NATIONAL UNIVERSITY OF IRELAND GALWAY

CHEMICAL AMENDMENT OF DAIRY CATTLE SLURRY FOR THE CONTROL OF PHOSPHORUS IN RUNOFF FROM GRASSLAND

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I would like to dedicate this work to my wonderful family, and to the memory of Eileen Armstrong, Helena Brennan and baby Helena Brennan.

‘Don't let your success determine your attitude, let your attitude determine your success.’

(Adapted from Ken Brown)

ABSTRACT

Phosphorus (P) loss from grassland to a waterbody can adversely affect water quality. Land application of dairy cattle slurry can result in incidental P losses to runoff in addition to increased chronic P losses from soil as a result of a build-up in Soil Test P (STP). A literature review identified chemical amendment of dairy cattle slurry as a possible mitigation measure to prevent such losses. This study comprised laboratory and field-scale experiments, which investigated the effectiveness and feasibility of chemical amendments in reducing P solubility, taking into account for the first time their pollution swapping potential.

First, a controlled agitator experiment was designed to identify the most effective chemical amendment to reduce Dissolved Reactive Phosphorus (DRP) release to water overlying grassed soil cores, which received un-amended and amended dairy cattle slurry. In addition to effectiveness, the feasibility of these amendments was determined based on several criteria: estimated cost of amendment, amendment delivery to farm, addition of amendment to slurry, and slurry spreading costs due to any volume increases. The four best amendments based on effectiveness and feasibility, at optimum application rates were: ferric chloride ($FeCl_2$), which reduced the DRP in overlying water by 88%, aluminium chloride ($AlCl_3$) (87%), alum (83%) and lime (81%). These amendments were then added to slurry immediately before it was surface applied to grassed soil in runoff boxes, which were subjected to simulated rainfall events. Analysis of overland flow showed that PAC (Poly-Aluminium Chloride, a commercially available form of $AlCl_3$) was the most effective amendment for decreasing DRP losses in runoff following slurry application, while alum proved to be the most effective for total P (TP) and particulate P (PP) reduction. The incidental loss of metals (aluminium (Al), calcium (Ca) and iron (Fe)) in runoff during all experiments was below the maximum allowable concentrations (MAC) for receiving waters.

Once the effectiveness of the amendments under laboratory conditions were quantified, their ‘pollution swapping’ potential was examined. A laboratory-scale gas chamber experiment was conducted to examine emissions of ammonia (NH_3), nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2). After considering pollution swapping in conjunction with amendment effectiveness, the amendments recommended for a micro plot study were, from best to worst: PAC, alum and lime. This component of the study investigated how soil and chemically amended slurry interactions affect amendment effectiveness under field conditions. The results of this micro-plot study validated the results from the laboratory-scale studies. Alum and PAC reduced average flow-weighted mean concentration (FWMC) and total loads of DRP, dissolved un-reactive phosphorus (DUP), PP and TP in runoff, while amendment of slurry with lime at the rate examined in this study was not effective at reducing P losses. Alum amendment significantly increased average FWMC of ammonium-N (NH_4-N) in runoff water during the first rainfall event after the slurry was applied (an 84% increase). This indicates that chemical amendment of dairy cattle slurry conducted on a large scale could increase soluble N losses. Finally, a 9-month incubation experiment was conducted using five Irish grassland soils to examine the effect of amendments on the long-term plant availability of P in soil and the effect of soil type on the stability of reductions in P solubility. The study showed that, with the exception of $FeCl_2$, the chemical amendments reduced water extractable phosphorus (WEP) without affecting STP.

This study showed that amendments are effective and that there is no major risk of pollution swapping associated with alum and PAC. This is a significant finding as there is now potential to use amendments strategically, in combination with existing POM (programme of measures), to mitigate P losses. The next step will be to examine the use of chemical amendments at catchment-scale. It is hoped that there will be economic incentives given to farmers to reduce nutrient losses. It is possible that P mitigating methods, such as chemical amendment of dairy cattle slurry, may be used strategically within a catchment to bind P in cow and pig slurries.

DECLARATION

This dissertation is the result of my own work, except where explicit reference is made to the work of others, and has not been submitted for another qualification to this or any other university.

Raymond Brennan

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ABBREVIATIONS

a	A constant related to the binding strength of molecules onto the amendments
AD	Anaerobic digestion
Al	Aluminium
$AlCl_3$	Aluminium chloride
Al_2O_3	Aluminium oxide
Alum	aluminium sulphate (analytical grade ($Al_2(SO_4)_3nH_2O$) and commercial grade)
Al-WTR-1	Al-WTR-alum-based water treatment residual which was dried and crushed to pass 2 mm sieve
Al-WTR-2	Al-WTR-alum-based water treatment residual in sludge form
AOD	Above ordnance datum
APHA	American Public Health Association
AVC	Ammonia volatilisation chamber
b	The theoretical amount of P adsorbed to form a complete monolayer on the surface
bgl	Below ground level
BOD_5	Five day biological oxygen demand
BS	British Standards
C	The final P concentration of the solution in isotherm test
Ca	Calcium
$CaCO_3$	Calcium carbonate
$CaCl_2$	Calcium chloride
$Ca(OH)_2$	Lime
CC	Container capacity approximate field capacity in incubation experiment
C_e	The concentration of P in solution at equilibrium (mg L^{-1})
CH_4	Methane
CO_2	Carbon dioxide

CSA	Critical source areas
CSO	Central Statistics Office
CWs	Constructed wetlands
DAFF	Department of Agriculture, Fisheries and Food
d	Day
DM	Dry matter
DRP	Dissolved reactive phosphorus
DUP	Dissolved un-reactive phosphorus
EC	Electrical conductivity
EEC	European Economic Community
EPA	Environment Protection Agency
EPC_0	Equilibrium P concentration (i.e. the point where no net desorption or sorption occurs) in Langmuir Isotherm
EU	European Union
Fe	Iron
$FeCl_2$	Ferrous chloride
$FeCL_3$	Ferric chloride
$FeSO_4$	Ferric chloride
FGD	Flue gas desulphurization
FWMC	Flow-weighted mean concentration
FWS	Free water surface
GHG	Green house gas
GWP	Global warming potential
H	Hour
ha	Hectare
H_2	Hydrogen gas
H_2S	Hydrogen sulphide
H_2SO_4	Sulphuric acid
HCl	Hydrochloric acid
ICP	Inductive coupled plasma
IPCC	Intergovernmental Panel on Climate Change

K	Potassium
k_d	The slope of the relationship between S' and C
LOI	Loss on ignition
M3	Mehlich-III P
MAC	Max allowable concentration
Mg	Magnesium
$MgCl_2$	Magnesium chloride
N	Nitrogen
mo	Month
N_2	Nitrogen gas
N_2O	Nitrous oxide
NH_3	Ammonia
NH_4	Ammonium
NH_4	Ammonium ion
NH_4-N	Ammonium nitrogen
NO_2	Nitrite
NO_2-N	Nitrite nitrogen
NO_3	Nitrate
NO_3-N	Nitrate nitrogen
OJEC	Official Journal of the European Community
OM	Organic matter
P	Phosphorus
PAA	Photo-acoustic-analyser
PAC	Poly-aluminium chloride
PAM	Polyacrylamide
PDS	Particle size distribution
POM	Programme of measurements
PP	Particulate phosphorus
PSM	Phosphorus sorbing material
R^2	Regression coefficient
RS1	Rainfall simulation event 1

RS2	Rainfall simulation event 2
RS3	Rainfall simulation event 3
rpm	Revolutions per minute
S'	The mass of P adsorbed from slurry (mg kg^{-1}),
S_0	The amount of P originally sorbed to the amendment (mg L^{-1})
SAS	Statistical Analysis Software
SI	Statutory Instrument
SS	Suspended sediment
STP	Soil test phosphorus
$T_{0.5}$	The time for half of ammonia losses to occur
TAN	Total ammonical nitrogen
TDP	Total dissolved phosphorus in water
TDS	Total dissolved solids
TK	Total potassium
TN	Total nitrogen
TON	Total oxidized nitrogen
TP	Total phosphorus
TR	Time from commencement of simulated rainfall event and start of runoff
UK	United Nations
UN	United Nations
U.S.A.	United States of America
USDA	United States Department of Agriculture
USEPA	United States Environment Protection Agency
WEP	Water extractable phosphorus
WFD	Water Framework Directive
WTR	Water treatment residuals
x/m	The mass of P adsorbed per unit mass of amendments (g kg^{-1}) at C_e
Ω	Stream power of overland flow

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1 Introduction

1.1. Overview

In Ireland, agriculture is an important national industry that involves approximately 270,000 people, 6.191 million cattle, 4.257 million sheep, 1.678 million pigs and 10.7 million poultry (CSO, 2006). It utilizes 64% of Ireland's land area (Fingleton and Cushion, 1999), of which 91% is devoted to grass, silage and hay, and rough grazing (DAFF, 2008). Livestock production is associated with external inputs of nitrogen (N) and phosphorus (P), which include inorganic and organic fertilizers. Land application of fertilisers followed by a rainfall event can result in incidental losses of P to runoff. In addition, chronic P losses from the soil as a result of a build up in soil test P (STP) can also contribute to losses in other times of the agricultural calendar. Land application of fertilisers also result in N leaching through the soil to surface and ground waters. In practice P is of particular importance as it is the critical nutrient in fresh water systems. In order for Ireland to comply with the requirements of the European Union Water Framework Directive (EU WFD; 2000/60/EC, OJEC, 2000) to achieve at least 'good status' of all surface and groundwater by 2015, programmes of measures (POM) should be in place to prevent such losses. Ireland's agricultural POM is the Nitrates Directive (SI 610 of 2010). These measures have addressed the problem by limiting fertiliser application rates and improving manure management. Particular focus has been given to time of application and increasing slurry storage capacity on farms. A possible supplementary mitigation method is the chemical amendment of slurries. However, before chemical amendment of dairy cattle slurry may be considered for implementation in Ireland, there is a need for an extensive study of their use.

The aim of this study is to examine the: (1) effectiveness of different amendments to prevent P losses in runoff (2) feasibility of the different amendments to be used on a farm (3) risk of metal release to overland flow and (4) possibility of 'pollution swapping' (defined by Stevens and Quinton (2009) as the increase in one pollutant as a result of a measure introduced to reduce a different pollutant). The present study comprised laboratory and field-scale experiments, which were designed to address knowledge gaps in these areas. For the first time in Ireland, a series of experiments were conducted to examine the possibility of bringing such a supplementary mitigation measure to Irish farms.

The specific objectives of this study were:

1. To review existing and emerging P mitigation measures for the control of P losses arising from the land application of dairy cattle slurry to grasslands in Ireland. Following this, the study aimed to select a measure suitable for further study and to identify knowledge gaps which need to be addressed in order for this measure to be considered for implementation at farm scale.

2. To evaluate the effectiveness and feasibility of potential chemical amendments and to use such criteria to select the most suitable amendment for trial at field scale.

3. In parallel to the P mitigation experiments, to examine the effects of pollution swapping, the loss of N chemical species in runoff and gaseous emissions of ammonia (NH_3) and greenhouse gases (GHG) to the atmosphere. In addition, this study aims to examine the effect of chemical amendment of dairy cattle of slurry on metal losses in runoff.

4. To examine the effect of chemical amendment of dairy cattle slurry prior to application to soil on long-term soil water extractable phosphorus (WEP) and plant available P.

5. To examine the effect of soil type on P solubility in amended slurry applied to soil.

1.2. Procedure

A literature review of P loss mitigation technologies with the potential to reduce P losses arising from land application of dairy cattle slurry was undertaken. Chemical amendment of dairy cattle slurry was chosen for further study as chemical amendments have the ability to be quickly implemented, are cost effective and capable of being used in strategic locations for maximum benefit i.e. no capital cost or need to transport slurry long distances. Several knowledge gaps were identified and experiments were designed accordingly.

Following this, a novel experiment (an ‘agitator test’) was used to determine the most suitable amendments for addition to dairy cattle slurry with the aim of reducing P loss in runoff. In this experiment, potential amendments (alum, aluminium chloride, ferric chloride ($FeCl_2$), flyash, flue gas desulphurisation by-product (FGD), lime, poly-aluminium chloride hydroxide (PAC) and water treatment residuals (WTR)) were added to slurry before slurry was applied to intact soil cores, which were overlain by water in a 1-L beaker. The overlying water was then stirred to simulate overland flow. The agitator test successfully identified amendments with the potential to reduce dissolved reactive phosphorus (DRP) in overlying water.

The most feasible amendments (alum, PAC, $FeCl_2$ and lime) were then examined in a runoff study conducted using laboratory runoff boxes subjected to simulated rainfall applied at an intensity of 11.5 mm h^{-1} to develop a greater understanding of how chemical amendments affected different forms of P in runoff.

It is critical that the potential for ‘pollution swapping’ is examined when evaluating a potential P mitigating technology such as those examined in this study. In particular, the effects of any proposed treatments on GHG emissions must be examined. To address this, a laboratory chamber experiment was used to examine the effect of chemical amendment of dairy cattle slurry on emissions of NH_3, nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2). This allowed for the pollution swapping potential of amendments to be considered in the selection of amendments chosen for field scale study.

The most feasible amendments were then examined at micro field plot-scale in Johnstown Castle, Co. Wexford. Twenty five plots, each measuring 0.4 m-wide by 0.9 m-long, were hydraulically isolated before being amended with untreated or chemically amended dairy cattle slurry. Three rainfall simulations were conducted over a period of one month and the surface runoff was collected for half an hour during each event.

Finally, a laboratory incubation experiment was conducted to examine (1) the effect of amendments on the long-term plant availability of P in soil and (2) the effect of soil type on stability of reductions in P solubility. Five soils were subjected to six treatments (soil only, slurry only and four chemically amended slurries) and destructively sampled at 0, 3, 6 and 9 months from the start of the experiment.

1.3. Structure of dissertation

Chapter 2 reviews the current water quality status in Ireland and the impact of agriculture, particularly dairy cattle slurry, on water quality. Chapter 2 also focuses on Ireland's performance in relation to WFD water guidelines, with particular focus on the potential need to explore P mitigating measures for possible implementation if current measures are not sufficient to meet targets. Chapter 3 details the results of the agitator test which was used to evaluate the effectiveness and appropriate application rates for amendments. Chapter 3 also examines the feasibility of amendments and a detailed cost analysis is presented. Chapter 4 describes the results of a laboratory-scale runoff-box study. Chapter 5 details the results of the gas chamber experiments designed to examine the pollution swapping potential of amendments. Chapter 6 details the results of a plot-scale runoff experiment conducted in Johnstown Castle Research Centre. Chapter 7 details the results of the nine-month incubation experiment. Finally, in Chapter 8, conclusions from the study are presented and recommendations for future research work are made.

To date, two international peer review papers have been published from this work:

Brennan, R.B., Fenton, O., Rodgers, M., Healy, M.G. 2011. Evaluation of chemical amendments to control phosphorus losses from dairy slurry. Soil Use and Management 27: 238-246.

Brennan, R.B., Fenton, O., Grant, J., Healy, M.G. 2011. Impact of chemical amendment of dairy cattle slurry on phosphorus, suspended sediment and metal loss to runoff from a grassland soil. Science of the Total Environment 403(23): 5111-5118.

A number of international and national conference papers have also been published describing this work. A list of outputs and manuscripts in preparation for submission to international journals are listed in Appendix A.

Chapter 2 Literature review

2.1. Overview

This chapter introduces Irish agriculture, details Ireland's current water status under the WFD and comments on the impact which agriculture has on this status. In addition it details where nutrient losses occur from an agriculture system and investigates several mitigation options to prevent such losses.

2.2. Agriculture in Ireland

Agriculture accounts for approximately 56% of land use in the Republic of Ireland (CSO, 2009). Each year approximately 29 million tonnes of slurry are produced in Ireland, of which 28% is produced by dairy cattle (Hyde and Carton, 2005). Dairy produce and ingredients amounted to 29% of the value of all agricultural goods, and were estimated at €5.7 billion at producer prices in 2007 (Common Agricultural Policy, 2011). This is expected to increase as worldwide demand for dairy products increases (More, 2009).

Dairy cattle slurry may be defined as either 'the excreta produced by livestock while in a building or yard, or a mixture of such excreta with rainwater, washings or other extraneous material, or any combination of these' (Statutory Instrument (SI) 610 of 2010). In Ireland intensive dairy farms (intensively managed farms operate with the objective of maximising output per unit area with high levels of artificial inputs i.e. concentrated feeds and artificial fertiliser). Cattle are typically housed in slatted sheds for between 16 and 18 weeks in the winter months, during which time they are fed silage and concentrates. During this time, the cow manure and urine produced are collected and stored in storage tanks for the winter period. Slurry is rich in nutrients (particularly N, P and potassium (K)), and is generally land applied in the spring and summer months as a fertiliser. An average Irish slurry sample contains 5 kg total nitrogen (TN) m^{-3} and 0.8 kg total phosphorus (TP) m^{-3} (SI 610 of 2010). Martínez-Suller et al. (2010) conducted a study of Irish cattle slurry, the results of which are shown in Table 2.1. Slurry is a valuable fertiliser (Lalor and Schulte, 2008a) and it is important that any change in slurry management takes account of the fertiliser value of slurry. Immediately prior to land application, slurry is agitated to improve workability of slurry, to ensure consistency of nutrient concentrations in the slurry and to allow uniform application. After agitation, slurry is land applied using a slurry spreader. Although research has been carried out on alternative spreading techniques such as trailing shoe application (Lalor and Schulte, 2008b) the majority of slurry is applied using a splash plate slurry spreader (Ryan, 2005).

Table 2.1 Summary statistics from 41 Irish cattle slurry samples (Martínez-Suller et al., 2010)

Variable	Mean	Median	Maximum	Minimum	sd	CV (%)
pH	7.3	7.3	7.8	6.8	0.2	2.9
EC (S m^{-1})	1.43	1.6	2.33	4.1	4.9	34
Dry Matter (g kg^{-1})	62.7	65.1	97.3	5.7	20.7	33
N (kg m^{-3})	3.43	3.27	7.03	0.36	1.4	41
P (kg m^{-3})	0.56	0.61	1.13	0.04	0.25	44
K (kg m^{-3})	4.41	4.91	7.75	0.94	2.04	46

sd = standard deviation; CV = coefficient of variation

In concentrated feeding systems such as intensive dairy farms, P inputs into a farm may exceed P outputs (Tunney, 1990). This may give rise to a build-up of STP (Sharpley et al., 2004) as a result of land application of dairy cattle slurry to grassland, which poses a risk to water quality. In addition, losses during and after land spreading also pose risk to a waterbody. Therefore, there is a need for the development of management practices, which allow maximum production with minimum negative environmental impacts i.e. livestock numbers will not reduce.

2.3. Legislation and compliance

The EU WFD (OJEC, 2000) aims to achieve at least “good ecological status” in all waterbodies by 2015 through the implementation of POM by 2012. In Ireland the agricultural POM is the Nitrates Directive (EEC, 1991). The Nitrates Directive has been implemented since 2009. Huge investment in farm infrastructure has resulted in reduced P losses from agricultural point sources. Guidelines for farm management provide best management practice for slurry and inorganic fertiliser application to grassland to minimize diffuse P losses and increased STP. An Agricultural Catchments Programme has been established to evaluate catchment-scale evaluation of their effectiveness (Schulte et al., 2010a).

The statutory instrument which governs agricultural practice in Ireland is The European Communities (Good Agricultural Practice for Protection of Waters) Regulations 2010 (SI 610 of 2010). This places a responsibility on the individual farmer and the public authority to adhere to the conditions set out within the Nitrates Directive (EEC, 1991) and the WFD. Individual farmers are required to maintain records of activities with regard to soil testing, storage capacity, nutrient management, minimum storage period, and periods when application to land is prohibited. Land spreading of slurry is forbidden if (1) heavy rainfall is forecast within the 48 h of application (2) land is frozen or snow-covered (3) the land slopes steeply towards a river or stream, or (4) slurry is to be applied directly to bedrock (SI 610 of 2010). In addition to the POM, the WFD recommends research and development of new pollution mitigation measures to achieve the 2015 target.

2.4. Current water quality status in Ireland

The Irish Environment Protection Agency (EPA) has reported findings based on analyses of 2,985 sampling locations on 1,151 rivers between 2007 and 2009 (McGarrigle et al., 2011). Approximately 68.9% of Ireland’s rivers were unpolluted, 20.7% were slightly polluted, 10% were moderately polluted and 0.4% were seriously polluted (McGarrigle et al., 2011). When these rivers were assessed for ecological status, based on the various biological and physico-chemical quality elements, only 52% of water bodies achieved 'good status'. Diffuse losses (including those from agricultural and other sources) were responsible for approximately half of the polluted sites monitored. Similarly, using the traditional method of assessment, 92.1% of lakes were in an un-enriched, oligotropic status - similar to that observed for 2004-2006 period. However, according to the requirements of the WFD, 47.5% were of 'good status'. The report also examined measurements from 211 groundwater monitoring stations: 84.7% of ground water bodies were in good status, while 15.3% were in poor status. Figure 2.1 shows the decline in poor status for groundwater. This reduction was attributed to increased rainfall, reductions in inorganic fertiliser usage, improved organic fertiliser storage, and implementation restrictions on timing of land applications. The McGarrigle et al. (2011) report concluded that substantial measures will be required for Ireland to comply with the objectives of the WFD.

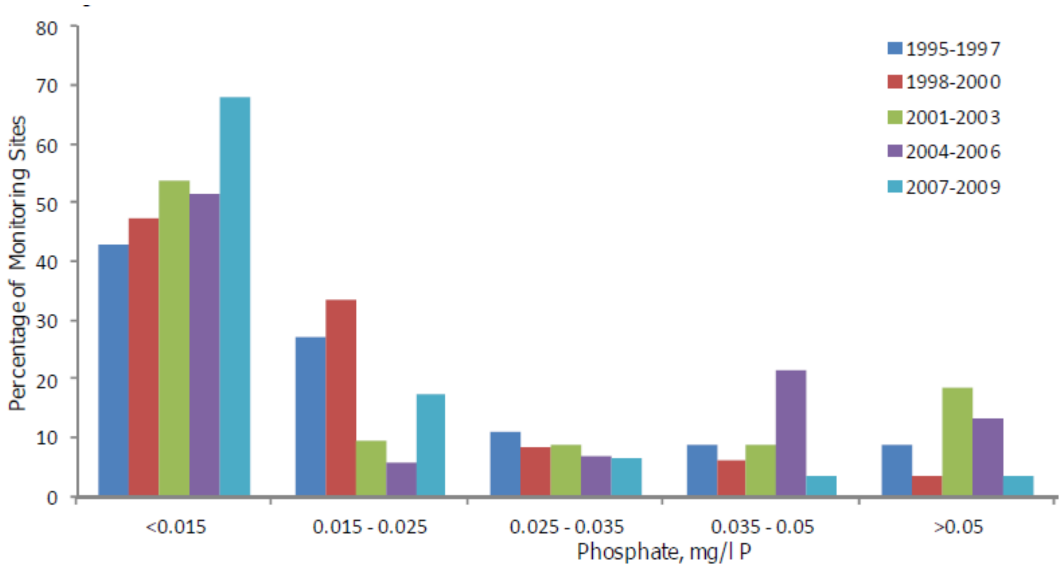


Figure 2.1 Number of ground water monitoring sites with phosphate concentrations from 1995 to 2009 (McGarrigle et al., 2011)

2.5. Impact of agriculture on water quality

Agricultural activities are thought to be responsible for approximately 38% of slightly polluted rivers, 23% of moderately polluted, and 29% seriously polluted rivers (McGarrigle et al., 2011). Figure 2.2 shows the number of reported fish kills attributed to agriculture from 1971 to 2009 (McGarrigle et al., 2011). The impact of agriculture on water has reduced steadily since 1997; however, further reductions are required to meet the requirements of the WFD (McGarrigle et al., 2011). It is important to note that research constantly challenges the accuracy of the estimated contribution which agriculture makes to pollution of Irish rivers. This contribution is currently being examined as part of the Agricultural Catchments Programme.

McGarrigle et al. (2011) found that 0.3% of the waterbodies in the Republic of Ireland were of ‘poor status’ due to nitrate (NO_3), compared to 13.3% due to P. Therefore, in Ireland future mitigation measures must focus on P losses with emphasis on diffuse losses from agriculture.

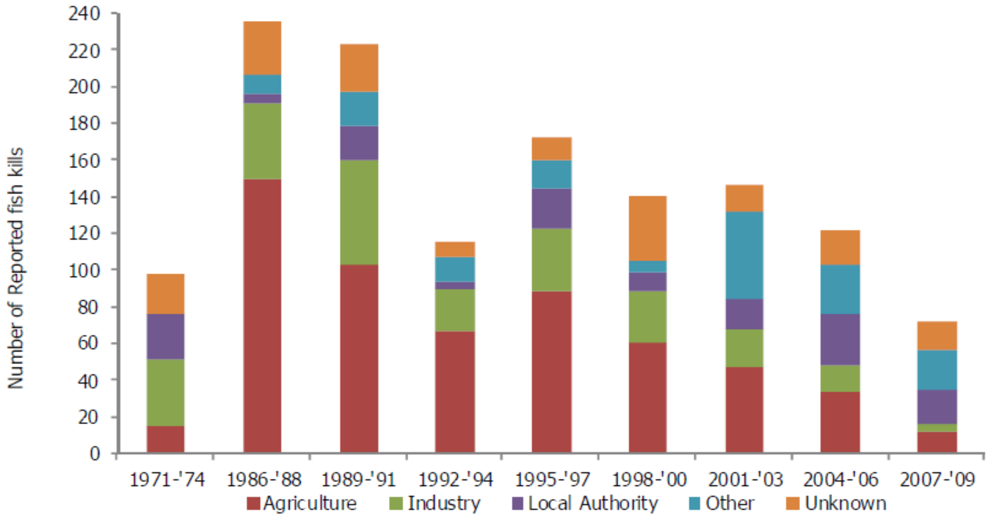


Figure 2.2 Number of reported fish kills attributed to agriculture, industry, local authority, other and unknown sources (McGarrigle et al., 2011)

2.6. Nutrients loss and pathways during land application of dairy slurry

Throughout the EU and U.S.A. agricultural management has been identified as a landscape pressure impacting on water quality (Sharpley et al., 2001a, b; Schulte et al, 2006; Stark and Richards, 2008; Kronvang et al., 2009). Transfers of N and P from agriculture to water can lead to eutrophication and may occur in three ways: (1) as point source losses from farmyards because of excessive rates of soiled water application through the use of rotational irrigators; (2) as diffuse losses from soil, which are related to soil P and N concentrations in excess of crop requirements; and 3) as incidental losses from direct losses of fertilizer or manures to water during slurry application, or where a rainfall event occurs immediately after application (Preedy et al., 2001). Diffuse P losses, specifically incidental and chronic P losses arising from land application of dairy cattle slurry to grasslands in Ireland, are thus the focus of this study.

2.7. Phosphorus

Phosphorus is an essential nutrient for plant growth, and land application of organic and inorganic P fertiliser is needed to maintain profitable animal and crop production (Sharpley et al., 2003). In concentrated feeding systems such as intensive dairy farms, P inputs into a farm can exceed P outputs (Tunney, 1990). This can give rise to high STP soils which pose a risk to water quality. Phosphorus is also of particular importance in fresh water systems as it is the limiting nutrient for the occurrence of eutrophication (Correll, 1998; Sharpley and Tunney, 2000). Transfers of P from agriculture to water can lead to eutrophication of a waterbody (Carpenter et al., 1998). Land application of dairy slurry can result in incidental and chronic P losses to a waterbody (Buda et al., 2009). Incidental P losses take place when a rainfall event occurs shortly after slurry application and before slurry infiltrates the soil, while chronic P losses is a long-term loss of P from soil as a result of a build-up in STP caused by application of inorganic fertilisers and manure (Buda et al., 2009). Table 2.2 shows a summary of the results of laboratory and plot-scale runoff studies examining the effect of land application of dairy cattle slurry on DRP and TP concentrations in runoff water from grasslands. These results show the importance of timing of rainfall event following slurry application. In addition this table identifies a need to examine runoff from slurry at lower more realistic rainfall intensities.

Table 2.2 Results of laboratory and plot-scale runoff studies examining the effect of land application of dairy cattle slurry on P in runoff water from grasslands

Reference	Type	Size	Intensity	WEP	TP	DRP	TP	Time after application	Runoff
				------ slurry ------		----- runoff ------			
		m^2	mm h^{-1}	kg ha^{-1}	kg ha^{-1}	mg L^{-1}	mg L^{-1}	Days	mm
Kleinman and Sharpley (2003)	Box	1 x 0.2	70	14	50	3.2	6.35	3	
						1.85	3.2	10	
						1.5	2	24	
Smith et al. (2001c)	Plot	2 x 15	Natural		43		0.35	130[a]	5.4
Elliott et al. (2005)	Box	1 x 0.2	71	41.6	122		10.9	3	
Hanrahan et al. (2009)	Box	1 x 0.2	30		30	10.3	48	2	
						3.1	5	5	
						3.6	4.1	9	
Preedy et al. (2001)	Plot	3 x 10	Natural		29		7	7*	48

[a] Runoff collected for duration of study

2.7.1. Phosphorus in soil

The soil P cycle is shown in Figure 2.3. Phosphorus exists in organic and inorganic forms, and may be simplified into three types of P: (1) slow inorganic P (2) rapid cycling organic and inorganic P and (3) slow organic P. This is a dynamic equilibrium system and transformations between forms occur continuously (Sharpley, 1995). The availability of P to plants and water in contact with soil is controlled by chemical processes within the soil (Sharpley, 1995).

2.7.2. Methods used to determine risk of P loss to water

The slow inorganic pool provides P to replenish the solution P pool, and comprises inorganic P attached to small particles or elements, such as aluminium (Al) and calcium (Ca), and organic P that is easily mineralised. The rapid cycling of organic and inorganic P makes up a small proportion of total P in the soil, and is the most available to plants and to overland and subsurface flow. It is constantly being depleted and replenished from slow organic and inorganic P pools. Microbial P has an important role in short-term dynamics of organic P transformations and has a significant effect on P availability. Inorganic manure applications increase microbial activity in the soil, which leads to increased P availability. The slow organic pool contains compounds that are insoluble and organic P, which is less liable to mineralisation.

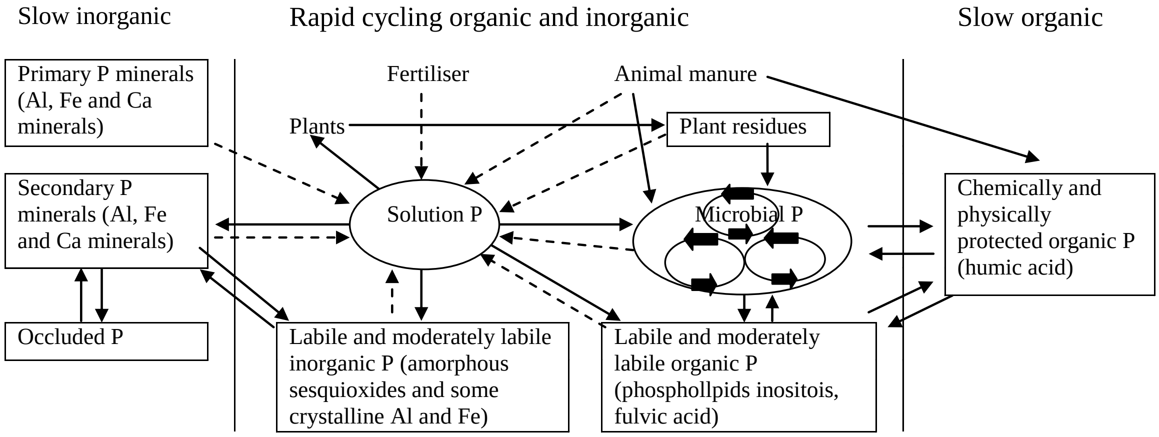


Figure 2.3 The soil P cycle: its components and measurable fractions (Steward and Sharpley, 1987)

Tests were initially developed to measure availability of P for agronomic purposes, with loss of P to water from soil not considered a priority. Studies found that P losses from soil were a major water quality concern (Sharpley and Rekolainen, 1997) and water quality became the focus of soil P testing. Commercial analysis is focused on testing methods which measure plant available P. However, researchers have found a relationship between STP and DRP in surface runoff (Regan et al, 2010; Little et al, 2007). Soil test P has been shown to be the main factor influencing P concentrations in runoff if no fertilisers have recently been applied (DeLaune et al., 2004; Dougherty et al., 2008). Different tests for the determination of STP have been adopted internationally depending on soil types and tradition (Table 2.3).

Studies have shown that the STP in the upper 20 mm of grassland soils tends to be higher than for the equivalent depth in tillage soils receiving the same manure (Ahuja et al., 1981). This is due to the absence of deep tilling, which ploughs the nutrients into the soil (Andraski et al., 2003; Sharpley, 2003). It has also been shown that the use of 100 mm sampling depth (used to determine the Morgan's P of the soil) underestimates P loss risk from soils and grasslands in particular (Humphreys et al.,1999). Mulqueen et al. (2004) recommended reducing the sampling depth to improve environmental risk prediction; however, Schroeder et al. (2004) reported that sample depth (2, 5 and 10 cm) had no effect on the relationship between soil P concentration and P concentration in runoff. Daly and Casey (2005) conducted an extensive review of sampling depth and concluded that the sampling depth of 100 mm was best. This was primarily due to the huge variability with smaller sampling depths. Torbert et al (2002) reported greater variation when sampling soil to a depth of 25 mm compared to 100 and 150 mm. It was suggested that this could be a result of a combination of an increased sensitivity of the testing procedure to 'hot spots' of manure in the field and difficulty in obtaining a consistent sample.

Table 2.3 Alternative soil test phosphorus analysis methods used around the world

Method	Soil	Countries
Bray 1 (Bray and Kurtz, 1945)	Acidic to slightly alkaline (<6 to 7.2)	UK and Australia
Mehlich 1 and Mehlich 3 (Mehlich 1984)	Acidic to slightly alkaline (<6 to 7.2)	Europe and U.S.A.
Olsen P (Olsen et al., 1954)	Slightly acidic to alkaline (6.0 to >7.2	UK
Morgan's P (Morgan, 1941)	Acidic to slightly alkaline (<6 to 7.2)	Ireland

The WEP test was developed to measure the environmental risk posed by P in any soil. The WEP test is also used to determine the risk of P loss from manures applied to grassland. In this test, soil is mixed with water to replicate soil and water interactions and to estimate dissolved P losses from soil. The general procedure is to weigh accurately a mass of soil into a known volume of distilled water in an un-reactive container and to shake for a time between 30 and 60 min. After shaking, the solution is centrifuged and passed through a 0.45 μm filter. Different dilution ratios commonly used are shown in Table 2.4.

Table 2.4 Dilution rates used to determine WEP of soil

Author	Dilution ratio	Type of study
Regan et al. (2010)	1:80	Runoff box
Pote et al. (2003)	1:25	Field
McDowell and Sharpley (2001)	1:5 1:100	Incubation

Schulte et al. (2010b) showed that it may take many years for elevated STP concentrations to be reduced to optimum levels to reduce risk to water quality. In Ireland, a P index system is used to quantify risk of P loss from a soil (Table 2.5). There are 4 categories, with Index 1 representing a P deficient soil and Index 4 (STP > 8 mg P L^{-1}) representing a grassland soil which presents a risk to water quality (Tunney, 2000). While the onset of reductions in excessive STP levels may be observed within five years, this reduction is a slow process and it may take up to 20 years for P index 4 soils to complete the reduction to the boundary Index 3 (a STP of between 5.1 and 8 mg P L^{-1}) (Schulte et al., 2010b).

Table 2.5 Phosphorus Index system used for Irish grasslands (Schulte et al, 2010b)

Soil P index	Morgan's soil P range for grassland soils (mg L^{-1})	Interpretation
1	0.0-3.0	Soil is P deficient; build-up of soil P required. Insignificant risk of P loss to water
2	3.1-5.0	Low soil P status: build-up of soil P is required for productive agriculture. Very low risk of P loss to water
3	5.1-8.0	Target soil P status: only maintenance rates of P required. Low risk of P loss to water
4	>8.0	Excess soil P status: no agronomic response to P applications. Risk of P loss to water increases within this index

The STP levels and the difference between available and total P for Irish soils can mostly be explained by land use, rock and soil type. Table 2.6 shows the average percentage of soils in each P index for all soil samples tested in Teagasc, Johnstown Castle between 2004 and 2006 (Mark Plunkett *pers com*, 2009). Phosphorus losses from agricultural soils are generally a result of an increase in STP caused by long-term applications of P fertilisers (Frossard et al., 2000).

Table 2.6 Average P index of soils tested in Johnstown castle for the period between 2004 and 2006 (Mark Plunkett, *pers com*, 2009)

Soil P index	STP mg L^{-1}	Grassland %	Tillage %
1	0.0-3.0	15	15
2	3.1-6.0	25	30
3	6.1-10.0	27	23
4	>10.0	33	32

In 2008 the Phosphorus Index system was amended (Lalor and Coulter, 2008).

2.8. Nitrogen

Nitrogen is the most abundant gas in the atmosphere and can exist in various compounds. The process by which N is transformed to its various forms is called the N cycle (Figure 2.4) (Ketterings et al., 2011). The major conversion processes which make up the N cycle are: N fixation, mineralisation, nitrification, denitrification, ammonia volatilisation, and immobilisation.

Biological N fixation is a process by which soil bacteria and plant roots interact to convert nitrogen gas (N_2) in the atmosphere to proteins. In industrial production, the Haber-Bosch process is used to combine N_2 and hydrogen gas (H_2) with a catalyst under intense heat and pressure for form NH_3, which is then used to make fertiliser. Biological N fixation requires plant energy so if available N exists, the plant will use this before biological fixation takes place (Ketterings et al., 2011). Mineralisation is the process that converts organic N in soil, manure and decaying plants to inorganic forms (ammonium (NH_4) and NH_3). Nitrification occurs when microbes use enzymes to convert NH_4 to nitrite (NO_2) and then NO_3 to obtain energy. Warm, moist and aerated conditions favour nitrification.

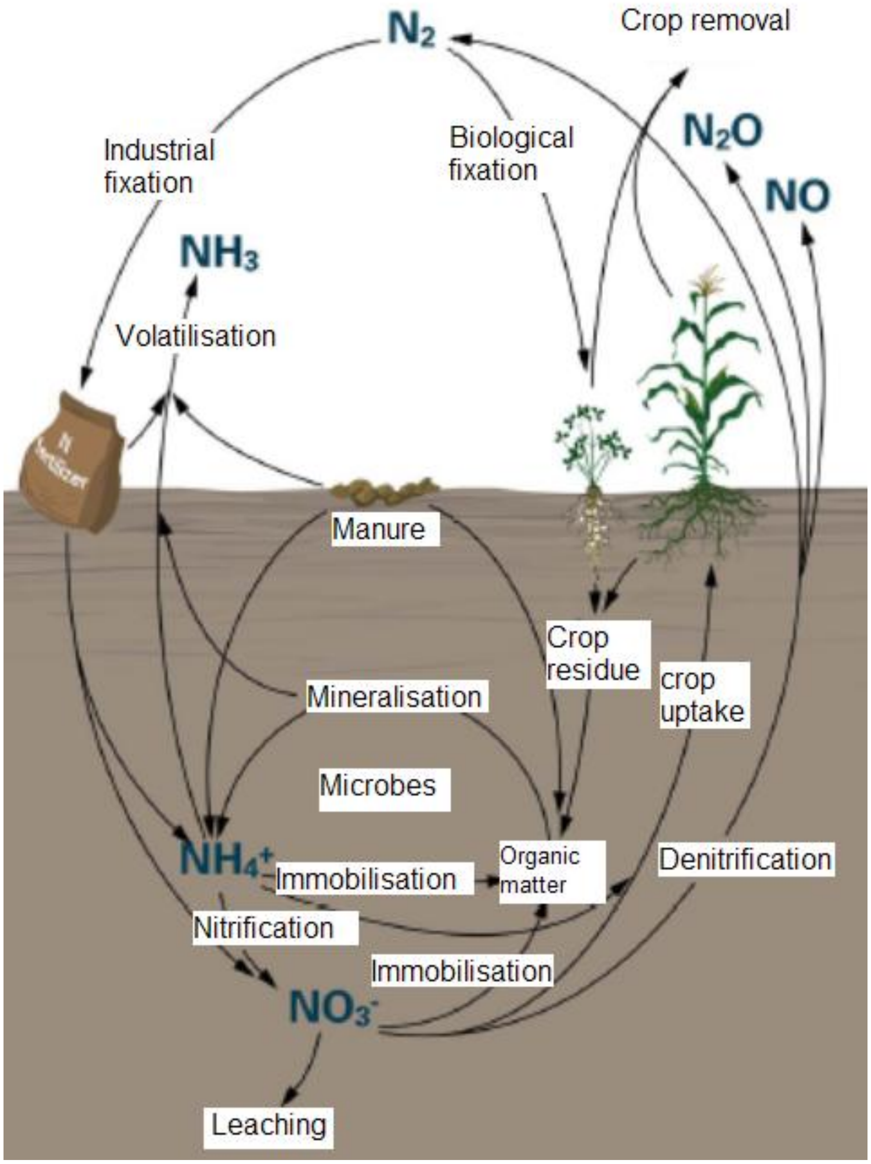


Figure 2.4 Schematic of the soil N cycle (Ketterings et al., 2011)

$$\text{Step 1:} \quad NH_4 \rightarrow NO_2 \tag{2.1}$$

$$\text{Step 2:} \quad NO_2^- \rightarrow NO_3 \tag{2.2}$$

Denitrification is the process by which N is lost from the soil through the conversion of NO_3 to various gaseous forms of N. Significantly, this reaction can produce N_2O, which is a potent GHG. Therefore, treatments such as chemical amendment of dairy cattle slurry which could potentially change the N cycle, and could impact N_2O release. Wet, poorly drained soil favours the occurrence of denitrification.

$$NO_3 \rightarrow NO_2 \rightarrow NO \rightarrow N_2O \rightarrow N_2 \tag{2.3}$$

Ammonia volatilisation is the production and release of NH_3 from NH_4 on the soil surface. Ammonia losses are greatest in soils with high pH and in dry, warm and windy weather (Ketterings et al., 2011). Immediately following land application of dairy cattle slurry, there is an initial peak in NH_3 emissions and it is estimated that 60% of ammonical nitrogen (NH_4-N) applied is lost during land spreading of cattle slurry (Hyde et al., 2003). There exists a state of equilibrium between the NH_3 in the slurry/soil interface and the NH_3 in the air immediately above the soil surface (Génermont and Cellier, 1997). The pH of the slurry/soil combination has also been observed to affect the rate of NH_3 volatilisation. Depending on the pH, NH_4-N can occur as NH_3 gas or the ammonium ion (NH_4^+) (Gay and Knowlton, 2005). The relationship between NH_4 and NH_3 as a function of pH is shown in Figure 2.5.

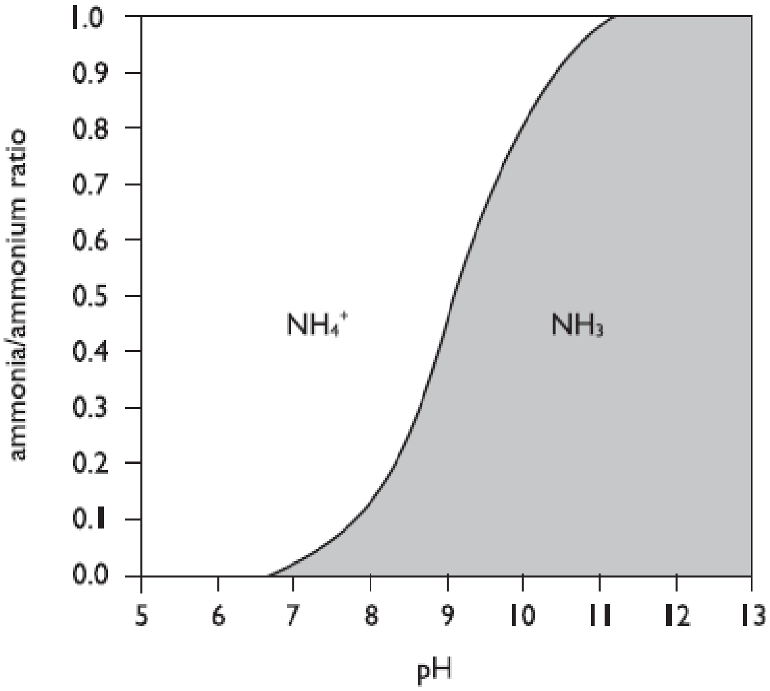


Figure 2.5 Relationship between the ammonia/ammonium (NH_3/NH_4^+) ratio and pH (Gay and Knowlton, 2005)

Immobilisation is the reverse of mineralisation and occurs when microbes temporarily bind available N in soil biomass (Ketterings et al., 2011). Nitrogen can be lost to surface ground waters (Stark and Richards, 2008) and to the atmosphere in gaseous form (Ketterings et al., 2011). On a farm, N losses are spatial in nature and occur from the entire farm, while P losses can be due to small portion of farm (Poinke et al., 2000) called Critical Source Areas (CSAs). Therefore, measures to reduce P loss that are applied through a farm may have a greater effect on N loss than P loss.

2.9. Loss of soluble and particulate nutrients in runoff

Nutrients can be lost to a surface waterbody in particulate and soluble forms. Suspended Sediment (SS) loss contributes to particulate phosphorus (PP) in runoff from tillage soils (Regan et al., 2010); however, in grasslands most P loss is in dissolved form with Total Dissolved Phosphorus (TDP) and DRP making up 69% and 60% of TP load in surface runoff (Haygarth et al., 1998). Incidental SS losses following slurry application can result in high concentrations of SS in runoff, resulting in increased PP losses (Preedy et al., 2001). This PP can be mineralised and become available to algae (Sharpley, 1993). Withers et al. (2003) examined the results of a number of studies examining P losses following land application of dairy cattle slurry at different rates and under different climatic conditions (Smith et al., 2001c; Withers et al., 2001; Withers and Bailey, 2003) and found that incidental P losses can account for between 50 and 90% of P losses from land to water. These variations are due to difference site and climatic conditions.

2.9.1. Soluble nutrient loss

The processes involved in transfer of soluble P from soil or slurry to water are similar. Phosphorus release occurs as a result of the processes of precipitation-dissolution and adsorption-desorption (Frossard et al., 2000). Soluble P losses dominate P loss from grasslands (Sharpley et al., 1992). Kleinman et al. (2006) found that concentration of water soluble P in manure was strongly related to DRP in runoff from three soils examined.

Nitrate is the form of N most available to plants and to runoff, and makes up to approximately 2% of soil N at any time (Ryan et al., 2008). This NO_3 is constantly replenished if N is lost, and is very soluble and easily taken up from soil by runoff (Ryan et al., 2008). Although P is the limiting nutrient in freshwater systems (Correll, 1998), N losses also pose a significant risk to water quality (Johnes et al., 2007; Vitousek et al., 2009). It is recommended that slurry should be applied in spring time to maximise N efficiency (Lalor and Schulte, 2008) and to reduce risk of leaching of N to groundwater, as less NO_3 is lost when plants are growing and fertiliser is applied at rates corresponding to the requirements of the crop being grown (Power and Schepers, 1989). In a lysimeter study which examined NO_3 losses from five different soil types, Ryan and Fanning (1996) found that winter applications of pig and dairy cattle slurry resulted in higher NO_3 losses than spring applications. This is most likely due to uptake of NO_3 by plants during the spring when plants are growing.

2.9.2. Particulate nutrient loss

Erosion of soil or surface runoff of land applied slurry by water occurs predominantly as a result of the processes of detachment (caused by the impact of the raindrops on the soil/slurry surface) or by erosion mechanisms such as entrainment and re-entrainment. As the processes of soil erosion and runoff of land applied slurry are analogous to one another, the fundamental mechanisms of surface runoff of land applied slurry will be discussed in the context of soil erosion.

Detachment of the soil particles from the soil surface is due to the impact of the raindrops falling under gravity on the ground (Figure 2.6). The cohesive bonds between the soil particles are brittle, and, once broken, the cohesive strength of the soil is lost. Provided the infiltration rate is greater than the rainfall rate, the soil particles will return to the soil surface. If rainwater accumulates on the surface, erosion can occur and the detachment process will continue. The risk of SS and P loss to surface waters in a rainfall event decreases dramatically with an increase in time from slurry application to start of the rainfall event (Smith et al., 2007; Allen and Mallarino, 2008; Hanrahan et al., 2009).

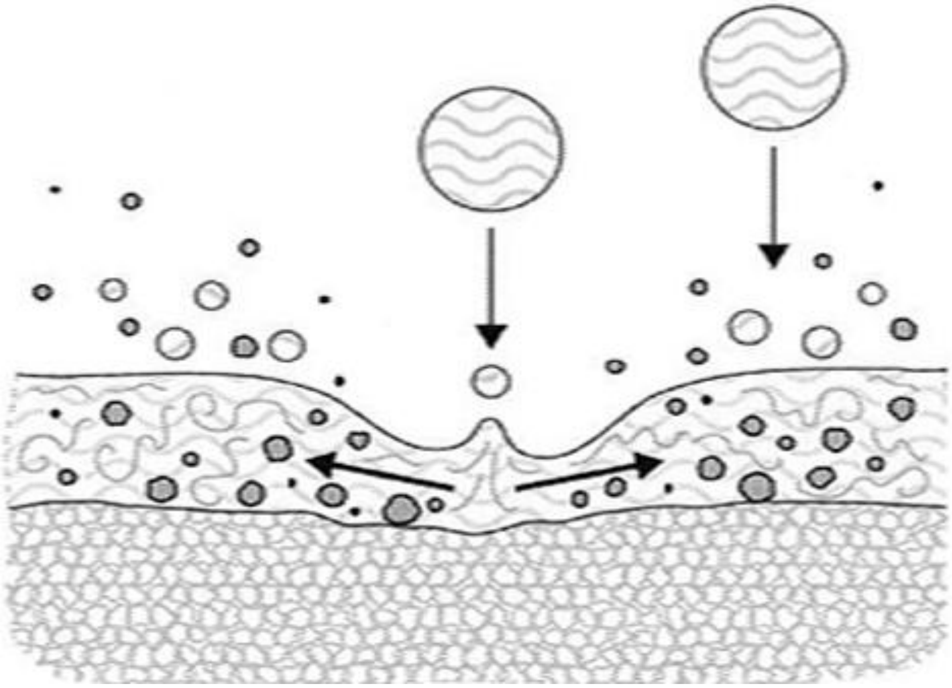


Figure 2.6 Detachment of soil particles in a rainfall event (Rose, 2004)

The potential for P loss peaks and then declines over time, as P applied in slurry interacts with the soil (Edwards and Daniel, 1993). The processes for slurry SS loss are similar to soil erosion processes. Hanrahan et al. (2009) reported that TP and DRP concentrations were reduced by 89 and 65%, respectively, by delaying rainfall from 2 to 5 d after dairy cattle slurry application. In addition, McDowell and Sharpley (2002a) found that flow path length had a significant effect on P fractions in runoff following land application of dairy swine slurry. Therefore, when examining the effect of changes in slurry management, these factors must be taken into consideration.

Rose (2004) considered the difference between the rate of detachment and the rate of sediment deposition to be responsible for the initial development of sediment runoff in surface water. As P is adsorbed to sediment (Torbert et al., 2002), the settling velocity of eroded soil particles is of critical importance. Smaller particles will take much longer to settle and have the potential to travel greater distances than larger particles in the same conditions (Figure 2.7). The distance which these particles can travel is determined based on Stokes law (Batchelor, 1967).

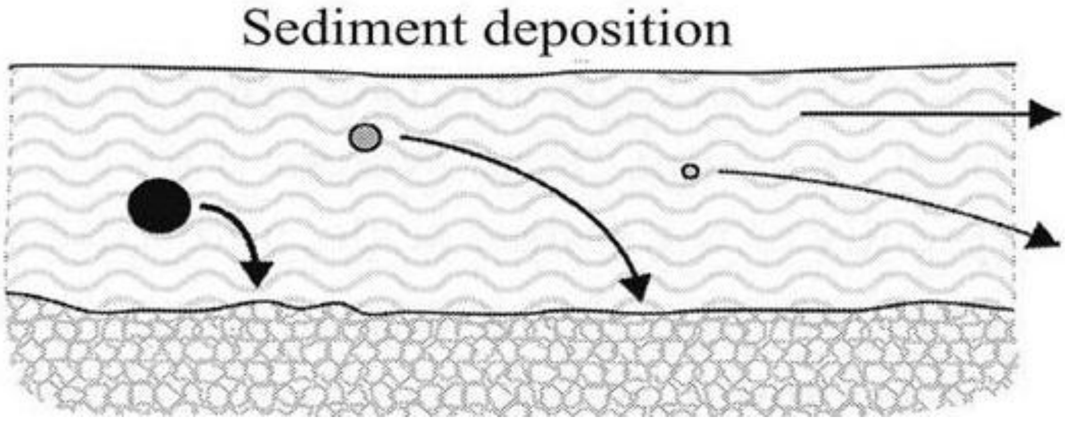


Figure 2.7 Rate of sediment deposition in surface runoff (Rose, 2004)

The gradual formation of a surface seal under prolonged rainfall and submergence may cause reduced infiltration rates into the soil and, consequently, may induce increased erosion in some soils. This phenomenon occurs when the impact of the falling rain damages the structure of the soil so that the permeability of the soil surface is reduced or when rain falls on damaged clay soils with very low permeability. This theory suggests that the soil particles are held together in bundles or aggregates. The action of the rain falling can break these bundles apart and, in some cases, may cause the pores on the soil surface to seal (Rose, 2004).

