Minimum, maximum and mean TPN concentrations in overland flow from 'no animals' (N) plots during the rainfall simulations at the Dairy Farm.

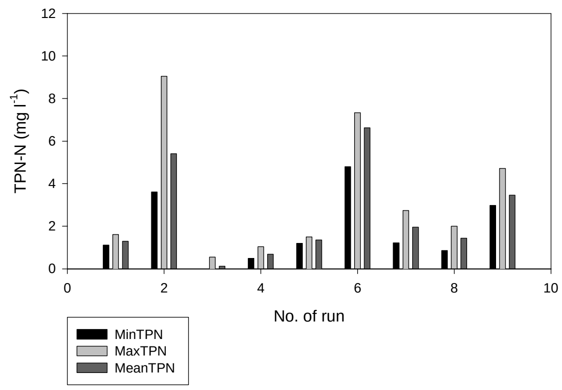

Figure 3.17. Minimum, maximum and mean TPN concentrations in overland flow from 'animals' (A) plots during the rainfall simulations at the Dairy Farm.

TON levels and a considerable increase in TA levels after the management procedures.

The K concentrations in the A plots were increased following the management operations (Fig. 3.22). The K levels in the two events after the management operations were also elevated in the N plots but comparable levels of K had occurred during Run 3. The elevated K levels in overland flow from N plots during Runs 6 and 7 can, therefore, not be attributed to the management procedures (Fig. 3.23).

Dissolved sulphur levels were highest during the first simulation trial in both treatments. No clear pattern to relate the dissolved or particulate sulphur data to the presence of grazing animals became apparent (Figs 3.24–3.27). A similar situation applies to the ss data. The ss concentrations were clearly higher in the A than in the N plots during the simulation trial following the management operations (Figs 3.28 and 3.29). However, in ss levels differences of comparable order of magnitude between the treatments also occurred in Trial 2, but the ss concentrations were higher in overland flow from the N than from the A plot.

3.4.3 *Interactions between flow and water quality*

The scatterplots of TP, TN, K and sulphate against the rates of overland flow (Figs 3.30–3.33) indicate that the concentrations of the nutrients measured in this study were not greatly affected by the rate of overland flow.

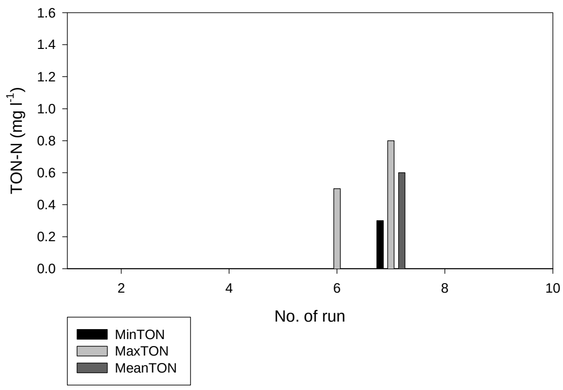

Figure 3.18. Minimum, maximum and mean TON concentrations in overland flow from 'no animals' (N) plots during the rainfall simulations at the Dairy Farm.

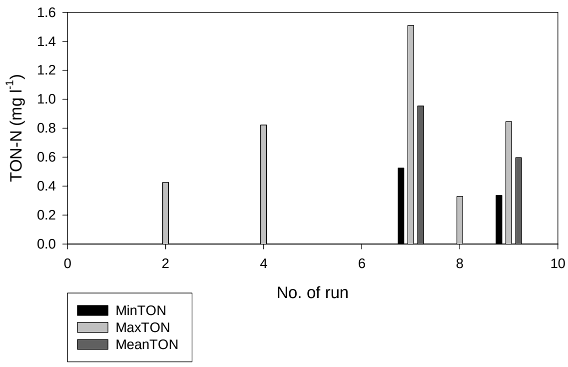

Figure 3.19. Minimum, maximum and mean TON concentrations in overland flow from 'animals' (A) plots during the rainfall simulations at the Dairy Farm.