Detachment is the dominant process responsible for sediment erosion in the early stages of a rainfall event (Rose et al., 1983). As the runoff event increases in magnitude, the rainwater can no longer infiltrate the soil surface and overland flow occurs. This phenomenon is also known as capping or infiltration excess (Horton, 1933). Entrainment is the process which involves the surface runoff eroding the soil particles (Figure 2.8). The erosion processes for slurry are similar to soil.

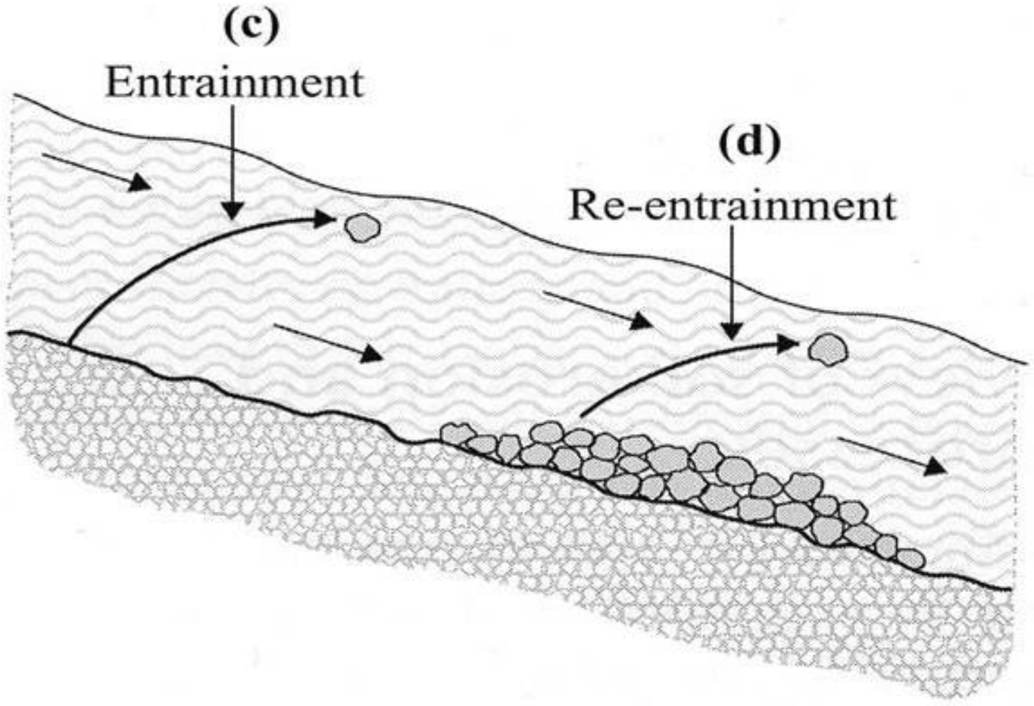


Figure 2.8 Entrainment and re-entrainment of sediment (Rose, 2004).

The ability of flowing water to erode sediment is related to the stream power, Ω, which is a function of shear stress and the velocity of the surface runoff (Rose, 2004). Once Ω exceeds a threshold value, Ωo, sediment is eroded. Detachment processes are less significant in deep surface flow. However, rain falling on shallow water will increase turbulence and liberate particles. Particles which are put into suspension after entrainment are then deposited according to their settling velocity. Over time, these particles accumulate and begin to rebuild the eroded soil surface. These particles have insufficient time to gain cohesive strength and are more easily eroded than the original deposited sediment. This erosion process is known as re-entrainment. Re-entrainment moves the particles in the general direction of flow by saltation (Figure 2.8). The processes by slurry particles are moved in surface water are similar.

2.10. Gaseous emissions and the importance of considering pollution swapping when selecting a P mitigation measure

Agricultural activities contribute to the production of NH_3 and GHG such as CO_2, N_2O and CH_4. In particular, land application of dairy slurry can result in the release of NH_3 (Amon et al., 2006), N_2O (Ellis et al., 1998), and CH_4 (Chadwick and Pain, 1997). It is critical that the potential for pollution swapping is examined when evaluating a potential technology. In particular, the effects of any proposed treatments on GHG emissions must be examined. Under the 1997 Kyoto Protocol of the United Nations Framework Convention on Climate Change (UN, 1998), participating nations agreed to publish national inventories of anthropogenic emissions of several GHG and to reduce future emissions below 1990 levels. In Ireland, agricultural activities were responsible for approximately 26% of total GHG emissions in 2008 (McGettigan et al., 2010) and account for virtually all NH_3 emissions, with animal manure alone responsible for 92% of NH_3 emissions (EPA, 2010). While NH_3 is not a GHG, it contributes to acidification of soils, atmospheric pollution, and the eutrophication of surface and ground water systems (Goulding et al., 1998). An estimated 5% of global N_2O emissions results from the conversion of NH_3 into N_2O in the atmosphere (Ferm, 1998).

2.11. Present and emerging P mitigation measures

The general consensus held by researchers in Ireland is that Ireland will not meet its water quality targets by 2015 (Schulte et al., 2010b; McGarrigle et al., 2011). This failure to achieve the required improvements in water quality status is a common problem being faced throughout Europe and in the US. It is largely accepted that supplementary measures, in particular the development of P mitigating technologies, will be critical to develop short-term farm management practices which will reduce nutrient losses to waterbodies (Buda et al., 2010). These mitigation methods, together with best management practices which are already in place, will enable the achievement of water quality requirements in shorter time period. This will allow for the development of long-term, sustainable management practices to minimise risk of P loss to water.

In Ireland, attempts to reduce diffuse P loss from agriculture have focused on increasing nutrient efficiency and improving slurry management strategies. To address the time lag between implementation of these strategies and reduction of STP to the boundary index 3 in high P-index farms (Table 2.6), short-term P mitigation technologies are required. Current guidelines state that farmers may only apply dairy cattle slurry to high STP soil in the absence of low STP soil. On such farms, treatment of dairy cattle may be considered for use in tandem with existing management practice to reduce the solubility of P during this ‘time lag’ period. Mitigation methods to reduce incidental P losses include incorporating slurry into soil immediately after land application (Tabbara, 2003), increasing length of buffer zones between slurry application areas and drains and streams (Mayer et al, 2006), enhanced buffers strips (Uusi-Kämppä et al., 2010), timing of slurry application (Hanrahan et al., 2009), chemical amendment (Dao and Daniel, 2002; Dou et al., 2003) and diet manipulation (O’Rourke et al., 2010). The risk of P loss from slurry is strongly related to the WEP in the slurry (Dou et al., 2003) and amendments which reduce P solubility should reduce P loss to runoff. In this section, current management practices, along with new technologies, to treat dairy cattle slurry and to mitigate P losses from land application of dairy cattle slurry are discussed.

2.11.1. Constructed wetlands

To date, free-water surface (FWS) Constructed Wetlands (CWs) (reed beds) are the most widely used, low-cost and low-maintenance alternative to land spreading of dairy wastewaters in Ireland. Constructed wetlands provide an environment for the physical/physico-chemical retention and biological reduction of organic matter (OM) and nutrients (Knight et al., 2000). Depending on the organic loading and retention time (Karpiscak et al., 1999), constructed wetlands can have a significant nutrient removal capacity. However, due to the effect of varying temperatures, the treatment efficiency of these systems tends to vary throughout the year (Healy and Cawley, 2002).

Constructed wetlands may be planted with plants found in natural wetlands and lined with soil to trap nutrients and solids from wastewaters. They may be used to treat runoff from intensively farmed soils in close proximity to sensitive water bodies (Tanner et al., 2005), or alternatively, to treat wastewaters before water is land applied to reduce potential for pollution (Healy et al., 2007). There is a long history of use of CWs to treat municipal wastewaters and they have more recently been adopted to treat dairy waste water and screened dairy slurry (the liquid portion of dairy cattle slurry following separation) (Healy et al., 2007).

Guidelines for the design loading of surface-flow wetlands (Healy et al., 2007) recommend an area loading rate of approximately 5 g of 5-day biological oxygen demand (BOD_5) $m^{-2}d^{-1}$. Although CWs have been shown to be very effective achieving good reductions in municipal and dilute dairy waste waters (soiled dairy water etc), the high solids content and the high nutrient concentrations of agricultural slurries make them difficult to treat. New Zealand guidelines for the disposal of farm dairy wastewaters (Tanner and Kloosterman, 1997) recommended that an FWS CWs should only succeed two waste stabilization ponds (an anaerobic and an aerobic pond, respectively) before entering the wetland with an organic loading rate not exceeding 3 g BOD_5 m^{-2} d^{-1}. The anaerobic pond reduces the BOD_5 and SS, and the aerobic pond carries out further biological reductions. Mantovi et al. (2003) suggests that the milking parlour should be designed to allow parlour washings and washings from the holding room to be separated, so as the wetland only treats the effluent of lower organic and nutrient content.

The removal of NH_4-N from strong waste waters is generally inadequate in most CWs (Sun et al., 2005; Toet et al., 2005). Inorganic nitrogen removal is also often unsatisfactory (Luederitz et al., 2001) and in Europe, average percentage removal of NH_4-N during long-term operation is approximately 35%, with a maximum of 50% (Verhoeven and Meuleman, 1999).

The ability of CWs to retain P is dependent on the P loading rate, the media type, vegetation, and duration of operation (Healy et al., 2007), although changes in pH and redox potential could also release P from the system. Healy et al. (2007) reported that between 65 and 95% of P may be removed at loading rates of less than 5 g TP m^{-2} yr^{-1}.

Phosphorus is removed through short-term or long-term storage, with most removal often occurring near the inlet initially, before extending throughout the wetland over time as those sites become P-saturated (Jamieson et al., 2002). Uptake by bacteria, algae and duckweed (*Lemma spp.*), and macrophytes provides an initial removal mechanism. However, this is only a short-term P storage as 35 to 75% of P stored is eventually released back into the water upon dieback of algae and microbes, as well as plant residues. The only long-term P storage in the wetland is via peat accumulation and substrate fixation, the efficiency of which is a function of the loading rate and the amount of native iron (Fe), Ca, Al, and OM in the substrate. Henry et al. (2003) reported reductions of total dissolved solids (TDS), NH_4-N, TN, and TP were 58%, 83%, 90%, and 84%, respectively, in the first 3 years of operation. These were above the national averages for CWs. However, these results indicate that CWs can be effective when properly managed. Although there is much evidence to support use of CWs, the P mitigating processes and long-term viability of CWs for P control are not sufficiently understood to pursue CWs as a potential management decision to control short-term P surplus. The also perform poorly when it is raining and are susceptible to incidental P loss during storm events.

2.11.2. Anaerobic digestion

Digestion of organic wastes results in the production of slurry with lower pollution potential and which is more suitable for use as a fertiliser while producing renewable energy (Singh et al., 2010a). Anaerobic digestion (AD) is now seen as the best manure management practice, as it offers the opportunity to reduce gaseous emissions from manure, increase N availability, produce biogas and reduce GHG emissions (Holm-Nielsen et al., 2009; Masse et al, 2011). Although AD reduces WEP of slurry without reducing plant availability of P (Moller and Stinner, 2009), the main benefit of AD in terms of P mitigation is that the digested slurry can be separated and the solid fraction exported off-farm for use as a soil conditioner, or further processed into a granular organic fertiliser, or a combustible fuel which has a commercial value. Anaerobic digestion reduces gaseous losses from slurry (Amon et al., 2006; Clemens et al., 2006) and increases N availability in slurry (Moller et al., 2008). Amon et al. (2006) reported that AD reduced N_2O losses from dairy cattle slurry by approximately 28% compared to a slurry-control. Anon et al. (2006) also reported that CH_4 losses following land application of digested dairy cattle are lower and there are no adverse effects on NH_3 emissions compared to untreated dairy cattle slurry (Amon et al., 2006; Clemens et al., 2006). In addition, AD can lower the odour from farm slurries by up to 80% (Pain et al., 1990), lower survival of pathogens in the slurry (Masse et al, 2010; Cote et al., 2006), and kill many weed seeds, reducing need for herbicides (Frost and Gilkinson, 2010). There are extensive AD plants in mainland Europe; however, there are only pilot-scale plants in Ireland (Anon, 2011). Although AD is not currently considered a P management option, Gungor and Karthikeyan (2008) reported that AD decreases water soluble P faction by between 22 and 47% compared to undigested slurry.

Although the advantages of AD are immense, there are some difficulties which have restricted their adoption in Ireland. The main barriers to their use are the high capital cost necessary to establish them, the low dry matter (DM) content of slurry on many dairy farms, the energy requirement to maintain temperatures sufficient for the digester to operate, and a long hydraulic retention time. This means that a large AD reactor is necessary for high volumes of slurry (Frost and Gilkinson, 2010). Moller et al. (2007) examined the feasibility of separating slurry prior to AD and recommended that pre-separation may increase yield, but the feasibility depends on the cost of separation and transportation of slurry from farm to AD plant. Although AD is the most environmentally sustainable means of treating slurry in the long-term, it is unlikely that AD can be implemented specifically to mitigate P losses in sufficient time to meet requirements of the WFD. Many German farmers make a living producing biogas from such operations; however, their government provides financial supports for such enterprise (Anon, 2011). In the long-term, with improvements in technology and with the support of government initiatives, AD may become a management practice in Ireland.

2.11.3. Biochar

Biochar is produced when biomass is burnt in the absence of oxygen at temperatures <700°C (Lehmann and Joseph, 2009). There is growing acceptance that biochar may play a part in reducing GHG emissions from agriculture (Winsley, 2007). There are two biochar P mitigation management systems currently being examined for the treatment of dairy cattle slurry: (1) slurry can undergo pyrolysis and be converted to a biochar, which can be applied to soils as a soil conditioner and fertiliser and to reduce losses of metals from soils (Cao and Harris, 2010) and (2) biochar produced from another biomass source can be used to sequester P and then land applied in another location (Streubel et al., 2010).

These technologies have the potential for use as part of sustainable manure management to allow transport of biochar produced from slurry, or biochar enriched with nutrients, to soils with low STP. Biochar has a much lower volume than slurry used to produce it and would be much more attractive as a fertiliser and soil conditioner to a wide range of uses not limited to agriculture. Land application of biochar can restore fertility in degraded soils (Novak et al., 2010), improve health of the soil (O'Neill et al., 2009; Van Zwieten et al., 2010), reduce nutrient leaching (Singh et al., 2010b), reduce GHG losses (Gaunt and Lehmann, 2008; Rogovska et al., 2011) and improve fertiliser efficiency in some soils (Van Zwieten et al., 2010).

Streubel et al. (2010) investigated the potential for using biochar produced from pyrolysis of AD sludge to sequester P from dairy lagoons and found that 50% reduction of soluble P in dairy slurry lagoon was achieved while the plant available P in the biochar increased from 4 to 45 mg kg^{-1} Olsen P. This system allows the nutrients to be trapped and transported to areas with low P soil where they can be used a soil conditioner and fertiliser. Although there is excellent potential for GHG emission reduction (Gaunt and Lehmann, 2008) and potential to reduce P loss from agriculture by transporting saleable product from areas with P surplus, this technology is not developed sufficiently for widespread implementation. There are high capital costs and these systems would need to be validated at farm-scale before being recommended for use in Ireland. The low DM of dairy cattle slurry results in a very high cost of drying slurry and this is one of the main barriers to the production of biochar from slurry (Xinmin Zhan *pers com*, 2011). Systems using biochar to sorb P from slurry lagoons are not as likely to be attractive to farmers in Europe as in the U.S.A., as slurry lagoons are not as common in Europe. In addition, the risk of pollution swapping associated with slurry lagoons is a problem. The main barrier to use of biochar technology is that there is no legislation in place regarding of biochar for use by agriculture and before biochar can be used as an amendment for soils, standards need to be established (Kwapinski et al., 2010).

2.11.4. Buffer strips and enhanced buffer strips

Buffer strips have been implemented to reduce P losses from waters entering waterways (Hoffmann et al., 2009). Buffer-strips are particularly effective at reducing PP and current best farming practice stipulates a 2.5 m buffer-strip between edges of slurry application and a stream or drain. This is a natural buffer-strip which acts to reduce risk of P loss to surface waters. Studies have reported conflicting results (Table 2.7). The consensus is that buffer-strips are not very effective at trapping DRP (Watts and Torbert, 2009) and are generally more effective in reducing PP losses (Hoffmann et al., 2009). They are a cost effective TP and PP mitigation method and offer an attractive means of treating runoff from high STP soils. However, they are not always effective in storm events.

Many researchers have examined the potential to enhance DRP sorbing potential of buffer strips using amendments (Dayton and Basta, 2005; Uusi-Kämppä et al., 2010). Uusi-Kämppä et al. (2010) examined the potential for use of amendments in buffer strips to increase P retention and found that, while gypsum and $CaCO_3$ did not change DRP and TP loss to runoff during simulated runoff events, Fe-gypsum and granulated ferric sulphate increased DRP and TP retention between 74-85 and 47 to 64%, respectively. Dayton and Basta (2005) enhanced a buffer strip down-slope of soil receiving poultry litter using WTRs (20 Mg ha^{-1} WTR). This resulted in a reduction in DRP in runoff by between 67 and 86% compared to the buffer strip without any WTR incorporated. Watts and Torbert (2009) applied gypsum at 0, 1, 3.2 and 5.6 Mg ha^{-1} to a 1.52 m-wide buffer-strip down-slope of a soil receiving poultry litter. The unamended buffer-strip reduced DRP loss by 18%. This increased to 32-40% for all gypsum amended buffer-strips with the rate of gypsum applied having no significant effect.

Table 2.7 Performance of buffer strips in reducing total and soluble phosphorus in runoff (adapted from Kay et al., 2009)

Pollutant	Reduction	Reference
Total phosphorus	6% reduction	McKergow et al. (2003)
	10 to 98% reduction	Heathwaite et al. (1998)
	0 to 97% reduction	Uusi-Kämppäetal. (2000)
	31% reduction	Abu-Zreig. (2001)
	8 to 97% reduction	Dorioz et al. (2006)
	27% decrease to 41% increase	Borin et al. (2005)
Soluble phosphorus	16% reduction	Vaananen et al. (2006)
	61% increase	McKergow et al. (2003)
	17% decrease–475% increase	Borin et al. (2005)
	0 to 30% decrease	Dorioz et al. (2006)

Although these systems mainly use waste products (such as WTR, FGD, etc), they would be unfeasible on a large-scale due to availability of the waste products and cost of installing systems on a large-scale. Therefore, these P mitigation technologies are recommended for use in CSA; areas where pollution due to runoff or leaching is likely to occur) only.

2.11.5. Composting

Aerobic composting of organic waste is a very effective method of stabilising and sterilising waste materials. Composting manure reduces water content and reduces pathogen survival, kills weed seeds, and is easier to land apply (Eghball and Gilley, 1999). Slurry must be separated before it can be composted and this is the major barrier to their widespread use. Miller et al. (2006) reported that land application of composted cattle manure, rather than fresh cattle manure, may be a potential management tool to control P and N in surface water. Although composting does not sequester P, it converts the manure from a high water content, low nutrient concentration odorous material to a low water content, soil-like material, which is rich in nutrients and can be transported long distances and be used by farmers, or sold to other industries and households as a fertiliser. While composting manure reduces GHG emissions effectively (Pattey et al., 2005), it can cause increases in NH_3 emissions (Parkinson et al., 2004).

2.11.6. In-stream and edge of field filters

The alternative to reducing P lost to runoff is to recover P from drainage waters. In-stream and edge-of-field filters have been examined by many researchers throughout the world (Shipitalo et al., 2010a; McDowell et al., 2008; Bryant et al, 2010; Uusi-Kämppä et al., 2010). Remediation techniques which treat water in-stream include filter socks (Shipitalo et al., 2010a), backfilling tile-drains with P sorbing material (McDowell et al., 2008); various reactive barriers placed along field drains and drainage ways (Bryant et al., 2010; Uusi-Kämppä et al., 2010), reactive materials placed in sub-surface drains (Penn and McGrath, 2011) and ferric sulphate dispensing units (Narvanen et al., 2008).

Shipitalo et al. (2010a) found that compost-filled socks (Figure 2.9) were ineffective in reducing P loss from a grassland catchment. In a subsequent study, Shipitalo et al. (2010b) amended the compost with a nutrient sorbent to improve nutrient retention. This resulted in a 27% reduction in DRP in drain water after passing through the filter sock.

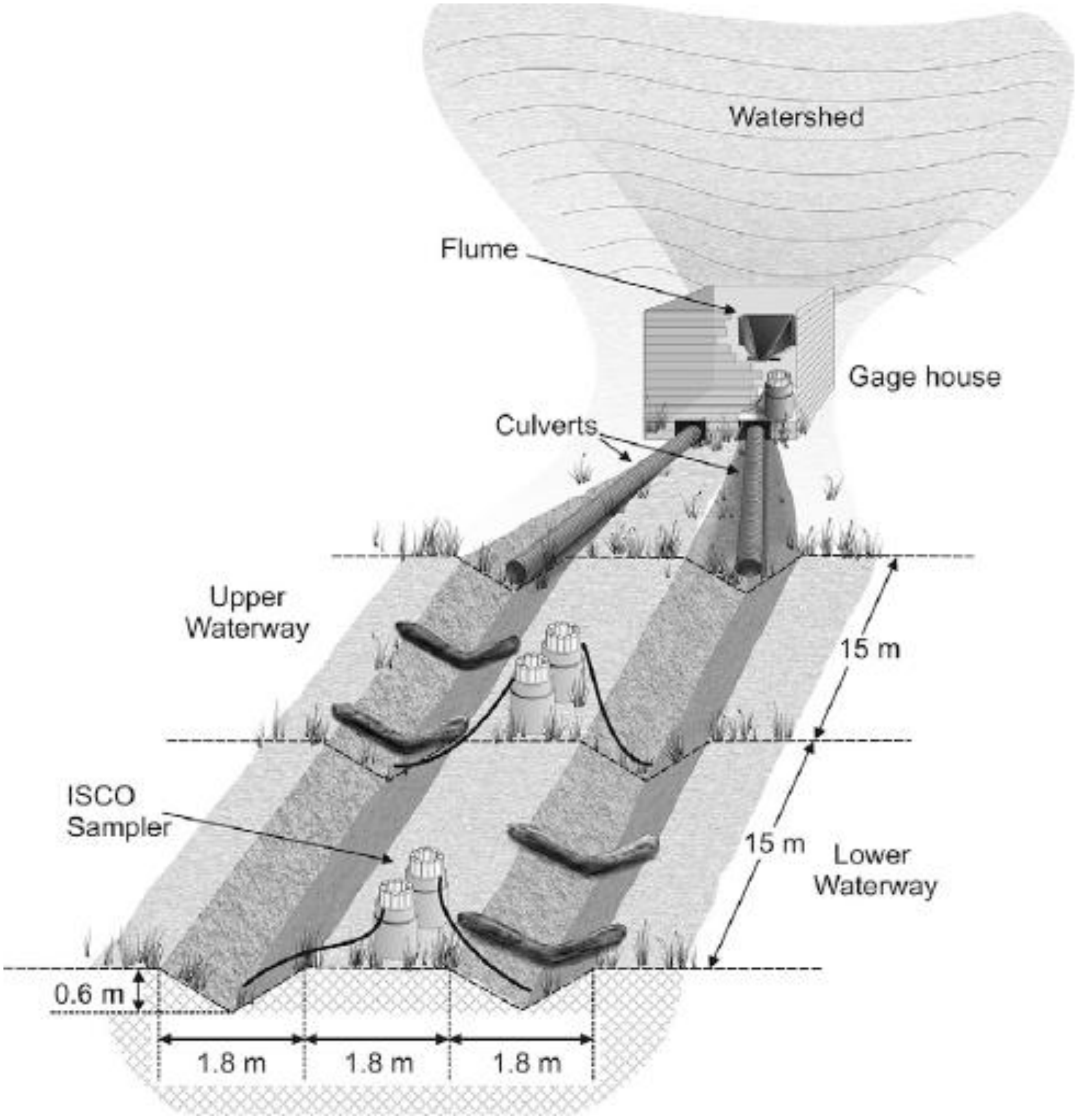


Figure 2.9 Compost filled socks in instrumented drainage channel (Shipitalo et al., 2010a)

Compost socks are not the most effective P sorbing systems. The initial aim of compost filter socks was to prevent SS loss and as the focus has shifted to P loss, researchers have examined more effective P sorbing materials. McDowell et al. (2008) examined the potential for use of industrial by-products to reduce P loss from tiled drained land. In this study, backfilling tile drains with a mixture of 90% melter slag and 10% basic slag reduced DRP and TP from 0.33 mg DRP L^{-1} and 1.20 mg TP L^{-1} for control to 0.09 mg DRP L^{-1} and 0.36 mg TP L^{-1}.

Bryant et al. (2010) used a permeable FGD gypsum barrier to intersect ditch water and to precipitate soluble P as calcium phosphate. Between 35 to 90 % of the P from ditch flow that passed through the filter was removed. However, during large flow events, the water flowed over the barrier and this was identified as the main problem associated with such P mitigation systems. Figure 2.10 shows the general layout of such edge of field filters.

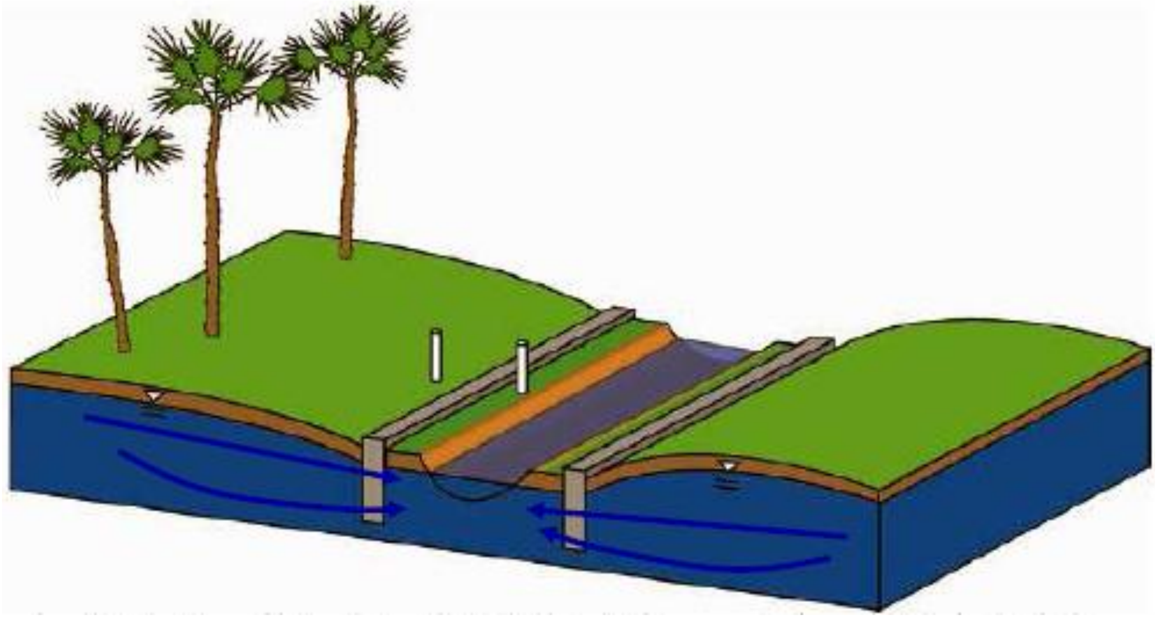


Figure 2.10 Permeable edge of field barriers (O'Connor et al., 2010)

The ideal situation would be to use materials which can be replenished. Penn and McGrath (2011) examined the ability of steel slag and a surface-modified slag to sorb P in golf course runoff in a flow-through system, and found that both treatments reduced DRP by approximately 31% with the need to replenish slag when it becomes saturated with P. Narvanen et al. (2008) designed a ferric-sulphate doser to treat runoff from a CSA (Figure 2.11). Immediately following chemical treatment, water was passed through a settling pond and then filtered in a sand bed. This system resulted in reductions in DRP and TP in runoff from CSA of 95 and 81%.

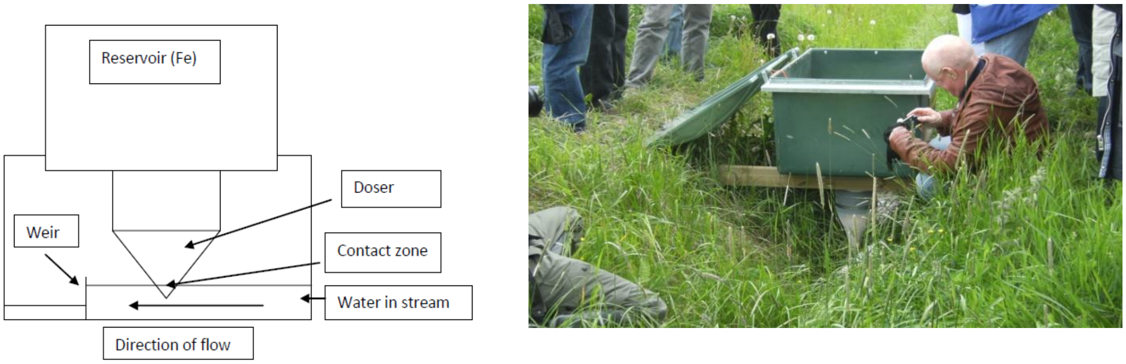


Figure 2.11 Schematic and photo of ferric-sulphate doser in operation in Jokioinen, Finland (Narvanen et al., 2008)

2.11.7. Sand and woodchip filter systems

Researchers have examined the use of sand (Healy et al. 2004) and woodchip filters (Ruane et al., 2011) to treat dairy soiled water. Recently, Carney et al (2011) have examined the effectiveness of wood chip filters in treating the liquid portion of pig slurry following separation (Figure 2.12). There is potential that such systems could be used to treat the liquid portion of dairy cattle slurry following separation. While sand and woodchip filters have been shown to significantly reduce BOD_5 and N losses (Healy et al., 2004; Ruane et al., 2011; Carney et al., 2011), they do not reduce P concentrations sufficiently to allow release of wastewaters to waterways.

The performance of filters depends on composition of influent and any filter system would require maintenance and constant monitoring to ensure that system was performing properly. While further steps could be included at subsequent stages of treatment to remove P, these systems would require further capital investment.

2.11.8. Slurry separation

The objective of slurry separation is to split the slurry into a liquid with low solids content and a solid with high DM. There are three main types of separator: brushed screen separator, decanting separator and screw-press separator. Gilkinson and Frost

(2007) carried out a comprehensive study of the brushed screen separator and decanting separator, and found that there was a strong correlation between DM and TP in slurry. Their report conduced that mechanical separation may be an option for farmers with a P and N surplus on farm. Slurry separation requires a significant initial investment and this is likely to be the biggest barrier to implementation. Slurry separation is the first step in treatment as the solid portion of the slurry must be further treated and liquid land applied.

Figure 2.12 Pilot scale wood chip filter used to treat the liquid portion of pig slurry following separation (Carney et al., 2011)

There has been extensive research into separation of slurry in the US. Currently, approximately 1-2% of dairy farmers in the US use polymers with a flocculent such $AlCl_3$ to help with solids separation (Philip Moore *pers com*, 2010). Such systems are very effective in reducing TP and soluble P in the liquid portion of separated slurry (Powers et al., 1995; Barrow et al., 1997; Krumpelman et al., 2005). This liquid portion can be land applied on farm to meet N requirements and the solid portion, which is high in P, can be transported off-farm. A summary of reductions of WEP and TP in slurry shown in Table 2.8.

Table 2.8 Review of laboratory-scale studies examining chemical aided separation to reduce P in liquid fraction of separated dairy cattle slurry

Reference	Chemical added	TP %	SS %
Powers et al. (1995)	[0.75g $CaCO_3$ + 0.5 ml $Fe_2(SO_4)_3$] L^{-1}	54	
	[0.75g CaO + 0.5 ml $Fe_2(SO_4)_3$] L^{-1}	93	
	[0.5 ml $Fe_2(SO_4)_3$ + 5 drops polymer] L^{-1}	62	
Krumpelman et al. (2005)	804 mg Fe L^{-1} + 150 ml 225G-PAM	74	54
	384 mg Al L^{-1} + 100 ml 225G-PAM	77	67
Barrow el al. (1997)	278 mg Fe L^{-1} as $FeCl_3$	88	89
	358 mg Ca L^{-1} as CaO	92	93

2.11.9. Use of P sorbing amendments

Fenton et al. (2008) recommended the addition of amendments to dairy cattle slurry prior to land spreading as a management practice to reduce P losses arising from land application of dairy cattle slurry Ireland. In the U.S.A., chemical amendment of poultry litter has been proven to be effective in reducing P losses from poultry litter and has been used as best management practice for over 30 years (Moore and Edwards, 2005). There has been limited work involving chemical amendment of dairy manure (Dao, 1999; Dou et al., 2003; Kalbasi and Karthikeyan, 2004), however, much more work is needed before chemical amendment can be recommended for implementation as a management practice in Ireland. Phosphorus sorbing amendments can be incorporated into soil to reduce soluble P in soils with high STP (Anderson et al, 1995; Novak and Watts, 2005); or, for incidental losses, added directly to the manure before land application to control P in manure being applied (Moore et al., 1999), or applied after manure application to reduce P losses from applied manure (Torbert et al, 2005).

2.11.9.1. Amendments applied directly to soil

Addition of chemical amendments to soils has been shown to reduce P solubility in high P soils and thus the potential to reduce the risk of P loss to waterbodies in surface runoff. Anderson et al. (1995) amended soils with a history of receiving dairy manure in an incubation experiment with calcium carbonate (with the slurry pH adjusted to 7.5), gypsum (0 to 100 g kg^{-1} soil), ferrous sulphate (0 to 1 g kg^{-1} as Fe) and alum (0 to 1 g kg^{-1} as Al). Calcium carbonate effectiveness was limited to soils with $pH < 7.0$ and gypsum was effective over a broad range of manure loading, pH and redox conditions. Although Al and Fe amendments to soil increased P retention by 400% relative to an unamended control, the authors acknowledged elevated costs associated with amendments and potential biological toxicity. In a laboratory incubation study, Novak and Watts (2005) incorporated an alum-based WTR into three soils with a Mehlich-3 P (M3) of between 145 mg kg^{-1} and 371 mg kg^{-1}, and found that the amendment reduced WEP in the soil by between 45% and 91% after an 84-d incubation period. They also found that WTR was efficient at reducing M3 of soils with a M3 of between 145 and 235 mg kg^{-1}, but not soil with a M3 of 371 mg kg^{-1} soil. Stout et al. (1998) amended soil with flyash at 0.01 kg kg^{-1} soil in a laboratory incubation experiment, and found that M3 and WEP were lowered by 13% and 71%, respectively. Flue gas desulphurisation by-product, applied at 0.01 kg kg^{-1} soil, lowered M3 by 8% and WEP by 48%. Table 2.9 shows chemical amendments studies with manure type, study type and percentage reductions in WEP of slurry and slurry amended soil.

2.11.9.2. Amendments to slurry

The present study examines for the first time the effect of chemical amendment of dairy cattle slurry on P, N and metal (namely Al, Fe and Ca) losses to runoff, whereas most previous studies only examined the effect of amendments on P solubility (Dao, 1999; Dao and Daniel, 2002; Dou et al., 2003). Dou et al. (2003) found that technical grade alum, added at 0.1 kg kg^{-1} (kg alum per kg slurry) and 0.25 kg kg^{-1}, reduced WEP in swine and dairy slurry by 80% and 99%, respectively. Dao (1999) amended farm yard manure with caliche, alum and flyash in an incubation experiment, and reported WEP reductions in amended manure compared to the control of 21, 60 and 85%, respectively. Kalbasi and Karthikeyan (2004) applied untreated and amended dairy slurry to a soil and incubated it for 2 years; alum and $FeCl_2$ were observed to decrease P solubility, while lime amendments increased WEP.

Table 2.9 Results of laboratory and plot-scale chemical amendments studies to date

Reference	Chemical	Rate	Manure type	Study type	% soluble P reduction in:		
					Runoff	WEP_{waste}	$WEP_{soil+waste}$
Dao (1999)	Alum	0.1 kg kg^{-1}	Cattle stockpiled	Laboratory			60
		0.1 kg kg^{-1}	Cattle composted				83
	Caliche	0.1 kg kg^{-1}	Cattle stockpiled	Laboratory			21
		0.1 kg kg^{-1}	Cattle composted				50
	Flyash	0.1 kg kg^{-1}	Cattle stockpiled	Laboratory			85
		0.1 kg kg^{-1}	Cattle composted				93
Dao and Daniel (2002)	Alum	0.01 kg kg^{-1}	Dairy slurry	Laboratory		66	63
	$FeCl_3$	0.01 kg kg^{-1}	Dairy slurry	Laboratory			18
	Flyash	0.01 kg kg^{-1}	Dairy slurry	Laboratory		44	82
Dou et al. (2003)	Alum	0.1 kg kg^{-1}	Dairy	Laboratory		99	
	Flyash	400 g kg^{-1}	Dairy			50-60	
	FGD	400 g kg^{-1}	Dairy			50-60	
Lefcourt and Meisinger (2001)	Alum	0.4% (w/w)	Dairy slurry	Laboratory		75	
		2.5% (w/w)				97	
McFarland el al. (2003)	Alum	0.78 kg m^{-2}	Dairy effluent	Plot			90
	Gypsum	0.78 kg m^{-2}	Dairy effluent	Plot	52		
Meisinger et al. (2001)	Alum	6.25% (w/w)	Dairy slurry	Laboratory			
Novak and Watts (2005)	Al-WTR	1-6% (v/v)	None	Incubation			45-91
Smith et al. (2001a)	Alum	215 mg Al L^{-1}	Swine	Plot		33	
		430 mg Al L^{-1}				84	
	$AlCl_3$	215 mg Al L^{-1}				45	
		430 mg Al L^{-1}				84	
Stout et al. (1998)	Flyash	0.01 kg kg^{-1}	None	Laboratory			71
	FGD						48
Zhang et al. (2004)	Flyash	0.4 kg kg^{-1}	Dairy manure	Laboratory		50-60	
Fenton et al. (2009)	Ochre	50 g L^{-1}	Dairy effluent	Laboratory		99	
Torbert et al (2005)	Lime	3:1 metal to P	Dairy slurry		0		
	Gypsum	3:1 metal to P			0		
	$FeSO_4$	3:1 metal to P			66		

A limited number of runoff studies have been carried out with chemical amendment of dairy cattle slurry (Elliot et al, 2005; Torbert et al, 2005) and swine slurry (Smith et al, 2001a). Torbert et al. (2005) amended landspread composted dairy manure with lime (3:1 metal-to-TP ratio) immediately prior to a 40-min rainfall event (overland flow equivalent to a rainfall intensity of 12.4 cm h^{-1}). Lime amendments increased DRP loss. In a plot study, Smith et al. (2001a) amended swine manure with alum and $AlCl_3$ at two stoichiometric ratios (0.5:1 and 1:1 Al: TP). Dissolved reactive phosphorus reductions for alum and $AlCl_3$ at the lower ratio were 33% and 45%, respectively, with 84% for both amendments at the higher ratio.

Chemical amendments of slurry using Al, Fe, or Ca based compounds reduce P solubility in manure (Dao, 1999; Dou et al., 2003; Kalbasi and Karthikeyan, 2004) and reduce P in runoff from plots receiving alum amended poultry litter (Moore and Edwards, 2005) with negligible effect on metal loss (McFarland et al., 2003). Chemical amendments reduce incidental P losses by a combination of the formation of stable metal-phosphorus precipitates (such as Al-P phosphates in the case of alum) and flocculation of the particles in the slurry to form larger particles, which are less prone to erosion (Tchobanoglous et al., 2003). Previous studies have found that there was no risk of increased metal release posed by chemical amendment of poultry litter (Moore et al., 1998), dirty water (McFarland et al., 2003), or horse manure (Edwards et al., 1999).

2.12. Recommendations and knowledge gaps

In Ireland, point source pollution caused by agriculture has been overcome by infrastructural investment on farms and by the removal of point sources in catchments. Attempts to reduce diffuse P loss from agriculture have focused on increasing nutrient efficiency and improving slurry management strategies. In order to meet our water quality obligations, it is becoming apparent that (1) the efficacy of the Nitrates Directive (Ireland’s agricultural POM) will need time to be assessed and (2) further investigation of mitigation measures (supplementary measures within the WFD), such as those outlined within the EU COST 869 project (coming to a conclusion in October 2011), will be necessary.

This review has identified a need for a short-term, cost effective management practice, which can be implemented to reduce the solubility of P in slurry and reduce the risk of incidental and chronic P losses. It is critical that the P mitigation measure selected can mitigate both of these losses. In the long-term, it is likely that a wide range of these technologies will be harnessed in parallel with land application of slurry.

In the short-term, however any P mitigation measure must have the ability to be quickly implemented within the existing farm slurry management structure, be cost effective and capable of being used in strategic locations for maximum effect. Chemical amendment of dairy cattle slurry was chosen for further investigation in the present study. Specifically, there have been limited studies involving chemical amendment of dairy cattle slurry and such studies have not considered the feasibility of using amendments at farm-scale, or the changes to the hydrology of a system through their use, pollution swapping and the long-term effects on STP. This is the first study to examine a range of potential chemical amendments for mitigation of P losses from dairy cattle slurry in Ireland.

The following knowledge gaps were identified in the present review:

1. There have been no studies conducted to evaluate the effectiveness and feasibility of potential chemical amendments in Ireland. There is a need for such a study if amendments are to be considered for implementation in Ireland.
2. There is a need for a study to examine the effect of chemical amendment of dairy cattle slurry on metal loss to runoff.
3. The effect of chemical amendment of dairy cattle slurry on pollution swapping, in particular N loss to runoff and GHG emissions, needs to be examined
4. The effect of chemical amendment of dairy cattle slurry prior to application to soil on long-term soil WEP and STP.
5. To examine the effect of soil type on the solubility of P in soil following application of amended slurry to soil.
6. To investigate the role chemical amendments may have in mitigation of P losses from dairy cattle slurry in Ireland.
7. To examine conditions in which they work and discuss limitations in use.

Chapter 3 Evaluation of chemical amendments to control phosphorus losses from dairy slurry

3.1. Overview

Land application of dairy slurry can result in incidental losses of P to runoff in addition to increased loss of P from soil as a result of a build up in STP. A novel agitator test was used to identify the most effective amendments to reduce DRP loss from the soil surface after land application of chemically amended dairy cattle slurry.

3.2. Introduction

Batch experiments, although allowing quick determination of adsorption capacities of amendments, are unrealistic when considering nutrient losses in runoff following manure application. These small-scale tests do not account for the interaction between applied slurry and soil, and the effect of infiltration and skin formation on the release of P to surface runoff. An 'agitator test', wherein an intact soil core, placed in a beaker, is overlain with continuously-stirred water (Mulqueen et al., 2004), enables achievement of batch experiment results, but also simulates the situation in which slurry is applied to soil, allowed to dry, and then subjected to overland flow (Figure 3.1). The test provides standardised conditions for assessment of the effectiveness of various amendments to slurry at reducing the release of P that may relate to land-applied slurry.

The objectives of this study were to: (1) use a laboratory agitator test to identify the most effective chemical amendments to reduce P loss from the soil surface after land application of amended dairy cattle slurry (2) identify optimum amendment application rates for a similar P reduction in different amendments (3) estimate the cost of each treatment, and (4) discuss the feasibility of using treatments in a real on-farm scenario.

Figure 3.1 Beakers placed in flocculator during agitator test

3.3. Materials and methods

3.3.1. Soil preparation and analysis

Soil samples were collected from a dry stock farm (53°21’ N, 8°34’ W) in Galway, Republic of Ireland. 120-mm-high, 100-mm-diameter Al coring rings were used to collect undisturbed soil core samples.

Soil samples (n=3) – taken from upper 100 mm from the same location - were air dried at 40 °C for 72 h, crushed to pass a 2 mm sieve and analysed for P using M3 extracting solution (Mehlich, 1984) and Morgan’s P using Morgan’s extracting solution (Morgan

1941). Soil pH (n=3) was determined using a pH probe and a 2:1 ratio of deionised water-to-soil. Shoemacher-McLean-Pratt (SMP) buffer pH was determined and the lime requirement (LR) of the soil was calculated after Pratt and Blair (1963). The particle size distribution (PSD) was determined using a sieving and pipette method (B.S.1377-2; BSI, 1990a) and the organic content of the soil was determined using the loss of ignition test (B.S.1377-3; BSI, 1990b).The soil used was a poorly-drained, silty loam topsoil, with 15% sand, 72% silt, 13% clay, and an OM content of 16.2±0.2%. The soil texture was classified using the US Department of Agriculture (USDA) soil texture triangle (Figure 3.2). The soil had a M3 concentration of 50±2.8 mg P kg^{-1} dry soil, Morgan's P of 4.6±0.49 mg L^{-1} (Index 2) and a soil pH of 5.6±0.1. The soil SMP buffer pH was 6.1±0.2 and the LR was 9.9±1 t ha^{-1}.

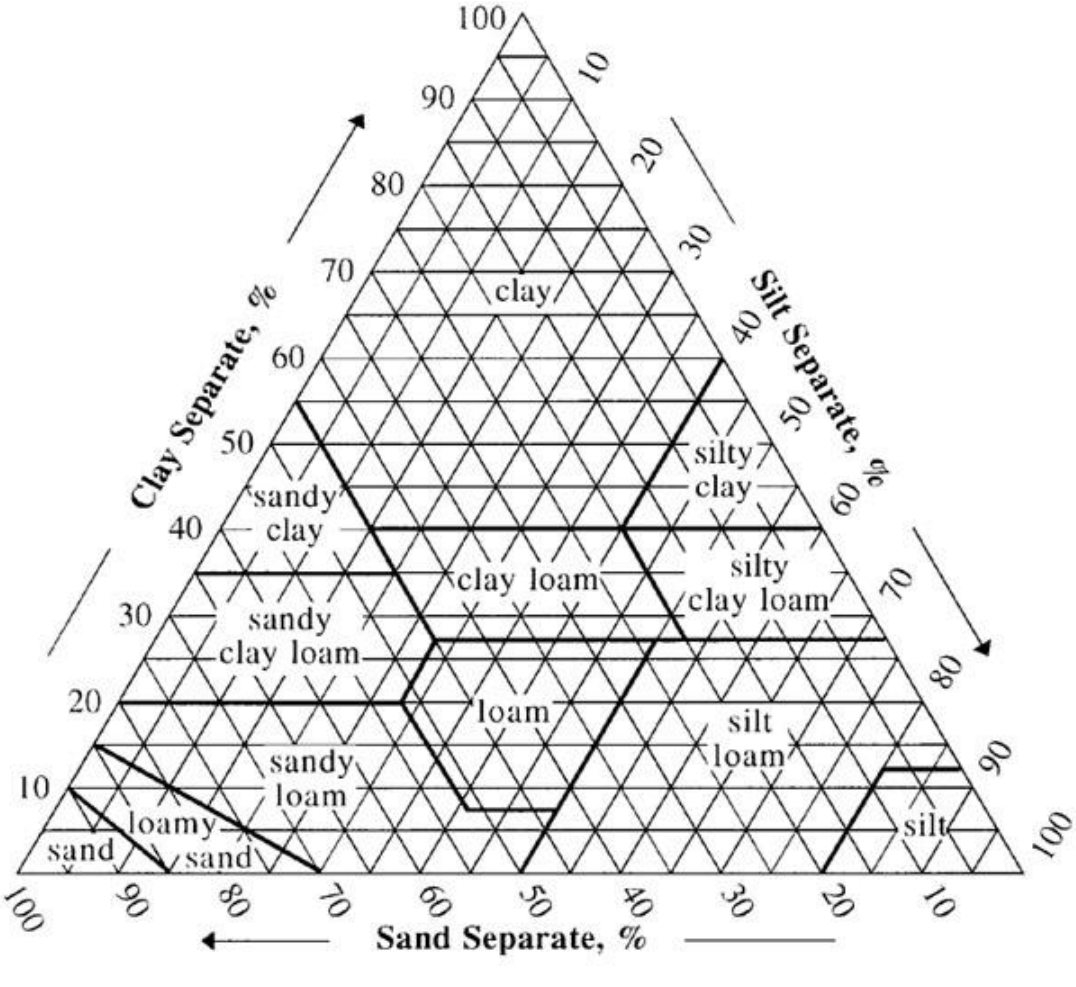


Figure 3.2 United States Department of Agriculture (USDA) soil texture classification triangle used to determine soil texture

3.3.2. Slurry sampling and analysis

Cattle slurry from dairy replacement heifers was taken from a dairy farm (53°18' N, 8°47' W) in Galway, Republic of Ireland. The storage tanks were agitated and slurry samples were transported to the laboratory in 10 Litre drums. Slurry samples were stored at 4°C. Slurry pH was determined using a pH probe (WTW, Germany) at 0 h and 24 h; the latter time corresponded with the time the slurry was interacting with the soil in the beaker before being saturated with water. The WEP of slurry was measured at 24 h as suggested by Kleinman et al. (2007). The TP of the dairy cattle slurry was determined after Byrne (1979). Potassium and magnesium (Mg) were analyzed using a Varian Spectra 400 Atomic Absorption instrument, and analyses for N and P were carried out colorimetrically using an automatic flow-through unit. The slurry had a TN concentration of 3982±274 mg L^{-1}, TP of 811±37 mg L^{-1}, total K (TK) of 4009±482 mg L^{-1}, and a pH of 7.3±0.5.

3.3.3. PSM sourcing and analysis

The Al-WTR was provided by Galway City water treatment plant (53°17' N, 9°03' W). Coal combustion by-products were provided by the Electricity Supply Board. The pH of the PSM was measured using 2:1 deionised water: dry amendment ratio. It was possible to measure the pH of the Al-WTR sludge with a pH probe. Dry matter content was determined by drying at 40°C for 72 h. Total metal and P of the PSM was measured by 'aqua regia' digestion using a Gerhard Block digestion system (Cottenie and Kiekens, 1984), which is described by Fenton et al. (2009). The WEP of the PSM was determined after Dayton and Basta (2001).

The characteristics of all Al-WTR-1, Al-WTR-2, flyash and FGD are presented in Table 3.1. Al-WTR-1 and Al-WTR-2 had respective Al contents of 11.1% and 5.3% (Table 3.1). Flyash contained 5.6% Al, 4.9% Ca, 2.5% Fe, 12,200 mg kg^{-1} Mg and 5,460 mg kg^{-1} TP. FGD contained 20% Ca, 2,950 mg kg^{-1} Mg and trace amounts of Fe (0.1%) and Al (0.1%). The composition of the commercial grade alum used is also shown. Analytical grade aluminium chloride (13% Al), ferrous chloride (18% Fe) and lime (54% Ca) were used in the experiment.

3.3.4. Agitator test

The agitator test comprised 10 different treatments: a grassed sod-only treatment; grassed sod receiving dairy cattle slurry at a rate equivalent to 40 kg TP ha^{-1} (the study control), and grassed soil receiving 8 different chemically-treated slurries (Table 3.2) applied at a rate equivalent to 40 kg TP ha^{-1}. Amendments were added to slurry in a beaker and mixed for 10 min using a jar test flocculator set at 100 rpm. Each of the 8 amendments were applied at 3 different rates (high, medium and low) in triplicate (n=3). All agitator tests were carried out within 21 d of sample collection. These rates were based results of batch test (Appendix B).

Prior to the start of the agitator test, the intact soil samples - at approximately field capacity - were cut to approximately 45 mm depth and transferred from the sampling cores into beakers. This depth of soil in the beakers was considered sufficient to include the full depth of influence on release of P to overland flow (Mulqueen et al., 2004). The chemically-amended slurry was applied to the soil with a spatula (t=0 h), and was then allowed to interact for 24 h prior to saturation of the sample. After 24 h (t=24 h), samples were saturated by gently adding deionised water to the soil sample at intermittent time intervals until water pooled on the soil surface (over 24 h). Immediately after saturation was complete (t=48 h), 500 ml of deionised water was added to the beaker. The agitator paddle was then lowered to mid-depth in the overlying water and rotated at 20 rpm for 24 h, as an attempt to (Figure 3.3).