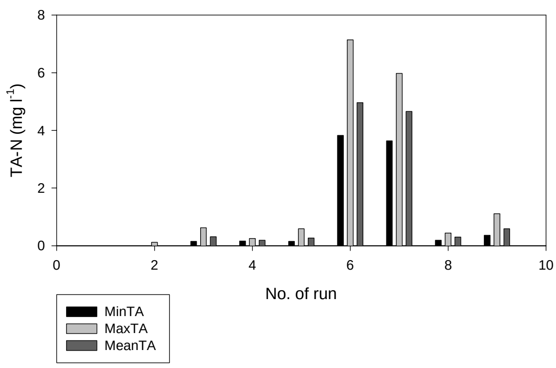

Figure 3.20. Minimum, maximum and mean TA concentrations in overland flow from 'no animals' (N) plots during the rainfall simulations at the Dairy Farm.

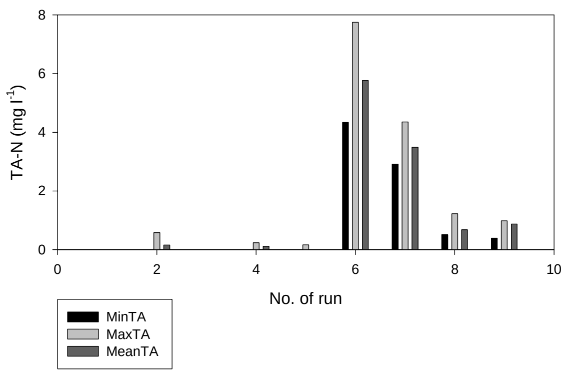

Figure 3.21. Minimum, maximum and mean TA concentrations in overland flow from 'animals' (A) plots during the rainfall simulations at the Dairy Farm.

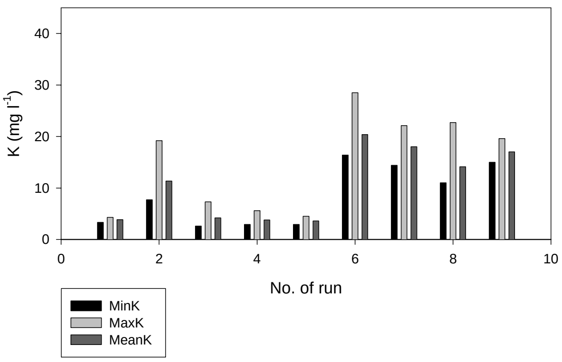

Figure 3.22. Minimum, maximum and mean K concentrations in overland flow from ‘animals’ (A) plots during the rainfall simulations at the Dairy Farm.

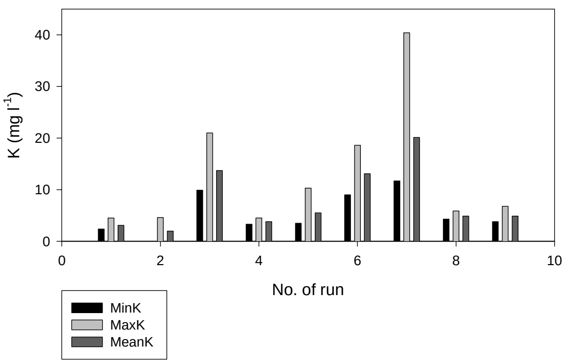

Figure 3.23. Minimum, maximum and mean K concentrations in overland flow from ‘no animals’ (N) plots during the rainfall simulations at the Dairy Farm.

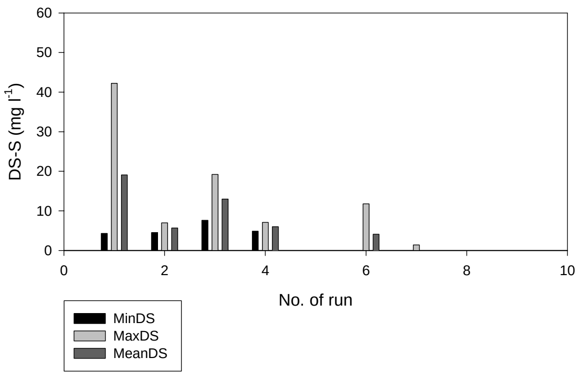

Figure 3.24. Minimum, maximum and mean DS concentrations in overland flow from ‘no animals’ (N) plots during the rainfall simulations at the Dairy Farm.

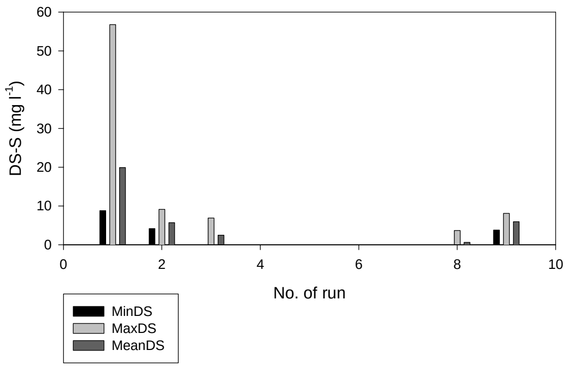

Figure 3.25. Minimum, maximum and mean DS concentrations in overland flow from ‘animals’ (A) plots during the rainfall simulations at the Dairy Farm.

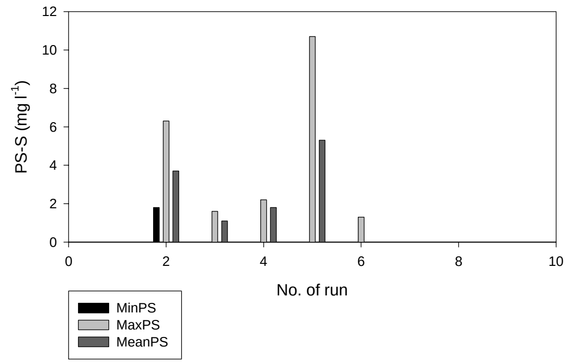

Figure 3.26. Minimum, maximum and mean PS concentrations in overland flow from ‘no animals’ (N) plots during the rainfall simulations at the Dairy Farm.

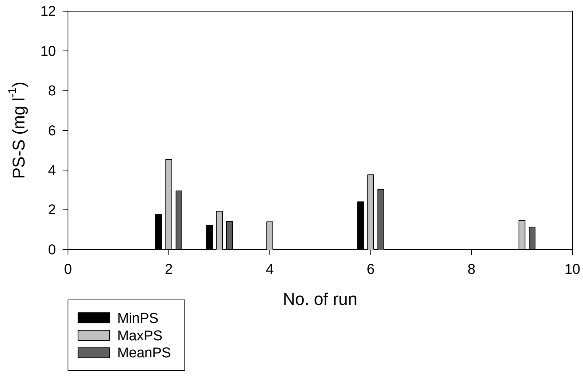

Figure 3.27. Minimum, maximum and mean PS concentrations in overland flow from ‘animals’ (A) plots during the rainfall simulations at the Dairy Farm.

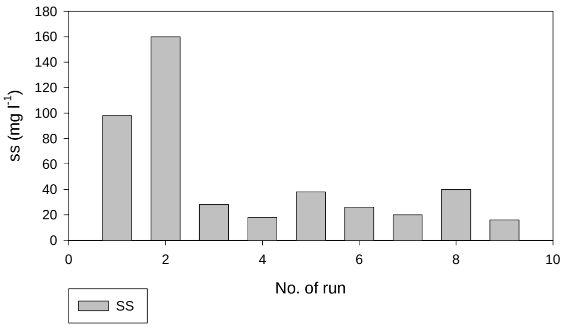

Figure 3.28. Suspended solids concentrations in overland flow from 'no animals' (N) plots during the rainfall simulations at the Dairy Farm.