Table 3.1 Characterisation of PSMs and alum used in the agitator test (mean ± standard deviation) tests carried out in triplicate

Amendment		Al-WTR-1	Al-WTR-2	Flyash	FGD	Alum
		(2 mm)	(sludge)			$(Al_2(SO_4)_3nH_2O)$
pH		7.9± 0.1	6.9± 0.2	11.2± 0.04	8.6± 0.0	1.25
WEP	mg kg^{-1}	<0.01		<0.01	<0.01	0
Al	%	11± 0.0	5.3± 0.2	5.7± 0.2	0.1± 0.0	4.23
Ca		1.3± 0.1	0.11	4.9± 0.2	20± 0.3	
Fe		0.2± 0.0	0.01	2.2± 0.1	0.1± 0.0	<0.01
K		0.03± 0.0	<0.01	0.1	0.03	
As	mg kg^{-1}	6.2±1.1	<0.01	13± 0.6	<0.01	1
Cd		0.16± 0.0	<0.01	0.6± 0.0	0.2± 0.02	0.21
Co		0.5± 0.3	<0.01	33± 1	0.3± 0.1	
Cr		3.8± 0.21	0.3± 0.02	88± 2	3± 0.1	2.1
Cu		31.7± 1.5	0.6± 0.03	32.7±1.5	37± 13	
Mg		165± 33	3.2± 1.7	12,200± 610	2,950± 58	
Mn		79± 1	6.9± 0.1	347± 160	31± 0.6	
Mo		0.47± 0.2	<0.01	7.7± 0.5	0.73± 0.3	
Na		611± 180	65± 14	1370± 610	660± 93	
Ni		4.8± 0.06	0.6±0.2	44± 1	11± 0.6	1.4
P		234± 5.3	18.7± 1.6	5460± 630	65± 20	
Pb		1.2± 0.8	<0.01	30± 2	0.74± 0.4	2.8
V		3± 0.2	0.2± 0.01	155± 5	49± 2	
Zn		17	0.8± 0.1	75± 31	9.4± 2	

WEP-water extractable phosphorus; Al-WTR-alum-based water treatment residual; FGD-flue gas desulphurisation product.

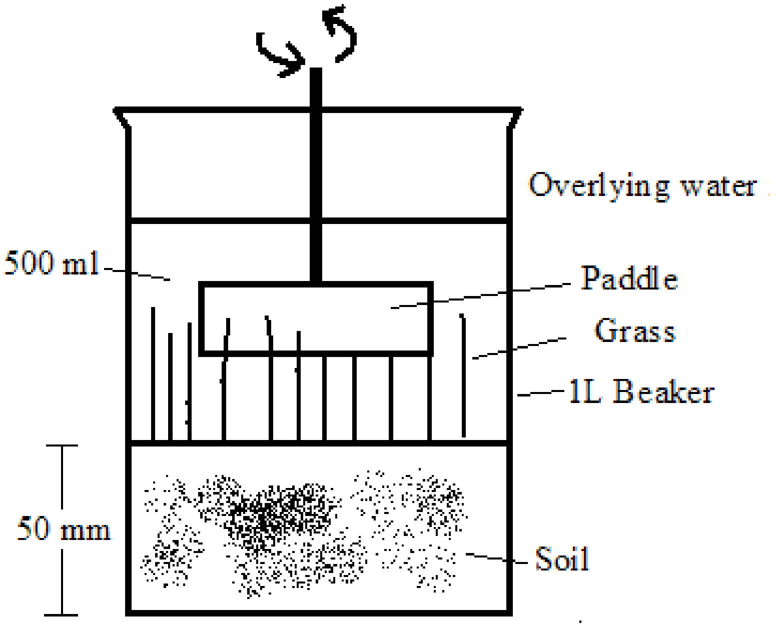


Figure 3.3 Schematic diagram of soil sample in agitator

Eight amendments were examined in an agitator test to control diffuse incidental P losses in runoff from slurry applied to permanent grassland. The amendments were divided into commercially available products (chemical amendments) including: industrial grade liquid alum ($Al_2(SO_4)_3.nH_2O$) containing 8% aluminium oxide (Al_2O_3); laboratory grade aluminum chloride ($AlCl_3.6H_2O$); $FeCl_2$ and burnt lime ($Ca(OH)_2$); and P sorbing materials (PSM): aluminium-based water treatment residuals, sieved to less than 2 mm (Al-WTR-1); Al-WTR homogenised sludge (Al-WTR-2); flyash; and FGD.Chemical amendments were applied based on Al:TP stoichiometric rate, and PSM were applied based on a kg kg^{-1} weight basis (slurry DM). The pH of the amended slurry was measured prior to application at t=0 h. Samples were taken to determine DM and WEP of the amended slurry (Kleinman et al., 2007). Slurry and amended slurry were applied to the surface of the grassed soil at a rate equivalent to 40 kg TP ha^{-1} (50 m^3 ha^{-1} slurry). For each treatment, slurry samples (n=3) - with the same volume as applied to the grassed sample in the agitator test - were spread at the bottom of another beaker to allow pH and WEP to be measured at 24 h without disturbing the sample used in the agitator test.

Table 3.2 Table showing amendments in order of effectiveness score, breakdown of costs[a], cost/m^3 slurry[b], cost for 100 cow farm, percentage reduction in DRP in overlying water and WEP of slurry at 24 h

Chemical[c]	Effectiveness score	Addition rate	Cost[d]	Rate	Cost amendment	Spreading	Agitation	Cost water[e]	Total	100 cow farm	DRP	WEP (t=24h)	WEP
			€ tonne^{-1}	kg m^{-3}		€ m^{-3}	€ m^{-3}	€ m^{-3}	€ m^{-3}	€ farm^{-1}	% P	mg kg^{-1}	%
Control					0.00	1.58	0.33	0.00	1.91	1010		2.64± 0.15	
$FeCl_2$	1	2:1 Fe: P	250	12	2.92	1.57	0.34	0.00	4.82	2550	88	1.7± 0.27	36
$(FeCl_3)$		5:1 Fe: P		29	7.29	1.60	0.34	0.00	9.23	4870	90	0.2± 0.06	72
		10:1 Fe: P		58	14.59	1.64	0.35	0.00	16.58	8750	99	0.5± 0.02	81
$AlCl_3$	2	0.98:1 Al: P	280	17	4.76	1.58	0.34	0.00	6.67	3520	87	2.06± 0.06	21
(PAC)		1.22:1 Al: P		19	5.23	1.58	0.34	0.00	7.15	3770	92	1.43± 0.02	46
		2.44:1 Al: P		37	10.45	1.61	0.35	0.00	12.41	6550	99	0.16± 0.02	94
Alum	3	0.98:1 Al: P	150	19	2.82	1.60	0.34	0.00	4.76	2520	83	0.51± 0.01	81
		1.22:1 Al: P		24	3.53	1.59	0.34	0.00	5.46	2880	94	0.27± 0.07	90
		2.44:1 Al: P		47	7.07	1.62	0.35	0.00	9.04	4770	99	0.03± 0.0	99
FGD	4	1.33 kg kg^{-1}	14	150	2.03	3.23	0.69	2.14	8.09	4270	72	0.09± 0.0	97
		2.65 kg kg^{-1}		300	4.05	4.90	1.05	4.28	14.28	7540	89	0.05± 0.0	98
		3.5 kg kg^{-1}		400	5.40	5.84	1.26	5.45	17.95	9480	91	0.04± 0.0	99
Flyash	5	2.1 kg kg^{-1}	14	150	2.03	2.50	0.54	1.07	6.13	3240	43	0.92± 0.14	65
		4.2 kg kg^{-1}		300	4.05	3.62	0.78	2.37	10.82	5710	72	0.24± 0.08	91
		5.6 kg kg^{-1}		400	5.40	4.25	0.92	3.09	13.66	7210	81	0.22± 0.04	92
$Ca(OH)_2$	6	1:1 Ca: P	312	2	0.48	1.55	0.33	0.00	2.37	1250	0	2.43± 0.06	9
		5:1 Ca: P		8	2.40	1.56	0.34	0.00	4.30	2270	74	1.52± 0.02	42
		10:1 Ca: P		15	4.81	1.57	0.34	0.00	6.72	3550	81	0.4± 0.0	85
Al-WTR-1	7	0.28 kg kg^{-1}		20	-	-	-	-	-	-	31	2.49± 0.06	6
(<2 mm)		0.69 kg kg^{-1}		50	-	-	-	-	-	-	77	1.73± 0.02	34
		1.4 kg kg^{-1}		100	-	-	-	-	-	-	74	0.93± 0.02	65
Al-WTR-2	8	0.28 kg kg^{-1}	5	63	0.31	1.65	0.35	0.00	2.31	1220	0	1.13± 0.05	57
(sludge)		0.69 kg kg^{-1}		156	0.78	1.88	0.40	0.13	3.20	1690	71	0.28± 0.01	89
		1.4 kg kg^{-1}		313	1.56	2.52	0.54	0.72	5.34	2820	67	0.07± 0.0	97

DRP-dissolved reactive P; WEP-water extractable P; Al-WTR-alum-based water treatment residual; FGD-flue gas desulphurisation product; [a]Calculations based on a dairy farm with 100 cows, or equivalent stocking rate, with a 18-wk winter; [b]Slurry properties: TP = 811 mg L^{-1} and 7.2% DM; [c]Where analytical grade products were used, cost was estimated using the most similar commercial product on the market (in brackets); [d]Cost includes delivery of material and addition of material to slurry in storage tank; [e]Addition of some amendments resulted in DM >10%-water addition needed for spreading.

3.3.5. Water sampling and analysis

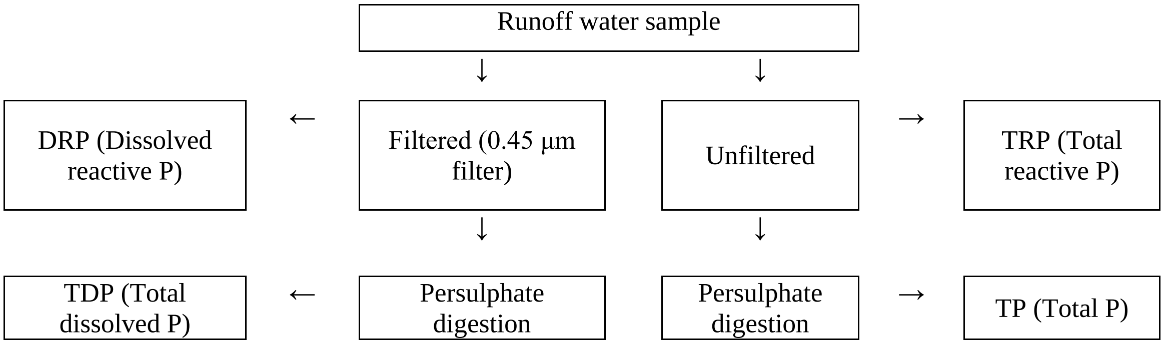
Water samples (4 ml) were taken from mid-depth of the water overlying the soil at 0.25, 0.5, 1, 2, 4, 8, 12 and 24 h after the start of each test (i.e after the 500 ml was added). All samples were filtered immediately after sample collection using 0.45 μm filters and placed in a freezer (APHA, 1995) prior to being analysed colorimetrically for DRP using a nutrient analyser (Konelab 20, Thermo Clinical Labsystems, Finland). The DRP concentrations were used to calculate the mass of DRP in the water overlying the soil samples in the beaker, taking into account the water volume reduction as the test progressed. All water samples were tested in accordance with standard methods (APHA, 1995). Figure 3.4 shows the P classification system used in this study (adapted from APHA).

3.3.6. Statistical Analysis

Proc Mixed (SAS, 2004) was used to model the factorial structures (amendment*application rate; and amendment*application rate*time) in the experiment in order to allow for heterogeneous variance across treatments. A group variable was fitted to allow comparisons between the control treatments and the factorial combinations. A multiple comparisons procedure (Tukey) was used to compare means.

3.3.7. Cost analysis

The cost of chemical amendment was calculated based on the estimated cost of chemical, chemical delivered to farm, addition of chemical to slurry, increases in slurry agitation, and slurry spreading costs as a result of increased volume of slurry due to the addition of the amendments. Slurry spreading costs were estimated based on data from Lalor (2008) and slurry agitating costs were estimated based on data from Anon (2008). The cost of water required to maintain DM at less than 10% was included, as DM must be less than 10% for ease of handling (Stan Lalor *pers com*, 2010). The feasibility of amendments was determined based on effectiveness, rate, potential barriers to use and cost of implementation.



DUP (Dissolved unreactive P) = TDP-DRP

PP (Particulate P) = TP-TDP

Figure 3.4 Phosphorus classification system used in this study (APHA, 1995)

3.4. Results

3.4.1. Results of agitator test

The amendments that were most effective at reducing DRP in overlying water were: $FeCl_2$ (99%), $AlCl_3$ (99%), alum (99%), FGD (91%), flyash (81%), lime (81%), Al-WTR-1 (71%) and Al-WTR-2 (77%). Figure 3.5 shows the mass of DRP in overlying for each treatment at each rate is shown in Figure 3.6. The amendments are ranked in decreasing order of effectiveness in Table 3.3. The irregularity between the 0.69 and 1.4 kg kg^{-1} amendment rates for Al-WTR-1 and Al-WTR-2 treatments were consistent across sieved and sludge treatments. However, this was not statistically significant. The overall statistical analysis showed that there was a significant interaction between treatment and application rate, but that the interaction effects were small compared to the main effects. Optimum application rates were determined based on achieving a similar level of P reduction for each of the amendments, while applying the minimum amount of metals to land, thus reducing risk due to land spreading of metals. Based on this criterion, optimum amendment rates were: $FeCl_2$ (2:1 (Fe:P)), $AlCl_3$ and alum (0.98:1 (Al:P)), FGD (1.33 kg kg^{-1}), flyash (4.2 kg kg^{-1}), lime (5:1 (Ca:P)), Al-WTR-1 and Al-WTR-2 (0.69 kg kg^{-1}).

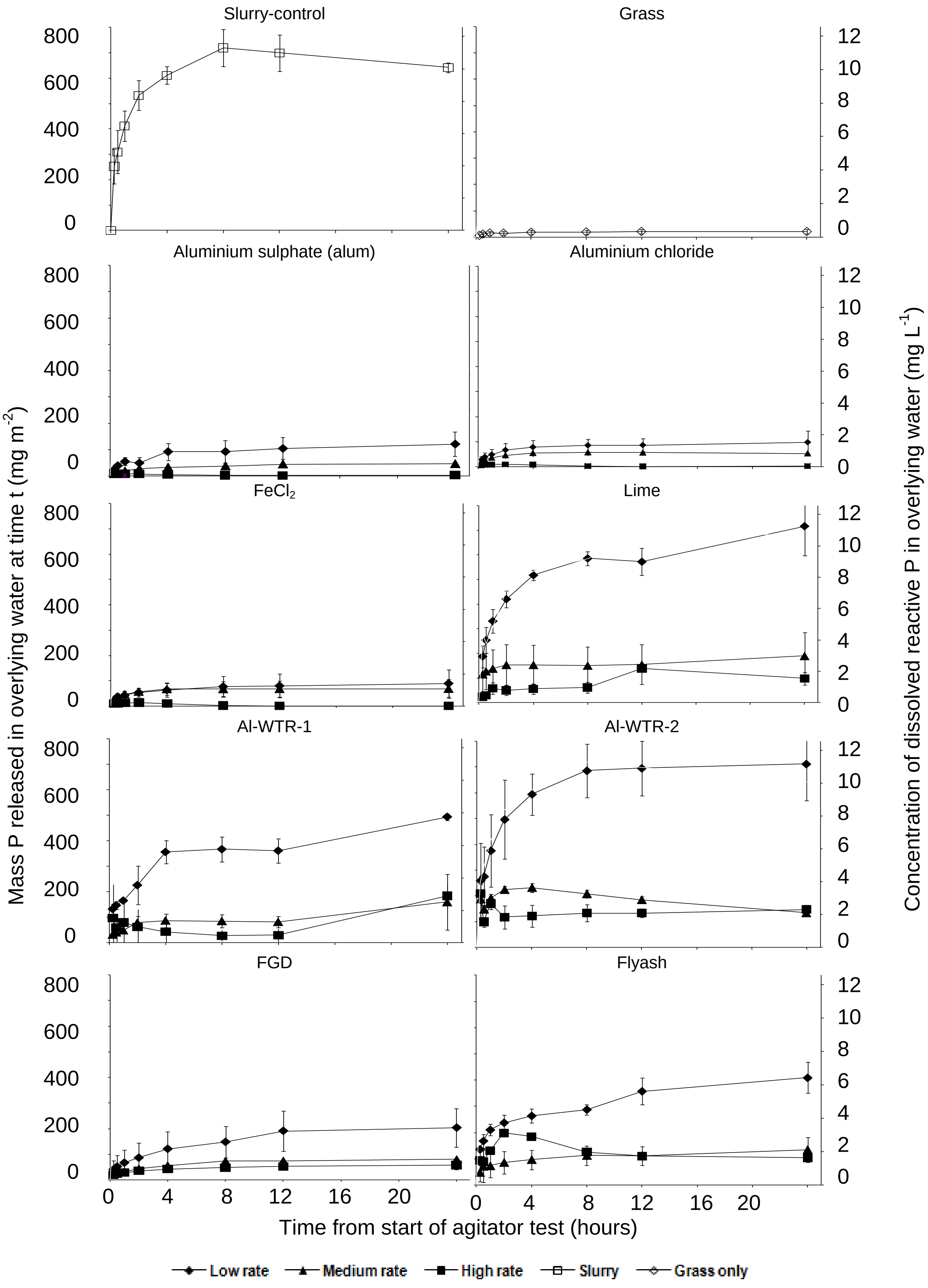


Figure 3.5 Mass of DRP and DRP concentration in overlying water

Linear regression showed a strong relationship between percentage reduction in slurry WEP and DRP in water overlying the soil for alum (R^2=0.95), $AlCl_3$ (R^2=0.99), Al-WTR-2 (R^2=0.94), flyash (R^2=0.96), FGD (R^2=0.83); and a smaller relationship for $FeCl_2$ (R^2=0.60), lime (R^2=0.75) and Al-WTR-1 (R^2=0.67). Only three rates were examined and there were insufficient points to quantify any relationship.

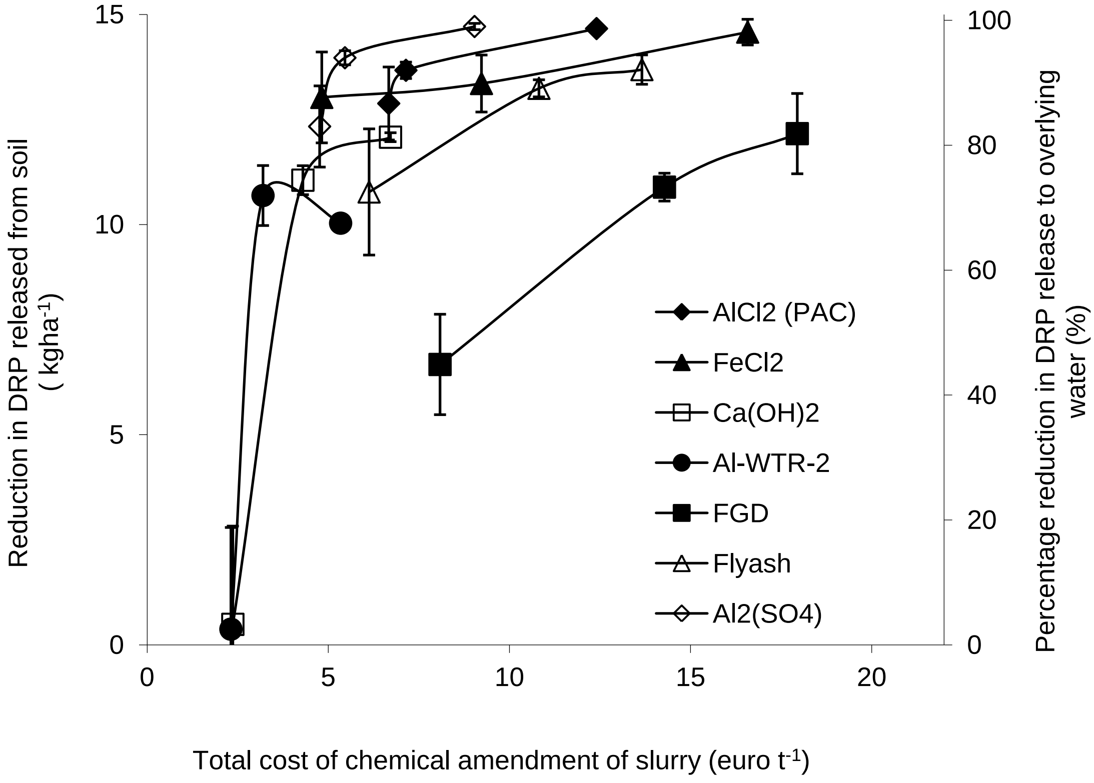


Figure 3.6 Total cost of chemical amendment of dairy cattle slurry plotted against the reduction in dissolved reactive phosphorus (DRP) lost to overlying water and the percentage reduction in DRP release to overlying water

3.4.2. Cost and feasibility analysis

The estimated cost of addition of amendments and increases in spreading and agitation costs due to amendments are presented in Table 3.2. The effects of amendments on slurry viscosity or handling were not considered in the cost analysis. It was assumed that amendments would be added upon delivery, so storage cost on site was excluded from the analysis. For analytical grade products, the cost was estimated using the most similar commercial product available on the market. Starting with the cheapest, the amendments were ranked as follows: Al-WTR-2 (€3.20 m^{-3}); $Ca(OH)_2$ (€4.30 m^{-3}); alum (€4.76 m^{-3}); $FeCl_3$ (€4.82 m^{-3}); poly aluminium chloride (€6.67 m^{-3}); FGD (€8.10 m^{-3}) and flyash (€10.80 m^{-3}).

Table 3.3 Feasibility of amendments

Chemical	Feasibility score	Addition rate	Total cost	Reduction in DRP	Notes
			€ m^{-3}	% P	
Alum	1	0.98:1 Al: P	4.76	83	Risk of effervescence Risk of release of H_2S due to anaerobic conditions and reduced pH Cheap and used widely in water treatment
$AlCl_3$(PAC)	2	0.98:1 Al: P	6.67	87	No risk of effervescence (Smith et al, 2004) $AlCl_3$ increased handling difficulty Expensive
$FeCl_2$($FeCl_3$)	3	2:1 Fe: P	4.82	88	Potential for Fe bonds to break down in anaerobic conditions Potential increased release of N_2O
$Ca(OH)_2$	4	5:1 Ca: P	4.30	74	Risk of increased NH_3 loss Strong odour Hazardous substance
Al-WTR-2 (sludge)	5	0.69 kg/kg	3.20	71	Waste product Risk of release of H_2S Composition varies with location and time Risk of P deficiency if over applied High application rates required Limited supply
FGD	6	1.33 kg/kg	8.10	72	High pH and therefore risk of increased NH_3 loss Strong odour Large application rates required Settles quickly Potentially toxic
Flyash	7	4.2 kg/kg	10.80	72	Contains heavy metals Huge volume of water required Settles quickly Potentially toxic
Al-WTR-1 (<2 mm)	8	0.69 kg/kg	-	77	Excluded from cost analysis

The effect of amendments on slurry pH is a potential barrier to their implementation, as it affects P sorbing ability (Penn et al., 2011) and NH_3 emissions from slurry (Lefcourt and

Meisinger, 2001). Slurry pH results are shown in Figure 3.7.The acidifying additives (alum, $AlCl_3$, $FeCl_2$) lowered the pH of the slurry. Lime and flyash addition increased the pH to 10.3 (p<0.0001) and 9.3 (p<0.0001), respectively. The use of these high pH amendments is likely to result in an increase in NH_3 emissions to the atmosphere from slurry. Risk of increased metal concentrations in overland flow is a significant barrier to the use of these amendments. No analysis of metals in the overlying water was undertaken in this experiment; therefore, feasibility considerations for metal application rates were based on the principal of applying the minimum metals necessary to reduce DRP in the overlying water. In addition, flyash was deemed unsuitable due to high concentrations of heavy metals contained within it.

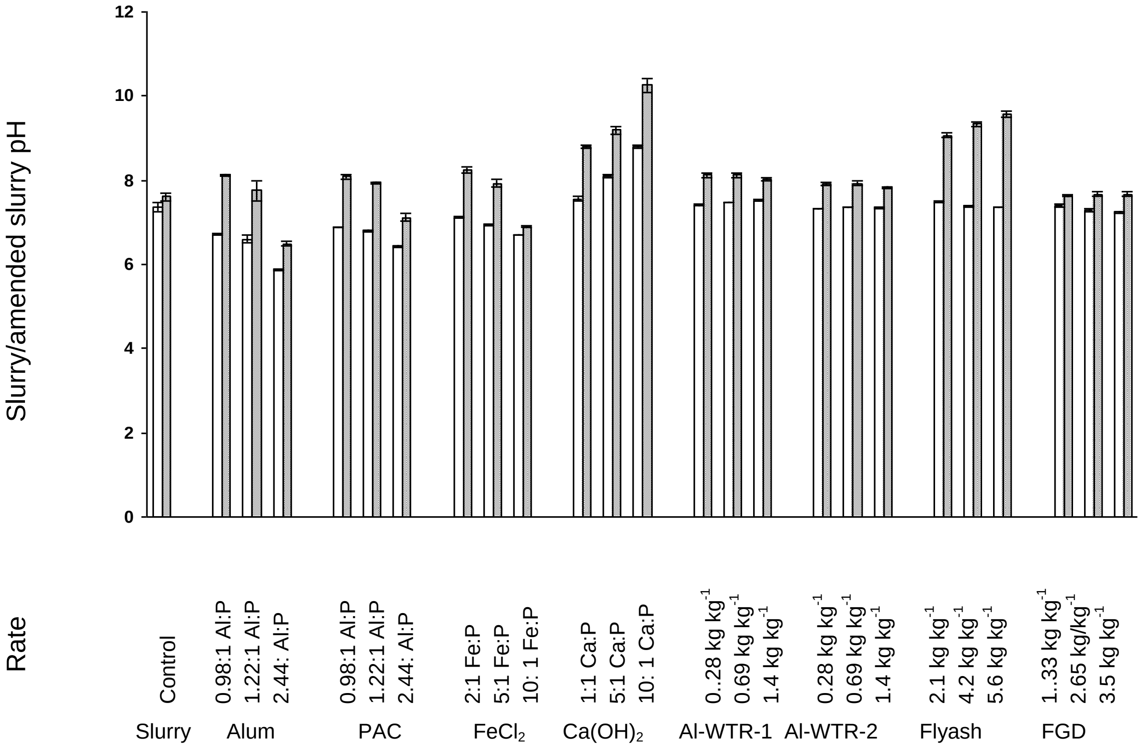


Figure 3.7 Histogram of slurry pH at time of amendment/application (clear box) and pH of slurry after 24 h (hatched box)

3.5. Discussion

Chemical amendment is an attractive means of mitigating against both incidental P losses from slurry and elevated P release from soil resulting from the increase in soil P due to slurry and chemical fertiliser application. It could be used in strategic areas for protection of a waterbody while allowing farmers to utilise other nutrients in slurry on farms with high STP. Ferric chloride, $AlCl_3$ and alum were the most effective amendments at optimum rates. Aluminium water treatment residuals, flyash and FGD are not feasible due to the large application rates needed and the risk of over-application of metals. Although chemical amendments are expensive, they are widely available and more efficient than PSM, and lower metal application rates are required to achieve adequate P reductions at optimum application rates.

The results for $FeCl_2$, $AlCl_3$, alum, and lime were in agreement with other studies. Lefcourt and Meisinger (2001) reported a 97% reduction in DRP of dairy cattle slurry when 2.5% by weight of alum was added in a laboratory batch experiment. The Al-WTR used in the present study was less effective than those observed in other studies. Penn et al. (2011) reported an 80% reduction in WEP of dairy slurry when slurry was amended at a rate equivalent to 0.2 kg kg^{-1} (compared to 71% observed in this study at 0.69 kg kg^{-1}). The results for the coal combustion by-products differed to previous studies. Dou et al. (2003) found that adding flyash to dairy manure at 0.4 kg kg^{-1} (manure DM) lowered soluble P by between 50 and 60% compared to 43% at 2.1 kg kg^{-1} in the present study. Penn et al. (2011) found that FGD was ineffective in treating dairy slurry when applied at 0.2 kg kg^{-1}, which was in contrast to the results of the present study (72% at 1.33 kg kg^{-1}). This difference could be due to the difference in composition of flyash. The mass of P released and DRP of the overlying water at any time for the duration of the experiment are shown in Figure 3.5. Throughout this study, an initial high rate of DRP release was followed by a period of slower release and, after 12 h, an approximate equilibrium DRP concentration was reached with the exception of the highest application rate of Al-WTR and all FGD treatments.

The stability, and thus the effectiveness, of different amendments over longer time spans (months, years) depends on farm management systems, drainage, and soils to which they are applied. For example, Al-P bonds are most stable in acidic soils, while Ca-P bonds are more stable in calcareous conditions (Wild, 1988). The effect of treatment on slurry pH at the time of application affects P sorption capacity of PSM containing Ca compounds, and NH_3 emissions from slurry. Changes in pH may reduce the pathogen load in slurry and subsequently pathogen transport to soil and runoff. Application of Al-WTR and FGD did not significantly change slurry pH. The soil used had optimum STP and only required P inputs sufficient to maintain P levels for future agronomic needs. Slurry amendment type (treatment), rate of amendment addition (rate), and their interaction had an effect on DRP in runoff ($p< 0.0001$; $R^2=0.96$). This strong relationship between slurry WEP and overlying water DRP would suggest that for this particular soil with this STP, soil type and STP had a minimum impact on results; in addition, any effect of STP would be constant across all treatments. Sharpley and Tunney (2000) reported that STP had little impact on the release of P to runoff for up to 14 d after dairy cattle slurry application.

There have been many reports of human and animal deaths from the release of the toxic hydrogen sulphide gas when slurry is being agitated on farms. The addition of chemicals such as alum that can lead to acidification of slurry and are likely to increase the release of toxic hydrogen sulphide gas and great care should be taken when adding acidifying chemicals to slurry on the farm.

Public and stakeholder opinion is the main obstacle for the use of chemical amendments. This study examined the feasibility of the amendments based on effectiveness, optimum rates and cost of treatment. Future work must address public concerns and examine the impact of amendments on gaseous emissions and metal build-up in the soil. If amendments to slurry are to be recommended (and adopted) as a method to prevent P losses in runoff, the impact of such applications on slurry-borne pathogens, as well as pathogen translocation to the soil and release in surface runoff, needs to be addressed. The long-term effects on microbial communities in soil must also be examined.

There is no provision for a licence to landspread any of these amendments in Ireland (lime is land applied in acidic soils to optimise soil pH for production) and if chemical amendment were to be used to mitigate P losses, a licensing system would have to be introduced by the Department of Agriculture in Ireland and relevant bodies in other countries.

3.6. Conclusions

The findings of this chemical amendment study are:

1. All amendments, when added to slurry, greatly reduced WEP of the slurry and DRP in water overlying soil.
2. Even at optimum amendment rates, the cost of slurry treatment increases slurry handling cost (between 250 and 560%) with the exception of Al-WTR, which is unfeasible due to high rates required, concerns over variation in composition, and limited supply.
3. These treatments currently seem to be expensive. However, they may be feasible if used strategically to mitigate P loss from dairy slurry in CSA within a farm, or as an alternative to applying slurry to high P soils.
4. Chemical amendments may have a role to play as part as P mitigation strategy

3.7. Summary

This chapter has determined the most effective amendments at reducing DRP release from land applied slurry to runoff. Chapter 4 details a runoff-box experiment designed to develop an understanding of the performance of chemical amendments under more realistic conditions. In addition to examining DRP, Chapter 4 examines how amendments affect SS, PP and TP losses. Chapter 4 also examines the effect of amendments on incidental loss of metals (Al, Ca and Fe) to runoff.

Chapter 4 Laboratory-scale rainfall simulation experiment

4.1. Overview

The agitator test identified amendments with great potential to reduce P solubility. A runoff box experiment was designed to develop our understanding of the performance of amendments under more realistic conditions.

4.2. Introduction

Chemical amendments of slurry using Al, Fe, or Ca based compounds reduce P solubility in manure (Dao, 1999; Dou et al., 2003; Kalbasi and Karthikeyan, 2004) and reduce P in runoff from plots receiving alum amended poultry litter (Moore and Edwards, 2005) with negligible effect on metal loss (McFarland et al., 2003). Chemical amendments reduce incidental P losses by a combination of the formation of stable metal-phosphorus precipitates (such as Al-P phosphates in the case of alum) and flocculation of the particles in the slurry to form larger particles, which are less prone to erosion (Tchobanoglous et al., 2003). Previous studies have found that there was no risk of increased metal release posed by chemical amendment of poultry litter (Moore et al., 1998), dirty water (McFarland et al., 2003), or horse manure (Edwards et al., 1999).The present study examines for the first time the effect of chemical amendment of dairy cattle slurry on both P and metal (namely Al, Fe and Ca) losses to runoff, whereas most previous studies only examined the effect of amendments on P solubility (Dao, 1999; Dao and Daniel, 2002; Dou et al., 2003).

4.3. Materials and Methods

4.3.1. Soil sample collection and analysis

Intact grassed-soil samples, 70 cm-long by 30 cm-wide by 10 cm deep, were collected from a dairy farm in Athenry, Co. Galway (53°21'N, 8°34' W). A second set of soil samples, taken to a depth of 10 cm below the ground surface from the same location, was air dried at 40 °C for 72 h, crushed to pass a 2 mm sieve, and analysed for Morgan's P (the national test used for the determination of plant available P in Ireland) using Morgan's extracting solution (Morgan, 1941). Soil pH (n=3) was determined using a pH probe and a 2:1 ratio of deionised water-to-soil. Particle size distribution was determined using B.S.1377-2:1990 (BSI, 1990a). Organic content of the soil was determined using the loss of ignition test (B.S.1377-3; BSI, 1990b). The soil was a poorly-drained sandy loam (58% sand, 27% silt, 15% clay) with a Morgan's P of 22±3.9 mg P L^{-1}, a pH of 7.45±0.15 and an OM content of 13±0.1%. The soil had a sandy loam texture, which points to moderate drainage on site. However, medium permeable subsoil limits drainage. Historic applications of organic P from an adjacent commercial-sized piggery have led to high STP in the soil used in this study.

4.3.2. Slurry collection and analysis

Cattle slurry from dairy replacement heifers was taken from a farm (53°18' N, 8°47' W) in County Galway, Republic of Ireland in Winter (February), 2010. The storage tanks were agitated and slurry samples were transported to the laboratory in 10-L drums. Slurry samples were stored at 4°C. Slurry and amended slurry pH was determined using a pH probe (WTW, Germany) and the WEP of slurry was measured at the time of land application after Kleinman et al. (2007). Dry matter content was determined by drying at 105 °C for 16 h. The TP of the dairy cattle slurry was determined after Byrne (1979). Total potassium, TN and TP were carried out colorimetrically using an automatic flow-through unit (Varian Spectra 400 Atomic Absorption instrument). Ammoniacal nitrogen of slurry and amended slurry was extracted from fresh slurry by shaking 10 g of slurry in

200 ml 0.1 M HCl on a peripheral shaker for 1 h and filtering through No 2 Whatman filter paper.

4.3.3. Slurry amendment and runoff set-up

The results of a laboratory micro-scale study (Chapter 3) (Data shown in Appendix C) were used to select chemical amendments to be examined in the present study. In addition to a grassed soil-only treatment, five treatments were examined: (1) slurry-only (the study control) (2) industrial grade liquid alum ($Al_2(SO_4)_3.nH2O$), comprising 8% aluminium oxide (Al_2O_3) applied at a rate of 1.11:1 (Al:TP) (3) industrial grade liquid poly-aluminium chloride hydroxide (PAC) ($Al_n(OH)_mCl_3n\text{-}m$) comprising 10% Al_2O_3 at a rate of 0.93:1 (Al:TP) (4) analytical grade $FeCl_2$ at a rate of 2:1 (Fe:TP), and (5) burnt lime ($Ca(OH)_2$) at a rate of 10:1 (Ca:TP). The rates used were based on the results of Chapter 3.

A batch experiment was also conducted using a range of amendment concentrations to construct a multi-point Langmuir isotherm (McBride, 2000):

$$\frac{P}{x/m} = \frac{1}{ab} + \frac{P}{b} \qquad (4.1)$$

where P is the concentration of P in solution at equilibrium (mg L^{-1}), x/m is the mass of P adsorbed per unit mass of amendments (g kg^{-1}) at P, *a* is a constant related to the binding strength of molecules onto the amendments, and *b* is the theoretical amount of P adsorbed to form a complete monolayer on the surface. This provided an estimate of the maximum adsorption capacity of the amendments (g kg^{-1}). These results are shown in Figure 4.1. The amendments were added at a range of rates to 500 g slurry samples and mixed rapidly for 10 min at 100 rpm using a jar test flocculator. The samples were incubated at 11°C for 24 h. Following incubation, 50 g of slurry/amended slurry was mixed with 250 ml of distilled water. The slurry-water solution was then placed on a reciprocating shaker for 1 h. Samples were centrifuged at 14,000 rpm for 5 min to separate the solids from the solution before being passed through a 0.45 µm filter and the P extract was determined using a Konelab nutrient analyser (Konelab 20, Thermo Clinical Labsystems, Finland).

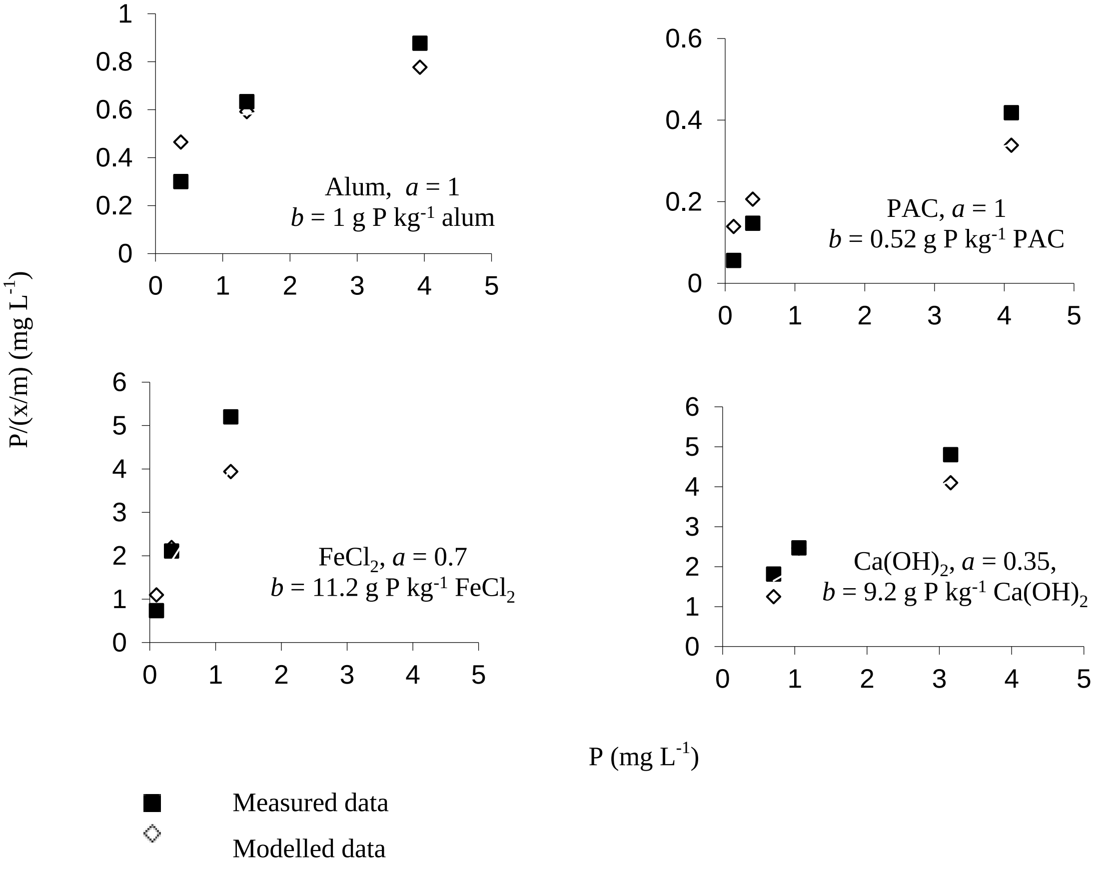


Figure 4.1 Langmuir isotherm fitted to phosphorus in amended slurry data

The equilibrium P concentration (EPC_0) (i.e. the point where no net desorption or sorption occurs) was derived using the following formula (Olsen and Watanabe, 1957):

$$S' = k_d P - S_0 \tag{4.2}$$

where S' is the mass of P adsorbed from slurry (mg kg^{-1}), P is the final P concentration of the solution, k_d is the slope of the relationship between S' and P, and S_0 is the amount of P originally sorbed to the amendment (mg L^{-1}). The EPC_0 was determined graphically (Figure 4.2).

A slurry sample (from the same storage tank as used in the surface runoff experiments) with a DM of 6%, TP of 550 mg L^{-1} and WEP of 2.26 g kg^{-1} was used for the isotherm study. An approximate metal: soluble P ratio for each amendment was calculated using the *b* term from the Langmuir isotherm and WEP of the slurry. The isotherm results indicated that lower application rates should be sufficient to bind P in slurry. However, as the experiment detailed in Chapter 3 was considered to best replicate runoff, it was decided to base the application rates on the results of Chapter 3 and not the batch test used to develop the Langmuir isotherm. As one of the main aims of the present study was to investigate the effect of amendments on metal release, it was considered to be reasonable and conservative to use results from Chapter 3.

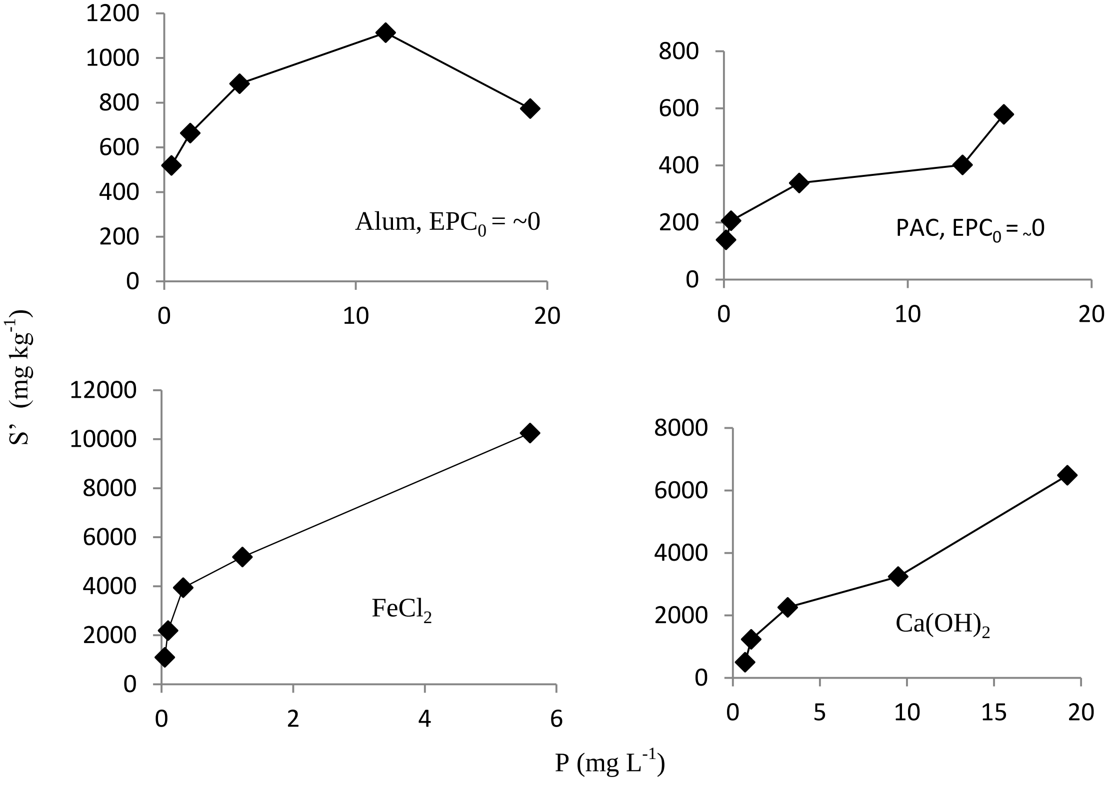


Figure 4.2 Phosphorus sorption isotherms for amended slurry data

A laboratory runoff box study was chosen over a field study as it was less expensive and allowed testing under standardized conditions. Such studies are a widely used tool in P transport research to compare treatments (Hart et al., 2004). This experiment used two laboratory runoff boxes, 200-cm-long by 22.5-cm-wide by 5-cm-deep with side walls 2.5 cm higher than the soil surface, and 0.5-cm-diameter drainage holes located at 30-cm-centres in the base (after Regan et al., 2010). Cheese cloth was placed at the base of each runoff box before placing the sods to prevent soil loss. Intact grassed sods from the study site were transported to the laboratory and stored at 11°C in a cold room prior to testing. All experiments were carried out within 14 d of sample collection and tests were conducted in triplicate (n=3). Immediately prior to the start of each runoff box experiment, new sods were trimmed and placed in the runoff box; each slab was butted against its adjacent slab to form a continuous surface. Molten candle wax was used to seal any gaps between the soil and the sides of the runoff box, while the joint between adjacent soil samples did not require molten wax.

The packed sods were then saturated using a rotating disc, variable-intensity rainfall simulator (after Williams et al., 1998), comprising a single 1/4HH-SS14SQW nozzle (Spraying Systems Co., Wheaton, IL) attached to a 450-cm-high metal frame, and calibrated to achieve an intensity of 11.5±1 mm h^{-1} and a droplet impact energy of 26 kJ cm^{-1} ha^{-1} at 85% uniformity. The sods were then left to drain for 24 h before the experiment commenced; the grassed sods were then assumed to be at an approximate 'field capacity' (Regan et al., 2010). Amendments were added to the slurry and mixed rapidly (10 min at 100 rpm) using a jar test flocculator immediately prior to land application. Slurry and amended slurry were applied directly to the surface of the intact grassed soil in runoff boxes at a rate equivalent to 33 m^3 slurry ha^{-1} (26 kg TP ha^{-1}), the rate most commonly used in Ireland (Coulter and Lalor, 2008). Figure 4.3 shows soil sods before and after slurry application.

During each rainfall simulation event, rain was applied until runoff water flowed continuously and then for 1 h while runoff water samples were collected. The drainage holes on the base of the runoff boxes were sealed to better replicate field conditions and to ensure that overland flow occurred. Figure 4.4 shows the laboratory setup.

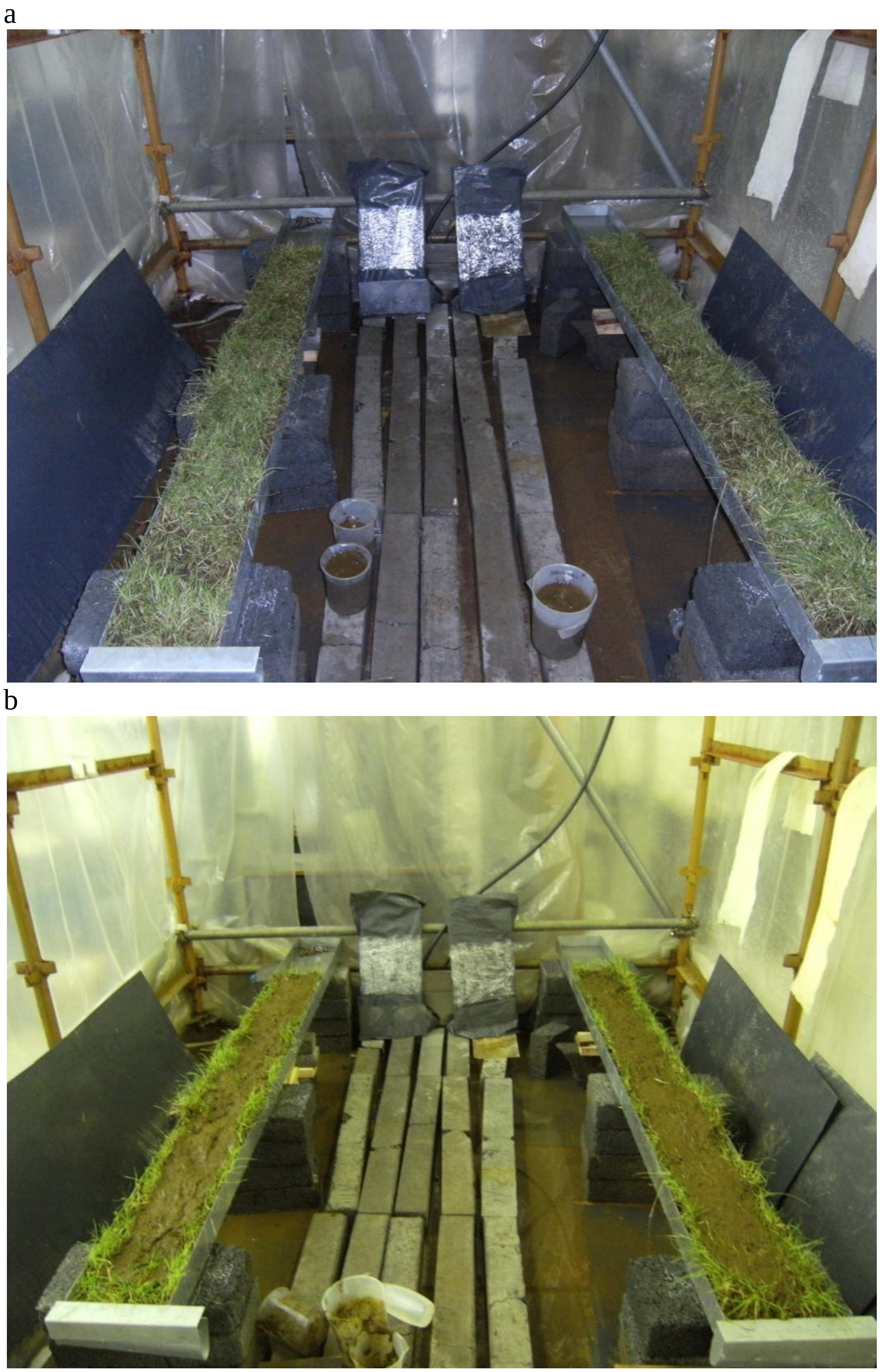


Figure 4.3 Runoff box immediately (a) before and (b) after slurry application

Runoff box cleaned prior to each rainfall simulation

Muslin cloth cut to length to prevent soil loss and aid drainage

Runoff box ready for soil to be placed

Soil sample trimmed immediately prior to placement

Soil samples placed in flume starting at lower end

View of runoff box with one sod

Figure 4.4 Photographs showing soil sod preparation and placement methodology

The first rainfall simulation (RS1) commenced 48 h after slurry application, then after a 1 h interval the second rainfall simulation (RS2) commenced. The drainage holes at the bottom of the runoff box were opened for a 24 h interval and then closed when the third rainfall event (RS3) commenced. As the soil samples were taken from the mid-slope of a field with a slope of approximately 5%, it would have been unrealistic to allow the soil to remain water-logged for 24 h between RS2 and RS3. All of the surface runoff was collected at 5-min intervals once runoff began. The source for the water used in the rainfall simulations had a DRP concentration of less than 0.005 mg L^{-1}, a pH of 7.7±0.2

and an electrical conductivity (EC) of 0.435 dS m^{-1}. Runoff water pH and EC were measured immediately prior to each event using a pH and EC meter.

4.3.4. Sample handling and analysis

Runoff samples were collected in 1 L containers (covered to prevent rain water entering container) at the bottom of the runoff box. Immediately after collection, a subsample of the runoff water was passed through a 0.45µm filter and a sub-sample was analysed colorimetrically for DRP using a nutrient analyser (Konelab 20, Thermo Clinical Labsystems, Finland). A second filtered sub-sample was analysed for TDP using potassium persulfate and sulfuric acid digestion (HACH LANGE, Germany). Unfiltered runoff water samples were also collected and TP was measured using the method used for TDP analysis. Particulate P was calculated by subtracting TDP from TP. The DRP was subtracted from the TDP to give the DUP.

Suspended sediment were determined for all samples by vacuum filtration of well-mixed, unfiltered runoff water through Whatman GF/C (pore size: 1.2 µm) filter paper. All water samples were tested in accordance with standard methods for the examination of water and wastewater (APHA, 1995). In order to address the concern of metal release from amendments, identified by Fenton et al. (2008), it was decided to measure Al, Ca and Fe as these were the active metals in the chemical amendments added to slurry. The metal content was determined using an ICP (inductively coupled plasma) VISTA-MPX (Varian, California). The limit of detection for Al and Fe was 0.01 mg L^{-1} and 1 mg L^{-1} for Ca.

4.3.5. Statistical analysis

The structure of the experiment was a one-way classification with the rainfall events being repeated measures on each experimental unit. Proc Mixed of SAS (2004) was used to analyse the concentrations of DRP, DUP, PP, TP, SS, Al, Ca and Fe with a covariance structure to account for correlations between the repeated measures. An unstructured covariance model was used for most variables and the outcome was interpreted as a factorial of treatment x event. In all cases, the treatment by event interactions were examined. The data for Al and Fe were censored by a limit of detection and PROC NLMIXED of SAS was used to fit a censored Normal-based model while accounting for the correlations by inducing a compound symmetry structure with a random effect.

4.4. Results

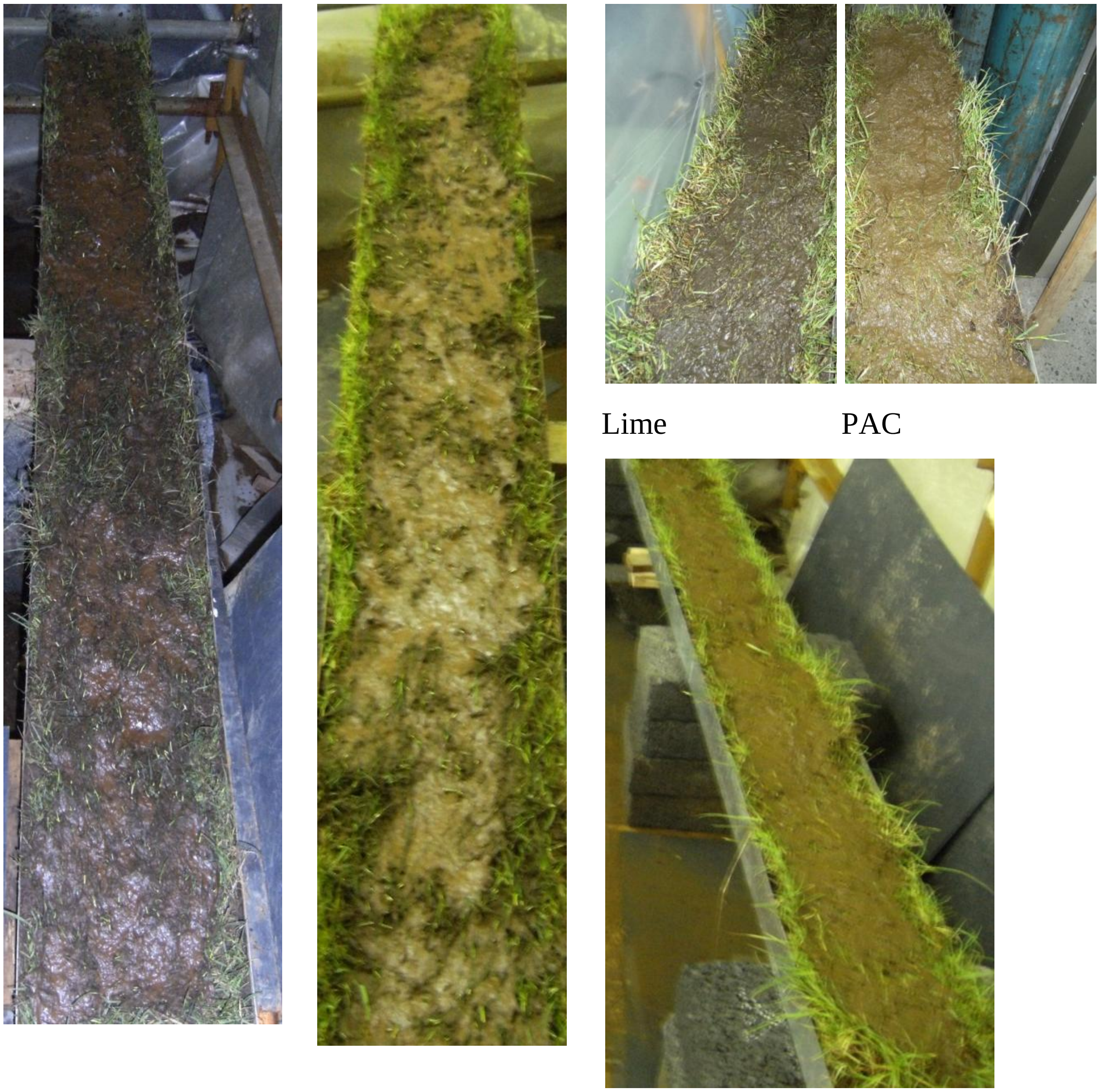
4.4.1. Slurry and amended slurry analysis

The results of the slurry analysis are shown in Table 4.1. The slurry sample was typical of slurry found on farms in Ireland (SI 610 of 2010) with a high DM on the upper limit for land application (Stan Lalor *pers com*, 2011). The slurry TP and TK remained relatively constant. At the rates used in this study, all of the amendments examined reduced the WEP of dairy cattle slurry by approximately 99% compared to the slurry-control ($p<0.001$). Alum addition reduced slurry pH from approximately 7.5 (control) to 5.4, PAC reduced pH to 6.4 and $FeCl_2$ to 6.7 ($p<0.001$), while lime addition increased slurry pH to 12.2 ($p<0.001$). Chemical amendment also changed the appearance of slurry (Figure 4.5)

Table 4.1 Stoichiometric ratio at which the amendments were applied and slurry dry matter (DM), pH and average concentrations of NH_4- N, water extractable phosphorus (WEP), total nitrogen (TN), total phosphorus (TP) and total potassium (TK) (n=3)

	Rate	DM	pH	NH_4-N	WEP	TN	TP	TK
		%		mg L^{-1}	g kg^{-1} DM	mg L^{-1}	mg L^{-1}	mg L^{-1}
Slurry		10.5 (0.04)	7.47 (0.1)	1760 (123)	2.22 (0.34)	4430 (271)	1140 (76)	4480 (218)
Alum	1.1:1 [Al:TP]	9.4 (0.16)	5.40 (0.1)	1770 (21)	0.002 (0.0004)	4570 (176)	1140 (69)	4360 (84)
PAC	0.93 [Al:TP]	9.6 (0.28)	6.37 (0.1)	1760 (143)	0.0013 (0.0003)	4750 (448)	1180 (165)	4680 (448)
Lime	10:1 [Ca:TP]	8.2 (0.29)	12.2 (0.1)	1320 (141)	0.0056 (0.0003)	3190 (263)	1140 (96)	4810 (227)
$FeCl_2$	2:1 [Fe:TP]	10.1 (0.22)	6.7 (0.1)	1700 (11)	0.0022 (0.0006)	4340 (372)	1120 (51)	4720 (386)

(standard deviation in brackets)



Lime PAC

$FeCl_2$ Alum Slurry-control

Figure 4.5 Photographs of slurry and amended slurry immediately after application to grassed soil in boxes

4.4.2. Water quality analysis

The average flow-weighted mean concentrations (FWMC) of DRP, DUP and PP in runoff for the three rainfall events are shown in Figure 4.6. Alum (114 μg DRP L^{-1}) and PAC (89 μg DRP L^{-1}) were more effective at reducing DRP concentration than lime (200 μg DRP L^{-1}) and $FeCl_2$ (200 μg DRP L^{-1}). At the rates used, all of the treatments examined resulted in DRP concentrations in runoff greater than the MAC for surface waters. However, the buffering capacity of water means that the concentration of a surface waterbody will not be as high as the concentration of runoff, provided runoff from slurry flows over soil which has not received dairy cattle slurry (McDowell and Sharpley, 2002b).

The average concentrations of P in runoff water for the 3 rainfall simulation events were 171 µg DRP L^{-1}, 91 µg DUP L^{-1} and 373 µg TP L^{-1} for grassed soil-only treatment compared to 655 µg DRP L^{-1}, 1,290 µg DUP L^{-1} and 8,390 µg TP L^{-1} for the slurry-control. Incidental DRP and TP concentrations in runoff water following land application of dairy cattle slurry were 5 and 14 times greater than those from grassed-soil. In the present study, alum (p<0.001), PAC (p<0.001), lime (p<0.05) and $FeCl_2$ (p<0.05) reduced DRP losses significantly compared to the slurry-control with reductions similar to those observed in Chapter 3. The results of both studies are tabulated in Table 4.2. The average FWMC of TDP was significantly reduced compared to the slurry-control. The difference between grass-only, alum and PAC treatments was not significant and the difference between lime and $FeCl_2$ was also not significant. The average FWMC of DUP was also significantly reduced for all treatments compared to slurry-control.

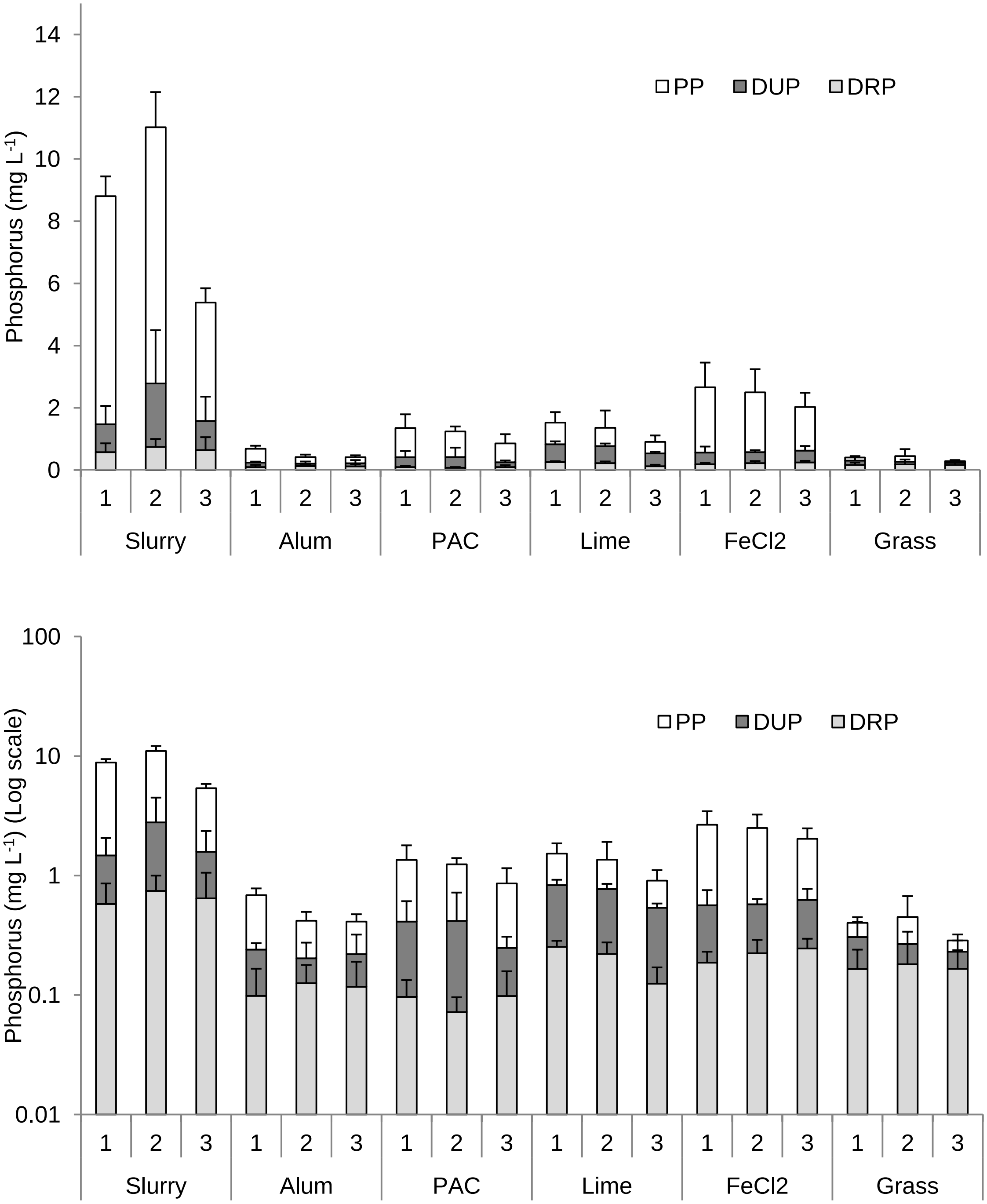


Figure 4.6 The average flow-weighted mean concentration of dissolved reactive phosphorus (DRP), dissolved unreactive phosphorus (DUP) and particulate phosphorus (PP), which comprise total phosphorus (TP) in runoff from three rainfall simulation events.

Table 4.2 Results from Chapter 3 and 4, showing cost of treatments and total phosphorus (TP) lost from runoff box

	Chapter 3 stoichiometric ratio	DRP reduction	Chapter 4 stoichiometric ratio	DRP reduction	Cost per m^3 slurry	TP lost as % TP applied	Cost per kg P reduction	P lost
	metal: TP	%	metal: TP	%	€ m^{-3}		€ kg P^{-1}	kg P ha^{-1}
Slurry	-	-	-	-	1.90	7.70	-	2.90
Alum	0.98:1	87	1.11:1	83	7.40	0.46	66.70	0.17
PAC	0.98:1	88	0.93:1	86	8.80	1.05	91.10	0.40
Lime	5:1	74	10:1	69	10.20	1.16	111.00	0.44
$FeCl_2$	2:1	88	2:1	67	7.00	2.20	61.00	0.19

[a] Taken from Chapter 3.

[b] The cost m^{-3} and cost effectiveness have been updated from Chapter 3 to reflect the slight change in ratio of metal:TP in the present runoff box study.

[c] Laboratory grade aluminium chloride ($Al_2(SO_4)_3.nH_2O$) was used in Chapter 3. Commercially available commercial grade liquid poly-aluminium chloride was used in the present study.

Note: All treatments were found to be significantly different to the control (p<0.001) in the Chapter 3 study. However, these were not significantly different to each other. In this study, all treatments were significantly different to the slurry-control. Alum and $AlCl_3$ were significantly different to lime and $FeCl_2$, but not to each other. (€1.00 is approximately equal to $1.37 or £1.59)

There was no significant difference between TP in runoff water from grass-only (373 μg L^{-1}) and alum treatments (506 μg L^{-1}). However, there was a significant difference between grass-only and PAC (1,150 μg L^{-1}) (p< 0.001), lime (1,270 μg L^{-1}) and $FeCl_2$ (2,400 μg L^{-1}) treatments for TP (p< 0.001), with a less significant difference between grass-only and PAC (790 μg L^{-1}) and Fe (1,730 μg L^{-1}) for PP (p< 0.001). Therefore, alum was the best amendment at reducing TP and PP loss to runoff. Table 4.2 shows the TP lost in the runoff expressed as a percentage of the slurry applied. The TP losses from the control were in agreement with Preedy et al. (2001), who reported that between 6 and 8% of TP applied was lost to runoff. The TP in runoff from the grass-only treatment comprised approximately 47% DRP compared to 69% reported by Haygarth et al. (1998). This difference may be a result of scale effects or differences in experiment design. While chemical amendment of dairy slurry significantly reduced DRP, DUP, PP and TP in runoff water, the proportions of each fraction in runoff from alum, PAC and $FeCl_2$ treatments were similar to the slurry-control (Figure 4.7).

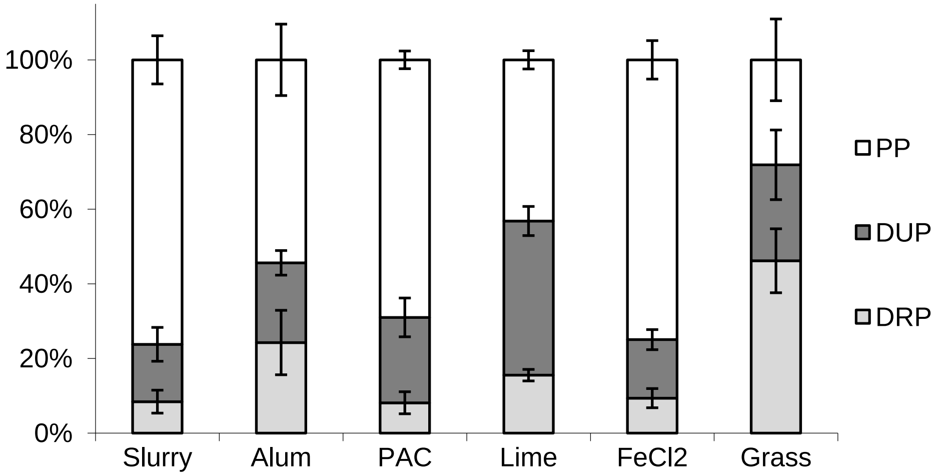


Figure 4.7 The average % of dissolved reactive phosphorus (DRP) dissolved unreactive phosphorus (DUP) and particulate phosphorus (PP), which comprise total phosphorus (TP) in runoff after three rainfall simulation events

Suspended sediment was 162 mg L^{-1} for the grass-only treatment compared to 3,030 mg L^{-1} for the slurry-control (Figure 4.8). Alum resulted in the greatest reduction in SS (an average of 88% for the three rainfall events compared to the slurry-control) (p<0.001). There was no statistical difference in average FWMC of SS between alum, PAC (83% reduction) and lime (82%). All of the treatments resulted in SS concentrations in the runoff which were significantly greater than the grass-only treatment (p<0.005).

4.4.3. Metals in runoff water

The average FWMC of Al, Ca and Fe for the 3 rainfall simulation events are shown in Figures 4.9, 4.10 and 4.11. The average concentrations of metals tested in runoff water for the 3 rainfall simulation events were greater for the slurry-control than the grass-only treatment. Aluminium concentrations increased from 60 to 91 µg Al L^{-1} (not statistically significant), Ca from 84 to 108 mg L^{-1} (p<0.01), and Fe increased from 71 to 151 µg L^{-1} (p=0.02, RS2).

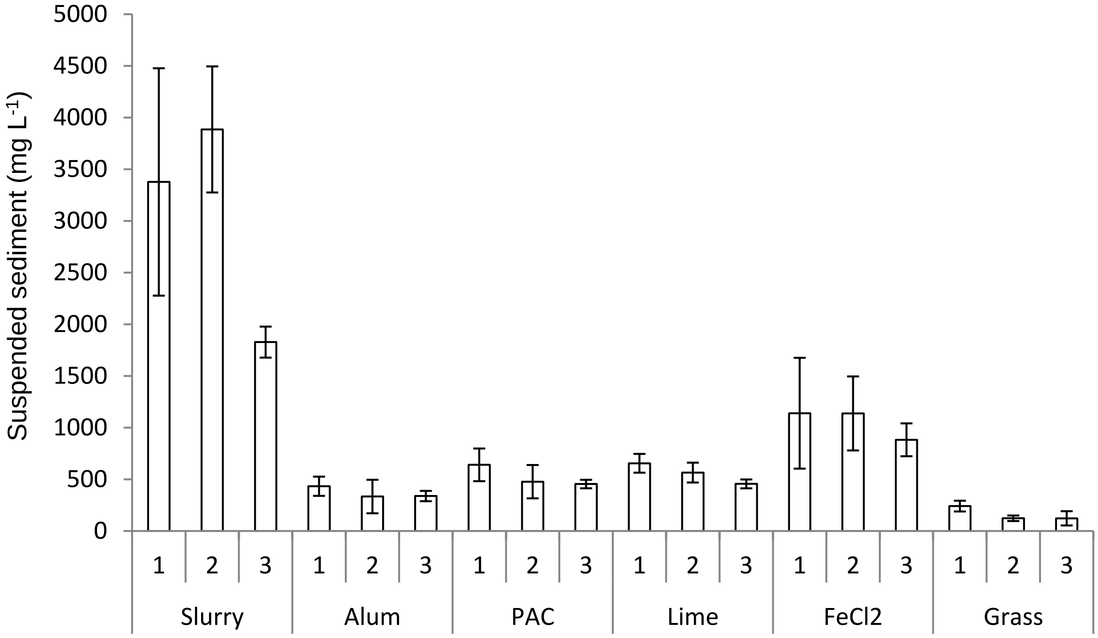


Figure 4.8 Average flow-weighted mean concentrations of suspended sediment in runoff

The FWMC of Al decreased for all treatments compared to the slurry-control (Figure 4.9). There was a significant treatment x event interaction (*p*<0.001) and differences between events within treatments and between treatments within events were tested. After multiple comparison adjustments, there were no statistically significant differences between treatments. There were some significant decreases to the RS3 event compared to RS1 and RS2 for the lime and slurry-control treatments (*p* =0.03 and *p* =0.006)**.** The FWMC of Ca in runoff from all chemically amended slurry treatments was significantly greater than from the slurry-control and the grass-only treatment (*p*<0.01) (Fig. 4.10).

The treatment by event interaction was significant and while no treatments were statistically different across all events, there were some differences between the grass treatment and both alum (*p*=0.02, RS1) and the slurry-control (*p*=0.02, RS2), and also between the $FeCl_2$ and the slurry-control (*p*=0.02, RS2).

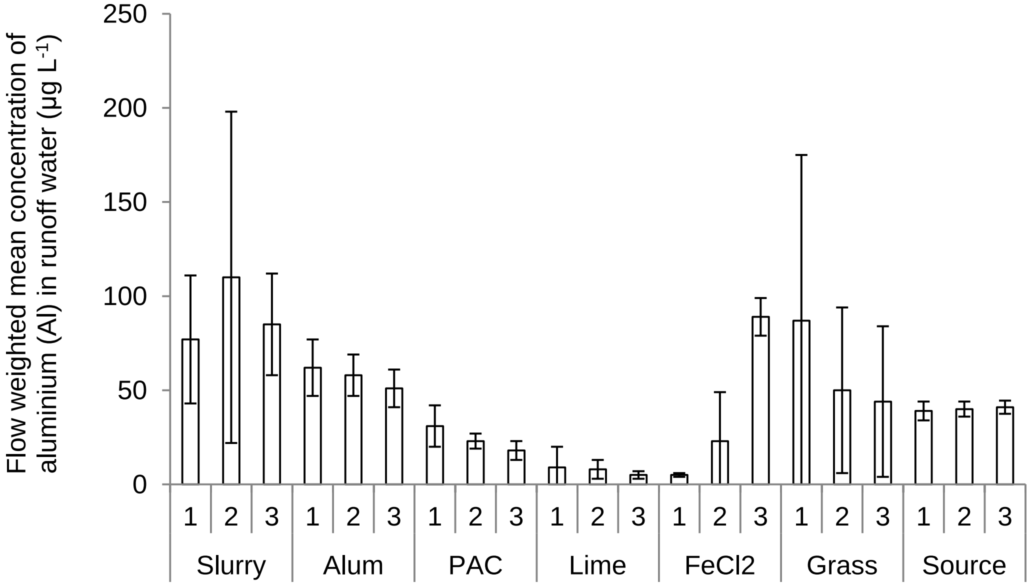


Figure 4.9 Average flow-weighted mean concentrations of Al in runoff and rain water

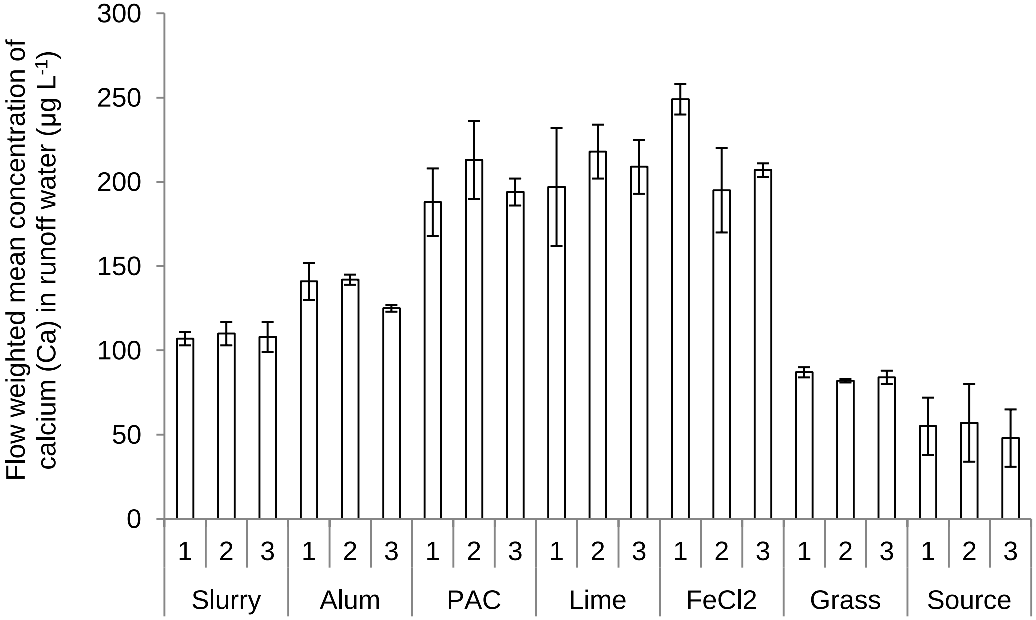


Figure 4.10 Average flow-weighted mean concentrations of Ca in runoff and rain water

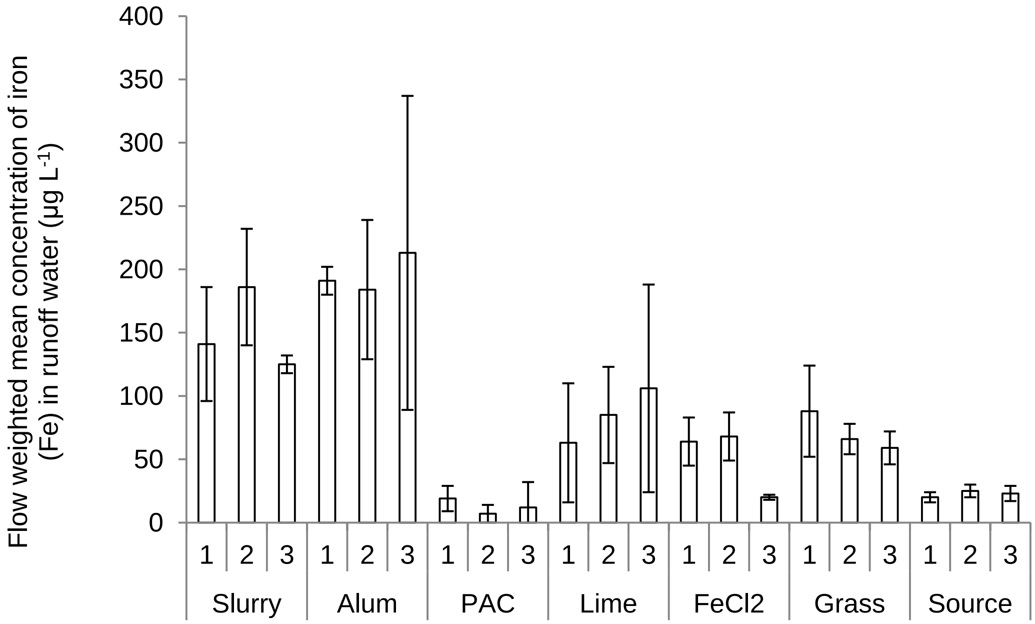


Figure 4.11 Average flow-weighted mean concentrations of Fe in runoff and rain water

4.5. Discussion

4.5.1. Slurry and amended slurry analysis

The amendments examined significantly reduced WEP in amended slurry compared to the control. This was in agreement with previous studies (Dao, 1999; Dou et al., 2003). Lefcourt and Meisinger (2001) reported a 97% reduction in WEP of dairy cattle slurry when 2.5% by weight of alum was added in a laboratory batch experiment. Dao and Daniel (2002) added alum (810 mg Al L^{-1}) and ferric chloride (810 mg Fe L^{-1}) (compared to 1250 mg Al L^{-1} and 2280 mg Fe L^{-1} in this study) to dairy slurry and observed that slurry WEP was reduced by 66 and 18%, respectively. At higher application ratios of metal-to-TP, this study showed that greater reductions in WEP are achievable.

The amendments also changed the pH of the slurry. Lime addition increased slurry pH significantly, resulting in a 25 and 30% reduction in NH_4-N and TN of slurry following amendment and mixing (Table 4.1). This was similar to findings of a study by Molloy and Tunney (1983), who reported an increase in pH to 7.8 and a 50% increase in NH_3 loss when $CaCl_2$ was added to dairy slurry. This loss in NH_4-N was most likely due to NH_3 volatilisation, as depending on the pH of a solution, NH_4-N can occur as NH_3 gas or the ammonium ion (NH_4) (Gay and Knowlton, 2005). This reduces the fertiliser value of the slurry and increases NH_3 emissions from slurry. Addition of alum, PAC and $FeCl_2$ to dairy cattle slurry significantly reduced the pH, as expected. This phenomenon has been reported by a number of studies examining the use of amendments to reduce NH_3 losses from dairy cattle slurry (Meisinger et al., 2001; Shi et al., 2001). Meisinger et al. (2001) reported a 60% reduction in NH_3 loss from dairy cattle slurry when 2.5% by weight of alum was added in a laboratory batch experiment. In a field study, Shi et al. (2001) reported a 92% reduction in NH_3 loss. Moore and Edwards (2005) have shown that chemical amendment improves yields due to increased N efficiency. Chapter 5 examines the impact of amendments on gaseous emissions and the risk of ‘pollution swapping’, which must be considered when evaluating amendments for possible recommendations to legislators.

4.5.2. Water quality

The DRP and TP concentrations in runoff water from grass only treatment was well in excess of the MAC of 30 μg DRP L^{-1} (Flanagan, 1990) and 25-100 μg TP L^{-1} (USEPA, 1986) for fresh waterbodies.

This study reinforced the results of a micro-scale study (Chapter 3) at meso-scale and demonstrated that PAC is the most effective chemical amendment to reduce incidental DRP losses, with alum being most effective at reducing DUP, PP, TP and SS losses arising from land application of dairy cattle slurry. A limited number of runoff studies have been carried out with chemical amendment of dairy cattle slurry (Elliot et al, 2005; Torbert et al., 2005) and swine slurry (Smith et al., 2001a). Torbert et al. (2005) amended landspread composted dairy manure with ferrous sulphate, gypsum and lime (each at 3:1 metal-to-TP ratio) immediately prior to a 40-min rainfall event with overland flow equivalent to a rainfall intensity of 124 mm h^{-1}. Ferrous sulphate reduced DRP loss by

66.3%, while gypsum and lime amendments increased DRP loss compared to control. Lime and gypsum were effective for a short time at the beginning of the event and the authors recommended that lime could be used in areas with infrequent and low volume runoff events. In the Torbert et al. (2005) study, amendments were surface applied to slurry immediately after slurry application and just before the first rainfall simulation event occurred. The differences between the results are likely due to a combination of the shorter contact time with lime before the first rainfall event and less mixing due to different amendment application methods used in each study. In a plot study, Smith et al. (2001a) amended swine manure with alum and $AlCl_3$ at two stoichiometric ratios (0.5:1 and 1:1 Al: TP). Dissolved reactive phosphorus reductions for alum and $AlCl_3$ at the lower ratio were 33 and 45%, respectively, with 84% for both amendments at the higher ratio, which was similar to reductions observed in the current study.

The reductions in P losses in the present study were similar to the percentage reductions obtained in other incidental P loss mitigation studies. Hanrahan et al. (2009) reported that incidental TP and DRP losses were reduced by 89 and 65%, respectively, by delaying rainfall from 2 to 5 d after dairy cattle slurry application. This was in agreement with results of O'Rourke et al. (2010). In a plot study, McDowell and Sharpley (2002b) applied dairy cattle slurry at 75 m^3 ha^{-1} to the upper end of plots with lengths varying from 1 to 10 m. Increasing the distance from the location where dairy slurry was applied to the runoff water collection point was shown to reduce incidental P concentrations in overland flow by between 70 and 90% when plots were subjected to simulated rainfall with an intensity of 70 mm h^{-1}. Therefore, as there are less expensive methods which can achieve similar reductions in incidental P losses, in future the focus of chemical amendment studies must be to find amendments to bind P in soil with the aim of reducing long-term P losses.

In order to minimise the effect of the larger variation in the study control than in runoff from grass-only and amended slurry runoff boxes and to detect differences between treatments, the slurry-control was excluded from the statistical analysis of TP and PP. The reduction in TP and PP losses when alum, PAC and $FeCl_2$ was added to slurry was a result of a combination of precipitation and floc formation, which led to a decrease in SS loss in runoff water. In the case of lime addition, the reductions were a result of the formation of Ca-P precipitates. The average FWMC of TP for the slurry-control during the three rainfall simulation events was 8,390 μg L^{-1}. This was similar to 7,000 μg L^{-1} reported by Preedy et al. (2001) in a rainfall simulation study to examine incidental P loss from dairy slurry.

Measures such as increasing the time between slurry application and the first rainfall event are as effective as chemical amendment at reducing incidental losses of P. Chemical amendment immobilises soluble P in slurry applied to soil and could therefore be included as a low capital cost management tool to reduce farm P status and chronic P losses. The cost of chemical amendments in comparison to other treatment methods (e.g. transporting to other farms, AD, separation and composting) is likely to be the most significant factor in the future implementation of chemical amendments. Economies of scale were not considered in this study and this could considerably reduce costs. The cost of amendment, calculated after results of Chapter 3, based on the estimated cost of chemical, chemical delivered to farm, addition of chemical to slurry, increases in slurry agitation, and slurry spreading costs as a result of increased volume of slurry due to the addition of the amendments to slurry, is shown in Table 4.2. At the scale of the present study, alum and ferric chloride provide the best value in reducing on TP loss from slurry. These are preliminary estimates and if the cost of using these amendments as a mitigation measure is to be accurately calculated, then the optimum dosage for each amendment at field-scale needs to be determined.

4.5.3. Metals in runoff water

Previous studies (Moore et al., 1998; Edwards et al., 1999) have reported that chemical amendment of poultry litter posed no significant risk of increased metal release to runoff water. The findings of the present study also validate this for chemical amendment of dairy cattle slurry. Moore et al. (1998) associated an increase in Ca release from alum treatment to a displacement of Ca in Ca-P bonds by Al. This is also likely to be the cause for PAC and $FeCl_2$ with Ca displaced by Al and Fe. The increase in Ca from the lime treatment was expected as a high rate of lime was applied. The FWMC of Fe (Figure 4.11) decreased for all treatments except alum, which increased Fe loss by 30% compared to the slurry-control; this was most likely a result of pH effect of alum, which increased the Fe solubility leading to higher Fe losses. There are acute (acute concentrations being short-term concentration and chronic being a long-term concentration) MAC (750 $\mu g\ L^{-1}$) and chronic MAC (87 $\mu g\ L^{-1}$) for Al in runoff (USEPA, 2009). The Al concentrations observed in the present study were below all MAC with the exception of slurry-control during RS2 and grass-only treatment in RS2, which exceeded chronic MAC. There is no MAC for Ca in water. Iron concentrations in runoff were all below the chronic MAC of 1,000 $\mu g\ L^{-1}$ (USEPA, 2009).

From previous studies, adverse effects are not expected due to alum amendment to manure. In a plot study, Moore el al. (1998) amended poultry litter with alum to examine the effect of alum amendment on runoff concentrations of metals. Alum treatment significantly reduced Fe in runoff. Runoff Al concentrations were not affected by treatment and Ca concentrations increased after treatment. Moore et al. (2000) also found Al loss from a small-scale catchment was unaffected by alum treatment. In order to determine the effect of long-term additions of alum to poultry litter, Moore and Edwards (2005) began a 20-yr study in 1995. The most significant findings of this study were that long-term land application of alum-amended poultry litter did not acidify soil in the same way as NH_4-N fertilisers and that Al availability was lower from plots receiving alum-treated poultry manure than NH_4-N fertiliser. McFarland et al. (2003) incorporated alum into soil prior to application of dairy dirty water and reported no difference in Al concentrations in runoff between control and alum amended plots.

4.6. Conclusions

The results of this study demonstrate that chemical amendment was very successful in reducing incidental losses of DRP, TP, PP, TDP, DUP and SS from land-applied slurry. The results of the study demonstrate that PAC was the most effective amendment for decreasing DRP losses in runoff following slurry application, while alum was the most effective for TP and PP reduction. Incidental loss of metals (Al, Ca and Fe) from chemically amended dairy cattle slurry was below the MAC for receiving waters. Future research must examine the long-term effect of amendments on P loss to runoff, gaseous emissions, plant availability of P and metal build-up in the soil. If amendments to slurry are to be recommended and adopted as a method to prevent P losses in runoff, the impact of such applications on slurry-borne pathogens, as well as pathogen translocation to the soil and release in surface runoff, needs to be addressed. The long-term effects on microbial communities in soil must also be examined. The results of this study show that even with chemical amendment, P concentration in runoff was above the MAC. Therefore, amendments may not be the best option for minimising incidental P losses, as timing of applications may be just as effective at controlling incidental P losses, and may be much more cost effective. However, chemical amendment immobilises soluble P in slurry and has the potential to reduce chronic P losses. The use of chemical amendments in combination with other mitigation methods such as grass buffer strips would likely increase the effectiveness of the measures. Future work should focus on using amendments to reduce P solubility in slurry to decrease P loss from high P soils by binding P in slurry once it is incorporated into the soil, thereby allowing farmers to apply slurry to soil without further increasing the potential for P loss.

4.7. Summary

The agitator test (Chapter 3) identified amendments with the best ability to reduce P solubility in dairy cattle slurry. Chapter 4 has shown that these amendments can effectively reduce all forms of P in runoff in realistic conditions. The next step is to examine these amendments at field-scale. However, before these amendments are examined at field-scale, there is a need to examine their impact on GHG and potential pollution swapping. Chapter 5 details the results of an experiment designed to examine GHG and pollution swapping. These results allow feasibility discussion (Chapter 3) to be developed further to include GHG and pollution swapping.

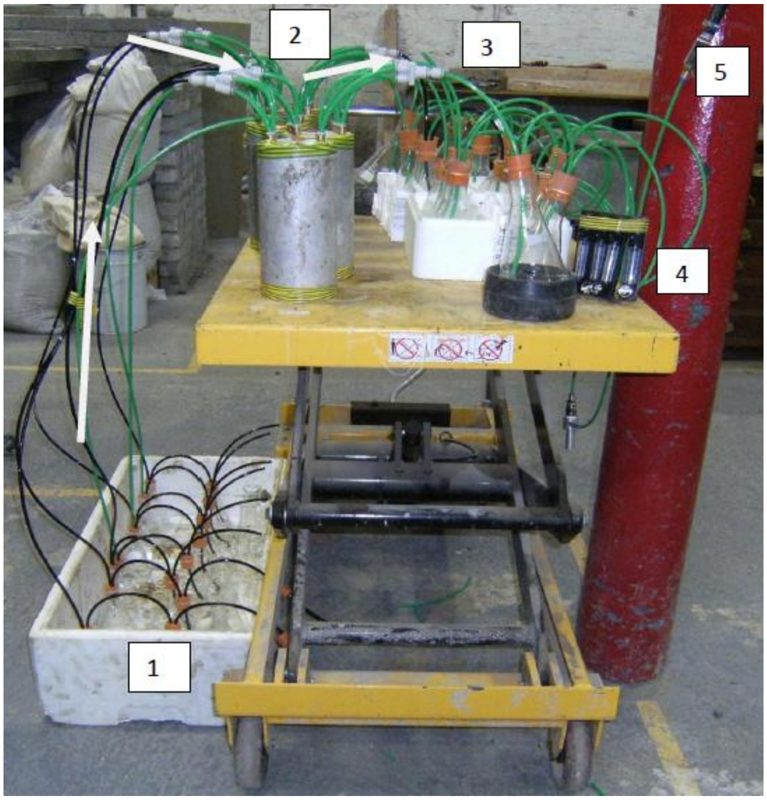
Chapter 5 Effect of chemical amendment of dairy cattle slurry on greenhouse gas and ammonia emissions

5.1. Overview

The previous two chapters examined the effectiveness and feasibility of amendments in reducing P solubility. This chapter considers the effect of chemical amendment of dairy cattle slurry on gaseous losses which, together with their impact on surface runoff, are critical in selecting most feasible amendments for recommendation to legislators.

5.2. Introduction

Organic manure is a valuable fertiliser resource in terms of N, P, K and micronutrients. Losses of N and P to both groundwater and the atmosphere not only act as significant sources of pollution, but can represent significant losses in terms of fertiliser value (Lalor, 2008). Whilst the efficacy of the various slurry amendments on P sequestration efficiency is well quantified (Dao, 1999; Lefcourt and Meisinger, 2001; Dao and Daniel, 2002; Dou et al., 2003; Chapters 2 and 4), there is less information on their effects on gaseous emissions and pollution swapping. This study will allow the feasibility ranking to be further refined to take account of GHG emissions and pollution swapping. An experiment was designed to facilitate the measurement of NH_3, N_2O, CH_4 and CO_2 emission following land application of dairy cattle slurry (Figure 5.1). Charcoal was included as an additional treatment as there is a large body of work involving biochars being carried out at present and there is the potential in their use for P mitigation and GHG control.



1 Air stripped of ammonia before entering dynamic chamber after Misselbrook et al. (2005)

2 Sealed dynamic chambers with air flowing continuously

3 Acid traps used to measure ammonia volatilisation after Misselbrook et al. (2005)

4 Flow meters used to measure and regulate flow throughout the study

5 Pump used to create vacuum to draw air over slurry in dynamic chambers

Figure 5.1 Photograph of dynamic chamber apparatus

5.3. Materials and Methods

5.3.1. Soil sample collection and analysis

Intact soil samples were collected from a dairy farm in Athenry, Co. Galway (53°21’N, 8°34’ W). 120-mm-high, 100-mm-diameter Al coring rings were used to collect undisturbed soil core samples (n=18). Soil samples, taken to a depth of 100 mm below the ground surface from the same location, were air dried at 40°C for 72 h, crushed to pass a 2 mm sieve, and analysed for Morgan’s P using Morgan’s extracting solution (Byrne, 1979). Soil pH (n=3) was determined using a pH probe and a 2:1 ratio of deionised water-to-soil. Soil texture was determined by PSD (B.S.1377-2:1990a). Organic matter content of the soil was determined using the LOI test (B.S.1377-3; BSI, 1990b). The soil was a poorly-drained sandy loam (58% sand, 27% silt, 15% clay) with a Morgan’s P of 22±3.9 mg P L^{-1}, a pH of 7.45±0.15 and an OM content of 13±0.1%.

Historic applications of organic P from an adjacent commercial sized piggery led to high STP in the soil used in this study.

5.3.2. Dairy slurry collection and analysis

Cattle slurry from dairy replacement heifers was taken from a dairy farm (53°21’ N, 8°34’ W) in County Galway, Republic of Ireland. Before sample collection, the storage tanks were agitated. Samples were transported to the laboratory in 10-L drums and stored at 4°C. Slurry and amended slurry pH was determined using a pH probe (WTW, Germany) and the WEP of slurry was measured at the time of land application after Kleinman et al. (2007). The TP of the dairy cattle slurry was determined after Byrne (1979). Potassium and Mg were analyzed using a Varian Spectra 400 Atomic Absorption instrument and analyses for N and P were carried out colorimetrically using an automatic flow-through unit. Ammoniacal nitrogen of slurry and amended slurry was extracted from fresh slurry by shaking 10g of slurry in 200 ml 0.1 M hydrochloric acid (HCl) on a peripheral shaker for 1 h and filtering through a No 2 Whatman filter paper.

5.3.3. Chemical amendment of slurry

The six treatments examined in this study, selected based on results of Chapter 3 and 4, were: slurry-only (the study control) and slurry amended with (1) industrial grade alum (8% Al_2O_3, $Al_2(SO_4)_3.nH_2O$) (2) industrial grade PAC (3) analytical grade $FeCl_2$ (4) lime ($Ca(OH)_2$) and (5) charcoal. With the exception of charcoal (analytical grade activated charcoal used as biochar can vary depending on material from which it is made), the amendments were applied at the following stoichiometric rates determined from Chapter 3: alum 1.11:1 (Al: TP); PAC 0.93:1 (Al:TP); $FeCl_2$ 2:1 (Fe:TP); and lime 10:1 (Ca: TP). Charcoal was applied at a rate equivalent to 3.96 m^3 ha^{-1}. This corresponded to a rate above which DM of slurry would become too high to allow landspreading without adding water (Stan Lalor *pers com*, 2010). The amendments were added to the slurry and mixed rapidly using a blender immediately before simulated land application. A grass only background was also examined but values measured were very low compared to emissions from slurry treated soil cores so these were excluded. Slurry and amended slurry were applied directly to the surface of the intact grassed soil at a rate equivalent to 26 kg TP ha^{-1} (33 m^{3} slurry ha^{-1}). Immediately after application, the chambers were sealed and the air flow through the system was started and maintained for 168 h.

5.3.4. Measurement of ammonia

The dynamic chamber used in this experiment was based on a design used by Misselbrook et al. (2005). Eight chambers were connected in parallel (Figure 5.2). Air was drawn through the system via a vacuum pump, with air flow through each chamber regulated at 5.1 L min^{-1}. This was to ensure that the number of headspace exchanges per minute was such that the emission of NH_3 would not be affected by small differences in flow rates between chambers (Kissel et al., 1977).

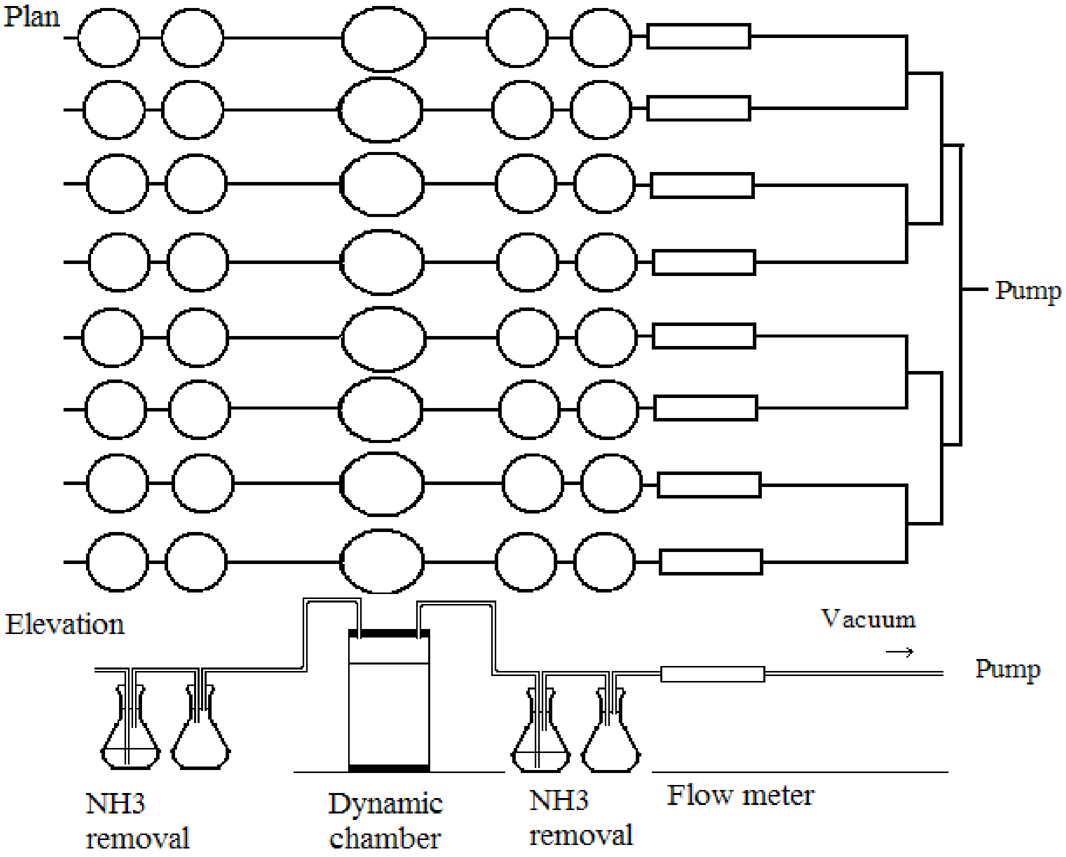


Figure 5.2 Diagram of apparatus used to measure ammonia emissions

Prior to entering each chamber, the ammonia contained in the ambient air was immobilised using an acid trapping method. The air was drawn over the soil surface using a vacuum pump (VTE 10 VACCUM PUMP, Irish Pneumatic Service LTD, Ireland) and gas mass flow meters were used to regulate and measure air flow (Cole-Parmer, Hanwell, UK).

The chambers comprised the same 200-mm-diameter Al cores used to collect the grassed soil samples, fitted with a polypropylene lid and base (Figure 5.3). The samples were saturated for 48 h and then allowed to drain for 48 h. During this time, the surfaces were covered to avoid evaporation losses. After approximate field capacity was achieved, the chambers were sealed at the base using silicon grease to ensure an air-tight seal. Each treatment was applied to the grassed-soil surface and a lid was fitted to each chamber. Each chamber had four inlet and outlet ports to ensure good mixing of air within the chamber (after Misselbrook et al., 2005). During the dynamic phase, the cores were attached to the dynamic chamber for 168 h. During this time, air was drawn through the chambers over the surface of the treated soil and through acid traps, which were used to measure NH_3.

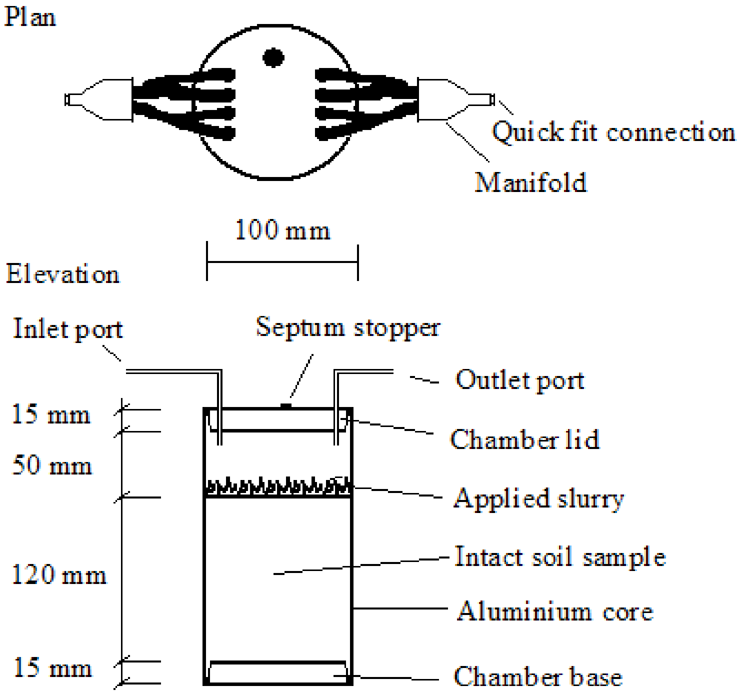


Figure 5.3 Dynamic chamber

5.3.5. Measurement of CH_4, N_2O and CO_2

Air samples were drawn from the head space of the ammonia volatilisation chamber (AVC) and analysed for CH_4, CO_2 and N_2O using a photo-acoustic-analyser (PAA; INNOVA 1412, Lumasense Inc, Denmark) (Figure 5.4). The majority of NH_3 volatilisation arising from spreading of slurry occurs in initial 48 h after spreading (Gary Lanigan *pers com*, 2011), while N_2O and CH_4 losses take place over a much longer time period (Gary Lanigan *pers com*, 2011). Therefore, it was only necessary to use the AVC for the first 168 h and then continue CH_4, CO_2 and N_2O sampling for a further 10 d. During the first 168 h (during which time NH_3 was measured), the chamber was disconnected from the AVC apparatus and the inlet and outlets were connected to the PAA for 6 min at t= -1 (1 h before treatment), 0, 2, 6, 24, 48, 72, 96, 144, 168. After 168 h, NH_3 measurement was discontinued and the Al cores, containing intact soil samples, were removed from the apparatus and incubated in the laboratory. During this time, a portable cap was fitted to each chamber and the PAA was used to measure fluxes at t = 9, 11, 13, 15 and 17 d. The mass of the sample, and therefore water content, was kept constant throughout the experiment by periodically adding deionised water to the surface of the soil samples.