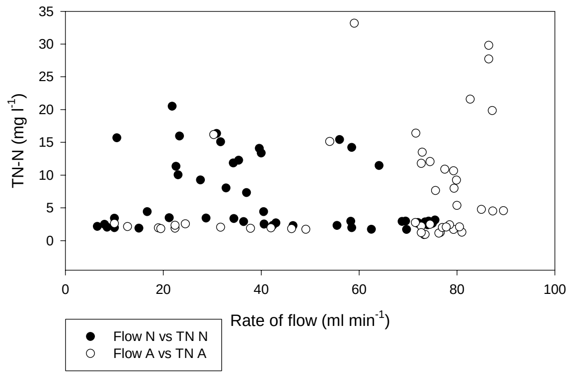

Figure 3.31. TN concentrations plotted against the rate of overland flow in 'no animals' (N) and 'animals' (A) plots.

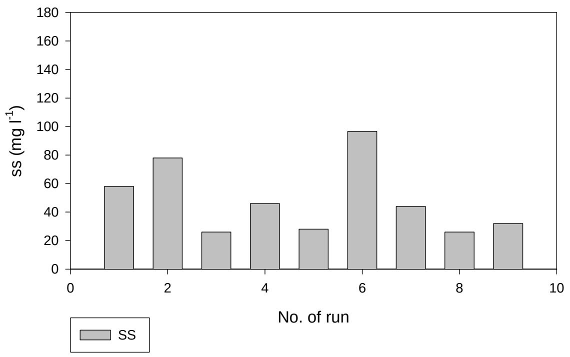

Figure 3.29. Suspended solids concentrations in overland flow from 'animals' (A) plots during the rainfall simulations at the Dairy Farm.

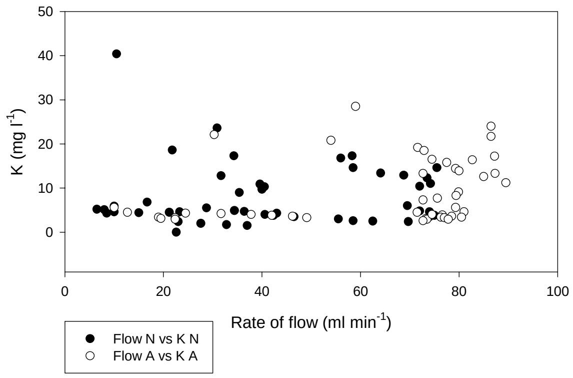

Figure 3.32. K concentrations plotted against the rate of overland flow in 'no animals' (N) and 'animals' (A) plots.

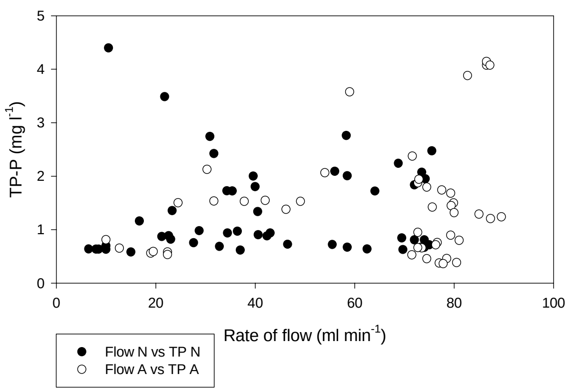

Figure 3.30. TP concentrations plotted against the rate of overland flow in 'no animals' (N) and 'animals' (A) plots.

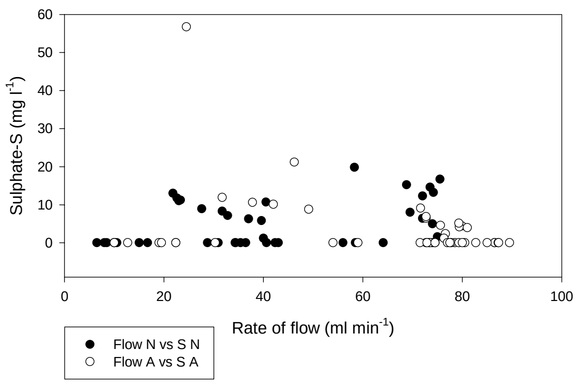

Figure 3.33. Sulphate concentrations plotted against the rate of overland flow in 'no animals' (N) and 'animals' (A) plots.