5.3.6. Statistical analysis

Data (Appendix D) were checked for normality and homogeneneity of variance by histograms, qq plots, and formal statistical tests as part of PROC UNIVARIATE procedure of SAS (SAS, 2004). The data were analysed using the PROC GLM procedure (SAS, 2004). The linear model included the fixed effects of treatment and, with the exception of slurry pH, CH_4 and CO_2, data were logarithmically transformed prior to analysis. A multiple comparisons procedure (Tukey) was used to compare means.

Figure 5.4 Photograph of PAA during carbon dioxide, methane and nitrous oxide measuring period

5.4. Results

5.4.1. Slurry and amended slurry results

The slurry had TN of 4430±271 mg L^{-1}, TP of 1140±76 mg L^{-1}, TK of 4480±218 mg L^{-1} and a pH of 7.5±0.05. The slurry TP and TK remained relatively constant, while the WEP was lowered significantly by all chemical amendments (Table 5.1). Alum, $FeCl_2$ and PAC addition reduced slurry pH from approximately 7.5 to 5.4, 6.7, and 6.4, respectively ($p<0.005$). The pH of alum-amended slurry was significantly different to all other treatments, while $FeCl_2$ and PAC were not significantly different to each other. Addition of lime increased slurry pH to 12.2 ($p<0.001$), while charcoal did not have a significant effect on slurry pH.

Table 5.1 Dairy cattle slurry and amended dairy cattle slurry properties

Treatment	DM (%)	pH	WEP (g/kg DM)
Slurry-control	10.5 (0.04)	7.5 (0.05)	1.81 (0.112)
Alum	9.4 (0.16)	5.4 (0.12)	0.008 (0.002)
Lime	8.2 (0.29)	12.2 (0.12)	0.014 (0.001)
$FeCl_2$	10.1 (0.22)	6.7 (0.06)	0.017 (0.001)
PAC	9.6 (0.28)	6.4 (0.05)	0.011 (0.002)
Charcoal	12.57 (0.45)	7.3 (0.4)	1.78 (0.23)

(Standard deviation in brackets)

5.4.2. Ammonia

Alum ($p<0.001$), $FeCl_2$ ($p<0.005$), PAC ($p<0.005$) and charcoal ($p<0.01$) reduced NH_3 emissions by 92, 54, 65 and 77% compared to the slurry-control, while lime increased emissions by 114% ($p<0.001$). Lime amendment resulted in the loss of 84% of TAN applied. Alum, PAC, $FeCl_2$ and char were not statistically different to each other. The NH_3 emissions from untreated and chemically amended slurry, expressed as a percentage of TN and NH_4-N in the applied slurry, are shown in Figure 5.5.

Ammonia release from slurry for all treatments followed a Michaelis-Menten response curve, with the majority of emissions occurring within the first six hours following application. With the exception of the lime treatment, chemical amendment of slurry prior to land application increased the time for half of ammonia losses to occur ($T_{0.5}$). Alum ($p<0.005$), $FeCl_2$ ($p<0.05$), PAC ($p<0.006$) and charcoal ($p<0.05$) increased $T_{0.5}$, compared to the slurry-control, from 1.5 to 4.1, 3.5, 4.3 and 3.4 h, respectively ($p<0.05$). The $T_{0.5}$ of lime-amended slurry was not significantly different to the slurry-control. Cumulative ammonia release from untreated slurry was 40% of TAN.

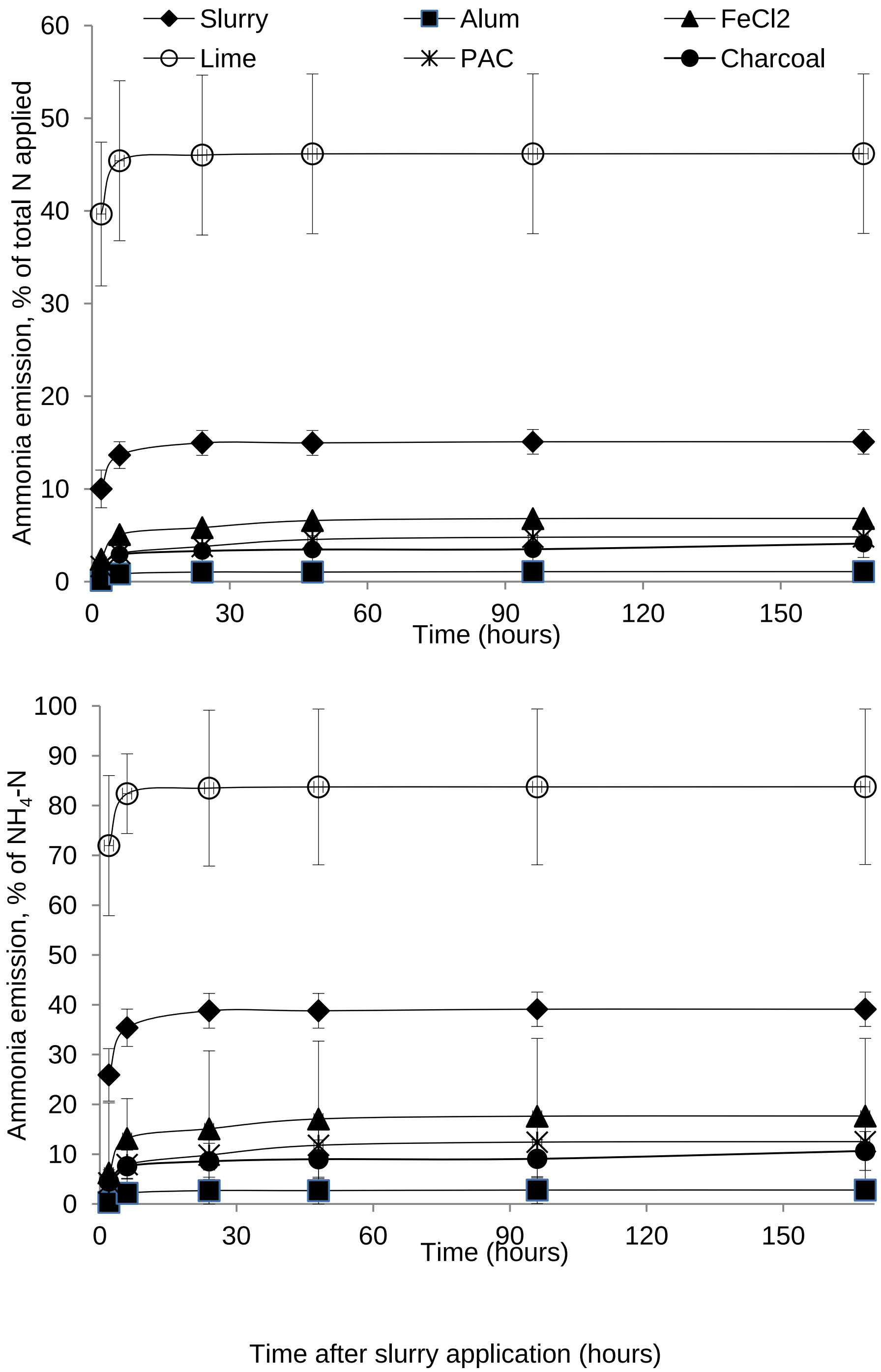


Figure 5.5 Cumulative ammonia emissions from untreated and chemically amended slurry expressed as a percentage of total nitrogen in slurry and ammoniacal nitrogen in slurry

5.4.3. Nitrous oxide

Cumulative N_2O emissions of dairy cattle slurry increased when amended with alum ($p<0.2$) and $FeCl_2$ ($p<0.2$) by 202 and 154 % compared to the slurry-control. Lime ($p<0.5$), PAC ($p<0.01$) and charcoal ($p<0.01$) resulted in a reduction of 44, 29 and 63% in cumulative direct N_2O loss compared to the slurry-control.

In this study, nitrous oxide emissions following land application of dairy cattle slurry were observed to increase from 0.18 g N_2O-N ha^{-1} h^{-1} to a peak of 4 g N_2O-N ha^{-1} h^{-1} at 24 h post application (Figure 5.6). Emissions of N_2O from alum were similar in magnitude and temporal dynamics to those from the slurry-control. Ferric chloride addition resulted in no increase in N_2O emissions until the 72 h sampling event, and a peak flux of 4.7 g N_2O-N ha^{-1} h^{-1} was measured at 96 h. Lime, PAC and charcoal addition resulted in much lower emissions, with peak emissions occurring after 24-48 h.

5.4.4. Carbon dioxide

In general, addition of amendments to slurry did not significantly affect soil CO_2 release during the study (Figure 5.7), with cumulative emissions for the period ranging from 320 – 380 kg CO_2 ha^{-1} (Figure 5.8). However, significant reductions in CO_2 efflux were observed upon charcoal addition, with an 84% reduction in cumulative CO_2 emissions observed ($p<0.05$).

Immediately following land application of dairy cattle slurry and chemically amended slurry, there was generally a peak in CO_2 emissions followed by a steady release for the duration of the study. The lime amended slurry behaved differently to the other treatments and the slurry-control, and acted as a CO_2 sink immediately after land application. However, the cumulative emissions were similar to PAC and $FeCl_2$ treated slurry.

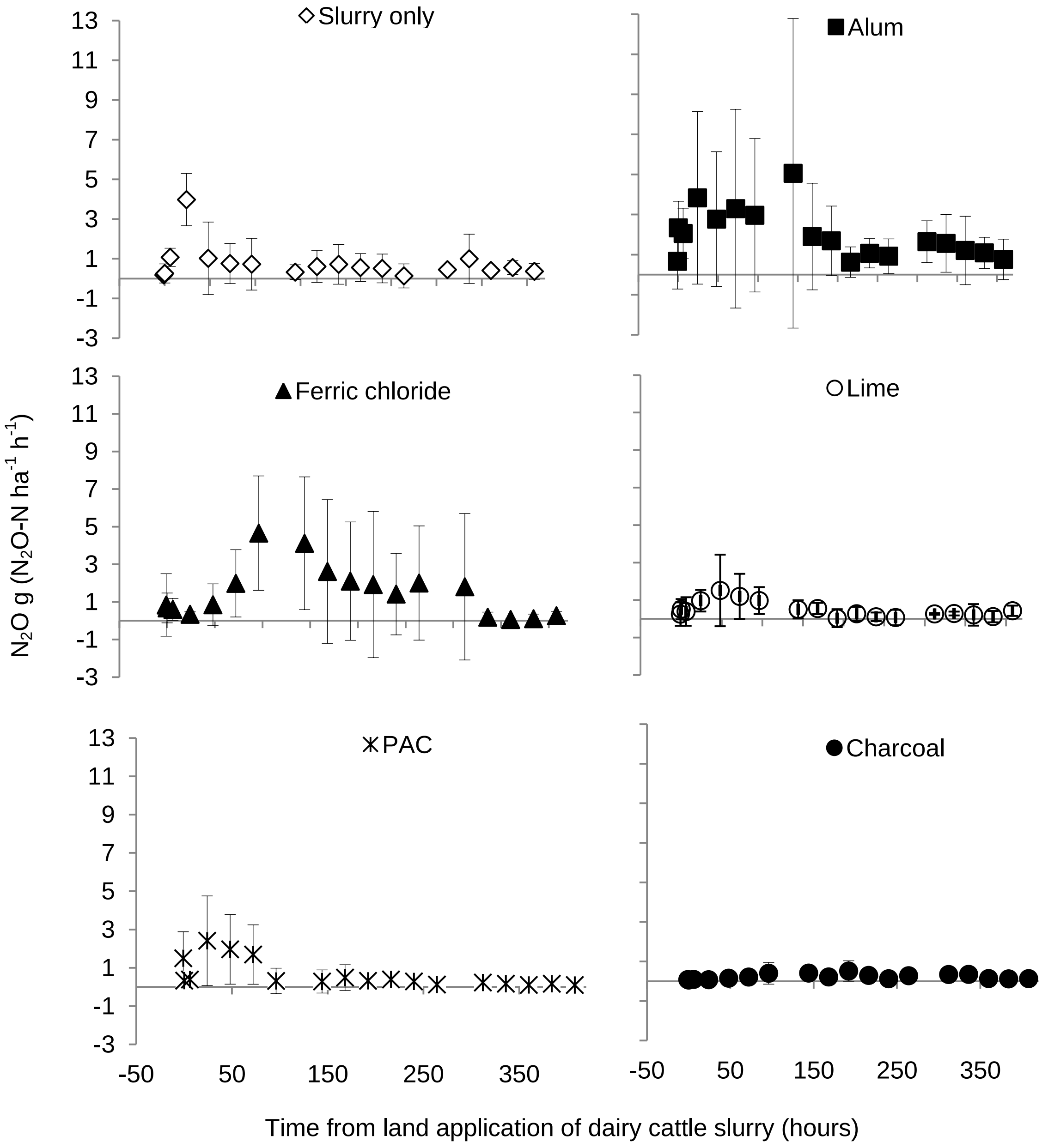


Figure 5.6 Nitrous oxide emissions from slurry and amended slurry in chambers (Mean ± standard error)

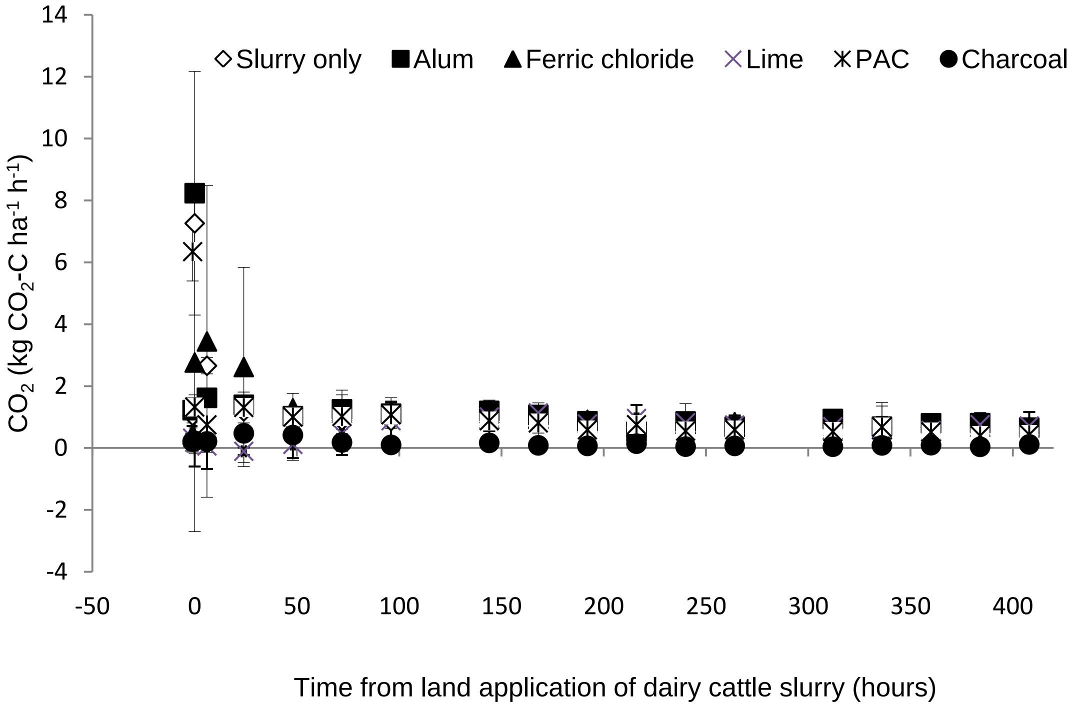


Figure 5.7 Carbon dioxide emissions from slurry and amended slurry in chambers. (Mean ± standard error)

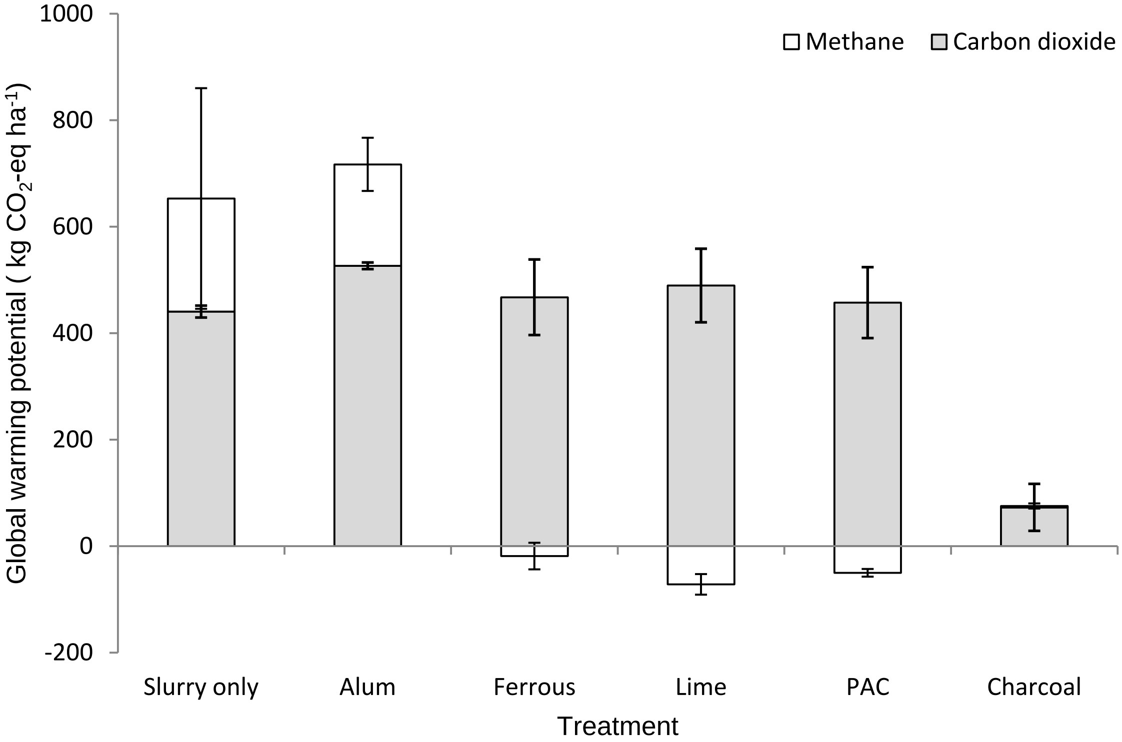


Figure 5.8 Cumulative carbon dioxide emissions from chambers for duration of study. (Mean ± standard error)

5.4.5. Methane emissions

Methane emissions increased from -0.18 g CH_4-C ha^{-1} h^{-1} to 94 g CH_4-C ha^{-1} h^{-1} upon application of dairy cattle slurry (Figure 5.9). These levels decreased rapidly to approximately 7 g CH_4-C ha^{-1} h^{-1} by 48 h and remained relatively constant until the 312 h sampling event. Following this, methane losses were much more variable. There was a similar trend for all of the amended slurries applied with an initial increase in losses followed by a rapid decrease and then steady release for the duration of the study. All of the amendments examined reduced the initial peak in CH_4 emissions compared to the slurry-control ($p<0.0001$). Lime ($p<0.05$), PAC ($p<0.08$) and $FeCl_2$ ($p<0.09$) reduced cumulative CH_4 emissions compared to the slurry-control by 134, 121 and 99%, respectively. Alum, charcoal and the slurry-control were not significantly different to each other.

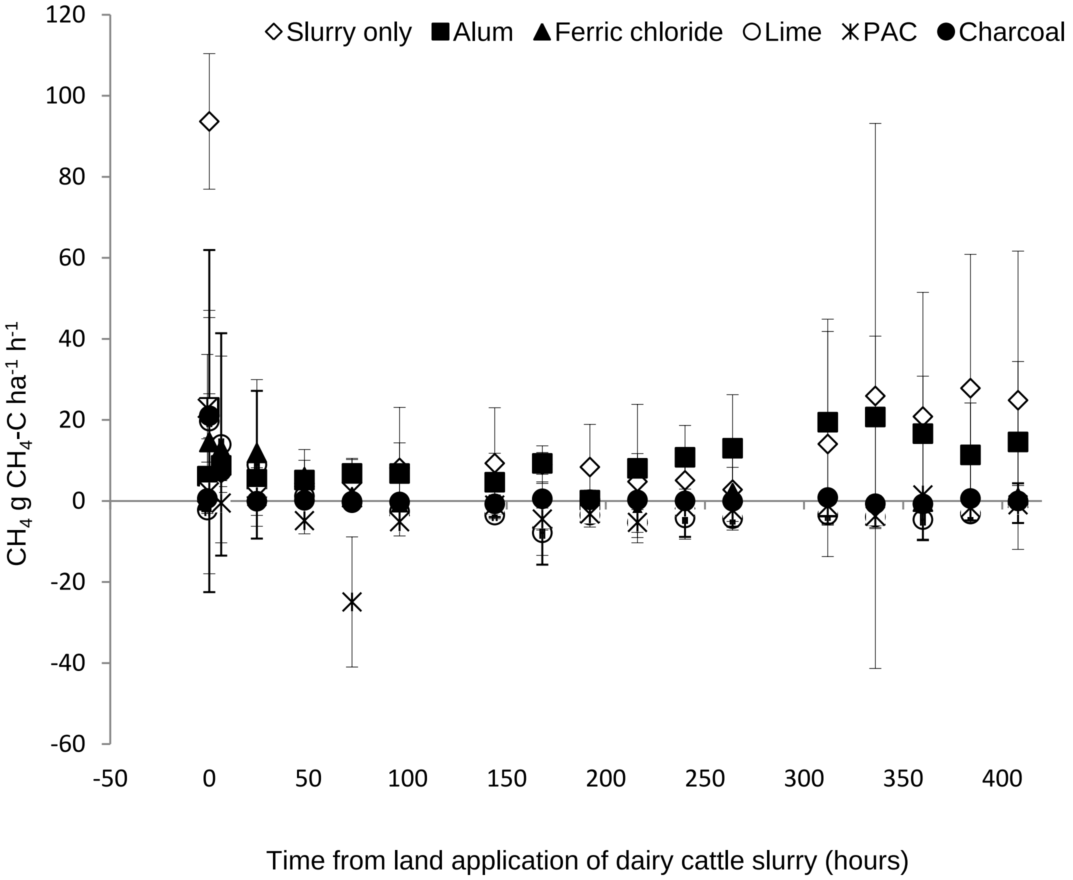


Figure 5.9 Methane emissions from slurry and amended slurry in chambers. (Mean ± standard error)

5.4.6. Impact of amendments on global warming potential

Chemical amendment of dairy cattle slurry has been proposed as a possible P mitigation measure for the control of P solubility in dairy cattle slurry (Chapters 3 and 4). In order to access the pollution swapping potential of the treatments, all emissions were expressed in CO_2 equivalents. Cumulative direct and indirect N_2O emissions from slurry and amended slurry in the chambers during the study are shown in Figure 5.10.

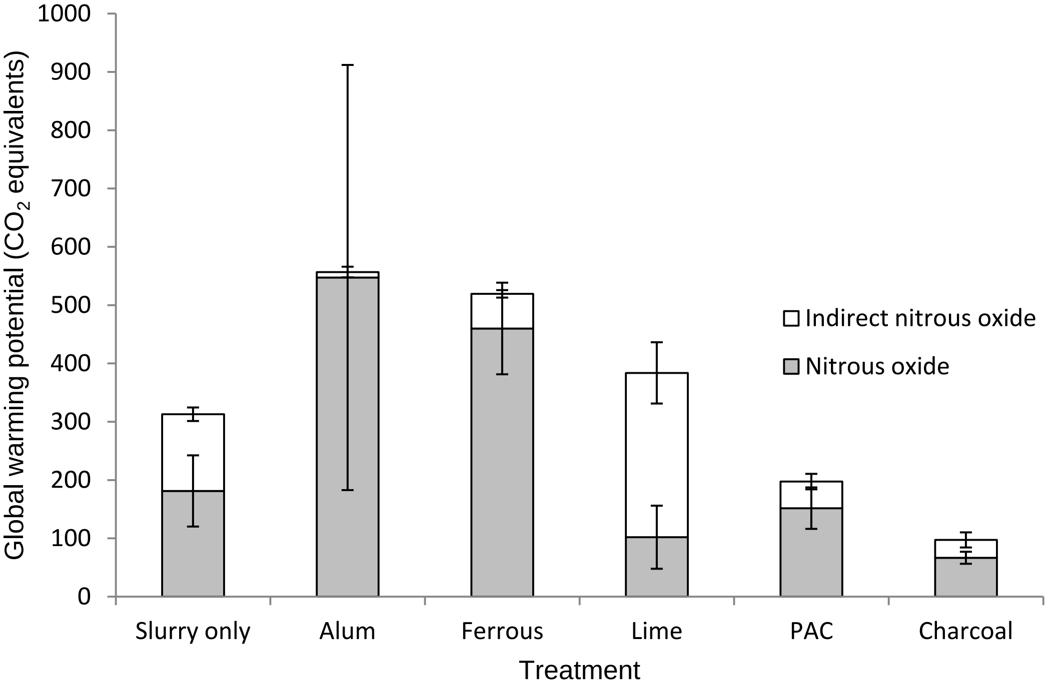


Figure 5.10 Nitrogen cumulative emissions (Nitrous oxide and indirect emissions resulting from ammonia losses) expressed in CO_2 equivalents**.** (Mean ± standard error)

Indirect N_2O emissions were calculated based on the assumption that all the NH_3 would be re-deposited within a 2 km radius of the point of application, which allowed use of an emission factor of 1% (IPCC, 2006). Alum, $FeCl_2$, lime and PAC have no significant effect on the sum of the cumulative direct and indirect N_2O emissions, while charcoal reduced total N_2O emissions from by 69% compared to the slurry-control ($p<0.01$). The total N_2O emissions from charcoal treated slurry – with the exception of PAC - were statistically different to slurry ($p<0.01$), alum ($p<0.01$), $FeCl_2$ ($p<0.001$), lime ($p<0.001$) treatments. Cumulative carbon dioxide and methane emissions are shown in Figure 5.8. Charcoal reduced total cumulative CO_2 and CH_4 emissions compared to the control ($p<0.001$) and was significantly different to alum ($p<0.001$), $FeCl_2$ ($p<0.05$), lime ($p<0.01$) and PAC ($p<0.05$). All gases measured have been expressed in CO_2 equivalents and are plotted in Figure 5.11. Amendment of slurry with charcoal significantly reduces greenhouse warming potential (GWP) following land application of dairy cattle slurry ($p<0.001$). In this study, there was no significant effect of any amendment of slurry on GWP caused by land application of dairy cattle slurry, with the exception of charcoal.

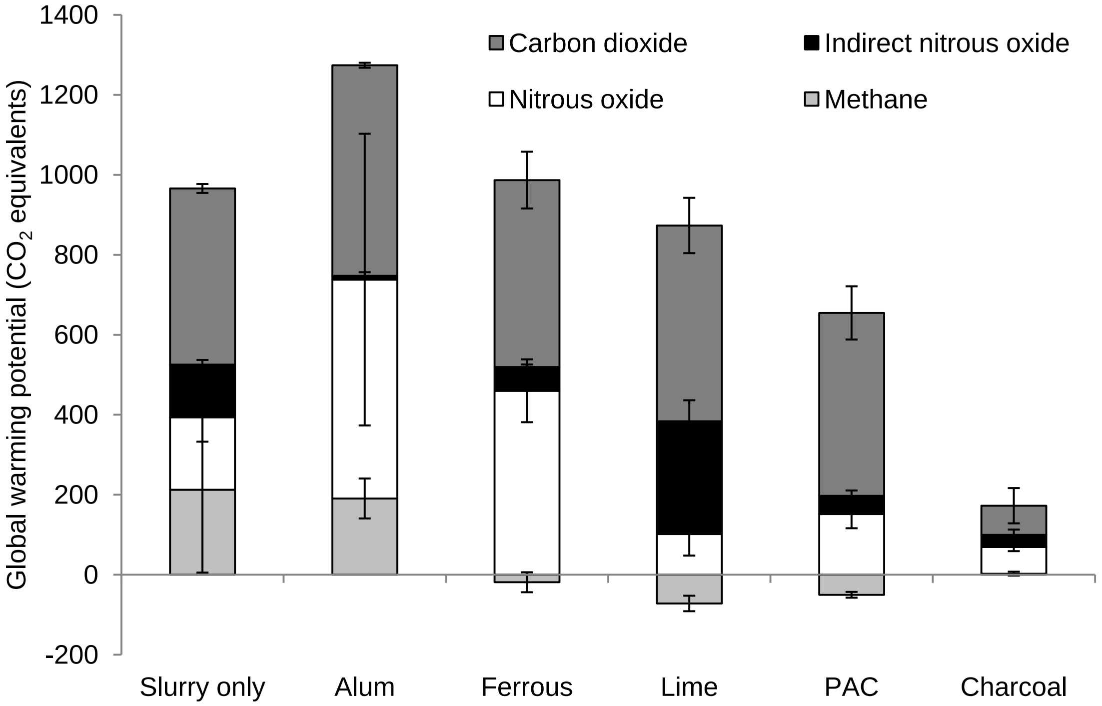


Figure 5.11 Cumulative carbon dioxide (CO_2), indirect nitrous oxide (N_2O), direct N_2O and methane (CH_4) measured during the study expressed in CO_2 equivalents. (Mean ± standard error)

5.5. Discussion

5.5.1. Ammonia emissions

Ammonia volatilisation from dairy cattle slurry following land application is controlled by: humidity, temperature, wind speed at the time, method of application, and the degree of infiltration of the slurry into the soil (Søgaard et al., 2002, Sommer et al., 2003, Sommer et al., 2006). In addition, slurry pH, DM and TAN content greatly influence the rate and amount of NH_3 volatilisation (Smith et al., 2000; Misselbrook et al., 2000; Meisinger et al., 2001). It is estimated that between 60-80% of TAN applied can be lost during broadcast land spreading of cattle slurry, particularly during the first 12 h post application (Pain et al., 1989, Hyde et al., 2003). In the present study, cumulative NH_3 loss from land applied dairy cattle slurry was 22.6 kg NH_3-N ha^{-1}, with approximately 39% of NH_4-N applied lost in initial 24 h; this was equivalent to 15% of TN applied.

With the exception of lime, all amendments used reduced NH_3 losses compared to the slurry-control. This reduction was expected as chemical amendments, such as alum, have been used extensively in the USA to reduce NH_3 emissions from poultry litter (Moore et al., 1999) and from dairy cattle slurry (Table 5.2). Meisinger et al. (2001) reported a 60% reduction in NH_3 loss from dairy cattle slurry when 2.5% by weight of alum was added in a laboratory batch experiment. In a field study, Shi et al. (2001) reported a 92% reduction in NH_3 loss. The results of the present study were in agreement with previous findings for alum, PAC and $FeCl_2$, and the ammonia abatement by alum, PAC and $FeCl_2$ was primarily due to reductions in pH (ie. N was held in the ammonium form).

The large reductions in ammonia emissions associated with charcoal addition (74%) may have been due to both ammonia gas and ammonium ion adsorption, as biochar can act as a cation exchange medium (Asada et al., 2002). During pyrolysis of woody material for biochar production, thermolysis of lignin and cellulose occurs, exposing acidic functional groups, such as carboxyl groups. This has been shown to result in an 80-100% removal efficiency for ammonia gas (Oya and Iu, 2002; Iyobe et al., 2004). Biochar addition during the composting of poultry litter reduced ammonia losses by 64%, even though pH increased (Steiner et al., 2010). As a result, the mechanism was thought to be due to the adsorption of ammonium ions as opposed to the immobilization of ammonia (Steiner et al., 2008). In addition, biochar has also been found to reduce N leaching by 15% due to adsorption of the ammonium ion predominantly by cation exchange (Ding et al., 2011).

Table 5.2. Summary of amendments used to reduce ammonia emissions in previous studies

Reference	Chemical	Amount added to slurry	Slurry type	Study type	% NH_3 reduction	pH slurry	Comments
Meisinger et al. (2001)	alum	2.5% (w/w)	Dairy	Lab	60	4.5	Simulated storage experiment
	zeolite	6.25% (w)			55	7.8	
Kai et al. (2007)	H_2SO_4	5 kg m^{-3}	Swine	Field	70	6.3	Farm scale storage and application
Smith et al. (2001a)	Alum	0.75% (v/v)	Swine	Plot	52		6-week study
Molloy and Tunney, (1983)	$FeSO_4$	0.8 g to 25 g	Dairy	Batch	81		Batch scale experiment
	$MgCl_2$	0.8 g to 25 g			23		
	$CaCl_2$	0.8 g to 25 g			50	7.8	
Shi et al. (2001)	Alum	4500 kg ha^{-1}	Dairy	Field	92	5.98[a]	Applied to surface of feedlot
	$CaCl_2$	4500 kg ha^{-1}			71	6.99[a]	
Husted et al. (1991)	HCL	240 m Eq	Dairy		90		
	$CaCl_2$	300 m Eq		Lab	15		

[a] pH referred to is the pH of soil and slurry mixture

Lime increased slurry pH to 12.2 and increased the NH_3 loss compared to the slurry-control. Molloy and Tunney (1983) reported an increase in pH to 7.8 and a 50% decrease in NH_3 loss when $CaCl_2$ was added to dairy cattle slurry. This suggests that, although there may be potential to reduce NH_3 loss using Ca-compounds such as lime, it is not feasible at application rates high enough to reduce P solubility in dairy cattle slurry. There was a linear relationship between slurry pH at time of application and NH_3 loss from slurry and amended slurry in this study (R^2=0.86) (Figure 5.12). This would indicate that the change in slurry pH was the main process responsible for the reduction in NH_3 loss from dairy cattle slurry. In addition, there was a significant relationship (R^2=0.98) between slurry pH at the time of application and the log of the $T_{0.5}$ (Figure 5.12). This would indicate that if large NH_3 losses do not occur in the short-term after land spreading, the potential for loss is significantly reduced i.e. chemical treatments are not just delaying NH_3 loss, but mitigating it completely.

In addition to environmental problems caused by NH_3 losses, such losses reduce the nutrient value of the fertiliser and increase NH_3 emissions from slurry. The value of N lost via ammonia and N_2O emissions from the slurry-control for the duration of the study amounted to approximately €0.63 per m^3 slurry applied based on cost of €1.10 per kg N (Stan Lalor *pers com*, 2011). Alum, $FeCl_2$, PAC and charcoal increased the fertiliser value of slurry by €0.56, €0.32, €0.41 and €0.48 per m^3 of slurry compared to the slurry-control.

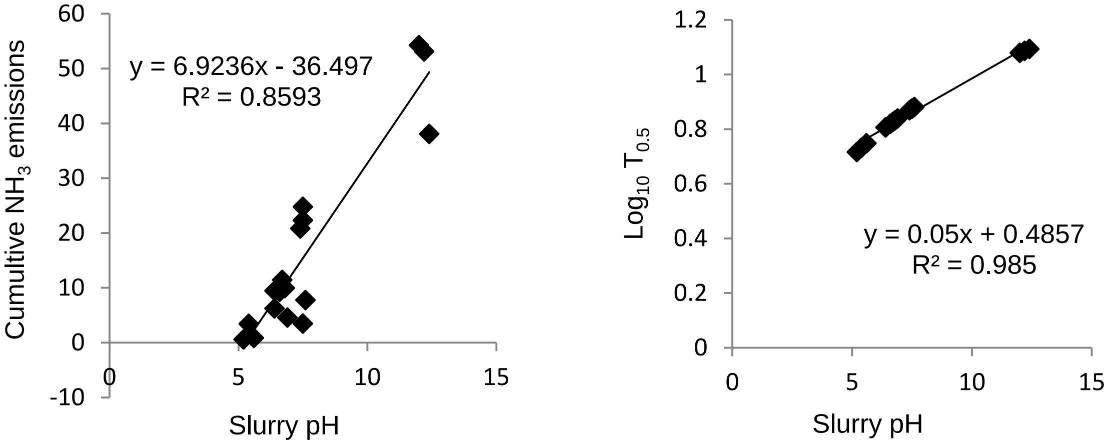


Figure 5.12 Relationship between slurry and amended slurry pH at time of application and (a) cumulative NH_3 emissions and (b) and log of time for half of ammonia emissions to occur ($T_{0.5}$)

5.5.2. Nitrous oxide

Land application of agricultural wastes results in an increase in N_2O emissions from soil (Velthof and Oenema, 1997). Nitrous oxide is of environmental importance as it contributes to global warming and the depletion of the ozone layer. It is produced by nitrification and denitrification processes. Nitrous oxide emissions are influenced by: soil moisture status, soil temperature; soil nitrate content and organic carbon content (Velthof et al., 2002). It was hypothesised that any reduction in NH_3 loss would result in a concomitant increase in N_2O in soil due to higher soil N available for nitrification/denitrification. Alum amendments were shown to double cumulative N_2O losses compared to the slurry only treatment, whilst lime addition resulted in a decrease in N_2O emissions. Although N_2O emissions of the treatments examined were not significantly different to the control, alum and charcoal were significantly different to each other ($p<0.01$). The low direct N_2O losses associated with lime addition were merely due to the fact that most of the available mineral N had been already lost during volatilisation. Ammonia volatilisation can also lead to indirect N_2O emissions as the majority of ammonia volatilised in the field is re-deposited within 2 – 5km *via* wet and dry deposition, and a proportion (1%) is re-emitted as N_2O (IPCC, 2006). When these indirect losses were calculated, lime addition accounted for an increase in indirect N_2O emissions from 283 g N_2O ha^{-1} for the slurry-control to 606 g N_2O ha^{-1}. These results highlight the need to account for all gaseous N losses as an analysis of ammonia or N_2O in isolation would give skewed results.

In terms of abating total N emissions, biochar was the most effective amendment reducing total N_2O losses by 63%. There is currently sparse information on the effect of biochar on N_2O emissions. Some laboratory studies have indicated that biochar may reduce N_2O by increasing soil aeration and hence reduce water-filled pore space (Yanai et al., 2007). Alternatively, if pH is increased upon charcoal addition, this may induce a shift towards total de-nitrification to N_2, thus reducing N_2O (Clough and Condron, 2010).

5.5.3. Carbon emissions

The majority of amendments had little effect on soil CO_2 respiration, demonstrating that the amendments neither stimulated nor retarded soil microbial processes. The reduction in CO_2 emissions associated with charcoal was surprising considering that a C source was added. Previous studies on charcoal application to organic manures have shown an increase in C emissions in the short-term (Steiner et al., 2010), while biochar addition to soils have also indicated a simulation of soil microbial respiration (Wardle et al. 2008).

After land application, CH_4 emissions are of minor importance compared to NH_3 and N_2O emissions (Wulf et al., 2002a, b). Methane is produced mainly by microbial decomposition of OM under anaerobic conditions. The highest efflux was for untreated slurry and alum, immediately post manure application would indicate CH_4 formation during manure storage, as there would not be sufficient time for its formation in the soil. It is produced during slurry storage and shortly after slurry application, after which time the OM is oxidised to CO_2 and H_2O as aerobic conditions prevail. Initial CH_4 emissions in the following few hours most likely originate from CH_4 contained in the manure diffusing from the viscous layer, while subsequent emissions were likely to be produced during the degradation of labile carbon compounds (Chadwick et al., 2000; Sherlock et al., 2002). Kasimir-Klemedtsson et al. (1997) reported similar base-line CH_4 soil emission levels of 1.1 kg CH_4-C ha^{-1} day^{-1} (3.01 g CH_4-C ha^{-1} day^{-1}) from Swedish cereal cropped soils, while Rodhe et al. (2006) recorded similar peak CH_4 emissions of approximately 75 g CH_4-C ha^{-1} day^{-1} immediately post application of cattle slurry to grassland. Chadwick and Pain (1997) also reported high emission levels following pig and dairy manure application to grassland soil in laboratory experiments.

5.5.4. Impacts of pollution swapping

Chemical amendment of dairy cattle slurry provides an opportunity to immediately reduce P solubility in dairy cattle slurry and could be included as a low capital cost management tool to reduce P solubility in manure and reduce farm P status in the short-term, as other management practices come into effect. This study allows for the effect of chemical amendment on gaseous emissions to be incorporated into the feasibility analysis of Chapter 3. The ranking system, determined in Chapter 3, was based on effectiveness, efficiency, potential barriers to use and cost of implementation. A new feasibility analysis was developed to include the results of this study and to give recommendations for the best amendment to mitigate DRP losses with the least potential for pollution swapping.

The results of this feasibility analysis are shown in Table 5.3. Charcoal was excluded as there is insufficient data on P sequestration potential to date. In order of decreasing feasibility, the amendments were ranked from best to worst as follows: PAC, alum, $FeCl_2$ and lime. Therefore, the amendments selected for recommendation for further study are, from best to worst: PAC, alum and lime. Ferric chloride was excluded due to risk of stability of Fe-P bonds in soil. Although there are similar concerns with lime, it is currently added to soil in Ireland to reduce acidity in soils and for this reason, it was decided to recommend lime over $FeCl_2$.

Table 5.3 Summary of feasibility of amendments (Adapted from Chapter 3). Marks for feasibility and pollution swapping are from 1 to 5. 1 = best 5 = worst.

Chemical	Ratio used Chapter 3	Feasibility score P	Pollution swapping	Combined feasibility	Notes
Alum	0.98:1 Al: P	1	5	6	Risk of effervescence Risk of release of H_2S due to anaerobic conditions and reduced pH Cheap and used widely in water treatment Reduced ammonia emissions
$AlCl_3$ (PAC)	0.98:1 Al: P	2	2	4	No risk of effervescence (Smith et al., 2004) $AlCl_3$ increased handling difficulty Expensive Reduced ammonia emissions
$FeCl_2$ ($FeCl_3$)	2:1 Fe: P	3	4	7	Potential for Fe bonds to break down in anaerobic conditions Increased release of N_2O Reduced ammonia emissions
$Ca(OH)_2$	5:1 Ca: P	4	3	7	Increased NH_3 loss Strong odour Hazardous substance
Charcoal			1		Potential to reduce P solubility limited work to date Improve soil microbial health Reduced GHG emissions Reduced ammonia emissions

5.6. Conclusions

This study showed that P mitigating amendments can result in pollution swapping. The amendments selected for recommendation for further study are, from best to worst, PAC, alum and lime. Charcoal has excellent potential to reduce GHG losses caused by the land application of dairy cattle slurry. There is a need to develop biochars which are efficient in sorbing P and can improve soil quality and reduce GHG emissions. In addition, at the current cost of treatment, the increase in fertiliser value of the slurry due to some treatments is not sufficient to offset the cost of treatment. In this study, there was no significant effect of any amendment of slurry on GWP caused by land application dairy cattle slurry, with the exception of charcoal

5.7. Summary

It is critical that when evaluating the feasibility of these amendments, ‘pollution swapping’ is considered. This study has identified the need for a field study to examine the effect of the amendments on gaseous losses. In addition, there is a need to examine the effect of amendments using different soil types and wetting and drying regimes. Chapter 6 details the results of a runoff study following the landspreading of chemically amended slurry at field-plot scale and Chapter 7 examines the impact of chemically amended slurry on soil properties over a 9-mo study duration.

Chapter 6 Plot-scale rainfall simulation study

6.1. Overview

This plot-scale runoff experiment was designed to develop an understanding of the performance of amendments under more realistic conditions. In this experiment, natural drainage occurred, which did not occur in the runoff box experiments. The plot and runoff characteristics such as soil volumetric water content, time to runoff and runoff volume were also measured to investigate potential adverse effects of amendments on runoff at a larger scale.

6.2. Introduction

The present study examines the effect of chemical amendment of dairy cattle slurry with alum, PAC and lime on both P and N losses to runoff, whereas plot and runoff-box experiments which have examined chemical amendment of dairy cattle slurry to date have focused almost entirely on P losses. Although P is the limiting nutrient in freshwater systems (Correll, 1998), N losses also pose a significant risk to water quality (Johnes et al., 2007; Vitousek et al., 2009). When chemical amendments are used to reduce P losses, it is important that the effects of amendments on N losses through runoff, leaching and volatilisation are also examined to ensure that ‘pollution swapping’ does not occur.

The experimental set-up of the present study tested the efficacy and feasibility of using a variety of chemical amendments in the field, but still under controlled conditions. The objectives of this study were to investigate the effect of chemical amendment of dairy cattle slurry on: (1) average FWMC of DRP, DUP, PP and TP (2) average FWMC of

NO_3, NO_2 and NH_4-N; and (3) plot and runoff characteristics such as soil volumetric water content, time to runoff and runoff volume.

6.3. Materials and Methods

6.3.1. Study site

This study was conducted on a 0.6 ha isolated plot on a beef farm located at Teagasc, Johnstown Castle, Environmental Research Centre (latitude 52º 17'N, longitude 6º 29'W), in the southeast of Ireland (Figure 6.1). This area has a cool maritime climate, a mean annual precipitation of 1002 mm (effective rainfall from between 400 to 500 mm), and a mean annual temperature of 9.6°C (Ryan and Fanning., 1996). The location of 25 experimental plots within the 0.6 ha site was determined by: topography/slope, soil texture/drainage, depth to watertable and soil analysis. For textural analysis, 100 mm-deep soil samples (n=3) were taken from a 1 m^2 area at the top, middle and bottom of the plot (Figure 6.1). Soil texture was determined using PSD analysis after B.S.1377-2:1990 (BSI, 1990a). An electromagnetic conductivity and resistivity survey was also used to infer textural and drainage characteristics.

The site had undulating topography with a 6.7% slope along its length and an average slope of 3.6% across the site. The topsoil was classified as a Haplic Stagnosol (Rachel Creamer *pers com,* 2011). Combining PSD and geophysical data together, textural classes ranged from a fine loam-to-clay loam within the plot. The top of the plot comprised gravelly clay with pockets of silty/clayey gravel underlain by silt/gravel (20 to 26 mSm^{-1}) and was relatively well-drained compared to the lower part of the site, which comprised silt/clay and was poorly drained (>26 $mS\ m^{-1}$). The median perched watertable depth in three piezometers (top, middle and bottom) was 0.6 m below ground level (bgl) on site. The nutrient status of the soil at these locations was determined using Morgan's P extractant (Morgan, 1941) and, together with K and Mg, are presented in Table 6.1. The soil was classified as P index 3 (>5.1 mg L^{-1} for grassland soils in accordance with SI 610 of 2010) throughout the site, meaning that it represented minimum risk of P loss to water.

Soil pH (n=3) was determined using a pH probe and a 2:1 ratio of deionised water to soil (Table 6.1).

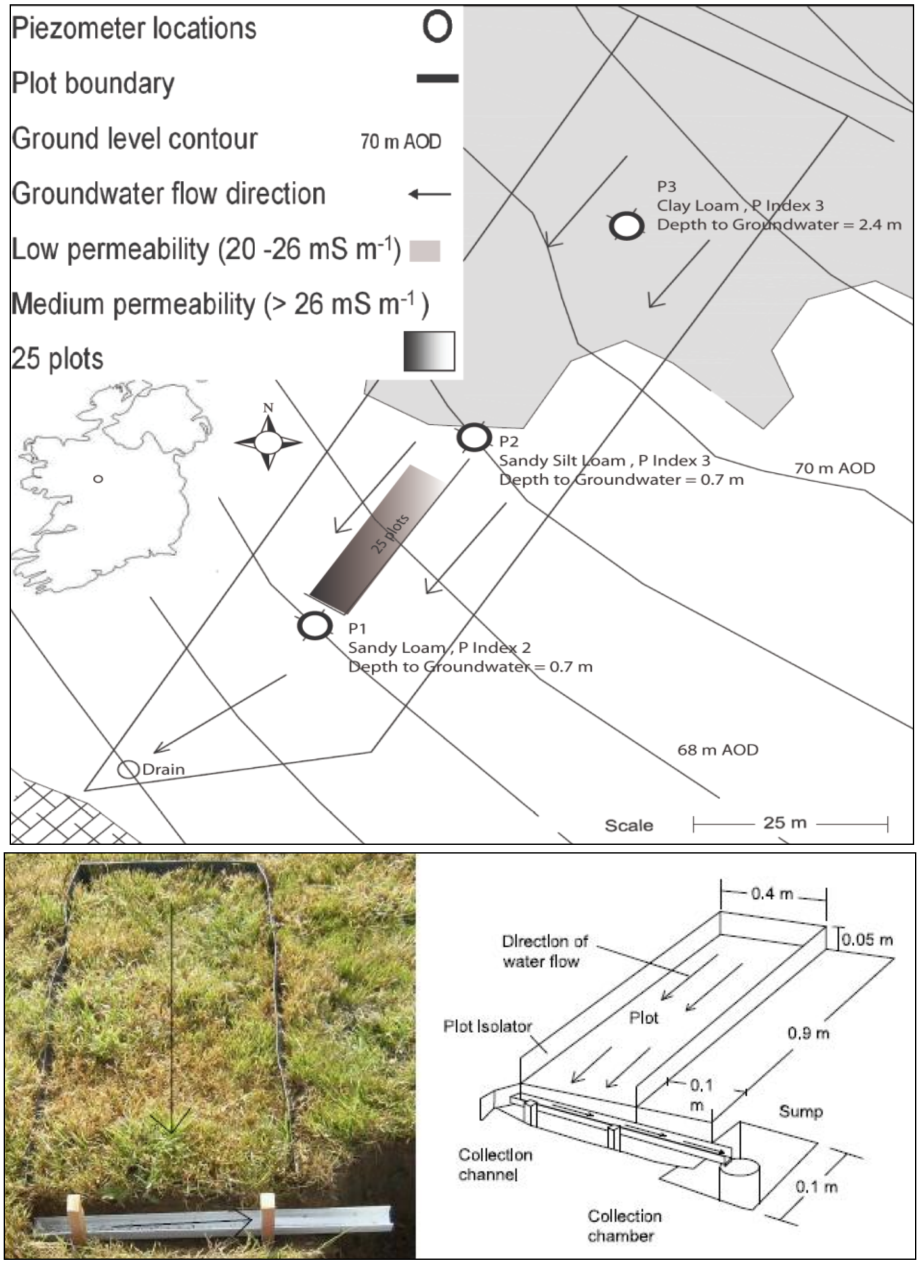


Figure 6.1 Map of study site showing ground elevation, topography, slope, soil conductivity, groundwater flow direction, location of subplots and of groundwater wells.

The location selected was of uniform topography, soil classification, texture and drainage characteristics. In addition, it was in the location of the site with the highest water table and had relatively constant soil nutrient status. Once the study location was selected, each plot was isolated and instrumented with a runoff collection channel (Figure 6.1).

Table 6.1 Soil pH, Morgan's extractable P, K and Mg, sand silt, clay fractions, and textural class of soil used in this study. The location of the piezometers is illustrated in Figure 6.1

Position	Piezometer No.	pH	Morgan's P mg L^{-1}	P index[a]	K mg L^{-1}	Mg mg L^{-1}	Sand %	Silt %	Clay %	Textural Class
Lower	1	5.8	2.6	2	173	171	52	30	18	Sandy Loam
Middle	2	5.9	3.2	3	140	195	47	36	18	Sandy Silt Loam
Upper	3	6.1	3.6	3	96	151	44	36	21	Clay Loam
Average		5.9	3.1		136	172	47.7	34.0	19.0	
Std dev		0.2	0.5		38.6	22	4	3.5	1.7	

[a]P index is the classification system used in Ireland to classify soil P status of soils (Schulte et al, 2010b)

The treatments were randomly assigned to twenty-five plots (0.9 m by 0.4 m) which were orientated along a line. Composite soil samples (100 mm) were taken from each plot and WEP was determined (n=3). Soil pH and Morgan's P were determined, and the slope of each plot was surveyed. Soil pH (5.96±0.22) was consistent across the 25 plots (Table 6.2). Soil test P (4.95±1.75 mg P L^{-1}) and WEP (7.24±4.52 mg P kg^{-1}) appeared to vary across the site, with lower values observed close to the location of the piezometers. Figure 6.2 shows photographs of site setup, plot installation and runoff collection troughs.

6.3.2. Slurry analysis

Cattle slurry was taken from the dairy farm at the Teagasc, Environmental Research Centre, Johnstown Castle, in August of 2010. The storage tanks were agitated and slurry samples were transported to the laboratory in 25-L drums. Slurry samples were stored at 4°C prior to land application. Slurry pH was determined using a pH probe (WTW, Germany). The TP of the dairy cattle slurry was determined after Byrne (1979). Total potassium, TN and TP were carried out colorimetrically using an automatic flow-through unit (Varian Spectra 400 Atomic Absorption instrument). The WEP of slurry and amended slurry was measured at the time of land application after Kleinman et al. (2007), and NH_4-N of slurry and amended slurry was extracted by shaking 50 g of slurry in 1 L of 0.1 M HCl on a peripheral shaker for 1 h and filtering through No. 2 Whatman filter paper at the time of application. The results of the slurry analysis are shown in Table 6.3. The slurry sample was typical of slurry found on farms in Ireland (SI 610 of 2010). The slurry TN, TP, NH_4-N and TK were constant with the exception of the lime-treated slurry, which had high TN, TP and TK. The WEP of slurry was lowered significantly by all alum and PAC amendments. Alum addition reduced the slurry pH from approximately 7.1 to 6.5, while lime addition increased the slurry pH to 8.8.