4 Discussion

4.1 Soil Hydrology

The treatment effects of about 30–50% on RP show that either bulk density or soil moisture or both differed greatly between A and N areas at all study sites. Decreasing SM levels are thought to result in increasing RP values (Vaz and Hopmans, 2001). Soil moisture should have been consistently lower in A than in N plots if SM was the reason for the significantly higher RP values measured in A than in N areas. However, the SM levels did not behave consistently in relation to the presence/absence of cattle. Differences in the RP are therefore likely to be indicative of relative changes of the bulk density in the two types of plots. The lack of a significant effect of SM on RP has also been described by Henderson *et al.* (1988). It is thought that the relationship between these two parameters becomes much more important and therefore evident below a threshold SM value (Henderson *et al.*, 1988).

The soil physical analyses confirm the conclusions drawn from the RP data. Significantly lower BD values were measured in N than in A plots following the exclusion of cattle from some areas during summer grazing. Macroporosity, on the other hand, was significantly higher in areas excluded from grazing than in grazed areas. Summer grazing thus led to compaction of the topsoil at our study sites, and to a substantial reduction of the gravity-drained pore space.

The existence of site-specific linear relationships between the RP and BD values highlights how heavily RP is influenced by BD. The fact that both sites at Johnstown Castle have a sandy loam topsoil and both sites at Grange a clay loam topsoil is probably the reason for the similarity of the RP/BD relationships. It is therefore likely that linear relationships could be drawn up between BD and RP at high soil moisture for each texture class. Resistance to penetration at high soil moisture would then be a quick way of assessing BD on soils of known texture.

At the Dairy Farm site and the Grange normal site, the treatment effect on RP was significantly greater after the second than after the first grazing season. Whether this was due to an increased recovery of the N area or a cumulative effect of the treatment with time cannot be determined from this data set. There are no clear trends in the actual RP values to show either a general increase in RP in the A plots or a general decrease of RP in the N plots. Thus, non-treatment-related factors (e.g. environmental conditions such as soil moisture and temperature) do affect RP but, by giving a direct comparison between N and A conditions, the design of the study excludes the effect of these factors.

Cumulative treatment effects on BD and MP with time were neither found at Cowlands nor at the Dairy Farm site. At Grange normal, on the other hand, the difference between BD and MP measured in the A and N plots was greater after the second than after the first grazing season. The same was true for the MP measurements at Grange extra. The trends described for BD and MP levels measured at Grange normal over time suggest that, during the second growing season, recovery of the soil structure continued in the N plots and compaction increased further in the A plots.

The maximum BD and minimum MP values at Grange were measured at the Grange normal and not the Grange extra site. There is thus no evidence to suggest that the extra grazing days during the winter had a negative impact on soil quality. These extra grazing days cannot be equated to an extended grazing system. They represented a small additional grazing pressure and were only undertaken when the land was dry. This option may not be available when extended grazing is carried out as a measure for reducing the amount of winter fodder required.

The presence and/or absence of cattle on the pastures studied here had a statistically significant effect on the structure of the topsoil. When considering the impact of grazing animals on nutrient losses to water, it is important to establish the effects that the soil physical degradation will have on the drainage pattern of a soil. Daniel *et al.* (2003) reported the occurrence of increased RP and BD as a consequence of grazing pressure on soils of clay loam and silt loam texture. Daniel *et al.* (2003) also assessed the saturated hydraulic conductivity of the topsoil and found that soil compaction attributable to grazing animals had clearly led to a decrease of the infiltration rates measured at the soil surface. A lowered infiltration capacity is, in turn, likely to lead to an increase in the amount of overland flow produced at a site. This can, however, only be the case if the rainfall rate exceeds the rate of infiltration measured in the areas affected by grazing animals. A decrease of the infiltration capacity due to grazing has also been reported for pastures in New Zealand (McColl *et al.*, 1985) and England (Heathwaite *et al.*, 1990). Heathwaite *et al.* (1990) confirmed that, in England, the reduced infiltration led to increases in overland flow on heavily grazed pastures.

Rainfall simulation in this study was conducted to obtain overland flow samples for chemical analysis. Still, the flow data gathered during the simulations may help to explore the implications of the soil physical changes described. The rainfall simulation experiments at the Dairy Farm showed that the presence of grazing animals decreased both the time to overland flow and the maximum amount of overland flow produced per mm of rain. The treatment effect on the rate of overland flow produced was greater after the grazing cycle. This may indicate that some recovery of the soil structure did take place over winter, when the animals were housed. However, the RP does not indicate such a recovery as the treatment effects were not consistently lower in spring 2003 than in autumn 2002. The simulations following the grazing cycle were, moreover, carried out at a time of increasing SMD, which may have affected the rates of overland flow produced.

The trends in the ratio of maximum overland flow to rate of rainfall suggest that the ratio is independent of SMD in the A plots but dependent on SMD in areas from which the cattle had been excluded. As the SMD increased, the proportion of rainfall contributing to overland flow became smaller and the rate of infiltration therefore increased in the N plots. This observation ties in with the results of Diamond and Shanley (2003), who concluded that infiltration at a rate dictated by the natural soil properties only occurs during the summer months. The macroporosity results reported here show that the network of gravity-drained pores at the soil surface was greatly affected by cattle grazing. The reduction in macroporosity in the A plots impeded the natural soil drainage at the Dairy Farm site to such an extent that it failed to re-establish itself as the soil dried out. The results presented here indicate that the presence of grazing animals reduced the time to overland flow and increased the amount of overland flow produced during rainstorms with a return period of 5 years.

4.2 Soil Nutrients

The considerable, statistically significant difference of K levels between A and N plots underlines the importance of the role grazing animals play in recycling K (Haynes and Williams, 1992; Alfaro *et al.*, 2003). As soil P levels were shown to change very slowly (Culleton *et al.*, 1999), it is surprising that there was a statistically significant difference in soil P between treatments at one of the study sites (Cowlands). Such differences were not found at the other study sites. Soil P at Cowlands was much higher than at the other study sites. At Cowlands, more P was therefore also recycled in urine and faeces and this is the P which was received by the A but not by the N plots. The difference between P 'applications' to N and A plots was therefore much greater at Cowlands than at the other sites. This occurrence may have given rise to a treatment effect on soil P at Cowlands alone.

When deciding to randomly distribute the N plots over the area of the study sites rather than selecting locations along the field boundaries, there was a risk of overland flow from surrounding grazed land affecting the N plots. The soil P and K results indicate that such interference did not occur to any great extent. The Cowlands site was the wettest of all the study sites. Still, excluding animals from the N plots gave rise to a statistically significant difference in soil P levels between the A and N areas. Potassium tends to be retained by soil (Williams *et al.*, 1989) even if not to the same extent as P (Calvert, 1975). The statistically significant treatment effect on soil K levels at all study sites therefore confirms that overland flow enriched with nutrients from A areas did not lead to a substantial increase in nutrient levels on the N plots.

4.3 Rainfall Simulation

The big variations in nutrient levels during and between events reflect the variability that was shown to occur at field scale (Kurz *et al.*, 2005b). The absence of relationships between the rate of flow and nutrient concentrations suggests that factors other than flow have an overwhelming influence on nutrient concentrations in overland flow. This trend was also described at field scale (Kurz *et al.*, 2005b).