Table 6.2 The average slope for each block, soil pH, water extractable phosphorus (WEP), Morgan's extractable P, potassium (K), and magnesium (Mg) before application of treatments.

Block	Slope %	pH	WEP g kg^{-1}	P mg L^{-1}	K mg L^{-1}	Mg mg L^{-1}
1	4.7 (1.5)	6.1 (0.22)	5.5 (2.3)	3.25 (0.82)	49.6 (5.7)	123 (4.5)
2	3.2 (1.8)	5.9 (0.14)	7.5 (3.3)	4.9 (1.9)	55.2 (8.2)	150 (5.7)
3	2.3 (1.9)	6.06 (0.26)	11.4 (5.9)	6.9 (0.83)	59.5 (7.8)	184 (6.7)
4	3.3 (1.7)	6.02 (0.22)	6.8 (5.1)	6.07 (0.85)	58.4 (6.57)	230 (1.2)
5	4.4 (1.1)	5.77 (0.16)	5 (3.6)	3.59 (0.72)	60.8 (4.5)	218 (5.7)
Average	3.58	5.97	7.24	4.94	56.7	181
Std deviation	0.97	0.13	2.53	1.6	4.5	45

(Standard deviations in brackets)

Table 6.3 Slurry DM, pH, water extractable phosphorus (WEP), total nitrogen (TN), total phosphorus (TP) and total potassium (TK) and average concentrations of NH_4- N (n=5)

Treatment	DM	pH	WEP g kg^{-1}	TN mg L^{-1}	TP mg L^{-1}	TK mg L^{-1}	NH_4^+-N mg L^{-1}
Slurry	9.1 (0.54)	7.1 (0.62)	3.19 (0.37)	3960 (741)	1240 (145)	5170 (870)	1200 (260)
Alum	9.6 (0.58	6.5 (0.44)	0.0028 (0.001)	4410 (590)	1260 (190)	5210 (640)	1160 (270)
PAC	9.42 (0.64)	6.9 (0.47)	0.0074 (0.008)	3980 (1280)	1200 (270)	4330 (1290)	1180 (290)
Lime	9.4 (0.38)	8.8 (0.67)	2.48 (0.99)	5010 (725)	1390 (150)	5610 (840)	1210 (300)
Average	9.38	7.325	1.4	4340	1270	5080	1190
Std dev	0.2	1.01	1.7	492	82.2	538	22.2

(Standard deviations in brackets)

Grass cut and plots isolated

Plot during micro-plot installation

Plot isolation

Runoff collection. Shield removed to allow photo to be taken

Figure 6.2 Plot set up and runoff collection photograph

6.3.3. Treatments

The five treatments examined in this study were: (1) grassed soil-only, (2) slurry-control (3) industrial grade liquid alum ($Al_2(SO_4)_3.nH_2O$), comprising 8% Al_2O_3 (4) industrial grade liquid poly-aluminium chloride hydroxide (PAC) ($Aln(OH)mCl_3n\text{-}m$) comprising 10% Al_2O_3 and (5) lime ($Ca(OH)_2$). Amendments were added to the slurry and mixed rapidly by shaking in 2-L containers immediately prior to land application. Two days before the first rainfall simulation, slurry and amended slurry were applied directly to the surface of the grassed soil. Slurry application rates were equivalent to 33 m^3 slurry ha^{-1} (42 kg TP ha^{-1}), the rate most commonly used in Ireland (Coulter and Lalor, 2008). Amendments were applied at stoichiometric ratios determined in Chapter 3. Alum was applied at a rate of 1:1 (Al: TP); poly-aluminium chloride at a rate of 0.85:1 (Al: TP); and lime at a rate of 3.9:1 (Ca: TP). Appendix E shows photographs of amended slurry.

6.3.4. Rainfall simulation

Two identical portable multi-drop 'Amsterdam type' rainfall simulators, described by Bowyer-Bower and Burt (1989), were used in this study. These rainfall simulators have been used on similar permanent grassland sites and soil types (Kurz et al, 2006; Kramers et al., 2009; O'Rourke et al, 2010). The rainfall simulators were designed to distribute rainfall over a surface area of 0.5 m^2 and were calibrated to deliver rainfall at an intensity of 11 mm h^{-1}. In order to ensure the absence of edge effects, the study plots – each measuring 0.36 m^2 in area - were positioned directly under the rainfall simulator. The plots were isolated using 2.2 m-long, 100 mm-deep rigid plastic sheets, which were pushed 50 mm into the soil to isolate three sides of the plot. The runoff collection channel was placed at the bottom of the slope (Figure 6.1). Plots were orientated with longest dimension in the direction of the slope (average 3.6 %). The runoff collector comprised a polypropylene plastic U-shaped channel piece, which was cut in half and wedged against the soil at a depth of approximately 25 mm below the soil surface (Figure 6.1).

A 400 mm-wide edging tool was used to ensure a good seal between soil and collector. The plots were left uncovered for two weeks prior to first rainfall simulation to allow natural rainfall to wash away soil disturbed by inserting the isolators. The grass on all plots was clipped to a height of 50 mm two days prior to the first simulated rainfall event. Figure 6.3 shows one of the rainfall simulators used in this study. Land application of treatments was staggered over three days and applied in blocks to allow for the first rainfall event (RS1) two days after land application of slurry. The second event (RS2) was 10 d after the original application (t = 12 d) and the third (RS3) after 28 d (t = 30 d).

Rainfall simulations were carried out between 17th September 2010 and 18th October 2010 (Figure 6.4).

Wind shield used to prevent rain from blowing rain

View of rainfall simulator before rainfall starts

Figure 6.3 Photographs of rainfall simulator

The allocation of the rainfall simulators was randomised between blocks and alternated for treatments. Runoff was judged to occur once 50 ml of water was collected from the runoff collection channel and the time from start of rainfall simulation to runoff of 50 ml being the time to runoff (TR). Samples were collected every 5 min for RS1, and every 10 min for RS2 and RS3. Surface runoff was collected for 30 min once runoff commenced to allow the FWMC to be calculated (Kurz et al., 2006). Rainfall simulator input water had the following average concentrations: 0.05 mg NH_4-N L^{-1}, 4.61 mg NO_3-N L^{-1}, 0.001 mg DRP L^{-1} and 0.004 mg TP L^{-1}; 0.00 mg NH_4-N L^{-1}, 4.53 mg NO_3-N L^{-1}, 0.004 mg DRP L^{-1} and 0.00 mg TP L^{-1}; 0.00 mg NH_4-N L^{-1}, 4.51 mg NO_3-N L^{-1}, 0.00 mg DRP L^{-1} and 0.00 mg TP L^{-1} for RS1, RS2 and RS3 respectively.

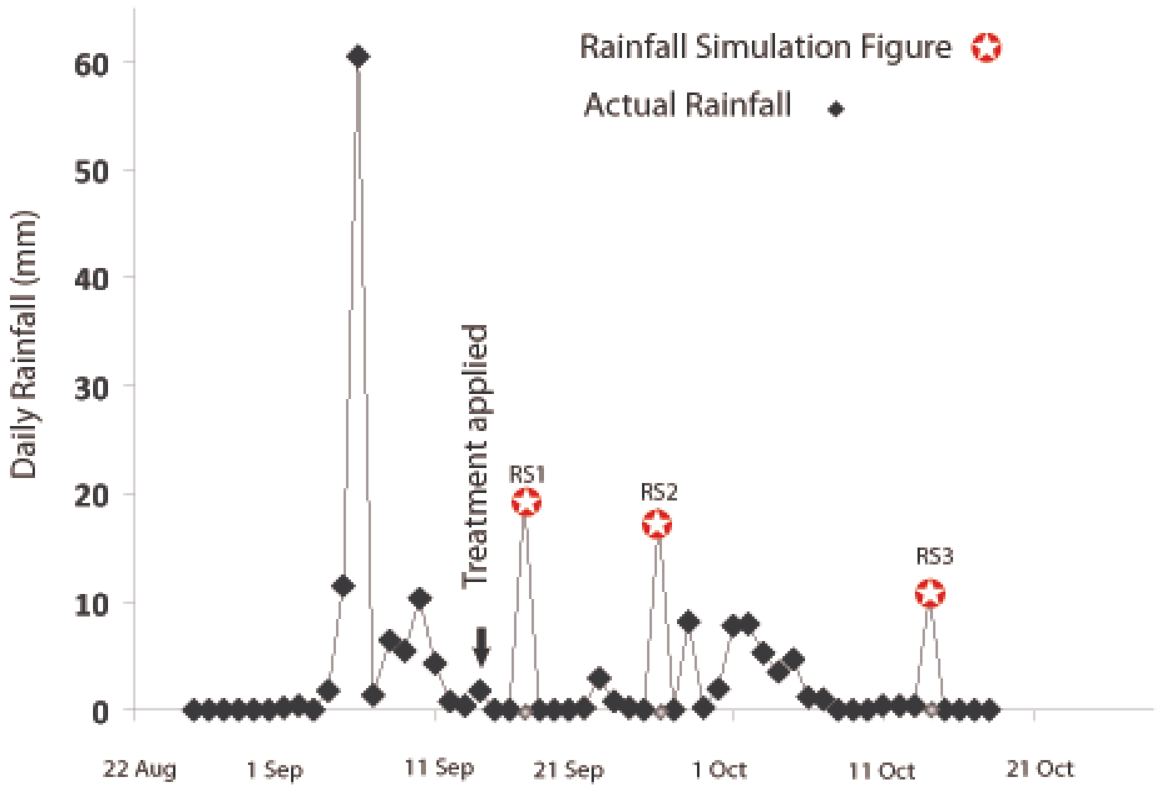


Figure 6.4 Natural rainfall and average depth of simulated rainfall received by the plots for each event

The volumetric water content of soil in each plot was measured immediately prior to each rainfall simulation event using time domain reflectrometry (Delta-T Devices Ltd., Cambridge, UK) (Figure 6.5), which was calibrated to measure resistivity in upper the 50 mm of the soil in each plot. Three readings were taken in each plot and the average was calculated.

Figure 6.5 Photo of the measurement of volumetric water content of soil using time domain reflectrometry

Immediately after collection, runoff water samples were filtered through 0.45µm filter paper and a subsample was analysed colorimetrically for DRP, total oxidized nitrogen (TON), NO_2-N and NH_4-N using a nutrient analyser (Konelab 20, Thermo Clinical Labsystems, Finland). Nitrate was calculated by subtracting NO_2-N from TON. A second filtered sample was analysed for TDP using acid persulphate digestion. Unfiltered runoff water samples were analysed for TP with an acid persulphate digestion. Particulate phosphorus was calculated by subtracting TDP from TP. The DRP was subtracted from the TDP to give the DUP. All samples were tested in accordance with the Standard Methods (APHA, 1995).

6.3.5. Statistical analysis

The structure of the data (Appendix F) set was a blocked one-way classification (treatments) with repeated measures over time (events). The analysis was conducted using Proc Mixed in SAS software (SAS, 2004) with the inclusion of a covariance model to estimate the correlation between events. A large number of covariates were recorded, including measurements on the simulators. For each analysis, this set of covariates was screened for any effects that should be included in an analysis of covariance. The interpretation was conducted as a treatment x time factorial. Comparisons between means were made with compensation for multiple testing effects using the Tukey adjustment to p-values. Significant interactions were interpreted using simple effects before making mean comparisons. In order to ensure that STP variation did not affect the experiment, STP was included as a variable in the statistical analysis. Slurry concentration, which was of much greater significance in terms of P concentrations in runoff following slurry application, was uniform within each block.

6.4. Results

6.4.1. Phosphorus (FWMC of DRP, DUP, PP and TP)

The average FWMC of DRP, DUP and PP, which comprise TP in runoff, are shown in Figure 6.6. During RS1, alum ($p<0.05$) and PAC ($p<0.001$) reduced DRP in runoff water compared to the slurry-control by 95 (0.13 mg P L^{-1}) and 98% (0.05 mg P L^{-1}), respectively. Alum and PAC, at $p<0.02$ and $p<0.01$, also reduced TP concentrations in runoff from the plots during RS1 by 92 (0.61 mg P L^{-1}) and 83% (1.37 mg P L^{-1}), respectively, compared to the slurry-control. None of the amendments examined reduced FWMC of DRP or TP losses to below the MAC during the study.

The FWMC of TP and DRP for the alum-amended plots did not show any discernable trend, although the average reduction in FWMC, compared to the slurry-control, over the three rainfall events, for TP and DRP was 81 and 77%, respectively. Comparatively, the FWMC of TP continued to reduce over the three rainfall events for the PAC-amended plots, although the DRP concentrations were still over the MAC for all runoff events. Alum-treated slurry and PAC-treated slurry were not significantly different to each other throughout the study. However, there was a significant difference in FWMC of TP in runoff during RS1 between soil-only ($p<0.05$), alum ($p<0.05$) and PAC ($p<0.01$) compared to the slurry-control.

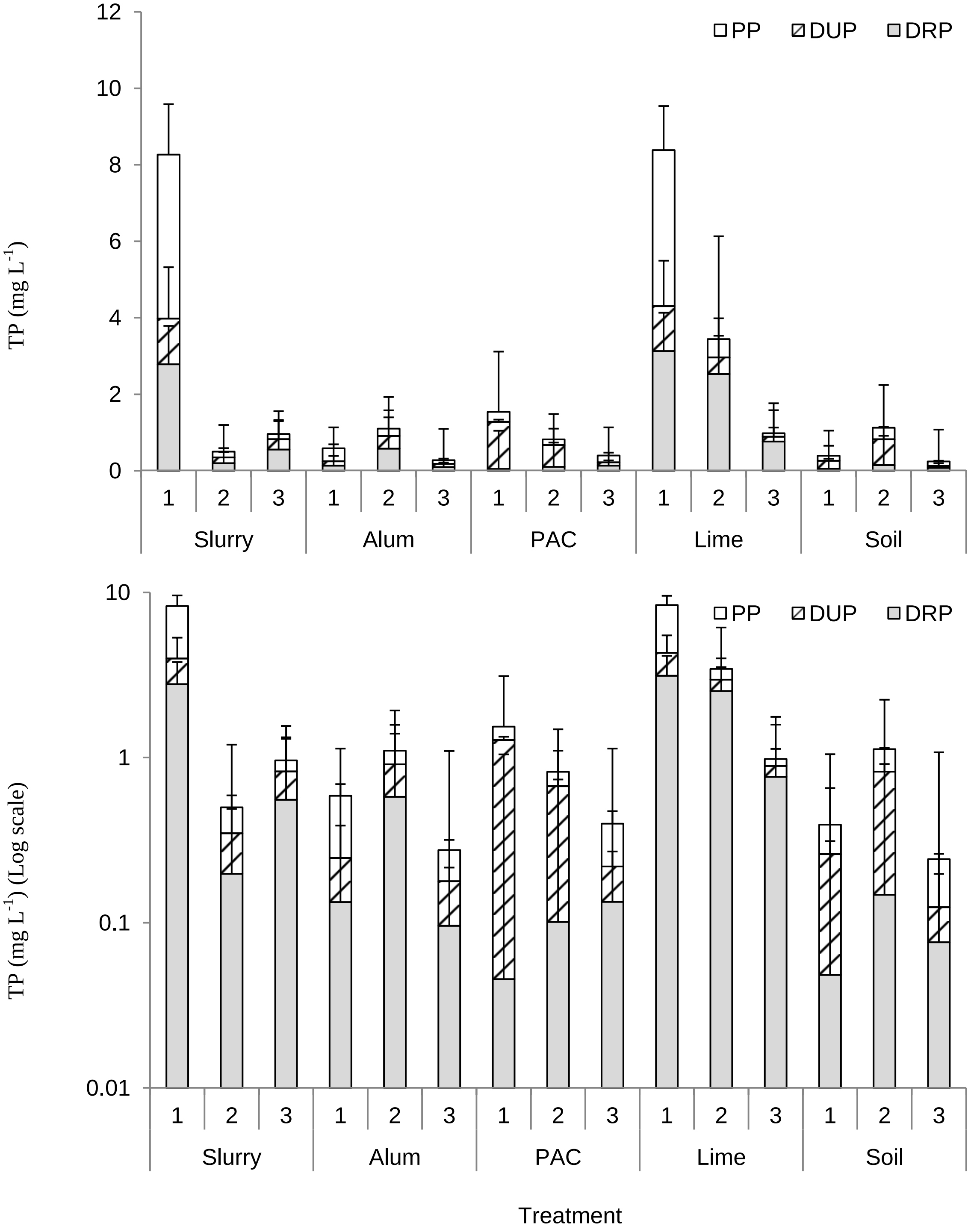


Figure 6.6 Average flow-weighted mean concentrations of dissolved reactive phosphorus (DRP), dissolved un-reactive P (DUP) and particulate P (PP) comprising total P (TP) for three rainfall simulation events, and maximum allowable concentrations (MAC) in waterways.

The addition of lime increased the average FWMC of DRP and TP over the three rainfall events, compared to the slurry-control, by 82 and 38%, respectively. This increase in P loss as a result of lime amendment may be due to the pH of the lime-amended slurry. Penn et al (2011) found that in order for Ca-phosphate bonds to remain stable, the pH must remain in a range of 6.5 to 7.5. The average pH of the soil on the site was 5.97 and the pH of the lime-amended slurry was 8.8 at the time of application. Chapter 3 showed that the pH of lime-amended dairy cattle slurry increased in the first 24 h following land application. The slurry pH was too high for Ca-P bonds to be stable during RS1 and when the slurry and soil interacted and reached equilibrium, the soil pH was lower than the optimal pH for the formation of Ca-P bonds. This may be why reductions were not observed during RS2 and RS3.

6.4.2. Nitrogen

The average FWMC of NO_3-N, NO_2-N and NH_4-N in runoff water for grassed soil-only plots for the three simulated rainfall events were 3.98 mg NO_3-N L^{-1}, 0.03 mg NO_2-N L^{-1} and 0.22 mg NH_4-N L^{-1} compared to 3.6 mg NO_3-N L^{-1}, 0.02 mg NO_2-N L^{-1} and 0.82 mg NH_4-N L^{-1} for the slurry-control (Figure 6.7). The NO_3-N and NO_2-N concentrations in runoff water from soil only plots were not in excess of the MAC of 11.3 mg NO_3-N L^{-1} (EEC, 1988) and 0.1 mg NO_2-N L^{-1} (OJEC, 2006) for salmonidal rivers. The addition of amendments had no significant effect on NO_3 concentration in runoff water. Ammonium concentrations in runoff from plots receiving alum-amended dairy cattle slurry, averaged across the rainfall events, were in excess of lower drinking water standards of 0.2 mg NH_4-N L^{-1}, but below the upper limit of 4 mg NH_4-N L^{-1} (EEC, 1989).

The alum amendment increased NH_4-N in runoff by 84% from 2.4 mg NH_4-N L^{-1} in the slurry-control to 4.3 mg NH_4-N L^{-1} during RS1, while PAC reduced NH_4-N in runoff by 80% (0.4 mg NH_4-N L^{-1}) compared to slurry-control during RS1. Lime had no significant effect on NH_4-N concentrations in runoff water. The peak in NH_4 loss during RS1 was a result of the application of dairy cattle slurry, which was high in NH_4.

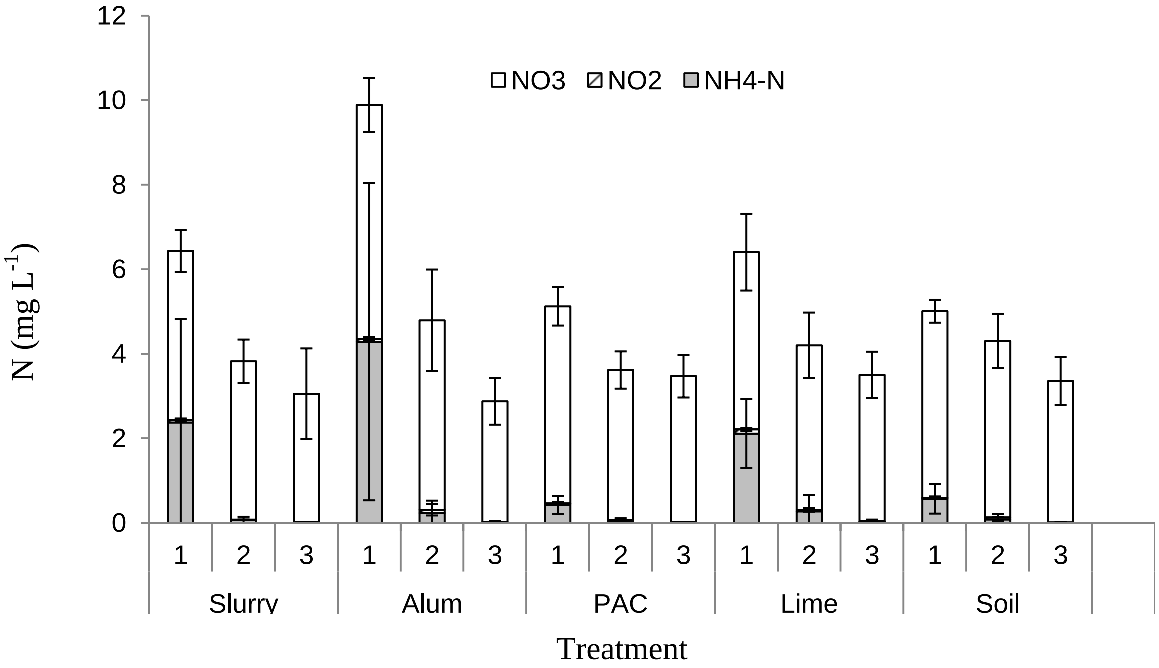


Figure 6.7 Average flow-weighted mean concentrations of ammonium nitrate (NH_4-N), nitrite (NO_2-N) and nitrate (NO_3-N) for three rainfall simulation events, and maximum allowable concentrations (MAC) in waterways.

6.4.3. Time to runoff, soil volumetric water content and runoff volume

The rainfall intensity, volume of runoff (converted to equivalent depth), time from start of rainfall application to start of runoff event, and volumetric water content of the soil at the start of each rainfall simulation are shown in Figure 6.8. Almost 90% of all rainfall applied drained away or leached through the soil, with 7.8% of water applied to soil-only being collected as runoff from the upper 25 mm of the soil surface, 9% for the slurry-control, 9.4% for alum-amended slurry, 15% for PAC-amended slurry and 14.3% for lime-amended slurry. The runoff volumes were not statistically different to each other.

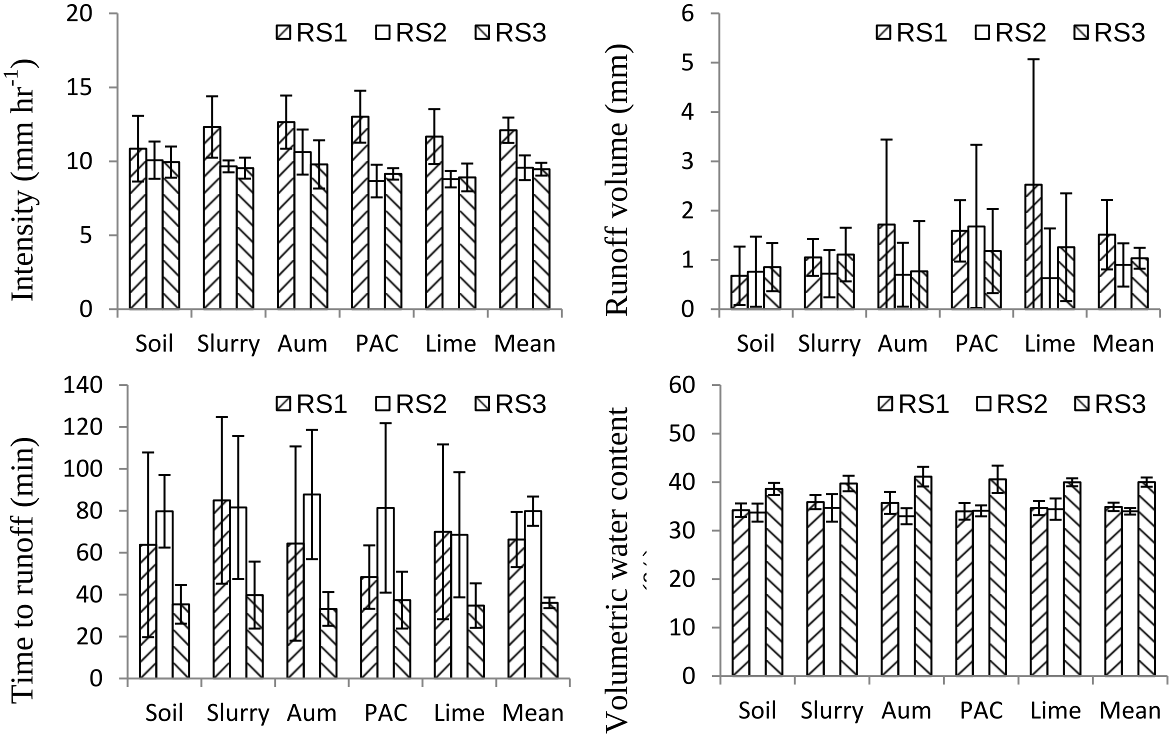


Figure 6.8 Average rainfall intensity, runoff volume, time to runoff and soil volumetric water content for the first (RS1), second (RS2) and third (RS3) rainfall events.

There was no statistical evidence of any effect of rainfall simulator on the experimental outcome**.** The average intensity for each rainfall simulation event for the two simulators was 10±1.8 mm h^{-1} and 10.7±1.93 mm h^{-1}, respectively. Rainfall intensity and soil water content did not have a significant effect on TR, runoff volume, or P and N losses. Covariate analysis of the logarithmic of the TR showed that event (p<0.001) and slope (p<0.01) of plots affected TR.

6.5. Discussion

6.5.1. Phosphorus (FWMC of DRP, DUP, PP and TP)

Throughout the study, the DRP concentrations in runoff water from soil-only plots were in excess of the MAC of 0.03 mg DRP L^{-1} for surface waterbodies in Ireland (Flanagan, 1990). The average FWMC of TP for the soil only treatment was in excess of water quality limit of 0.025-0.1 mg TP L^{-1} (USEPA, 1986) for surface water in the USA. The concentrations in runoff from the slurry-control plots were also all in excess of the MAC for DRP and TP for the duration of the study. However, the buffering capacity of water means that the concentration of the water in a surface waterbody will not be as high as the concentration of runoff, provided runoff from slurry flows over soil which has not received dairy cattle slurry (McDowell and Sharpley, 2002b).

The results of the present study show that chemical amendments can be used to reduce P solubility in dairy cattle slurry and thus reduce P loss to a surface waterbody. Alum and PAC reduced P losses significantly compared to the slurry-control. Possible reasons for this failure to achieve runoff concentrations below the MAC may be insufficient chemical amendment of slurry, rainfall intensity and insufficient contact time to achieve adsorption of P. Incidental P losses accounted for the majority of P losses from the slurry-control plot during the study, with approximately 75% of DRP, 72% of DUP, 94% of PP and 83% of TP losses, measured over the three rainfall events, occurring during RS1. While incidental losses were significantly reduced in the alum and PAC-amended plots, the effect of amendments on chronic loss of P from the plots was not clear as differences in runoff concentrations during RS3 and were not statistically significantly to slurry control.

The results show that even in low P Index soils, there is risk of DRP concentrations, which are in excess of the MAC in runoff, entering drains. In a similar plot study with simulated rainfall applied at 25 mm h^{-1}, Kruz et al. (2006) observed an average FWMC of DRP of 0.99 mg L^{-1} from soil with a Morgan's P varying between 5 mg P L^{-1} and 7 mg P L^{-1}. These concentrations are all similar to the soil only treatment in this study.

The results in this study were similar to previous work (Preedy et al., 2001; Kleinman and Shapley, 2003; Hanrahan et al., 2009). Kleinman and Sharpley (2003) applied dairy cattle slurry to grassed runoff boxes at 50 kg TP ha^{-1}. Runoff boxes were subjected to simulated rainfall at 70 mm h^{-1} three days after application, and DRP in runoff was 3.2 mg DRP L^{-1}. We have therefore shown that even when slurry was applied within guideline application rates, concentrations of P in runoff were still in excess of limits. In practice, runoff from fields receiving slurry will pass through a buffer area and undergo dilution before it enters a waterway. This means that the concentrations measured in this paper were higher than the actual concentration of the water that would enter the waterway if these treatments were used in practice. Timing of slurry application and incorporation of slurry may be a much more feasible way to reduce incidental P losses.

6.5.2. Nitrogen

On a low permeability soil, infiltration of N is unlikely and at this location N will predominantly be lost in runoff to rivers. Dairy cattle slurry is high in NH_4-N, which may explain the high NH_4-N in runoff during RS1. The reduction in NH_4 concentrations in runoff between RS1 and RS2 across all treatments, including the slurry-control, was likely due to nitrification occurring in the soil following slurry application, and interaction with the soil. Nitrification occurs when microbes use enzymes to convert NH_4 to NO_2 and then NO_3 to obtain energy (Ketterings et al., 2011). This also explains why there was so little NO_2 in the runoff water in comparison to NO_3.

Land application of dairy cattle slurry resulted in an increase in NH_4-N compared to soil only. Smith et al. (2001b) reported similar findings. Smith et al. (2001b) added dairy cattle slurry at a rate 75 m^3 ha^{-1} to grassed plots and reported soluble N (NH_4-N+NO_3-N) concentrations ranging from 2 mg L^{-1} to 14 mg L^{-1}, which was comparable to the average FWMC of soluble N observed in this study (6.3 mg L^{-1}). Nitrite losses were not significant and were equivalent to approximately 1.9% of NO_3 for most samples. Land application of dairy cattle slurry did not have a significant effect on NO_3 loss to runoff water; this was in agreement with results from Smith et al. (2001b). Alum increased NH_4-

N loss during first rainfall event, while PAC reduced NH_4-N loss compared to the slurry-control. These results indicate that chemical amendments could potentially increase N in runoff from dairy cattle slurry.

It is critical that the potential for ‘pollution swapping’ is examined when evaluating chemical amendment of dairy cattle slurry. In particular, the effects of any amendments on GHG emissions must be examined. Under the 1997 Kyoto Protocol of the United Nations Framework Convention on Climate Change (UN, 1998), participating nations agreed to publish national inventories of anthropogenic emissions of several GHG and to reduce future emissions below 1990 levels. In Ireland, agricultural activities were responsible for approximately 26% of total GHG emissions in 2008 (McGettigan et al., 2010) and account for virtually all NH_3 emissions, with animal manure alone responsible for 92% of NH_3 emissions (EPA, 2010). While NH_3 is not a GHG, it contributes to acidification of soils, atmospheric pollution, and the eutrophication of surface and ground water systems (Goulding et al., 1998). An estimated 5% of global N_2O emissions results from the conversion of NH_3 into N_2O in the atmosphere (Ferm, 1998). In addition to gaseous N losses (Amon et al., 2006), agricultural activities, such as land application of dairy cattle slurry, contribute to the production of NH_3 and GHG, such as CO_2, N_2O (Ellis et al., 1998) and CH_4 (Chadwick et al., 2000). Therefore, any chemical amendments which alter slurry properties may have an effect on GHG emissions.

6.5.3. Rainfall intensity, soil volumetric water content, time to runoff and runoff volume

Land spreading of dairy cattle slurry at high rates may result in sealing of the soil surface by slurry solids. Smith et al. (2001b) reported a 16% increase in runoff volume compared to soil-only control when dairy cattle slurry was applied to the soil surface at 40 m^3 ha^{-1}. This is similar to an 11.5% increase in runoff volume observed in the present study, this increase was not, however, statistically significant. Chemical amendments of slurry appeared to increase runoff volume compared to the slurry-control, but the differences in runoff volume were not statistically significant. The rainfall simulation event was found to have the greatest impact on runoff volume ($p<0.05$). There was a difference between plots, but the differences were not statistically significant.

There was no statistically significant effect of treatment on runoff or TR. This indicated that the effect of amendment on any surface sealing which may have occurred was minimal. However, the lack of a relationship between soil water content and runoff properties may be a result of scale effects. The soil around the plots received no rainfall; this may also have resulted in an artificially high TR. In a similar plot study, Kleinman et al. (2006) examined the role of rainfall intensity and hydrology in nutrient transport *via* surface runoff and observed that despite significant differences in runoff generation processes (volume of runoff and TR), the concentrations of DRP in runoff were related to the STP of the grassed soil. Similar results were observed in the present study, however the DRP concentrations were dependent on the WEP of the slurry applied and not STP of the soil.

Although amendments increased runoff at plot-scale, the effect of such an increase at field-scale cannot be fully known. There is potential that if runoff increased at a larger scale, increased erosion and loss of PP could occur. The variation observed in runoff has significant implications for comparing the results of this work with field-scale studies. Potential scale effects which must be considered include: (1) dilution due to different runoff volumes and TR (2) differing soil texture/permeability in between plots and (3) length of collection period, as the FWMC of the various measured water quality parameters may be artificially high since the water samples were not collected after rainfall stopped.

6.5.4. Outlook for future implementation of chemical amendment of dairy cattle slurry as a management practice for high P soils

This study demonstrated that PAC was the most effective chemical amendment to reduce incidental DRP losses from dairy cattle slurry, with alum being most effective at reducing DUP and TP losses. Alum and PAC significantly reduced P losses, particularly in RS1, while lime resulted in increased P losses and is not a suitable amendment at the rates examined in this study.

The estimated cost of chemical amendment, calculated in Chapter 3, and based on the estimated cost of chemical, chemical delivery to farm, addition of chemical to slurry, increases in slurry agitation, and slurry spreading costs as a result of increased volume of slurry, increases the cost of land application from approximately €1.90 m^{-3} for slurry only to €6.5 m^{-3} for alum-, €7.60 m^{-3} for PAC-, and 4.90 m^{-3} for lime-amended slurry. The TP lost from slurry-control plots during the study period had an approximate P fertiliser value of €5.48 ha^{-1} compared to €0.82 ha^{-1} lost from grass-only. Alum and PAC reduced the value of P lost to €1.45 ha^{-1} and €2.50 ha^{-1}, respectively, while lime increased the value of TP lost to €14.7 ha^{-1}. The value of TP applied to plots receiving dairy cattle slurry and un-amended slurry was €82.7 ha^{-1}.

Chemical amendment could be used in strategic areas (e.g. on farms with surplus P) to reduce P solubility in manure and P transfer to a surface and ground waters, whilst allowing farmers to utilise other nutrients in slurry on farms with high STP. In certain U.S states (Arkansas, Alabama, Tennessee and South Carolina), alum amendment of poultry litter is used as a standard conservation practice (Moore and Edwards, 2005). At present, there is no provision for a licence to landspread any of these amendments in Europe and if chemical amendment were to be used, a licensing system would have to be introduced by the relevant bodies. The plant availability of P in chemically amended manure is a major concern for stakeholders. Moore and Edwards (2005) has shown that chemical amendment improves yields due to increased N efficiency. In addition, in this study, chemical amendment is proposed for use to reduce P solubility where farmers have a short-term P surplus, and is recommended for strategic use within a catchment. Therefore, it should not be used in a site with low STP. Further work is required to access the long-term availability of P bound in Al bonds and if STP would decline as a result of chemical amendment of dairy cattle slurry prior to land spreading.

6.6. Conclusions

The results of this plot-scale study validated results from micro-scale and meso-scale studies conducted in the laboratory. Treatment was not found to have a significant effect on time to runoff or volume of runoff. When compared to the slurry-control, alum and PAC reduced DRP by 95 and 98%, respectively, in runoff following RS1. Alum and PAC also reduced TP losses during RS1 by 85 and 92%, respectively. Lime increased P losses compared to the slurry-control. Addition of amendments had no significant effect on NO_3-N in runoff water. Alum and lime increased the FWMC of NO_2-N in runoff by 120 and 114% compared to the slurry-control. Alum amendment increased NH_4-N in runoff by 84% compared to the slurry-control, while PAC reduced NH_4-N in runoff by 80% compared to the slurry-control. Lime had no effect on NH_4-N concentrations in runoff water. Alum amendment significantly increased average FWMC of NH_4-N in runoff water during the first rainfall event after slurry was applied. This indicates that amendment on a large scale could increase soluble N losses and that large scale disposal to land may pose a problem.

6.7. Summary

At the scale of the present study, alum and PAC provide the best value in reducing the TP loss from slurry; however, they are still very expensive. The next step is to examine the effects of long-term use of these amendments at field-scale and to quantify their effect on plant availability of P and GHG emissions. In addition, there is a need for a much greater examination of pollution swapping of N, with a focus on transfer of N to groundwater via leaching. Chapter 7 will examine the impact of chemically-amended slurry on soil WEP, plant available P and soil pH over a study with duration of 9 months.

Chapter 7 The long-term impact of the addition of chemically amended dairy slurry on phosphorus content and pH of five soil types

7.1. Overview

In this chapter, the impact of chemically amended dairy slurry application to land on soil WEP, plant available P and soil pH was examined across 5 different soil types in Ireland.

7.2. Introduction

A number of studies have examined the effect of chemical amendments on reducing P solubility in slurry (Dao, 1999), reducing P solubility in soil and slurry mixtures (Dao and Daniel, 2002), and reducing P in runoff from soils receiving amended slurry (Chapter 4). With the exception of Kalbasi and Karthikeyan (2004), there has been little research on the effect of chemical amendments on long-term P dynamics in soil following application of chemically amended dairy cattle slurry. Kalbasi and Karthikeyan (2004) examined three silt loam soils with different STPs in an incubation experiment conducted over a 24-mo period. Kalbasi and Karthikeyan (2004) amended the soils with either untreated dairy manure, alum-treated dairy manure, ferric chloride-treated dairy manure, or lime-treated dairy manure. Results showed the effect of chemical amendment depended on treatment type, P application rate and background STP. Kalbasi and Karthikeyan (2004) concluded that more work was needed to investigate the effects of soils varying in physical and chemical characteristics.

7.3. Materials and methods

7.3.1. Soil collection and analysis

Soils were selected from the upper 100 mm of 5 sites to represent some common soil types used in dairy farming in Ireland (Figure 7.1). The 5 soils collected were in the optimum range (5.1-8 mg L^{-1}) of STP for productive grasslands with the exception of soil from Site C (Table 7.1), which was P deficient, and the peaty soil (soil E), which had a high STP. The peat soil was included as there is a particular risk of P loss from peat soils as they have poor capacity to store P (Cummins and Farrell, 2003) and could represent a critical source if P was applied in excess of agronomic requirements of crops. Fay et al. (2007) reported that 50% of mineral and organic soils had respective STPs lower than 6.4 mg L^{-1} and 9.3 mg L^{-1} in the upper 100 mm. Soils with different texture, OM, and pH were selected to test the effectiveness of the amendments in a variety of conditions. The selected soils give an indication of the stability of metal-phosphate bonds formed as a result of chemical amendment in a wide variety of conditions.

Laboratory analysis was conducted to characterise the soil used in this study. The soil was air dried and crushed to pass a 2 mm sieve. Sub-samples were taken, dried at 40 °C for 72 h, and analysed for Morgan’s P using Morgan’s extracting solution (Morgan, 1941). Soil WEP (100:1 deionised water: soil) was determined after McDowell and Sharpley (2001). Soil pH (n=3) was determined using a pH probe and a 2:1 ratio of deionised water-to-soil. Particle size distribution was determined using B.S.1377-2:1990 (BSI, 1990a) and OM of the soil was determined using the LOI test (B.S.1377-3; BSI, 1990b). The results are presented in Table 7.1. Soil pH (n=3) was determined using a pH probe and a 2:1 ratio of deionised water-to-soil.

7.3.2. Slurry collection and analysis

Dairy cattle slurry from dairy replacement heifers was taken from a farm (53°18’ N, 8°47’ W) in County Galway, Republic of Ireland, in Summer (June), 2010. The storage tanks were agitated and slurry samples were transported to the laboratory in 10-L drums. Slurry samples were stored at 4°C prior to testing. Slurry pH was determined using a pH probe (WTW, Germany). The TP of the dairy cattle slurry was determined after Byrne (1979). Total potassium was analyzed using a Varian Spectra 400 Atomic Absorption instrument, and analyses for TN and TP were carried out colorimetrically using an automatic flow-through unit. The slurry application used in this experiment was based on an application rate of 33 m^3 ha^{-1}, which is common practice in Ireland (Coulter and Lalor, 2008). In order to facilitate randomisation, the same slurry application rate was selected for all soils. Amendment application rates to reduce soluble P in slurry were based on the results of Chapter 3.

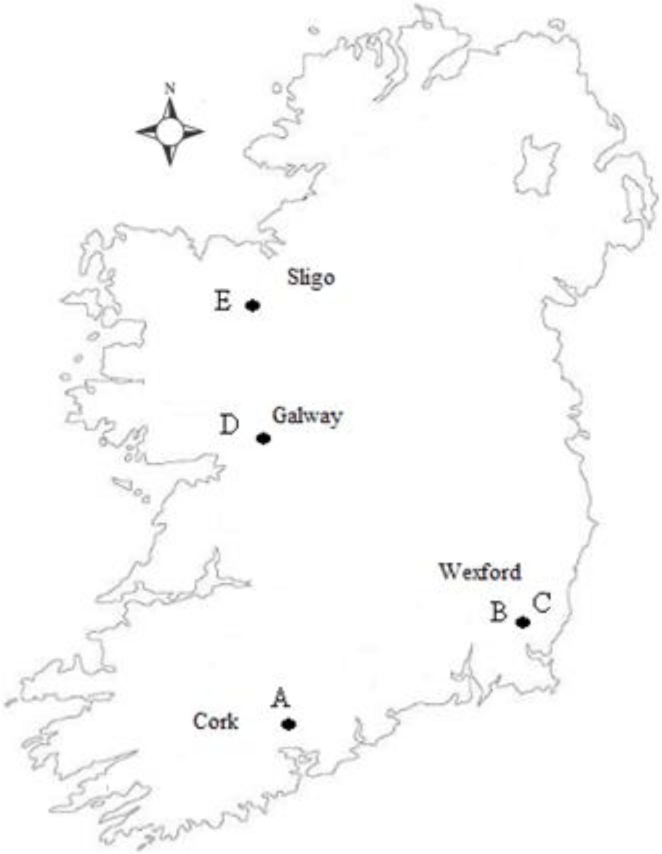


Figure 7.1 Site locations shown on map of Ireland

The slurry characterisation is shown in Table 7.2. The pH of slurry decreased for each of the acidifying amendments and increased for lime. The slurry sample was typical of slurry found on farms in Ireland (SI 610 of 2010). The slurry TN, TP, NH_4-N and TK were relatively constant with the exception of the lime-treated slurry, which had high TN, TP and TK. Alum, PAC and $FeCl_3$ addition reduced the slurry pH from approximately 7.2 to 5.1, 5.7 and 5.4 ($p<0.001$), respectively, while lime addition increased slurry pH to 12 ($p<0.001$).

7.3.3. Incubation experiment

This 9-mo incubation study comprised six treatments, conducted in triplicate (n=3), at a fixed temperature of 11°C on: (1) soil only (to take account of the effects of incubation) (2) soil mixed with dairy cattle slurry (the study control); and soil mixed with dairy cattle slurry, which was amended with either (3) alum (4) lime (5) PAC, or (6) $FeCl_3$ (In this study $FeCl_3$ was used instead of $FeCl_2$ as $FeCl_3$ is the most commercially available form).

First, 100 g samples of air dried soil, passed through a 2 mm sieve, were placed in 0.5-L containers. A volume of deionised water required to achieve 50% approximate field capacity was added and mixed with the soil using a spatula. Soil container capacity (CC), which is an approximate measurement of field capacity, was determined for each soil after Bond et al. (2006). To determine approximate field capacity, 100g of air-dried soil was placed in a container (with holes in the bottom) and saturated with deionised water. The container was then covered with para-film (perforated to allow air to circulate) and allowed to drain for 48 h through the drainage ports in the bottom of the container. It was then dried at 105° C and reweighed. This difference in weight was the CC (kg water kg^{-1} soil).

Table 7.1 Soil physical and chemical properties.

Site		Soil A	Soil B	Soil C	Soil D	Soil E
Coordinates		52°07' N,8°16' W	52°17' N,6°31' W	52°17' N,6°31' W	53°21'N, 8°34' W	54°04' N,8°52' W
Location		Cork	Wexford	Wexford	Galway	Sligo
Soil texture		Sandy loam	Clay loam	Clay loam	Silty loam	Peat soil (na)
Sand content	%	56.2 (1.1)	51.8 (4.2)	37.8 (1.1)	15 (1.4)	-
Silt content	%	25.8 (1.3)	28.1 (4.9)	31.1 (1.0)	72 (1.1)	-
Clay content	%	18 (2.4)	20.1 (2.2)	31.1 (2.1)	13 (1.2)	-
Water extractable phosphorus	mg kg^{-1}	7.2 (1.2)	6.2 (2.1)	2.7 (0.9)	3.2 (1.5)	42.5 (4.5)
Organic matter content	%	7.9 (0.6)	7.8 (0.26)	6.7 (0.5)	13.3 (0.23)	77.4 (0.2)
Soil pH		6.1 (0.85)	5.7 (0.08)	6.5 (0.02)	5.1 (0.04)	5.6 (0.05)
Potassium	mg L^{-1}	136 (5.4)	248 (2.9)	106 (1.1)	102 (6.1)	126 (6.4)
Magnesium	mg L^{-1}	217 (9.1)	377 (19.4)	225 (2.1)	124 (2.9)	527 (48.7)
Lime requirement of soil	t ha^{-1}	2 (0.6)	5 (0.3)	XLS	3 (0.3)	12 (0.3)
Soil test phosphorus (Morgan's)	mg L^{-1}	5.8 (0.34)	5.7 (0.1)	2.6 (0.2)	5.1 (0.42)	24.6 (0.2)
P Index[a]	Index[a]	3	3	1	3	4
Container capacity	kg water kg $soil^{-1}$	675 (32)	634 (12)	539 (8)	825 (43)	2110 (59)
Soil bulk density	kg m^{-3}	1.29	1.15	1.08	0.93	0.27

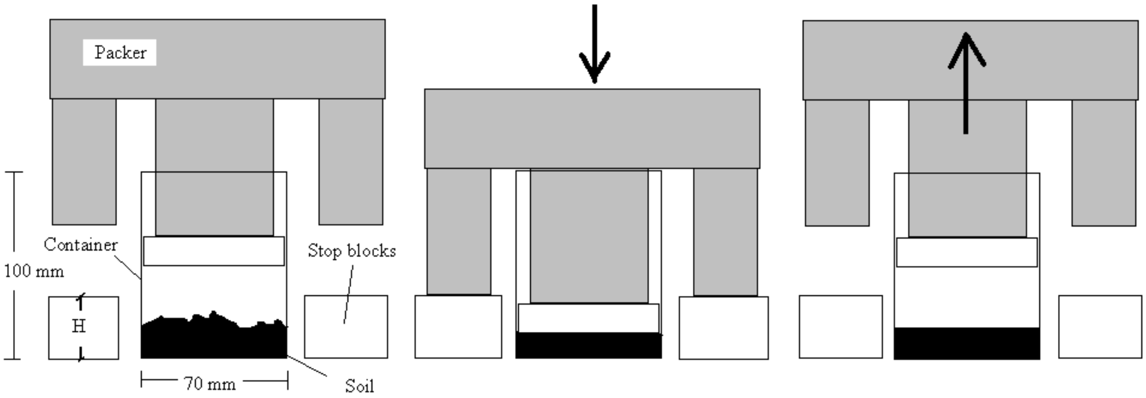
(Standard deviations in brackets), XLS: no lime requirement; [a]P Index: soils in Ireland ranked based on risk of P loss (Index 1 being low risk and 4 being the highest);

Table 7.2 Slurry properties

Treatment	Rate metal to TP	DM %	pH	TN mg L^{-1}	TP mg L^{-1}	TK mg L^{-1}
Slurry		10.45 (0.78)	7.2 (0.34)	4860 (425)	1140 (93)	3110 (254)
Alum	1.5:1 (Al:TP)	10.1 (0.35)	5.1 (0.35)	4660 (201)	1120 (19)	2840 (167)
Lime	16:1 (Ca:TP)	13.8 (0.17)	12 (0.25)	3590 (459)	944 (79)	2620 (430)
PAC	1.4:1 (Al:TP)	9.9 (0.35)	5.7 (0.4)	5320 (379)	1280 (154)	3060 (617)
FeCl$_3$	1.5:1 (Fe:TP)	11.4 (0.69)	5.4 (0.1)	5020 (283)	1180 (84)	3100 (153)

(Standard deviation in brackets)

The bulk density of each soil used in this study was determined based on the volume of 100g of sieved soil occupied in a container after field capacity was achieved (Table 7.1). Following this, slurry, or amended slurry, was added and mixed thoroughly (using a spatula) before being compacted to volume which was determined based on bulk density of soil and volume of slurry applied and water added. A packer was custom made (Figure 7.2) to compress soil to the approximate height. This height was determined based on soil bulk density, volume of water added and volume of slurry added (if added).



First, the soil, slurry and deionised water were mixed in the container. The height of the stop blocks required to achieve appropriate bulk density was selected and placed beside the container

The mixture was then compacted to an appropriate bulk density.

The packer was then removed and cleaned using deionised water and drying paper before being used again.

Figure 7.2 Schematic of packer used to achieve approximate bulk density

The amendments were applied at a stoichiometric rate based on the TP of the slurry (Table 7.2). The mineral soils examined have a mean bulk density of 1.12 ± 0.15 g cm^{-3} in the containers used to calculate field capacity and for the purpose of selecting slurry application rate, it was assumed that land applied slurry only interacts with the upper 20 mm of soil. Studies have shown that the STP in the upper 20 mm of grassland soils tends to be higher than for the equivalent depth in tillage soils receiving the same manure. This is due to the absence of tilling, which ploughs the nutrients into the soil (Andraski et al., 2003). Although the peat had a significantly different bulk density, it was decided to apply the same rate to the peat. The containers were covered with para-film. Throughout this study, water was added intermittently to ensure that approximately 50% field capacity was always maintained.

After 1, 3, 6 and 9 mo, the DM and WEP of the wet soil was first determined. The remaining soil sample was air dried and crushed to pass a 2 mm sieve. Sub-samples were taken, dried at 40 °C for 72 h, and analysed for soil pH and Morgan’s P using Morgan’s extracting solution.

7.3.4. Statistical analysis

The data (Appendix G) were analysed as a factorial design with soil type, month and treatment as factors. All interactions were examined. Soil type was a blocking effect in this structure, but its interactions with the randomised factors were of interest. The interactions were interpreted in the first instance by testing simple effects and then making comparisons of means, with adjustment for multiplicity of testing. The GLIMMIX procedure of SAS 9.2 was used to fit the analysis model. This procedure allowed the addition of heterogeneous variance structures and a number of options for examining a large number of means. Residual checks were made to check the assumptions of the analysis method.

7.4. Results

7.4.1. Water extractable phosphorus

There was a significant interaction between soil type, month and treatment for WEP ($p<0.001$). The WEP of incubated soil samples at each sampling time is shown in Figure 7.3. The WEP of the soil-only treatments for the four mineral soils examined was lower after 1 mo of incubation than the WEP of the soil before the start of the experiment. This was in agreement with Kalbasi and Karthikeyan (2004) and Penn and Bryant (2006). This was likely due to the effect of drying and re-wetting, and breaking down of soil as a result of sieving (Penn and Bryant, 2006). In general, the WEP of the soil-only treatment did not vary significantly during the study for soils A, B and E. The WEP of soil C was significantly higher at the 6 mo sampling event than at any other time in the study. The WEP of soil D increased significantly between mo 1 and 3, and stayed steady for the remainder of the study. In contrast, the WEP of the peat soil increased initially as a result of incubation; however, there was no significant variation during the study.

Addition of slurry increased the WEP of soil compared to the soil-only treatment for all soils. This was in agreement with result of other studies (Kalbasi and Karthikeyan, 2004; Murphy, 2007). However, in general, these increases were not statistically significant. The WEP of soil A, when amended with slurry, was significantly different to the soil-only treatment at the 3 mo sampling event. There were also significant differences for soil B (at the 1 and 3 mo sampling times) and for soil D (mo 1) ($p<0.05$).