The fact that there was a clear treatment effect (difference of concentrations between N and A plots) on the DUP and PP levels after the management operations indicates that the grazing cycle caused an increase in DUP and PP levels in overland flow. Dissolved unreactive P is made up of dissolved (and colloidal if colloids <0.45 µm) organic and condensed (oxidised organic compounds and inorganic polyphosphates (Ron Vaz *et al*., 1993)) forms of P. The negligible amounts of TRP indicate that very little of the PP was molybdate reactive. Most of the PP was therefore, like DUP, in organic and condensed form. Dissolved and particulate organic and condensed P are therefore the main P fractions transferred to overland flow from cattle dung and urine deposited on grassland. Even though such P is not immediately available to aquatic life, it becomes available over time (Ball and Hooper, 1963). Elevated levels of organic and condensed forms of P were also recorded, albeit in dissolved form, in overland flow produced by natural rainfall during, or shortly after, the presence of grazing animals in fields of pasture (Kurz *et al*., 2005b). The significance of organic and condensed forms of P in overland flow from freshly grazed land is therefore not a feature of the artificial rainfall or the small plot methodology employed in the study in hand.

Dissolved unreactive P, but not PP, levels increased in overland flow from N plots after the management cycle. This increase was considerably smaller than the one described for overland flow from A plots. Phosphorus is known to leach from plant material (Sharpley and Smith, 1989). It is conceivable that, by exposing freshly cut or chewed grass plants to overland flow, the release of P from grass to overland flow was enhanced. However, the grass within the overland flow collection frames was clipped before each rainfall simulation (see Section 2.5). The exposure of freshly cut plants to overland flow was therefore the same during all simulations.

Urea fertilisation may have triggered the release of organic and condensed forms of P to overland flow. The occurrence of increasing P (TP) levels in overland flow after urea fertilisation was also suspected at field scale but could not be shown conclusively due to the many factors influencing naturally occurring overland flow from field-sized areas (Kurz, 2002). The fact that the P fractions which may have been affected by urea application were identified as the condensed and organic forms points to an involvement of a biological component in the P release process. Lovell and Hatch (1998) observed an increase in the activity of soil microbial biomass following N fertiliser application in spring. An increase in soil microbial activity is likely to indicate a boost in mineralisation and the turnover of soil organic matter. This, in turn, may lead to an augmented release of organic and condensed forms of P to overland flow, which was observed during the rainfall simulation experiments.

The increase in TDN, TON and TA between Runs 5 and 6 can be attributed to the urea application prior to Run 6. There was no obvious effect of the presence of cattle on TDN, TON and TA levels. However, the big impact of urea application on nitrogen concentrations in overland flow may have masked other influences on TDN levels in overland flow. The rise of the levels of nitrogen associated with particles >0.45 µm can be put down to the presence of grazing animals though, because TPN concentrations increased in overland flow from the A plots relative to values measured in overland flow from the N areas.

There was no clear effect of the management operations on sulphate and ss concentrations in overland flow. The K concentrations, on the other hand, were higher in overland flow from the A plots after the grazing cycle. This ties in with observations made at field scale, where K levels were elevated in overland flow occurring while, or shortly after, cattle were grazing a field (Kurz, 2002). The absence of a clear difference between the K concentrations in overland flow produced on the two types of plots before the grazing cycle indicates that the statistically significant difference in soil K levels between treatments did not translate into a difference in the K contents in overland flow.

4.4 Synopsis

The above discussion shows that the part of the nutrient loss from grassland that can specifically be attributed to the presence of grazing animals is mainly to be found in the particulate nitrogen, the dissolved and particulate organic and condensed P fractions and in the K exports. The direct comparison of A and N conditions at specific sites made it possible to assign changes in overland flow quality to the treatment, without having to consider the effects of differences in site characteristics, management operations and environmental conditions. Rainfall simulations run in parallel on A and N areas were a very useful tool for this comparative study, even though the actual nutrient levels achieved in overland flow arising from artificially produced rainfall may not be a direct replication of the concentrations achieved in overland flow produced due to natural rainfall. In the case of TDP, for example, the concentrations in overland flow due to natural rainfall ranged from 0.084 mg/l to 1.862 mg/l between October 2002 and February 2004 (see Tunney *et al.*, 2006). The concentrations measured in overland flow during the rainfall simulation experiments were usually at the higher end of that range, or slightly above it. When it is considered that the simulations started about 6 weeks after a heavy application of P fertiliser, the TDP concentrations achieved in artificially produced overland flow compared reasonably well with those measured in overland flow from natural rainfall.

The lack of a clear difference between the quality of overland flow from A and from N plots prior to the management operations indicates that the effect of grazing animals on overland flow quality could no longer be discerned after the housing period. The last simulation was carried out 2 weeks after grazing. For how much longer the effect of the grazing cycle on overland flow quality would have been sustained is unknown. Maximum nutrient losses to water are often measured in connection with overland flow producing rainfall events during and shortly after the presence of animals (Sharpley and Syers, 1976; McColl, 1979; McColl and Gibson, 1979; Jawson *et al.*, 1982; Jordan and Smith, 1985). This is not surprising because the deposition of urine and faeces leads to very high, localised nutrient applications to pasture areas. These nutrients are in excess of grass demand and they are therefore available for loss.

The soil physical and hydrological data suggest that the presence of cattle has a more lasting influence on the drainage characteristics of the soils studied here than on overland flow quality. The quantity of overland flow produced on grazed areas is therefore likely to be enhanced as long as sites such as those described here are grazed during the summer. By favouring overland flow as a nutrient transport pathway, regular grazing may generally enhance P and N (other than nitrate) losses from an area. As the N treatment in this study consisted of excluding cattle from previously grazed areas, the data demonstrate that compaction and loss of macroporosity due to grazing animals is remedied by one (or several) growing season(s) without grazing pressure. If compaction by heavy machinery can be avoided, cutting silage from affected fields may allow the areas to recover.

5 Conclusions and Recommendations

5.1 Conclusions

The data presented in this report clearly show that the null hypothesis 'the presence of cattle does not influence the quantity or quality of overland flow produced at a site' must be rejected.

At the sites studied here, the presence of cattle led to physical changes in the topsoil. These changes favoured the occurrence of overland flow and altered the natural drainage characteristics of the soil. They persisted over the winter period when the animals were housed. Recovery of the soil did, however, occur when cattle were excluded from areas over the growing season.

The effect of cattle on the quality of overland flow could not be detected before the start of the grazing season, but was measurable in a number of water quality parameters after the first grazing cycle. The presence of grazing animals led to increased concentrations of particulate N, of dissolved and particulate organic and condensed P fractions and of K in overland flow.

The data presented here also show that urea application in spring was followed by enhanced levels of TDN, TON and TA in overland flow. There is evidence to suggest that the urea application triggered a surge in microbial activity and thus led to an enhanced release of organic and condensed forms of P from soil to overland flow.

This study adds to the body of knowledge on the impacts of agricultural management practices on soil hydrology and the quality of overland flow from agricultural land. The findings underline the importance of interactions between management practices, nutrients in soil and soil biology for the release of nutrients to drainage water.

The resistance to penetration at high SM is largely affected by BD and soil texture. Developing soil-texture-specific relationships between BD and RP at high SM may therefore allow BD to be estimated with the much less time-consuming measurement of RP at high SM.

5.2 Recommendations

- The complex interactions between agricultural management practices, nutrients in soil, soil biology and nutrient release to drainage water are best addressed by detailed nutrient management planning.
- Compaction and decrease in macroporosity of the topsoil, which were induced by the presence of grazing animals, could be remedied by closing pastures for silage. Such fields would need to be cut under dry conditions to avoid soil damage caused by heavy machinery. The fact that this measure may have economic implications must be considered. Many farmers use contractors to make silage. These contractors are paid by the acre and the best land is therefore usually closed for silage. If less productive fields are to be used, the cost for winter fodder will rise.
- As grazing animals were shown to have a substantial effect on particulate N and P levels in overland flow, filter strips of, ideally, natural riparian plant communities may lead to a removal of nutrients from overland flow before it enters a surface waterbody.
- To make nationwide surveys of the prevalence of compaction on farmland a realistic possibility, relationships between BD and RP at high SM should be developed for each soil texture class.
- Field-scale research should be conducted to determine whether or not the findings described at the small plot scale also apply to larger areas.

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