For the four mineral soils, alum-amended slurry reduced the average WEP of soil compared to the study control (average of 4 sampling events) by between 52 and 73%, lime by between 50 and 83%, PAC by between 21 and 64%, and $FeCl_3$ by between 0 and 38%. These reductions in WEP were not consistently statistically significant. After 1 mo of incubation, the WEP of alum-amended slurry was significantly different to the slurry-control for soil B (89%), soil C (98%) and soil D (94%). Lime addition was also effective at reducing WEP compared to the slurry-control and there were significant reductions after 1 mo for soils B (94%), C (98%) and D (97%) and after 3 mo for soils C (88%) and D (78%). Poly-aluminium chloride was less effective than alum or lime at reducing the WEP compared to the slurry-control with the only significant reductions occurring for soils C (81%) and D (54%) at the 1 mo sampling event. Ferric chloride was less effective than other amendments and much more variable: in soil C, WEP was significantly lower for soil which was mixed with $FeCl_3$ treated slurry than the slurry-control after 1 mo ($p<0.05$). After 3 mo, soils A and D were significantly different to the slurry-control ($p<0.05$). There were no significant differences between WEP of the slurry-control and the soil amended with chemically amended slurry at the 6 and 9 mo sampling event.

7.4.2. Soil test phosphorus

There was a significant interaction between soil type, month and treatment for the STP of the soil ($p<0.001$). The STP of incubated soil samples at each sampling time are shown in Figure 7.4. The STP of the soil only was observed to be much more stable than the WEP, and did not vary significantly during the course of the experiment. This was consistent with the results of Kalbasi and Karthikeyan (2004). The STP of soils which received dairy cattle slurry also remained relatively stable throughout the course of the experiment and although there were observed differences in STP between the control and soil-only treatments, these differences were not all statistically significant ($p<0.05$).

For the four mineral soils, during the first month, alum reduced average STP of soil amended with alum-treated slurry compared to the slurry-control by between 13 to 58%, lime by between 0 and 62%, and PAC by between 13 and 46%. Ferric chloride increased STP by up to 30% at 1 mo; this was in agreement with the findings of Kalbasi and Karthikeyan (2004). The STP of the soil amended with alum, lime, PAC and $FeCl_3$ was greater than the STP for each un-amended soil during the study. Chemical amendments did not have a significant effect on STP of the peat soil. These results indicated that there was no negative effect on plant available P with the use of a chemical amendment, with the exception of soil receiving $FeCl_3$ amended slurry, the STP of which was significantly different to the slurry-control for soil A (mo 9) and soil B (mo 6 and 9).

Tunney et al. (2000) found a strong association between STP (measured using Morgan's extracting solution) and DRP concentrations in overland flow in Irish grassland soils. This relationship can vary between different hydrological conditions (Kurz et al, 2005) and soil types (Daly et al., 2001). Daly et al (2001) examined 11 soils chosen to best represent important agricultural grassland soils in Ireland varying in parent material, drainage, soil type and soil chemical properties. Daly et al (2001) found that, although STP was an important factor controlling P desorption, soil type also affected levels of sorption and desorption. Regan et al. (2010) found a similar relationship for tillage soils.

7.4.3. Soil pH

There was a significant interaction between soil type, month and treatment for pH of soil ($p<0.001$). The pH of incubated soil samples at each sampling time are shown in Figure 7.5. The pH of the soil-only treatments did not significantly change as a result of the incubation experiment. Addition of dairy cattle slurry did not significantly alter soil pH for any of the soils examined. With the exception of $FeCl_3$ (soil A, mo 9) ($p<0.05$), none of the amendments examined appeared to significantly affect soil pH.

7.5. Discussion

7.5.1. WEP

The results of this study show that although there was an interaction with soil type, treatment and incubation duration, the WEP of soils mixed with chemically amended slurry was generally lower than the un-amended slurry-control. There were some instances where the WEP of soil which was incubated with $FeCl_3$ amended slurry was greater than the control. Although these increases were not statistically significant, this may indicate that $FeCl_3$ is not as stable as other amendments examined. These results indicate that chemical amendment may have beneficial impacts on the mitigation of long-term losses of P to surface runoff.

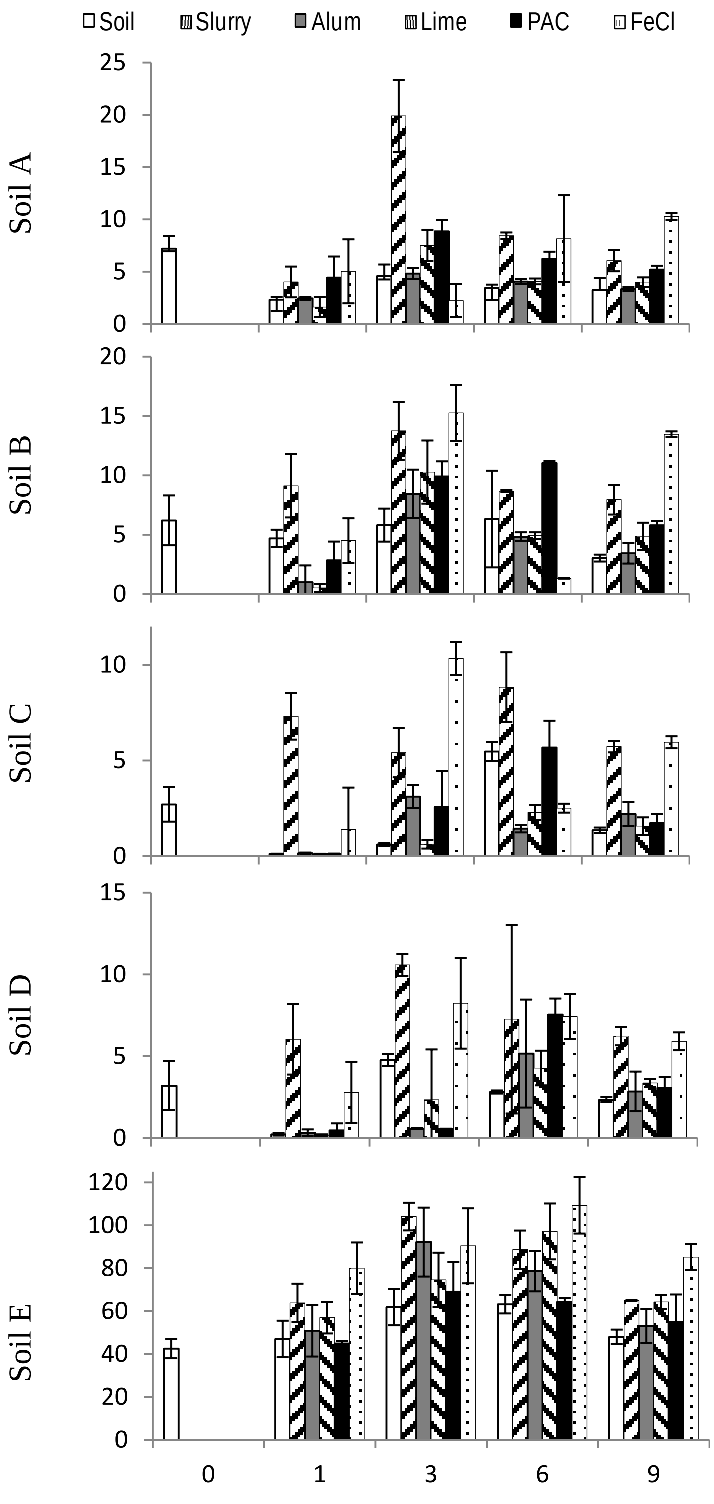


Figure 7.3 Water extractable phosphorus (WEP) of incubated soil samples at each sampling time (n=3)

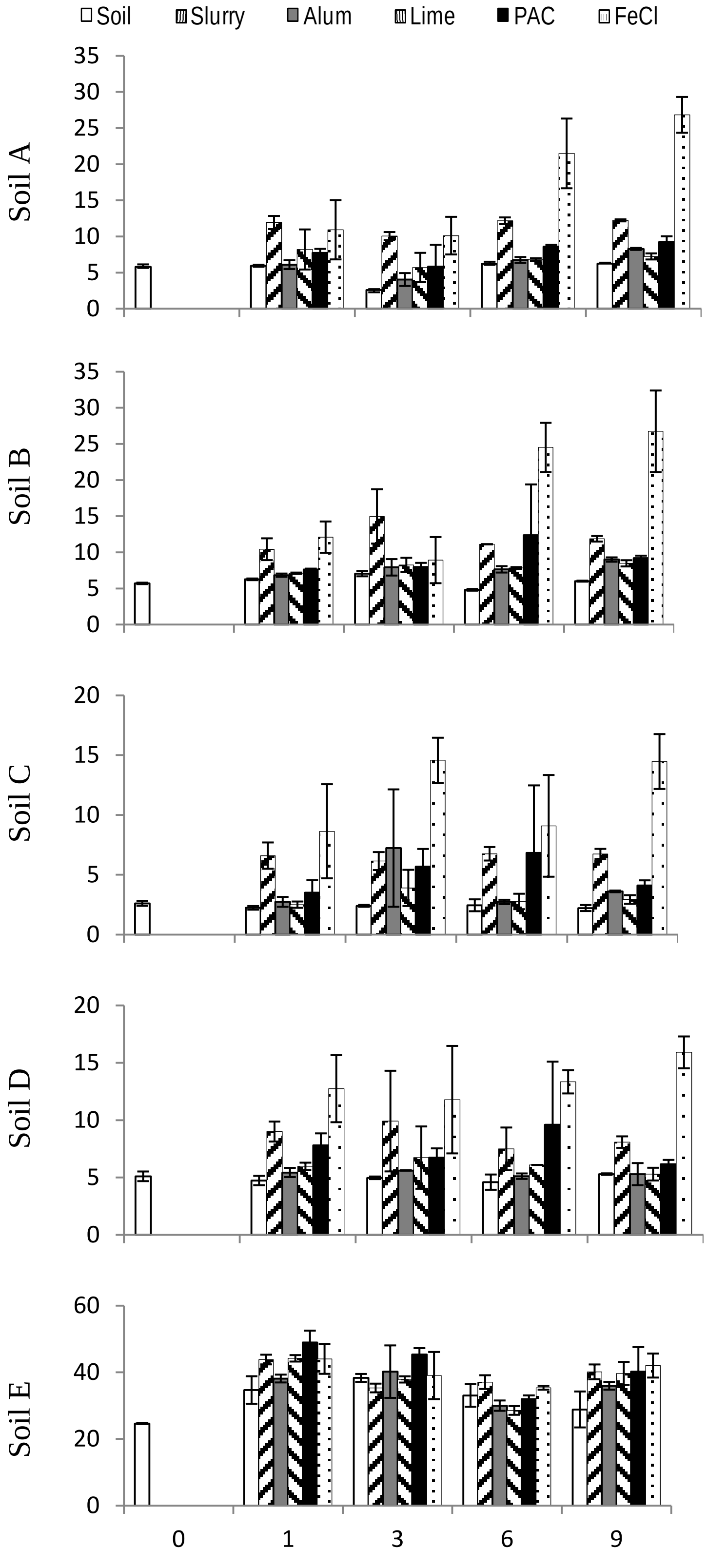


Figure 7.4 Soil test P of incubated soil samples at each sampling time (n=3)

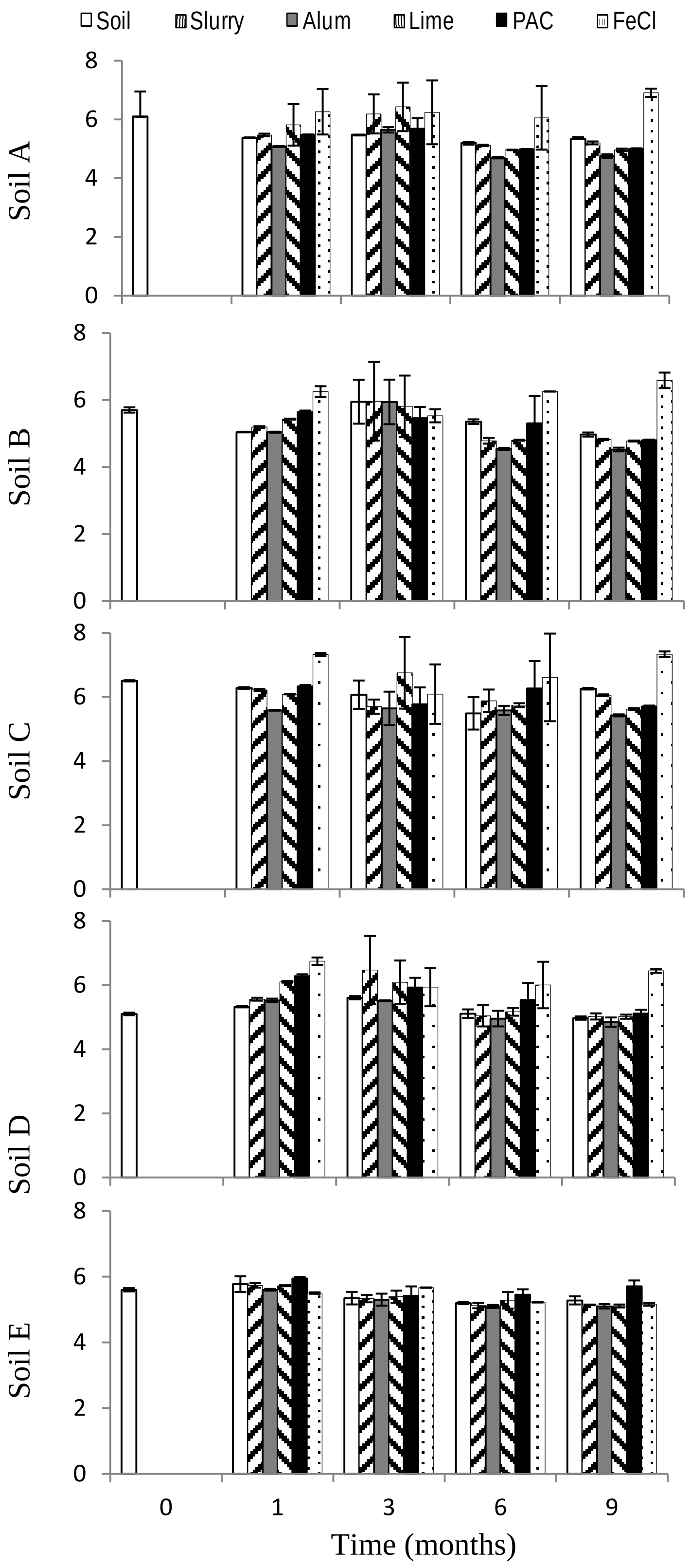


Figure 7.5 pH of incubated soil samples at each sampling time (n=3)

In a similar study, Kalbasi and Karthikeyan (2004) found that application of alum and $FeCl_3$ decreased P solubility in silt loam soil, while lime amendments increased WEP. This study found that Al-compounds (alum and PAC) reduced WEP in mineral soils. However, $FeCl_3$ was as effective as the Al compounds, and lime addition resulted in the greatest reduction in WEP. In this study, lime was applied at a higher rate (16:1 compared to 10:1 (Ca:TP) in the Kalbasi and Karthikeyan (2004) study) and this may explain the difference in effectiveness. Anderson et al. (1995) amended soils - with a history of receiving dairy manure - with calcium carbonate (with the slurry pH adjusted to 7.5), gypsum (0 to 100 g kg^{-1} soil), ferrous sulphate (0 to 1 g kg^{-1} as Fe) and alum (0 to 1 g kg^{-1} as Al) in an incubation experiment. Calcium carbonate effectiveness was limited to soils with $pH < 7.0$ and gypsum was effective over a broad range of manure loading, pH and redox conditions. Although Al and Fe amendments to soil increased P retention by 400% relative to an un-amended control, Anderson et al. (1995) acknowledged elevated costs associated with amendments and the potential for biological toxicity.

Runoff studies have been used to examine the addition of amendments to high STP soils to reduce P losses (McFarland et al, 2003; Novak and Watts, 2005; Brauer et al., 2005). Brauer et al. (2005) incorporated alum (127 kg Al ha^{-1}) and gypsum at two rates (349 and 1163 kg Ca ha^{-1}) into the upper 10 cm of a high STP soil on an annual basis for three years. Only the high gypsum treatment was observed to reduce WEP and STP values significantly during the study. A limited number of runoff studies have been carried out with chemical amendment of dairy cattle slurry (Elliot et al, 2005; Torbert et al, 2005) and swine slurry (Smith et al, 2001b), but little work has focused on the long-term effects of chemical amendments to slurry on the nutrient content of soil.

Although this study gives a good indication of the stability of these amendments in the soil used in this study, it did not examine the effect of chemical amendments on the rate of mineralisation of fixed P to soluble WEP following loss of soluble P in runoff, or in drainage water.

7.5.2. Soil test phosphorus

This study shows that one application of chemically amended slurry does not reduce plant availability of P in the soils examined in this study. In fact, in the case of $FeCl_3$, STP was significantly increased for certain soils at the end of the study. This indicates that chemical amendment of dairy cattle may be a short-term management practice to control P surplus on a farm, but does not pose a risk to plant availability of P. In addition, it validates the work of Kalbasi and Karthikeyan (2004) for a range of soils found in Ireland using commercially available amendments. The amendments were buffered by organics in the peat soil examined in this study. In a high OM soil with a pH of 5.5, there is no free Al available, and any metals in the amendments are immediately buffered by organics, which reduces their effectiveness in reducing P solubility. There is a need to examine the effect of repeated applications of slurry amended with chemical amendments on STP and other soil properties.

7.5.3. Soil pH

The pH of the mineral soils receiving $FeCl_3$-amended dairy cattle slurry was consistently higher than the slurry-control (Figure 7.5), background and all other treatments. The Cl^- in the $FeCl_3$ treatment may have replaced OH^- ions on the variable charge exchange sites in these soils, resulting in an increase in pH. This mechanism has been shown on HCl-treated mineral soils with low starting pH and free iron oxides (Wang and Yu, 1998). An elevated soil pH was not measured in soil E. This was likely due to the high buffering capacity and lack of free iron sites in this organic soil.

The national average soil pH is 5.5 for grasslands (Fay et al., 2007), which is below the recommended pH for optimum production of grass (6.3 for mineral soils and 5.5 for peat soils; Coulter and Lalor, 2008). Therefore, the soils examined in this study are representative of the pH range found in Ireland. The pH of a soil has a significant influence on nutrient availability (Tunney et al., 2010), and changes in pH can alter community composition and activity of microbes in soil (Sylvia et al., 2005). In addition, if the amendments adversely affect the microbes, the microbes could potentially change the pH by their activity. Therefore, pH was examined as a means of determining if the amendments had the potential to have a significant effect on soil microbiology.

7.6. Conclusions

This study found that although there were variations in the reductions in WEP of soil amended with dairy cattle slurry across soil types, the WEP of soil receiving chemically treated dairy cattle slurry was consistently, although not significantly, lower than the slurry-control. Soil test phosphorus and soil pH were not significantly affected by application of amended slurry, with the exception of $FeCl_3$ amended slurry in some instances. Therefore, chemical amendment of dairy cattle slurry as a short-term management practice to control P loss does not pose a risk to plant availability of soil. There is a need to examine long-term effects of repeated applications of chemically amended dairy cattle slurry to develop an understanding of how amendments affect soil P release processes over time.

7.7. Summary

This study indicates that the use of chemical amendment as a once-off management practice reduced WEP in soil compared to soil amended with slurry, but did not result in immobilisation of STP or have any significant effect on soil physical and chemical properties. Therefore, chemical amendment of dairy cattle slurry as a short-term management practice to control P loss does not pose an immediate risk to plant availability of soil.

Chapter 8 Conclusions and Recommendations

8.1. Overview

The objective of this study was to identify possible mitigation methods to prevent P loss to the environment during the land application of dairy cattle slurry. To address this, experiments were designed and conducted to evaluate the effectiveness, feasibility and pollution swapping potential of chemically amended dairy cattle slurry. The main conclusions of the study are now presented.

8.2. Conclusions

1. Experiments conducted at laboratory micro- and meso-scale, and micro plot-scale showed that chemical amendment was very successful in reducing incidental losses of DRP, TP, PP, TDP, DUP and SS from land-applied slurry. The results of the study demonstrate that PAC was the most effective amendment for decreasing DRP losses in runoff following slurry application, while alum was the most effective for TP and PP reduction. Incidental loss of metals (Al, Ca and Fe) from chemically amended dairy cattle slurry was below the MAC for receiving waters.

2. Although these treatments are expensive, they may be feasible if used strategically to mitigate P loss from dairy slurry in critical source areas within a farm.

3. The results of this study show that even with chemical amendment, P concentration in runoff was above the MAC. Therefore, amendments may not be

the best option for minimising incidental P losses, as timing of applications may be just as effective at controlling incidental P losses and may be much more cost effective.

4. This study showed that P mitigating amendments can result in pollution swapping. The amendments selected for recommendation for further study are, from best to worst, PAC, alum and lime (Table 8.1). In addition, at the current cost of treatment, the increase in fertiliser value of the slurry due to some treatments is not sufficient to offset the cost of treatment. In this study, there was no significant effect of any amendment, with the exception of charcoal, of slurry on GWP caused by the land application dairy cattle slurry.

5. Although there were variations in the reductions in WEP of soil amended with dairy cattle slurry across soil types, the WEP of soil receiving chemically treated dairy cattle slurry was consistently, although not significantly, lower than the slurry-control. Soil test phosphorus and soil pH were not significantly affected by the application of amended slurry, with the exception of $FeCl_3$-amended slurry in some instances. Therefore, chemical amendment of dairy cattle slurry as a short-term management practice to control P loss does not pose a risk to plant availability of soil.

Table 8.1 Summary of feasibility of amendments (adapted from Chapter 3). Marks for feasibility, pollution swapping, incubation study and plot study are from 1 to 5. 1 = best; 5 = worst.

Chemical	Agitator score P	Pollution swapping	Incubation study	Plot	Combined feasibility score	Notes
Alum	1	4	1	1	8	Risk of effervescence Risk of release of H_2S due to anaerobic conditions and reduced pH Cheap and used widely in water treatment Reduced ammonia emissions
$AlCl_3$ (PAC)	2	1	3	2	7	No risk of effervescence (Smith et al., 2004) $AlCl_3$ increased handling difficulty Expensive Reduced ammonia emissions
$FeCl_2$ ($FeCl_3$)	3	3	4	4	14	Potential for Fe bonds to break down in anaerobic conditions Increased release of N_2O Reduced ammonia emissions Not examined in plot study
$Ca(OH)_2$	4	2	2	3	11	Increased NH_3 loss Strong odour Hazardous substance Not effective in plot study

8.3. Recommendations for future work

1. This work indicates that if amendments are to be implemented, extensive catchment-scale experiments, carried out over a number of years, are necessary to examine how amendments affect N leaching, plant availability of P, soil microbiology and structure, metal build-up in the soil, long-term release of P to runoff, gaseous emissions and pollution swapping. Such work should use land spreading equipment at farm-scale.

2. These results suggest that chemical amendment of dairy cattle slurry with PAC could be used to control P solubility and thus reduce incidental P losses from soils

receiving dairy cattle slurry without adversely affecting metal and N losses. Future work must examine the long-term stability of metal-to-P bonds formed as a result of chemical amendment of dairy cattle slurry following land application. There is a need to examine the use of chemical amendments to slurry under a wide range of conditions.

3. Results show that a once-off application of any of the chemical amendments examined will not result in a significant change in chemical and chemical properties, an increase in GHG emissions, a release of metals to runoff, or significant pollution swapping. It is, however, critical that the long-term effect of repeated applications of amendments on STP, soil pH, soil WEP, soil microbiology and macro-biology be examined.

4. The results of the gas experiment indicated that if a biochar could be engineered to sequester P as effectively as alum and PAC, it would be the ideal amendment, as charcoal has the potential to dramatically reduce GHG emissions.

8.4. Context

Ireland has committed to meeting the requirements of the European Union Water Framework Directive (EU WFD; 2000/60/EC, OJEC, 2000) to achieve at least ‘good status’ of all surface and groundwater by 2015. It is expected that the current programmes of measures (POM) will not reduce P losses sufficiently within this timeframe and that that substantial measures will be required to fulfil these obligations. While current practices are effective, there will be a time-lag before current changes in farming practices will result in an observable reduction in nutrient losses and reduction in risk to water quality. This study showed that amendments are effective and that there is no major risk of pollution swapping associated with alum and PAC. This is a significant finding as there is now potential to use amendments strategically, in combination with existing programme of measures (POM), to mitigate P losses. The next step will be to examine the use of chemical amendments at catchment-scale.

In future, farm nutrient management in Ireland must focus on examining all farms within a catchment and identifying areas which pose the greatest risk. It is hoped that there will be economic incentives given to farmers to reduce nutrient losses. It is possible that P mitigating methods, such as chemical amendment of dairy cattle slurry, may be used strategically within a catchment to bind P in cow and pig slurries.

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APPENDIX

Appendix A List of publications

JOURNAL PAPERS (Accepted)

Brennan RB, Fenton O, Rodgers M, Healy MG. 2011. Evaluation of chemical amendments to control phosphorus losses from dairy slurry. Soil Use and Management 27: 238-246.

Brennan RB, Fenton O, Grant J, Healy MG. 2011. Impact of chemical amendment of dairy cattle slurry on phosphorus, suspended sediment and metal loss to runoff from a grassland soil. Science of the Total Environment 409(23):5111-8.

MANUCRIPTS IN PREPARATION

Brennan RB, Fenton O, Healy MG, Lanigan G. Effect of chemical amendment of dairy cattle slurry on greenhouse gas and ammonia emissions (Submitted: Biological Engineering)

Brennan RB, Fenton O, Grant J, Healy MG. Rainfall simulation study investigating the effect of chemical amendment of dairy cattle slurry on runoff characteristics and nutrient loss from grassland plots (Target journal: Science of the Total Environment).

Brennan RB, Fenton O, Grant J, Healy MG. The long term impact of adding chemically amended dairy slurry to WEP, soil test phosphorus and pH in five grassland soils (Submitted: Journal of Environmental Quality).

INTERNATIONAL CONFERENCE PAPERS

Brennan RB, Fenton O, Healy MG. 2010. Chemical amendment of dairy cattle slurry for control of phosphorus in runoff from grasslands. A05 symposium on emerging technologies to remove phosphorus. ASA-CSA-SSSA International Meetings, Long Beach, CA. 31 October - 4 November, 2010 (*Oral presentation*).

Brennan RB, Fenton O, Healy MG. 2010. Evaluation of chemical amendments to control soluble phosphorus losses from dairy cattle slurry. (Eds. Turtola E, Ekholm P, Chardon W). In: MTT Science 10. Novel methods for reducing agricultural nutrient loading and eutrophication: Meeting of COST 869, 14-16 June, Jokioinen, Finland. p. 18 (*Oral presentation*).

NATIONAL CONFERENCE PAPERS

Brennan RB, Healy MG, Lanigan G, Fenton O. 2011. Chemical amendment of dairy cattle slurry for control of P in runoff from grasslands. Walsh Fellowship Seminars. 12 July, RDS, Co Dublin (*Poster presentation*).

Brennan RB, Fenton O, Grant J, Healy MG. 2011. Mitigating incidental DRP losses from land application of dairy cattle slurry using chemical amendments. Agricultural Research Forum Conference. 14-15 March, Tullamore, Co. Offaly (*Oral presentation*).

Brennan RB, Fenton O, Rodgers M, Healy MG. 2010. Chemical amendment of dairy cattle slurry for control of phosphorus in runoff from grasslands. SEGH 2010. 27 June - 2 July, 2010. National University of Ireland, Galway (*Oral presentation*).

Brennan RB, Fenton O, Rodgers M, Healy MG. 2010. The addition of chemical amendments to dairy cattle slurry for the control of phosphorus in runoff from grasslands. BSAS/WPSA/Agricultural Research Forum Conference. Queen's University, Belfast. 12-14 April, 2010 (*Oral presentation*).

Brennan RB, Fenton O, Rodgers M, Healy MG. 2010. Chemical amendment of dairy cattle slurry to reduce P loss from grasslands. 19th World Congress of Soil Science. Brisbane, Australia, 1-6 August, 2010 (*Poster presentation*).

Appendix B Results of agitator test

Notation used in Appendix:

DRP, dissolved reactive phosphorus
Soil only – grassed soil sample
Slurry – slurry control
High, low and medium are rates as described in chapter 3
Alum, aluminium sulphate
Wtr dry, sieved and dried Al-WTR
Wtr wet, sludge Al-WTR
V_w; represents volume of sample removed for analysis
V_c, cumulative volume of sample removed during the experiment
P is the concentration of P in overlying water
P_{adj} is the P concentration adjusted to take account of the change in volume of the overlying water during the experiment
$AlCl_3$, aluminium chloride
$FeCl_2$ ferric chloride
FGD, flue gas desulphurisation by-product

Table B.1 Results of preliminary batch study

	Amendment g/kg slurry	pH	DRP (mg/L)	% reduction soluble P	Comment
WTR	0	7.3	23.9		Effective
	20	7.5	17.1	28.5	
	50	7.6	13.29	44.4	
	100	7.7	11.6	51.5	
	150	7.84	5.6	76.6	
	300	7.95	0.5	97.9	
$FeCl_2$	0	7.4	24.4		Effective
	1.6	7.2	5.6	77	
	5.5	6.84	0.33	98.6	
	10	6.6	0.1	99.6	
	20	6.2	0.05	99.8	
$FeSO_4$	0	7.38	20.4		Effective
	1	7.23	18	11.8	
	5	6.98	11.6	43.1	
	10	6.8	0.7	96.6	
	20	6.56	0.13	99.4	
$MgCl_2$	0	7.38	14.943		Not effective
	1	7.4	2.612	82.5	
	5	7.33	2.171	85.5	
	10	7.24	3.081	79.4	
	20	6.96	3.305	77.9	
	50	6.28	7.673	48.7	
$Ca(OH)_2$	0	7.5	31.707		Effective
	1	8.2	12.221	61.5	
	5	10.1	10.499	66.9	
	10	12.5	3.156	90	
	20	12.6	1.057	96.7	
	50	12.7	0.707	97.8	

CaO	0	7.4	22.681		Effective
	1	7.66	16.323	28	
	5	7.93	12.207	46.2	
	10	8.12	9.926	56.2	
	20	8.42	2.481	89.1	
	50	12.63	0.684	97	
$Al_2(SO_4)_3$	0	7.48	20.941		Effective
	1	6.64	17.457	16.6	
	5	4.37	5.128	75.5	
	10	3.89	5.13	75.5	
	20	3.55	2.971	85.8	
	50	2.97	0.939	95.5	
Fly ash	0	7.3	18.412		Effective
	10	7.43	16.953	7.9	
	20	7.49	13.387	27.3	
	50	7.56	15.182	17.5	
	100	7.62	9.331	49.3	
	150	7.72	5.385	70.8	
	300	7.76	2.926	84.1	
	400	7.92	1.38	92.5	
$Al_2(SO_4)_3$	0	7.31	24.512		Effective
	0.3	7.02	19.115	22	
	0.5	6.89	11.564	52.8	
	1	6.63	3.933	84	
	1.5	6.21	1.357	94.5	
	2	5.73	0.375	98.5	
Bottom ash	0	7.33	14.263		Not effective
	10	7.4	14.067	1.4	
	20	7.44	16.088	-12.8	
	50	7.52	14.185	0.5	
	100	7.63	15.203	-6.6	
	150	7.74	14.626	-2.5	
	300	7.79	13.654	4.3	
	400	7.92	13.325	6.6	
Ferriox	0	7.43			Effective
	1	7.41	20.921	9.8	
	5	7.32	18.866	37.6	
	10	7.17	13.057	82.2	
	20	6.69	3.729	98	
	50	5.41	0.415	99.5	
Septiox	0	7.34			Effective
	1	7.39	22.764	18.7	
	5	7.4	18.516	16.8	

	10	7.47	18.949	22.5	
	20	7.48	17.643	27.8	
	50	7.33	16.432	57.6	
FGD	0	7.13			Effective
	10	7.21	22.51	15.9	
	20	7.27	18.922	19.8	
	50	7.31	18.05	38.5	
	100	7.34	13.833	56.2	
	150	7.37	9.856	71.4	
	300	7.39	6.436	90.2	
	400	7.5	2.203	96.1	
Charcoal	100	7.32	18.57	8	Not effective
	0	7.37	20.185	0	
	2	7.34	16	20.7	
	10	7.45	18.7	7.4	
	50	7.5	26	-28.8	
Poly-aluminium chloride	0	7.18	20.921		Effective
	0.3	7.22	18.866	10	
	0.5	7.3	13.057	38	
	1	7.36	3.729	82	
	1.5	3.43	0.415	98	
	2	7.48	0.103	100	

Note: The rates used in this experiment were based on values found in the literature. The most effective amendments were selected and examined in the agitator test. There are some exceptions to this rule: Calcium oxide (CaO) was not chosen as it is hazardous. Ferric sulphate ($FeSO_4$) was not examined as it resulted in very strong smell. In addition commercial products Ferriox and Septiox were not examined further as they were expensive for this purpose.

Table B.2 Langmuir model applied to amendments which were effective in preliminary experiment and selected for use in agitator test (Chapter 3).

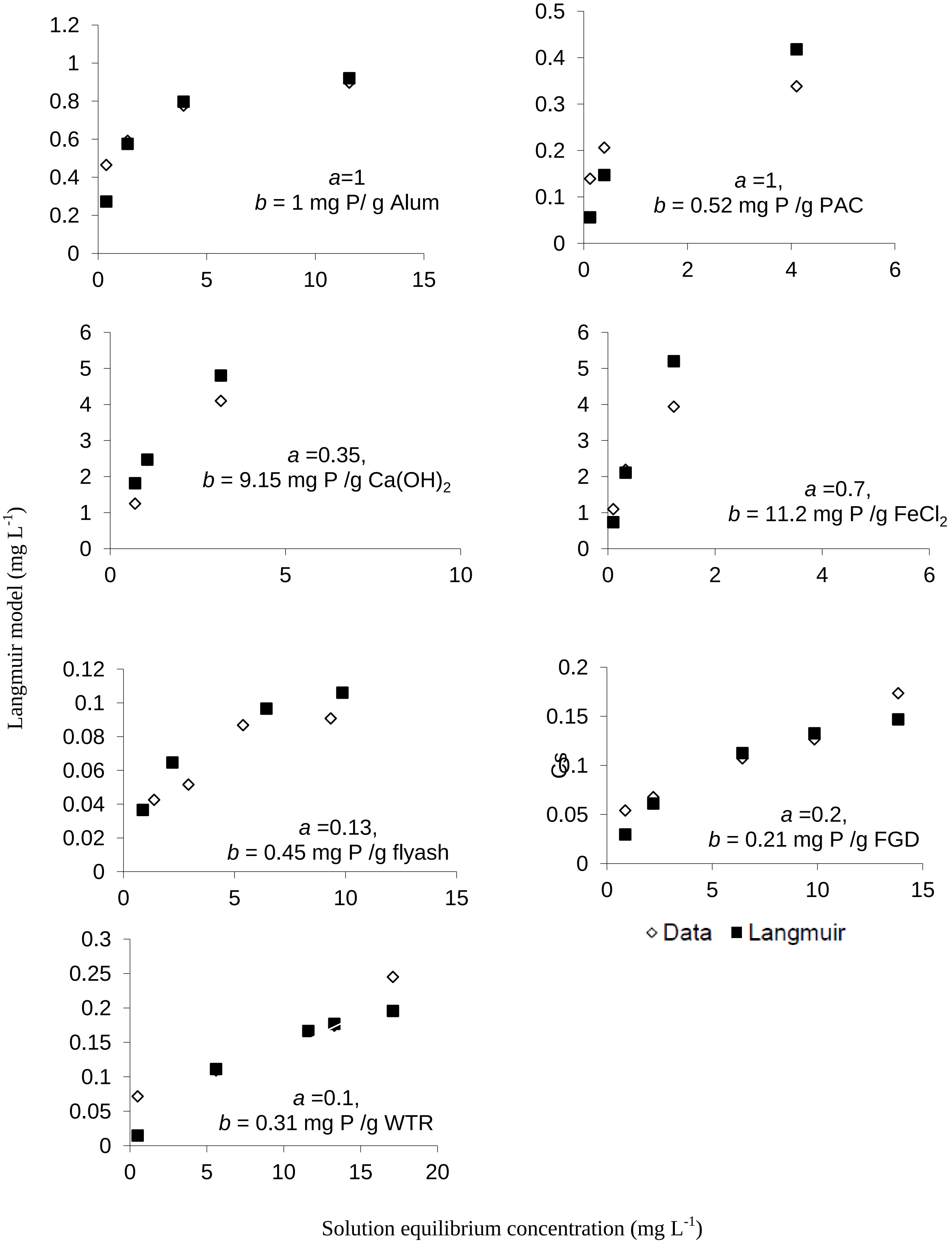
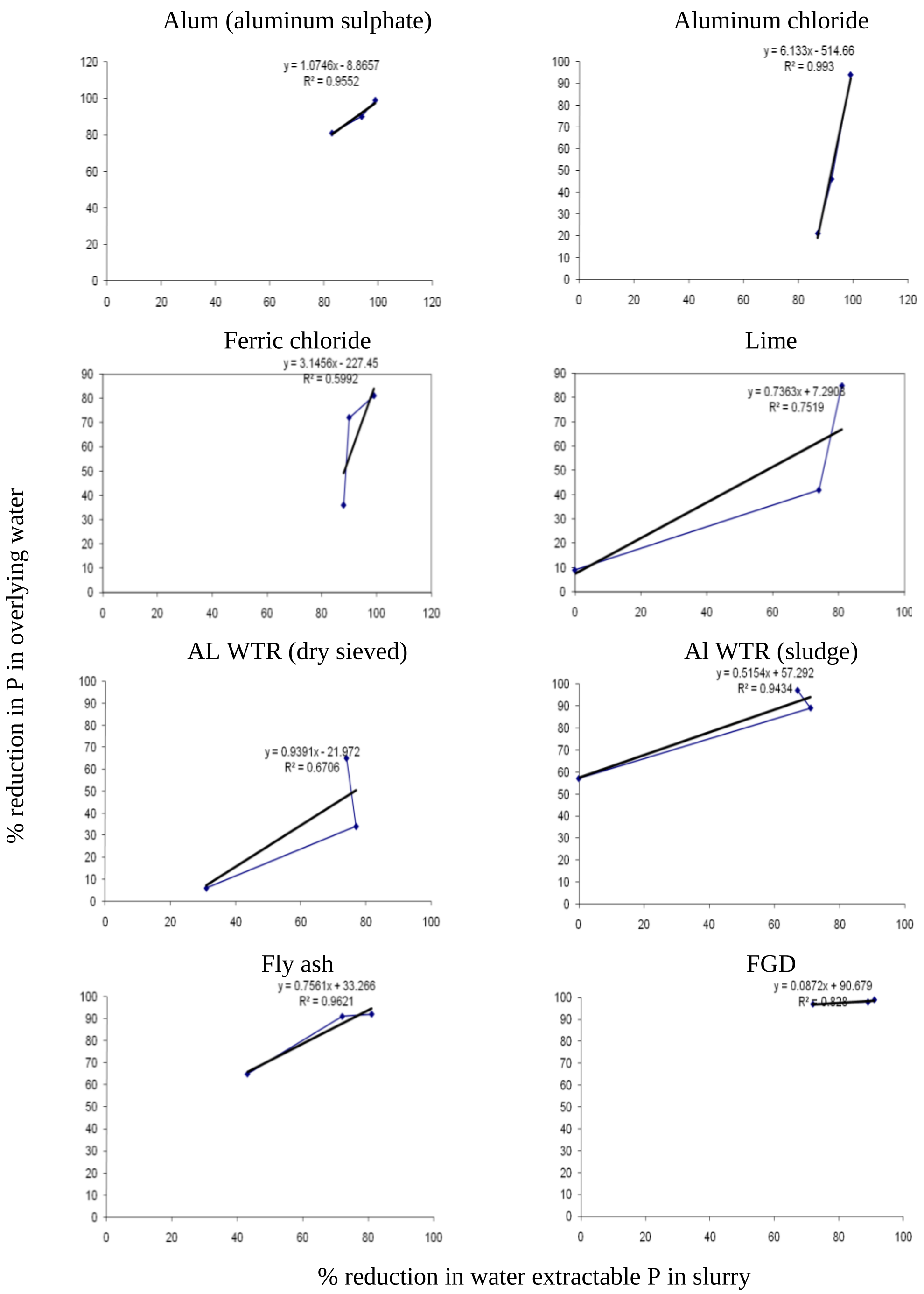


Table B.3 Relationship between percentage reductions in dissolved reactive phosphorus and percentage reduction in water extractable phosphorus of slurry (Chapter 3).


Alum (aluminum sulphate)

Aluminum chloride

Ferric chloride

Lime

AL WTR (dry sieved)

Al WTR (sludge)

Fly ash

FGD

Table B.4 Results of agitator test

		Control soil only				**Sample 1**	
		Volume of water added ml		500	ml		
Soil only	Time (h)		V_w	Vc	P	Padj	Mass P
			ml	ml	µg/l	µg/l	mg/m2
	0	2	2	0	0	0	24
	0.25	2	4	203	0.2	12.8	205
	0.5	4	8	240	0.2	15	334
	1	4	12	277	0.3	17.2	301
	2	4	16	282	0.3	17.4	367
	4	4	20	347	0.3	21.2	401
	8	4	24	363	0.3	22	448
	12	4	28	382	0.4	23	479
	24	4	32	379	0.4	22.6	460
Slurry	0		0	0	0	0	0
	0.25	4	4	3100	3.1	195.8	3700
	0.5	4	8	4100	4	256.8	4200
	1	4	12	5800	5.7	360.4	6400
	2	4	16	7600	7.4	468.3	8800
	4	4	20	9900	9.5	605	10600
	8	4	24	10700	10.2	648.5	13100
	12	4	28	10900	10.3	655.1	11000
	24	4	32	10900	10.2	649.5	11000
	36	4	36	10400	9.7	614.4	10200
		36		10900			13100
low alum	0		0	0	0	0	0
	0.25	4	4	324	0.3	20.5	487
	0.5	4	8	563	0.6	35.3	785
	1	4	12	709	0.7	44.1	1162
	2	4	16	454	0.4	28	856
	4	4	20	973	0.9	59.5	2025
	8	4	24	1042	1	63.2	2325
	12	4	28	1086	1	65.3	2470
	24	4	32	1163	1.1	69.3	2669
		32				69.3	
high alum	0		0	0	0	0	0
	0.25	4	4	549	0.5	34.7	500
	0.5	4	8	770	0.8	48.2	795
	1	4	12	1195	1.2	74.3	1295
	2	4	16	1512	1.5	93.2	1812
	4	4	20	1781	1.7	108.8	1981

	8	4	24	1943	1.8	117.8	2143
	12	4	28	2222	2.1	133.5	2348
	24	4	32	2721	2.5	162.1	2721
		32				162.1	
med alum	0		0	0	0	0	0
	0.25	4	4	199.054	0.2	12.6	269.079
	0.5	4	8	236.702	0.2	14.8	335.064
	1	4	12	325.291	0.3	20.2	429.671
	2	4	16	497.673	0.5	30.7	647.708
	4	4	20	592.011	0.6	36.2	760.275
	8	4	24	609.977	0.6	37	835
	12	4	28	831.11	0.8	49.9	1005.124
	24	4	32	901	0.8	53.7	984
		32				53.7	
low lime	0		0	0	0	0	0
	0.25	4	4	2859	2.8	180.6	2329
	0.5	4	8	4293	4.2	268.9	3112
	1	4	12	5730	5.6	356	4454
	2	4	16	7050	6.8	434.5	6194
	4	4	20	8485	8.1	518.6	8118
	8	4	24	9986	9.5	605.2	9888
	12	4	28	9513	9	571.7	8604
	24	4	32	12158	11.4	724.5	9960
		32				724.5	
med lime	0		0	0	0	0	0
	0.25	4	4	1438	1.4	90.8	1031
	0.5	4	8	1698	1.7	106.4	1500
	1	4	12	1739	1.7	108.1	1987
	2	4	16	1888	1.8	116.3	2512
	4	4	20	2184	2.1	133.5	2360
	8	4	24	2268	2.2	137.5	2419
	12	4	28	2912	2.7	175	2059
	24	4	32	3066	2.9	182.7	2990
		32				182.7	
high lime	0		0	0	0	0	0
	0.25	4	4	304	0.3	19.2	514
	0.5	4	8	365	0.4	22.9	670
	1	4	12	513	0.5	31.9	1154
	2	4	16	746	0.7	46	544

	4	4	20	674	0.6	41.2	1317
	8	4	24	796	0.8	48.2	1443
	12	4	28	2245	2.1	134.9	2289
	24	4	32	1359	1.3	81	2163
		32				134.9	
low dry wtr	0		0	0	0	0	0
	0.25	4	4	2016	2	127.3	2450
	0.5	4	8	2282	2.2	143	2642
	1	4	12	2670	2.6	165.9	2771
	2	4	16	3015	2.9	185.8	2919
	4	4	20	6672	6.4	407.8	5446
	8	4	24	6975	6.6	422.7	5570
	12	4	28	6920	6.5	415.9	5603
	24	4	32	8353	7.8	497.7	8058
		32				497.7	
med dry wtr	0		0	0	0	0	0
	0.25	4	4	626	0.6	39.5	433
	0.5	4	8	869	0.9	54.4	456
	1	4	12	819	0.8	50.9	673
	2	4	16	1701	1.6	104.8	877
	4	4	20	1887	1.8	115.3	1024
	8	4	24	1885	1.8	114.2	1066
	12	4	28	1795	1.7	107.9	1074
	24	4	32	4814	4.5	286.9	1760
		32				286.9	
high dry wtr	0		0	0	0	0	0
	0.25	4	4	393	0.4	24.8	224
	0.5	4	8	574	0.6	36	333
	1	4	12	419	0.4	26	355
	2	4	16	411	0.4	25.3	336
	4	4	20	361	0.3	22.1	287
	8	4	24	281	0.3	17	242
	12	4	28	295	0.3	17.7	236
	24	4	32	2221	2.1	132.3	3759
		32				132.3	
low wet wtr	0		0	0	0	0	0
	0.25	4	4	4345	4.3	274.4	6256
	0.5	4	8	4305	4.2	269.7	6258
	1	4	12	5720	5.6	355.4	8423

	2	4	16	7610	7.4	469	10748
	4	4	20	9656	9.3	590.1	11080
	8	4	24	11359	10.8	688.4	13012
	12	4	28	11722	11.1	704.5	13265
	24	4	32	13090	12.3	780	13553
		32				780	
med wet wtr	0		0	0	0	0	0
	0.25	4	4	2655	2.6	167.7	3482
	0.5	4	8	1268	1.2	79.4	1584
	1	4	12	2361	2.3	146.7	2749
	2	4	16	2739	2.7	168.8	1331
	4	4	20	2709	2.6	165.6	1924
	8	4	24	2313	2.2	140.2	2657
	12	4	28	1973	1.9	118.6	2145
	24	4	32	2148	2	128	2577
		32				168.8	
high wet wtr	0		0	0	0	0	0
	0.25	4	4	3591	3.6	226.8	3797
	0.5	4	8	2604	2.6	163.1	2385
	1	4	12	3354	3.3	208.4	3046
	2	4	16	3857	3.7	237.7	3409
	4	4	20	4027	3.9	246.1	3471
	8	4	24	3536	3.4	214.3	3130
	12	4	28	3151	3	189.4	2865
	24	4	32	2233	2.1	133.1	2063
		32				246.1	
Flyash high	0		0	0	0	0	0
	0.25	4	4	1029	1	65	1411
	0.5	4	8	2461	2.4	154.2	780
	1	4	12	2102	2.1	130.6	2191
	2	4	16	3045	2.9	187.6	3094
	4	4	20	2918	2.8	178.3	3108
	8	4	24	1825	1.7	110.6	2094
	12	4	28	1639	1.5	98.5	1639
	24	4	32	1426	1.3	85	1797
		32				187.6	
Flyash medium	0		0	0	0	0	0
	0.25	4	4	352	0.3	22.2	1391
	0.5	4	8	459	0.5	28.8	2277
	1	4	12	676	0.7	42	2001

	2	4	16	898	0.9	55.3	2198
	4	4	20	1143	1.1	69.9	2283
	8	4	24	1391	1.3	84.3	2563
	12	4	28	1399	1.3	84.1	2525
	24	4	32	1661	1.6	99	3171
		32				99	
Flyash low	0		0	0	0	0	0
	0.25	4	4	1965	1.9	124.1	2243
	0.5	4	8	2790	2.7	174.8	3016
	1	4	12	3240	3.2	201.3	3780
	2	4	16	4181	4	257.7	4083
	4	4	20	4732	4.5	289.2	4343
	8	4	24	5122	4.9	310.4	4641
	12	4	28	6888	6.5	413.9	5725
	24	4	32	7967	7.5	474.7	6640
		32				474.7	
FeCl low	0		0	0	0	0	0
	0.25	4	4	485	0.5	30.7	0
	0.5	4	8	610	0.6	38.3	819
	1	4	12	759	0.7	47.2	934
	2	4	16	1002	1	61.8	1109
	4	4	20	1331	1.3	81.4	1289
	8	4	24	1750	1.7	106.1	1598
	12	4	28	1945	1.8	116.9	1634
	24	4	32	2398	2.2	142.9	1556
		32				142.9	
$FeCl_2$ high	0		0	0	0	0	0
	0.25	4	4	428	0.4	27.1	73
	0.5	4	8	442	0.4	27.7	96
	1	4	12	430	0.4	26.7	107
	2	4	16	519	0.5	32	103
	4	4	20	367	0.4	22.5	97
	8	4	24	123	0.1	7.5	4.152
	12	4	28	57	0.1	3.5	14
	24	4	32	2	0	1.4	18
		32				32	
$FeCl_2$ med	0		0	0	0	0	0
	0.25	4	4	418	0.4	26.5	601
	0.5	4	8	552	0.5	34.6	732

	1	4	12	797	0.8	49.5	943
	2	4	16	1056	1	65.1	1086
	4	4	20	1519	1.5	92.8	1090
	8	4	24	1680	1.6	101.8	968
	12	4	28	1742	1.6	104.7	939
	24	4	32	1889	1.8	112.6	821
		32				112.6	
$AlCl_3$ low	0		0	0	0	0	0
	0.25	4	4	645	0.6	40.8	192
	0.5	4	8	914	0.9	57.2	360
	1	4	12	1124	1.1	69.8	448
	2	4	16	1536	1.5	94.7	700
	4	4	20	1730	1.7	105.7	860
	8	4	24	1809	1.7	109.7	1006
	12	4	28	1851	1.7	111.2	998
	24	4	32	2454	2.3	146.2	949
		32				146.2	
$AlCl_3$ med	0		0	0	0	0	0
	0.25	4	4	367	0.4	23.1	365
	0.5	4	8	553	0.5	34.7	415
	1	4	12	735	0.7	45.7	423
	2	4	16	932	0.9	57.4	519
	4	4	20	1063	1	65	606
	8	4	24	1055	1	63.9	713
	12	4	28	1085	1	65.2	745
	24	4	32	1037	1	61.8	811
		32				65.2	
$AlCl_3$ high	0		0	0	0	0	0
	0.25	4	4	105	0.1	6.7	96
	0.5	4	8	126	0.1	7.9	122
	1	4	12	142	0.1	8.8	148
	2	4	16	123	0.1	7.6	182
	4	4	20	100	0.1	6.1	189
	8	4	24	13	0	0.8	83
	12	4	28	16	0	0.9	30
	24	4	32	15	0	0.9	77
		32				8.8	
FGD high	0		0	0	0	0	0
	0.25	4	4	269	0.3	17	185

	0.5	4	8	348	0.3	21.8	281
	1	4	12	395	0.4	24.5	318
	2	4	16	482	0.5	29.7	467
	4	4	20	624	0.6	38.1	532
	8	4	24	809	0.8	49	679
	12	4	28	888	0.8	53.4	722
	24	4	32	880	0.8	52.4	744
		32				53.4	
FGD med	0		0	0	0	0	0
	0.25	4	4	354	0.4	22.4	287
	0.5	4	8	465	0.5	29.1	432
	1	4	12	602	0.6	37.4	506
	2	4	16	755	0.7	46.5	744
	4	4	20	942	0.9	57.6	976
	8	4	24	1206	1.1	73.1	1450
	12	4	28	1265	1.2	76	1378
	24	4	32	1445	1.4	86.1	1459
		32				86.1	
FGD low	0		0	0	0	0	0
	0.25	4	4	379	0.4	23.9	1269
	0.5	4	8	420	0.4	26.3	1634
	1	4	12	620	0.6	38.5	2018
	2	4	16	850	0.8	52.4	2477
	4	4	20	1282	1.2	78.4	3272
	8	4	24	1662	1.6	100.7	3611
	12	4	28	1938	1.8	116.5	4516
	24	4	32	2359	2.2	140.6	4815
		32				140.6	

	Sample 2		**Sample 3**				**Mean of adjusted values**	
	500	ml		500	ml			
Soil only	Padj	Mass P	P	Padj	Mass P		Mass P	
	µg/l	mg/m2	mg/l	mg/l	mg/m2	mg/m2	dev	t^(1/2)
	0.023904	1.5	0		0		0.88	0
	0.20	13	66	0.07	4.17	6.17	5.03	0.25
	0.33	20	79	0.08	4.95	10.98	8.08	0.5
	0.29	19	110	0.11	6.83	14.99	6.46	1
	0.36	23	131	0.13	8.07	14.72	7.37	2
	0.38	25	162	0.16	9.9	17.91	7.66	4
	0.43	27	171	0.16	10.36	18.96	8.6	8

	0.45	29	203	0.19	12.2	20.77	8.41	12
	0.43	27	174	0.16	10.37	20.58	8.78	24
Slurry	0	0	0	0	0		0	0
	4	234	5200	5.16	328.39	252.61	68.31	0.25
	4	263	6500	6.4	407.18	309.04	85.05	0.5
	6	398	7700	7.52	478.43	412.16	60.35	1
	9	543	9500	9.2	585.44	532.03	59.22	2
	10	647	9500	9.12	580.6	611.15	34.03	4
	12	794	11800	11.23	715.15	719.19	72.81	8
	10	661	13000	12.27	781.26	699.13	71.19	12
	10	655	10400	9.73	619.71	641.56	19.15	24
	9	603	10500	9.74	620.32	612.45	9.02	36
			13000			719.19		
low alum	0.00	0	0	0	0		0	0
	0.48	30	407	0.4	24.72	25.31	5.17	0.25
	0.77	49	563	0.55	33.91	39.45	8.45	0.5
	1.13	72	812	0.79	48.49	54.91	15.13	1
	0.83	52	1147	1.11	67.91	49.55	20.16	2
	1.94	124	1585	1.52	93.03	92.09	32.16	4
	2.21	141	1258	1.2	73.2	92.42	42.29	8
	2.33	148	1720	1.62	99.21	104.3	41.82	12
	2.50	159	2340	2.18	133.77	120.7	46.28	24
		159			133.77	120.7		0
high alum	0.00	0	0	0	0		0	0
	0.49	22	496	0.49	31.32	29.34	6.55	0.25
	0.78	35	877	0.86	54.94	45.93	10.35	0.5
	1.25	56	1493	1.46	92.77	74.25	18.52	1
	1.72	77	2011	1.95	123.93	98.05	23.81	2
	1.86	83	2371	2.28	144.9	112.33	30.98	4
	1.99	89	2429	2.31	147.21	117.97	29.13	8
	2.16	96	2500	2.36	150.24	126.68	27.63	12
	2.47	110	2524	2.36	150.4	140.9	27.25	24
		110			150.4	140.9		0
med alum	0.00	0	0	0	0		0	0
	0.26	17	169	0.17	10.68	13.41	3.24	0.25
	0.32	15	217	0.21	13.6	14.37	0.67	0.5
	0.41	19	277	0.27	17.23	18.71	1.49	1
	0.62	28	385	0.37	23.71	27.44	3.51	2
	0.72	33	502	0.48	30.71	33.14	2.79	4
	0.79	35	675	0.64	40.91	37.77	2.83	8
	0.95	42	710	0.67	42.68	44.97	4.32	12

	0.92	41	733	0.69	43.68	46.14	6.67	24
		42			43.68	46.14		0
low lime	0.00	0	0	0	0		0	0
	2.31	147	3730	3.7	235.56	187.73	44.67	0.25
	3.06	194	4761	4.68	298.25	254.04	53.23	0.5
	4.30	276	5823	5.68	361.81	331.53	47.53	1
	5.90	381	7233	7	445.73	420.63	34.18	2
	7.70	496	8816	8.46	538.79	517.83	21.34	4
	9.41	599	9139	8.7	553.88	586.12	28.08	8
	8.12	517	10465	9.88	628.91	572.56	55.93	12
	9.32	593	13972	13.08	832.56	716.84	119.72	24
		599			832.56	716.84		0
med lime	0.00	0		0	0		0	0
	1.02	65	2996	2.97	189.21	115.04	78.54	0.25
	1.48	93	2901	2.85	181.73	127.35	74.56	0.5
	1.94	123	2951	2.88	183.36	138.29	76.39	1
	2.43	154	3080	2.98	189.8	153.65	82.48	2
	2.27	144	3000	2.88	183.35	153.69	79.77	4
	2.30	146	2777	2.64	168.3	150.79	76.5	8
	1.94	123	2760	2.61	165.87	154.87	80.59	12
	2.80	178	3522	3.3	209.87	190.24	96.15	24
		178			209.87	190.24		0
high lime	0.00	0	0	0	0		0	0
	0.51	32	330	0.33	20.84	24.17	7.23	0.25
	0.66	42	407	0.4	25.5	30.11	10.36	0.5
	1.13	72	1144	1.12	71.08	58.22	22.82	1
	0.53	34	1148	1.11	70.75	50.08	18.95	2
	1.26	80	789	0.76	48.22	56.63	20.96	4
	1.37	87	806	0.77	48.85	61.52	22.47	8
	2.16	138	2416	2.28	145.19	139.22	5.34	12
	2.02	129	1448	1.36	86.28	98.72	26.26	24
		138			145.19	139.22		0
low dry wtr	0.00	0	0	0	0		0	0
	2.43	155	1837	1.82	116.01	132.7	19.92	0.25
	2.60	166	2142	2.11	134.18	147.55	16.16	0.5
	2.70	172	2572	2.51	159.8	165.97	6.19	1
	2.83	180	5090	4.93	313.67	226.45	75.59	2
	5.23	333	5378	5.16	328.68	356.43	44.51	4
	5.30	338	5639	5.37	341.76	367.35	48	8

	5.29	337	5528	5.22	332.22	361.6	47.05	12
	7.54	480	8478	7.94	505.18	494.36	12.85	24
		480			505.18	494.36		0
med dry wtr	0.00	0	0	0	0		0	0
	0.43	27	479	0.48	30.25	32.38	6.37	0.25
	0.45	29	650	0.64	40.72	41.24	12.94	0.5
	0.66	42	895	0.87	55.61	49.43	7.01	1
	0.85	54	1277	1.24	78.69	79.19	25.39	2
	0.98	63	1401	1.34	85.62	87.84	26.44	4
	1.01	65	1300	1.24	78.79	85.88	25.57	8
	1.01	65	1253	1.18	75.3	82.57	22.56	12
	1.65	105	1496	1.4	89.14	160.29	109.89	24
		105			89.14	160.29		0
high dry wtr	0.00	0	0	0	0		0	0
	0.22	14	3984	3.95	251.6	96.86	134.12	0.25
	0.33	21	1964	1.93	123.03	59.95	55.15	0.5
	0.35	22	3084	3.01	191.62	79.9	96.77	1
	0.33	21	2307	2.23	142.17	62.73	68.83	2
	0.28	18	1507	1.45	92.1	43.9	41.8	4
	0.23	15	888	0.85	53.82	28.51	21.95	8
	0.22	14	984	0.93	59.14	30.35	24.99	12
	3.52	224	3302	3.09	196.76	184.36	47.06	24
		224			251.6	184.36		0
low wet wtr	0.00	0	0	0	0		0	0
	6.21	395	1681	1.67	106.16	258.55	145.11	0.25
	6.16	392	2577	2.54	161.43	274.38	115.37	0.5
	8.22	523	3963	3.87	246.24	375	139.59	1
	10.40	662	5813	5.63	358.22	496.51	153.92	2
	10.64	677	8452	8.11	516.55	594.61	80.4	4
	12.39	789	9595	9.13	581.52	686.18	103.56	8
	12.52	797	9749	9.2	585.88	695.84	105.91	12
	12.69	808	9216	8.63	549.16	712.25	141.91	24
		808			585.88	712.25		0
med wet wtr	0.00	0	0	0	0		0	0
	3.45	220	3764	3.73	237.71	208.42	36.4	0.25
	1.56	99	1878	1.85	117.64	98.77	19.11	0.5
	2.68	171	3097	3.02	192.43	169.98	22.88	1
	1.29	82	1634	1.58	100.69	117.17	45.67	2
	1.85	118	1336	1.28	81.65	121.6	42.1	4
	2.53	161	1602	1.53	97.09	132.77	32.61	8

	2.02	129	2528	2.39	151.92	133.13	17.07	12
	2.41	154	2673	2.5	159.28	146.94	16.66	24
		220			237.71	208.42		0
high wet wtr	0.00	0	0	0	0		0	0
	3.77	240	1541	1.53	97.32	187.96	78.77	0.25
	2.35	149	2111	2.08	132.24	148.26	15.47	0.5
	2.97	189	2828	2.76	175.72	191.12	16.42	1
	3.30	210	3650	3.53	224.93	224.23	13.82	2
	3.33	212	3895	3.74	238.04	232.1	17.75	4
	2.98	190	3628	3.45	219.88	207.96	16.06	8
	2.70	172	3223	3.04	193.69	185.08	11.38	12
	1.93	123	2455	2.3	146.29	134.09	11.71	24
		240			238.04	232.1		0
Flyash high	0.00	0	0	0	0		0	0
	1.40	89	1994	1.98	125.93	93.34	30.69	0.25
	0.77	49	1007	0.99	63.08	88.7	57.14	0.5
	2.14	136	2020	1.97	125.51	130.75	5.31	1
	2.99	191	3531	3.42	217.6	198.64	16.49	2
	2.98	190	3036	2.91	185.55	184.61	5.86	4
	1.99	127	2318	2.21	140.49	126	14.96	8
	1.55	98	2254	2.13	135.46	110.82	21.34	12
	1.68	107	2026	1.9	120.72	104.26	18.04	24
		191			217.6	198.64		0
Fly ash medium	0.00	0	0	0	0		0	0
	1.38	88	551	0.55	34.8	48.29	34.83	0.25
	2.24	143	692	0.68	43.35	71.58	61.97	0.5
	1.95	124	861	0.84	53.5	73.28	44.59	1
	2.13	135	1101	1.07	67.85	86.21	43.1	2
	2.19	140	1335	1.28	81.59	96.99	37.3	4
	2.44	155	1623	1.55	98.36	112.67	37.61	8
	2.38	152	1619	1.53	97.3	111.04	35.87	12
	2.97	189	1965	1.84	117.09	135.01	47.59	24
		189			117.09	135.01		0
Fly ash low	0.00	0	0	0	0		0	0
	2.23	142	2204	2.19	139.19	134.98	9.51	0.25
	2.97	189	2197	2.16	137.63	167.11	26.5	0.5
	3.69	235	3113	3.04	193.42	209.87	22.01	1
	3.95	252	3286	3.18	202.5	237.26	30.25	2
	4.17	265	3860	3.71	235.91	263.51	26.7	4

	4.42	281	4463	4.25	270.49	287.39	20.66	8
	5.40	344	5248	4.95	315.39	357.8	50.7	12
	6.22	396	6007	5.62	357.94	409.45	59.6	24
		396			357.94	409.45		0
FeCl low	0.00	0	0	0	0		0	0
	0.00	0	332	0.33	20.97	17.21	15.67	0.25
	0.81	51	410	0.4	25.71	38.42	12.8	0.5
	0.91	58	437	0.43	27.18	44.14	15.66	1
	1.07	68	554	0.54	34.15	54.76	18.15	2
	1.24	79	539	0.52	32.97	64.38	27.23	4
	1.52	97	501	0.48	30.37	77.79	41.32	8
	1.54	98	458	0.43	27.55	80.88	47.12	12
	1.46	93	583	0.55	34.74	90.13	54.12	24
		98			34.74	90.13		0
FeCl high	0.00	0	0	0	0		0	0
	0.07	5	49	0.05	3.07	11.59	13.41	0.25
	0.09	6	58	0.06	3.64	12.46	13.25	0.5
	0.10	7	76	0.07	4.75	12.72	12.18	1
	0.10	6	77	0.07	4.77	14.39	15.27	2
	0.09	6	65	0.06	3.95	10.8	10.16	4
	0.00	0	7	0.01	0.4	2.7	4.12	8
	0.01	1	3	0	0.18	1.5	1.73	12
	0.02	1	19	0.02	1.13	1.22	0.2	24
		7			4.77	14.39		0
FeCl med	0.00	0	0	0	0		0	0
	0.60	38	289	0.29	18.23	27.55	9.92	0.25
	0.72	46	383	0.38	23.98	34.82	10.94	0.5
	0.92	59	539	0.53	33.46	47.2	12.73	1
	1.05	67	673	0.65	41.47	57.85	14.21	2
	1.05	67	734	0.7	44.86	68.11	24.03	4
	0.92	59	723	0.69	43.82	68.12	30.13	8
	0.89	56	750	0.71	45.07	68.75	31.68	12
	0.77	49	781	0.73	46.52	69.35	37.44	24
		67			46.52	69.35		0
AlCl3 low	0.00	0	0	0	0		0	0
	0.19	12	512	0.51	32.34	28.41	14.71	0.25
	0.35	23	625	0.61	39.13	39.64	17.35	0.5
	0.44	28	786	0.77	48.84	48.82	21	1
	0.68	43	1019	0.99	62.8	66.87	26.01	2

	0.83	53	1253	1.2	76.57	78.28	26.63	4
	0.96	61	1404	1.34	85.08	85.23	24.35	8
	0.94	60	1454	1.37	87.38	86.2	25.66	12
	0.89	57	1503	1.41	89.53	97.43	45.36	24
		61			89.53	97.43		0
AlCl3 med	0.00	0	0	0	0		0	0
	0.36	23	302	0.3	19.04	21.75	2.34	0.25
	0.41	26	455	0.45	28.52	29.73	4.46	0.5
	0.41	26	622	0.61	38.62	36.87	9.81	1
	0.50	32	820	0.79	50.55	46.64	13.18	2
	0.58	37	1034	0.99	63.19	55.07	15.63	4
	0.68	43	1080	1.03	65.46	57.54	12.43	8
	0.70	45	999	0.94	60.01	56.67	10.62	12
	0.76	48	857	0.8	51.07	53.72	7.12	24
		48			65.46	57.54		0
AlCl3 high	0.00	0	0	0	0		0	0
	0.10	6	94	0.09	5.94	6.23	0.38	0.25
	0.12	8	120	0.12	7.52	7.68	0.19	0.5
	0.14	9	145	0.14	9.01	9.01	0.19	1
	0.18	11	150	0.15	9.24	9.36	1.81	2
	0.18	12	145	0.14	8.86	8.85	2.73	4
	0.08	5	50	0.05	3.03	2.95	2.14	8
	0.03	2	25	0.02	1.5	1.41	0.44	12
	0.07	5	40	0.04	2.38	2.61	1.85	24
		12			9.24	9.36		0
FGD high	0.00	0	0	0	0		0	0
	0.18	12	527	0.52	33.25	20.64	11.24	0.25
	0.28	18	591	0.58	37.02	25.47	10.22	0.5
	0.31	20	683	0.67	42.43	28.91	11.95	1
	0.45	29	810	0.78	49.92	36.13	11.95	2
	0.51	33	929	0.89	56.76	42.47	12.69	4
	0.65	41	901	0.86	54.62	48.27	6.77	8
	0.68	43	1020	0.96	61.3	52.68	8.97	12
	0.70	44	1315	1.23	78.36	58.38	17.77	24
		44			78.36	58.38		0
FGD med	0.00	0	0	0	0		0	0
	0.28	18	431	0.43	27.22	22.57	4.55	0.25
	0.43	27	436	0.43	27.31	27.83	1.13	0.5
	0.49	31	481	0.47	29.89	32.91	3.97	1

	0.72	46	643	0.62	39.62	44	3.8	2
	0.94	60	846	0.81	51.7	56.31	4.12	4
	1.38	88	998	0.95	60.48	73.82	13.71	8
	1.30	83	1120	1.06	67.31	75.38	7.77	12
	1.37	87	1160	1.09	69.12	80.72	10.05	24
		88			69.12	80.72		0
FGD low	0.00	0	0	0	0		0	0
	1.26	80	361	0.36	22.8	42.29	32.78	0.25
	1.61	102	496	0.49	31.07	53.25	42.6	0.5
	1.97	125	658	0.64	40.88	68.26	49.48	1
	2.40	153	928	0.9	57.19	87.4	56.55	2
	3.14	200	1416	1.36	86.54	121.62	67.98	4
	3.44	219	2071	1.97	125.52	148.36	62.29	8
	4.26	271	3084	2.91	185.34	191.07	77.62	12
	4.51	287	3071	2.87	182.99	203.49	75.3	24
		287			185.34	203.49		0

Appendix C Runoff box study results

Notation used in Appendix C

Treatment: treatments as described in chapter 4

Event: This number corresponds to the number of the rainfall simulation event

Volume runoff: total volume of runoff collected during 1 hr runoff event

SS FWMC: flow-weighted mean concentration of suspended solids

DRP FWMC: flow-weighted mean concentration of dissolved reactive phosphorus

TP FWMC: flow-weighted mean concentration of total phosphorus

PP FWMC: flow-weighted mean concentration of particulate phosphorus

Cd: flow-weighted mean concentration of cadmium

Cr: flow-weighted mean concentration of chromium

Cu: flow-weighted mean concentration of copper

K: flow-weighted mean concentration of potassium

Ni: flow-weighted mean concentration of nickel

Pb: flow-weighted mean concentration of lead

Zn: flow-weighted mean concentration of zinc

Al: flow-weighted mean concentration of aluminium

Ca: flow-weighted mean concentration of calcium

Fe: flow-weighted mean concentration of iron

Time to runoff, time from start of rainfall simulator to start of event and thus start of 1 hr collection period

WEP: Slurry WEP at time of application

DM: slurry DM at time of application

pH runoff water: pH of runoff collected

RS rainfall simulation event as described in Chapter 4

Tank: source mains water in NUI Galway

Table C.1. Runoff box study flow weighted mean concentrations

Treatment	Event	Volume runoff ml	Intensity mm/hr	SSFWMC mg/l	DRPFWMC µg/l	PPFWMC µg/l	TPFWMC mg/l	Cd µg/l
Grass	1	4610.7	10	296	87.66	124.74	0.32	1.89
Grass	2	4764.36	11	93	100.80	76.03	0.23	1.25
Grass	3	4688.3	10	82	85.15	50.73	0.18	1.41
Grass	1	4697.4	10	235	169.39	42.59	0.23	1.52
Grass	2	4752.2	11	139	171.49	36.10	0.24	1.27
Grass	3	4770.2	11	202	188.61	24.43	0.25	1.72
Grass	1	5198	12	192	238.44	122.95	0.59	0.15
Grass	2	4495	12	138	271.73	438.16	0.88	0.05
Grass	3	5576	10	84	222.78	93.82	0.45	0.38
slurryonly	1	4647	10	4552	896.26	7847.17	9.17	0.92
slurryonly	2	4975.7	11	4573	952.73	9362.10	11.15	0.12
slurryonly	3	4849.3	11	1763	342.29	4183.47	5.02	1.45
slurryonly	1	3982	9	3217	358.98	7527.58	9.45	0.05
slurryonly	2	4685	10	3409	821.19	8242.42	10.35	0.21
slurryonly	3	4648	10	1999	1114.64	3931.55	5.52	1.51
slurryonly	1	4476	10	2362	477.02	6622.45	7.79	0.29
slurryonly	2	4696	10	3673	459.10	7108.90	11.57	0.24
slurryonly	3	4784	11	1720	478.21	3291.73	5.60	0.63
alum	1	4519	10	406	66.34	397.81	0.64	0.47
alum	2	4516	10	231	104.55	218.33	0.36	0.50
alum	3	4560	10	330	61.13	204.44	0.33	1.69

alum	1	4916	11	357	176.48	555.08	0.84	1.33
alum	2	4871	11	249	185.55	136.40	0.36	1.02
alum	3	4609	10	293	200.02	247.20	0.51	0.85
alum	1	4226	9	536	52.15	385.32	0.58	0.96
alum	2	4403	10	520	86.92	293.28	0.54	0.04
alum	3	4565.8	10	392	90.55	123.70	0.39	0.88
PAC	1	4712	10	772	83.49	1269.21	1.59	0.00
PAC	2	4766	11	478	50.13	935.78	1.13	0.00
PAC	3	4474	10	450	73.06	899.53	1.08	0.00
PAC	1	4181	9	683	138.13	439.34	1.12	0.00
PAC	2	4029	9	638	97.66	639.87	1.44	0.00
PAC	3	4213	9	497	166.55	309.39	0.69	0.00
PAC	1	4524	10	465	67.99	1110.15	1.35	0.00
PAC	2	4559	10	316	68.17	896.58	1.16	0.00
PAC	3	4352	10	416	55.16	621.26	0.80	0.00
lime	1	5399.6	12	753	277.47	936.10	1.77	0.00
lime	2	4251	9	582	283.89	620.63	1.53	0.00
lime	3	4689	10	462	114.31	205.23	0.70	0.00
lime	1	5930	13	641	264.65	838.61	1.78	0.00
lime	2	5119	11	652	195.07	1125.78	1.88	0.00
lime	3	5061.8	11	496	84.67	601.92	1.08	0.00
lime	1	4343	10	572	216.34	312.81	1.03	0.00
lime	2	4650	10	462	183.95	16.85	0.67	0.00
lime	3	4769	11	410	174.58	298.41	0.94	0.00
ferrous	1	4533	10	1758	152.26	2971.16	3.31	0.00
ferrous	2	4679	10	1406	246.03	2488.45	3.25	0.00
ferrous	3	4638	10	1023	254.56	1910.10	2.69	
ferrous	1	4226	9	852	171.94	1420.25	1.97	0.00
ferrous	2	4315	10	731	149.38	1002.18	1.56	0.00
ferrous	3	4278	10	711	190.67	1020.95	1.45	
ferrous	1	4210	9	808	236.03	1898.58	2.70	0.00
ferrous	2	4243	9	1275	275.97	1878.18	2.67	0.00
ferrous	3	4342	10	913	291.02	1268.48	1.94	0.00

Treatment	Event	Cr	Cu	K	Ni	Pb	Zn	Al	Ca	Fe	Time to runoff	pH tank water
		µg/l	µg/l	mg/l	µg/l	µg/l	µg/l	µg/l	mg/l	µg/l	min	
Grass	1	5.34	22.26	38.99	0	6.4	407.9	176.3	91.3	128.7	10	8
Grass	2	2.11	11.91	31.06	0	11.0	460.8	67.5	83.2	74.6	7	8
Grass	3	2.17	15.07	26.17	0.7857	5.8	718.9	79.4	87.8	67.5	11	8
Grass	1	1.09	14.33	21.21	0	4.2	279.2	83.5	85.4	61.2	10	8
Grass	2	1.00	9.88	16.69	0.4031	2.0	419.6	81.5	80.5	70.6	7	8
Grass	3	1.29	15.09	16.31	1.1919	13.9	752.5	51.2	84.2	65.5	11	7.9
Grass	1	0.12	23.14	14.02	2.0594	1.2	419.2	54.3	83.9	73.1	10.45	8
Grass	2	0.82	9.69	11.24	8.065	7.2	413.8	56.8	81.3	53.0	8	8.1
Grass	3	2.19	12.32	11.74	2.2605	8.4	520.4	45.3	80.8	44.8	9	8
slurryonly	1	5.84	29.17	21.27	4.5977	3.5	258.9	63.4	106.3	128.0	17	8
slurryonly	2	4.01	32.78	35.02	3.0928	1.7	349.2	52.0	110.7	190.6	9	7.6
slurryonly	3	4.54	66.03	74.17	38.751	3.0	216.4	116.2	103.3	103.6	26	7.8
slurryonly	1	3.38	33.38	51.49	6.416	3.0	333.1	59.3	117.4	194.0	20	8
slurryonly	2	2.16	28.52	60.51	1.3506	4.4	332.3	59.1	110.5	227.7	12	8
slurryonly	3	3.46	73.17	81.82	15.89	17.4	345.3	210.9	102.6	137.1	20	4
slurryonly	1	3.43	20.67	56.12	0.1083	0.1	446.7	59.7	114.7	127.2	18	8
slurryonly	2	2.28	18.56	53.13	1.1696	4.3	440.1	81.9	107.5	116.9	10	8
slurryonly	3	3.83	59.41	78.69	9.9897	10.3	263.3	112.9	97.3	131.1	23	8
alum	1	2.47	14.22	129.86	1.3875	6.5	666.8	65.6	141.8	110.8	21	8
alum	2	2.53	20.39	149.74	3.9019	12.3	1413.1	65.6	150.3	148.3	13	8

alum	3	3.14	27.12	87.78	6.2817	6.2	1737.1	65.6	129.3	313.7	19	8
alum	1	2.70	23.89	112.96	8.6688	1.9	1762.9	54.4	140.7	240.6	21	8
alum	2	2.92	12.58	131.18	0.4569	0.5	618.9	54.4	146.4	131.5	13	8
alum	3	1.92	12.48	119.57	1.7282	2.4	1349.5	54.4	142.3	178.9	19	8
alum	1	1.96	20.24	88.42	4.5567	0.9	1742.3	50.6	127.0	353.8	14	8
alum	2	3.61	14.20	83.54	0.2449	15.4	749.2	50.6	126.4	123.4	10	8
alum	3	3.90	16.55	74.85	0.9945	11.6	1237.2	50.6	122.8	161.2	12	8
PAC	1	0.00	8.29	33.95	0	0	1317.7	25.6	165.8	18.8	17	7.9
PAC	2	0.00	1.21	50.13	0	0	1312.7	23.3	194.3	9.1	10	8
PAC	3	0.00	4.58	59.73	0	0	1064.8	43.6	203.0	28.1	20	8
PAC	1	0.00	3.00	54.47	0	0	1476.4	23.7	207.6	13.6	29	8
PAC	2	0.00	3.00	61.21	0	0	1471.2	25.8	193.1	0.0	8	8
PAC	3	0.00	6.26	75.61	0	0	1114.0	17.8	238.9	7.5	15	8
PAC	1	0.00	9.10	60.01	0	0	1801.5	22.0	203.3	0.0	17	7.98
PAC	2	0.00	1.32	58.22	0	0	1967.8	18.7	192.3	1.1	10	8
PAC	3	0.00	11.64	53.86	0	0	1323.8	12.8	187.4	34.4	20	8.3
lime	1	0.00	3.29	37.16	0	0	467.1	2.1	156.3	54.7	29	8
lime	2	0.00	0.00	53.27	0	0	595.2	2.1	216.6	113.5	12	8
lime	3	0.00	1.72	57.34	0	0	961.9	21.6	218.2	21.3	17	7.8
lime	1	0.00	1.80	68.34	0	0	633.1	4.7	234.3	85.1	27	8
lime	2	0.00	8.41	69.40	0	0	690.2	5.4	203.1	122.5	12	8
lime	3	0.00	0.10	61.94	0	0	949.4	14.2	217.1	47.2	14	8
lime	1	0.00	1.44	79.36	0	0	628.3	5.4	225.1	93.4	29	8
lime	2	0.00	0.00	83.94	0	0	591.1	2.9	194.2	193.7	8	8
lime	3	0.00	13.62	48.56	0	0	567.7	6.0	206.0	30.7	16	8
ferrous	1	0.00	1.58	71.88	0	0	367.9	4.9	242.5	50.8	19	8.1
ferrous	2	0.00	0.18	79.16	0	0	371.3	6.0	254.7	77.9	6	8
ferrous	3										16	8
ferrous	1	0.00	32.79	72.28	0	0	645.8	40.7	177.2	54.3	20	8
ferrous	2	0.00	0.00	75.76	0	0	445.4	4.4	213.0	81.5	5	8
ferrous	3										12	8
ferrous	1	0.00	28.83	85.67	0	0	978.0	89.0	207.0	19.6	17	8
ferrous	2	0.00	23.84	64.64	0	0	879.6	78.0	215.5	21.6	6	8.1
ferrous	3	0.00	17.83	75.64	0	0	1010.5	98.0	213.2	17.5	16	8.1

Treatment	Event	Water extractable P of slurry at time of application	Slurry DM at time of application	pH runoff water
		mg/kg	%	
Grass	1			7.5
Grass	2			7.6
Grass	3			7.6
Grass	1			7.6
Grass	2			7.7
Grass	3			7.6
Grass	1			7.5
Grass	2			7.6
Grass	3			7.9
slurryonly	1	1.9364	10.56	7.6
slurryonly	2	1.9364		7.6
slurryonly	3	1.9364		7.5
slurryonly	1	1.7387	10.49	7.8
slurryonly	2	1.7387		7.8
slurryonly	3	1.7387		7.7
slurryonly	1	1.8468	10.4	7.8
slurryonly	2	1.8468		7.7
slurryonly	3	1.8468		7.8

alum	1	1.8468	9.4	7.5
alum	2	1.8468		7.4
alum	3	1.8468		7.5
alum	1	1.8468	9.6	7.44
alum	2	1.8468		7.4
alum	3	1.8468		7.6
alum	1	0.0074	9.3	7.47
alum	2	0.0074		7.5
alum	3	0.0074		7.5
PAC	1	0.012	9.3	7.9
PAC	2	0.012		7.9
PAC	3	0.012		7.9
PAC	1	0.013	9.63	7.8
PAC	2	0.013		7.8
PAC	3	0.013		7.8
PAC	1	0.0094	9.86	7.9
PAC	2	0.0094		7.9
PAC	3	0.0094		7.9
lime	1	0.0153	8	7.4
lime	2	0.0153		7.5
lime	3	0.0153		7.45
lime	1	0.0124	8.6	7.4
lime	2	0.0124		7.5
lime	3	0.0124		7.6
lime	1	0.0134		7.6
lime	2	0.0134		7.6
lime	3	0.0134		7.6
ferrous	1	0.0171	9.8	7.7
ferrous	2	0.0171		7.8
ferrous	3	0.0171		7.8
ferrous	1	0.0187	10.25	7.5
ferrous	2	0.0187		7.5
ferrous	3	0.0187		7.5
ferrous	1	0.0159	10.16	7.8
ferrous	2	0.0159		7.8
ferrous	3	0.0159		7.8

Table C.2. Runoff box study flow weighted mean metal concentrations

	RS	Cd	Cr	Cu	K	Ni	Pb	Zn
		µg/l	µg/l	µg/l	mg/l	µg/l	µg/l	µg/l
Slurry	1	0.8 (0.7)	4.8 (0.9)	42.7 (20.3)	43.5 (27.5)	15.5 (20)	2.7 (1)	274 (67)
	2	0.6 (0.8)	3 (0.7)	45 (24.5)	64.6 (15.6)	7.9 (7.4)	8.3 (7.9)	337 (7)
	3	0.4 (0.2)	3.2 (0.8)	32.9 (23)	62.6 (14)	3.8 (5.4)	4.9 (5.5)	383 (104)
alum	1	0.9 (0.7)	2.7 (0.4)	20.6 (6.5)	122.5 (31.6)	3.9 (2.5)	8.3 (3.4)	1272 (549)
	2	1.1 (0.2)	2.5 (0.5)	16.3 (6.6)	121.2 (9.2)	3.6 (4.2)	1.6 (1)	1244 (579)
	3	0.6 (0.5)	3.2 (1)	17 (3.1)	82.3 (6.9)	1.9 (2.2)	9.3 (7.5)	1243 (497)
PAC	1	< limit	< limit	4.7 (3.5)	47.9 (13)	< limit	< limit	1232 (145)
	2	< limit	< limit	2.2 (3.5)	63.7 (10.8)	< limit	< limit	1354 (208)
	3	< limit	< limit	7.4 (5.4)	57.4 (3.2)	< limit	< limit	1698 (344)
Lime	1	< limit	< limit	1.7 (1.7)	49.3 (10.7)	< limit	< limit	674 (257)
	2	< limit	< limit	3.4 (4.4)	66.6 (4)	< limit	< limit	758 (169)
	3	< limit	< limit	5 (7.5)	70.6 (19.2)	< limit	< limit	596 (31)
Fe	1	< limit	< limit	0.9 (1)	75.5 (5.5)	< limit	< limit	370 (23)
	2	< limit	< limit	16.4 (23.2)	74 (2.5)	< limit	< limit	546 (142)
	3	< limit	< limit	24.8 (5.5)	75.6 (10.5)	< limit	< limit	978 (68)
Grass	1	1.2 (0.9)	2.2 (2.8)	19.9 (4.9)	24.7 (12.9)	0.7 (1.2)	4 (2.6)	369 (78)
	2	0.9 (0.7)	1.3 (0.7)	10.5 (1.2)	19.7 (10.2)	2.8 (4.5)	6.8 (4.5)	431 (26)
	3	1.2 (0.7)	1.9 (0.5)	14.2 (1.6)	18.1 (7.4)	1.4 (0.8)	9.4 (4.2)	664 (125)
Tank		< limit	0.7 (0.1)	22.1 (1.5)	1.8 (0.1)	6.3 (3.2)	< limit	613 (136)

Table C.3 Runoff box study box nutrient concentrations (Chapter 4)

Date	Treatment	RS	Time after 0 min	pH runoff	Vol runoff mg	SS mg/l	DRP µg/l	PP µg/l	TP µg/l	DUP µg/l	TDP µg/l
10-May	alum	1	2.5	7.44	438	393	189	374	615	53	242
	alum	1	7.5	7.39	374	419	188	504	773	81	269
	alum	1	12.5	7.4	377	459	174	482	780	124	298
	alum	1	17.5	7.4	402	430	224	572	871	76	299
	alum	1	22.5	7.4	428	404	152	447	745	146	298
	alum	1	27.5	7.4	389	383	177	700	989	112	289
	alum	1	32.5	7.4	416	228	157	626	926	143	300
	alum	1	37.5	7.4	410	427	174	278	599	146	320
	alum	1	42.5	7.4	449	325	171	600	893	122	293
	alum	1	47.5	7.4	389	340	181	678	949	89	271
	alum	1	52.5	7.4	454	138	171	688	958	99	270
	alum	1	57.5	7.4	390	372	162	721	993	110	271
	alum	2	2.5	7.4	345	276	149	164	404	90	239
	alum	2	7.5	7.4	390	288	161	196	431	74	235
	alum	2	12.5	7.4	436	308	149	149	362	65	214
	alum	2	17.5	7.4	399	280	165	137	356	54	219
	alum	2	22.5	7.4	410	253	187	139	364	38	225
	alum	2	27.5	7.4	426	261	198	100	327	28	227
	alum	2	32.5	7.4	415	224	199	107	334	28	227
	alum	2	37.5	7.4	411	255	210	103	327	13	224
	alum	2	42.5	7.4	410	199	177	122	318	19	196
	alum	2	47.5	7.4	474	218	207	157	375	11	218
	alum	2	52.5	7.4	370	224	196	165	368	7	203
	alum	2	57.5	7.4	385	202	221	105	360	34	255
	alum	3	2.5	7.6	356	410	153	414	620	54	207
	alum	3	7.5	7.5	315	476	168	417	590	4	173
	alum	3	12.5	7.5	374	365	194	63	317	60	254
	alum	3	17.5	7.5	374	302	198	206	463	60	257
	alum	3	22.5	7.5	382	218	192	284	510	34	226
	alum	3	27.5	7.5	425	326	206	203	491	82	288
	alum	3	32.5	7.5	359	251	215	231	533	86	302
	alum	3	37.5	7.5	408	357	188	51	341	101	289
	alum	3	42.5	7.5	375	226	192	249	496	56	248
	alum	3	47.5	7.5	391	237	224	250	547	73	297
	alum	3	52.5	7.5	395	211	231	332	607	44	275
	alum	3	57.5	7.5	455	189	225	306	599	67	292
	Grass	1	2.5	7.6	255	288	177	44	264	44	221
	Grass	1	7.5	7.6	357	305	174	57	231	0	174
	Grass	1	12.5	7.6	352	102	175	111	296	9	185
	Grass	1	17.5	7.6	413	357	168	96	282	19	187
	Grass	1	22.5	7.6	412	184	164	56	235	14	178
	Grass	1	27.5	7.6	411	204	187	15	204	1	189
	Grass	1	32.5	7.6	420	227	147	31	219	41	188
	Grass	1	37.5	7.6	420	327	145	10	191	36	181
	Grass	1	42.5	7.6	430	350	166	14	195	14	181
	Grass	1	47.5	7.6	410	150	172	21	220	26	199
	Grass	1	52.5	7.6	407	200	203	24	233	6	210
	Grass	1	57.5	7.6	411	125	159	47	212	7	166
	Grass	2	2.5	7.7	267	131	198	24	273	51	249
	Grass	2	7.5	7.6	316	206	175	75	269	19	194
	Grass	2	12.5	7.6	386	84	158	72	273	43	201

	Grass	2	17.5	7.6	395	46	147	95	283	40	188
	Grass	2	22.5	7.6	418	179	163	15	228	50	213
	Grass	2	27.5	7.7	438	88	138	27	222	57	195
	Grass	2	32.5	7.7	442	25	153	48	236	34	188
	Grass	2	37.5	7.7	420	313	157	46	242	39	196
	Grass	2	42.5	7.7	417	268	238	20	272	14	251
	Grass	2	47.5	7.7	412	235	198	18	267	51	249
	Grass	2	52.5	7.7	422	52	167	56	246	22	189
	Grass	2	57.5	7.7	420	57	177	22	211	12	189
	Grass	3	2.5	7.6	298	536	121	129	278	28	149
	Grass	3	7.5	7.6	368	159	202	43	267	22	224
	Grass	3	12.5	7.6	386	175	260	31	312	21	281
	Grass	3	17.5	7.6	438	129	290	30	387	67	357
	Grass	3	22.5	7.6	440	72	182	31	253	40	222
	Grass	3	27.5	7.6	372	190	185	29	263	49	234
	Grass	3	32.5	7.6	437	247	204	29	316	83	287
	Grass	3	37.5	7.6	410	167	186	20	315	109	295
	Grass	3	42.5	7.6	399	290	174	66	357	117	291
	Grass	3	47.5	7.6	411	132	177	47	235	11	188
	Grass	3	52.5	7.6	396	200	187	89	278	2	189
	Grass	3	57.5	7.6	415	229	182	32	221	7	189
17-May-10	PAC	1	2.5	7.9	353	197	23	1725	1981	233	256
	PAC	1	7.5	7.9	345	225	89	1850	2017	78	167
	PAC	1	12.5	7.9	374	367	86	1828	2100	185	271
	PAC	1	17.5	7.9	363	392	85	1915	2182	183	268
	PAC	1	22.5	7.9	384	219	75	1981	2245	189	264
	PAC	1	27.5	7.9	384	390	75	772	1000	153	228
	PAC	1	32.5	7.9	398	570	82	652	844	110	193
	PAC	1	37.5	7.9	398	570	82	652	844	110	192
	PAC	1	42.5	7.9	383	550	26	555	789	208	234
	PAC	1	47.5	7.9	383	550	26	557	789	205	232
	PAC	1	52.5	7.9	380	750	82	520	783	181	263
	PAC	1	57.5	7.9	380	750	82	520	783	181	263
	PAC	2	2.5	7.9	307	290	90	862	1107	155	245
	PAC	2	7.5	7.9	391	450	33	973	1225	219	252
	PAC	2	12.5	7.9	381	320	86	895	1251	270	356
	PAC	2	17.5	7.9	390	240	26	979	1277	272	298
	PAC	2	22.5	7.9	335	220	87	1126	1367	154	241
	PAC	2	27.5	7.9	335	440	87	1090	1345	168	255
	PAC	2	32.5	7.9	386	290	30	1156	1424	239	268
	PAC	2	37.5	7.9	386	290	30	1156	1424	239	268
	PAC	2	42.5	7.9	444	280	86	969	1234	179	265
	PAC	2	47.5	7.9	444	280	86	946	1234	202	288
	PAC	2	52.5	7.9	382	350	91	616	907	200	291
	PAC	2	57.5	7.9	382	350	91	616	907	200	291
	PAC	3	2.5	7.9	347	180	69	1183	1384	133	201
	PAC	3	7.5	7.9	340	410	73	1113	1291	105	178
	PAC	3	12.5	7.9	321	940	24	1035	1256	197	221
	PAC	3	17.5	7.9	374	390	82	1021	1221	119	200
	PAC	3	22.5	7.9	369	280	28	153	332	152	179
	PAC	3	27.5	7.9	369	280	28	247	450	175	203
	PAC	3	32.5	7.9	367	320	84	335	562	143	227
	PAC	3	37.5	7.9	367	320	84	335	562	143	227
	PAC	3	42.5	7.9	374	530	58	489	689	142	200
	PAC	3	47.5	7.9	374	530	58	489	689	142	200
	PAC	3	52.5	7.9	377	430	37	495	668	136	174
	PAC	3	57.5	7.9	377	430	37	495	668	136	174

	slurry	1	2.5	7.6	366	1933	701	947	1791	144	845
	slurry	1	7.5	7.5	363	4200	636	1623	2372	113	750
	slurry	1	12.5	7.5	376	3267	766	2982	3861	113	879
	slurry	1	17.5	7.5	376	5000	837	4553	5402	11	848
	slurry	1	22.5	7.5	388	3333	874	6157	7050	18	892
	slurry	1	27.5	7.5	393	4000	992	7461	8536	82	1074
	slurry	1	32.5	7.5	388	4133	944	8867	10230	420	1364
	slurry	1	37.5	7.5	405	4867	1054	10672	12131	405	1459
	slurry	1	42.5	7.5	392	5533	1055	11213	12751	483	1538
	slurry	1	47.5	7.5	395	5933	1047	11834	13559	678	1725
	slurry	1	52.5	7.5	405	6600	881	13760	15754	1113	1994
	slurry	1	57.5	7.5	400	5467	922	12427	14814	1465	2387
	slurry	2	2.5	7.6	356	7300	705	9595	11196	896	1601
	slurry	2	7.5	7.6	404	5933	783	9198	10904	923	1706
	slurry	2	12.5	7.6	444	3509	891	9996	11668	781	1673
	slurry	2	17.5	7.6	507	5404	812	10352	12160	996	1808
	slurry	2	22.5	7.6	358	4759	941	9902	11707	863	1805
	slurry	2	27.5	7.6	367	3950	1050	11742	13617	825	1875
	slurry	2	32.5	7.6	417	3600	1142	9206	10919	571	1713
	slurry	2	37.5	7.6	408	5250	995	9890	11721	837	1831
	slurry	2	42.5	7.6	433	2500	1003	9154	11003	846	1849
	slurry	2	47.5	7.6	427	4600	1109	6763	8628	756	1865
	slurry	2	52.5	7.6	433	4000	1193	4697	6606	717	1910
	slurry	2	57.5	7.6	422	4467	799	12212	13980	969	1768
	slurry	3	2.5	7.5	347	1640	176	4286	5038	576	752
	slurry	3	7.5	7.5	395	1353	128	4105	4907	674	802
	slurry	3	12.5	7.5	400	2238	305	4465	5251	481	786
	slurry	3	17.5	7.5	401	1793	346	4603	5472	522	869
	slurry	3	22.5	7.5	406	1231	305	4950	5798	544	848
	slurry	3	27.5	7.5	419	1792	389	5246	6128	493	881
	slurry	3	32.5	7.5	419	1950	341	4108	4913	464	805
	slurry	3	37.5	7.5	391	750	376	4404	5275	494	871
	slurry	3	42.5	7.5	426	2235	441	3703	4572	428	869
	slurry	3	47.5	7.5	425	2467	431	3026	3883	425	856
	slurry	3	52.5	7.5	391	1563	403	1760	2658	494	898
	slurry	3	57.5	7.5	429	2000	423	5460	6291	408	831
24-May-10	Fe	1	2.5	7.7	394	1600	110	1647	2241	484	594
	Fe	1	7.5	7.7	337	1960	110	2226	2925	590	699
	Fe	1	12.5	7.7	371	1280	102	2513	3313	699	801
	Fe	1	17.5	7.7	359	1460	145	2471	3313	697	842
	Fe	1	22.5	7.7	398	1580	169	2643	3488	676	845
	Fe	1	27.5	7.8	398	1580	194	2621	3488	673	867
	Fe	1	32.5	7.8	371	1740	152	2612	3488	724	876
	Fe	1	37.5	7.7	371	1740	152	2679	3488	657	809
	Fe	1	42.5	7.7	385	1560	106	2699	3501	696	802
	Fe	1	47.5	7.7	385	1560	106	2712	3501	683	789
	Fe	1	52.5	7.7	383	1620	322	2733	3501	446	768
	Fe	1	57.5	7.7	383	1620	322	2702	3501	476	798
	Fe	2	2.5	7.8	395	1500	156	2349	3086	581	737
	Fe	2	7.5	7.8	371	1300	196	2696	3395	503	699
	Fe	2	12.5	7.8	371	940	171	2788	3545	586	756
	Fe	2	17.5	7.8	371	1400	174	2774	3545	597	771
	Fe	2	22.5	7.8	390	1440	248	2376	3165	541	789
	Fe	2	27.5	7.8	390	1440	214	2377	3165	574	788
	Fe	2	32.5	7.8	403	1560	236	2400	3165	529	765
	Fe	2	37.5	7.8	403	1560	236	2427	3165	502	738
	Fe	2	42.5	7.8	413	1500	325	2562	3218	332	656

	Fe	2	47.5	7.8	413	1500	325	2450	3218	444	768
	Fe	2	52.5	7.8	381	1340	330	2353	3218	535	865
	Fe	2	57.5	7.8	381	1340	330	2345	3218	544	873
	Fe	3	2.5	7.8	370	760	162	1419	2062	480	642
	Fe	3	7.5	7.8	372	460	95	1661	2415	658	754
	Fe	3	12.5	7.9	439	1660	299	1939	2711	473	772
	Fe	3	17.5	7.8	342	920	298	1924	2711	490	788
	Fe	3	22.5	7.8	398	1000	312	1996	2796	488	800
	Fe	3	27.5	7.8	398	1000	349	2015	2796	432	781
	Fe	3	32.5	7.8	411	1120	355	1967	2756	434	789
	Fe	3	37.5	7.8	411	1120	355	1941	2756	461	816
	Fe	3	42.5	7.8	389	880	194	1977	2823	652	846
	Fe	3	47.5	7.8	389	880	194	2022	2823	607	801
	Fe	3	52.5	7.8	360	1180	184	2034	2823	605	789
	Fe	3	57.5	7.8	360	1180	224	1997	2823	602	825
	Fe	1	2.5	7.5	315	550	218	1283	1616	115	333
	Fe	1	7.5	7.5	293	600	202	1153	1616	261	464
	Fe	1	12.5	7.5	324	680	198	1165	1703	340	538
	Fe	1	17.5	7.5	349	530	183	1158	1730	390	572
	Fe	1	22.5	7.5	326	850	184	1151	1758	423	607
	Fe	1	27.5	7.5	333	850	184	1461	2057	412	596
	Fe	1	32.5	7.5	367	940	161	1771	2355	423	584
	Fe	1	37.5	7.5	360	940	161	1771	2355	423	584
	Fe	1	42.5	7.5	378	940	149	1588	2134	397	546
	Fe	1	47.5	7.5	380	940	149	1569	2136	418	567
	Fe	1	52.5	7.5	456	1110	150	1414	2000	436	586
	Fe	1	57.5	7.5	345	1110	150	1414	2000	436	586
	Fe	2	2.5	7.5	284	470	154	1302	1857	401	555
	Fe	2	7.5	7.5	384	690	155	1241	1857	461	616
	Fe	2	12.5	7.5	347	660	150	946	1539	444	594
	Fe	2	17.5	7.5	360	650	155	886	1473	431	587
	Fe	2	22.5	7.5	370	830	149	827	1406	430	579
	Fe	2	27.5	7.5	365	830	149	935	1498	414	563
	Fe	2	32.5	7.5	375	640	151	1043	1591	396	547
	Fe	2	37.5	7.5	369	640	151	1043	1591	396	547
	Fe	2	42.5	7.5	371	840	148	1042	1498	308	456
	Fe	2	47.5	7.5	370	840	148	913	1468	407	555
	Fe	2	52.5	7.5	360	810	141	949	1500	410	551
	Fe	2	57.5	7.5	360	810	141	949	1500	410	551
	Fe	3	2.5	7.5	280	720	188	1029	1441	224	412
	Fe	3	7.5	7.5	342	670	180	984	1441	277	457
	Fe	3	12.5	7.5	380	620	187	918	1345	240	427
	Fe	3	17.5	7.5	334	700	183	1030	1401	188	371
	Fe	3	22.5	7.5	431	690	190	1142	1456	124	314
	Fe	3	27.5	7.5	431	690	190	1077	1448	181	371
	Fe	3	32.5	7.5	299	720	185	1012	1440	243	428
	Fe	3	37.5	7.5	299	720	185	1012	1440	243	428
	Fe	3	42.5	7.5	361	680	194	1111	1567	262	456
	Fe	3	47.5	7.5	361	680	194	1000	1456	262	456
	Fe	3	52.5	7.5	381	820	203	910	1456	343	546
	Fe	3	57.5	7.5	381	820	203	1003	1456	250	453
31-May-10	PAC	1	2.5	7.9	352	360	101	886	1141	154	256
	PAC	1	7.5	7.9	356	250	106	825	1133	202	307
	PAC	1	12.5	7.9	386	467	103	1236	1504	165	269
	PAC	1	17.5	7.9	383	404	65	1589	1876	222	287
	PAC	1	22.5	7.9	431	923	130	1595	1899	174	305
	PAC	1	27.5	7.9	431	900	130	1688	2000	182	312

PAC	1	32.5	7.9	378	925	36	1618	1938	284	320
PAC	1	37.5	7.9	378	925	36	1618	1938	284	320
PAC	1	42.5	7.9	410	1000	59	1155	1500	286	345
PAC	1	47.5	7.9	410	1000	59	1156	1500	285	344
PAC	1	52.5	7.9	399	981	85	884	1268	299	384
PAC	1	57.5	7.9	399	981	85	884	1268	299	384
PAC	2	2.5	7.9	372	580	38	742	1043	263	301
PAC	2	7.5	7.9	442	390	30	918	1252	304	334
PAC	2	12.5	7.9	343	100	38	954	1213	222	259
PAC	2	17.5	7.9	432	30	25	911	1174	239	264
PAC	2	22.5	7.9	352	596	97	1044	1312	171	268
PAC	2	27.5	7.9	352	741	97	972	1200	131	228
PAC	2	32.5	7.9	414	702	50	818	1006	139	189
PAC	2	37.5	7.9	414	702	50	818	1006	139	189
PAC	2	42.5	7.9	422	444	42	849	1050	159	201
PAC	2	47.5	7.9	422	444	42	896	1050	112	154
PAC	2	52.5	7.9	402	520	54	1027	1133	52	106
PAC	2	57.5	7.9	402	520	54	1027	1133	52	106
PAC	3	2.5	7.9	283	440	33	762	873	78	111
PAC	3	7.5	7.9	303	360	91	1043	1154	19	110
PAC	3	12.5	7.9	351	460	82	926	1099	90	173
PAC	3	17.5	7.9	401	440	52	865	1043	127	179
PAC	3	22.5	7.9	386	460	116	312	497	69	185
PAC	3	27.5	7.9	386	460	116	411	600	74	189
PAC	3	32.5	7.9	397	410	116	545	739	78	194
PAC	3	37.5	7.9	397	410	116	545	739	78	194
PAC	3	42.5	7.9	395	480	32	967	1200	201	233
PAC	3	47.5	7.9	395	480	32	976	1200	192	224
PAC	3	52.5	7.9	392	490	44	1637	1865	184	228
PAC	3	57.5	7.9	392	490	44	1637	1865	184	228
PAC	1	2.5	7.8	339	617	258	1410	2087	419	677
PAC	1	7.5	7.8	290	783	125	1261	2046	659	785
PAC	1	12.5	7.8	377	783	245	915	1586	426	671
PAC	1	17.5	7.8	310	967	59	310	1127	757	817
PAC	1	22.5	7.8	384	667	237	178	943	528	765
PAC	1	27.5	7.8	384	667	237	20	760	502	739
PAC	1	32.5	7.8	324	500	61	46	760	653	714
PAC	1	37.5	7.8	324	500	61	46	760	653	714
PAC	1	42.5	7.8	363	700	110	89	823	624	734
PAC	1	47.5	7.8	363	700	110	89	823	624	734
PAC	1	52.5	7.8	362	667	58	210	956	688	746
PAC	1	57.5	7.8	362	667	58	210	956	688	746
PAC	2	2.5	7.8	181	717	62	134	926	730	792
PAC	2	7.5	7.8	245	850	49	338	1058	671	720
PAC	2	12.5	7.8	323	783	54	673	1295	567	622
PAC	2	17.5	7.8	333	600	61	876	1532	595	656
PAC	2	22.5	7.8	359	633	45	966	1586	575	620
PAC	2	27.5	7.8	359	633	45	926	1640	669	713
PAC	2	32.5	7.8	356	650	100	833	1640	706	807
PAC	2	37.5	7.8	356	650	100	833	1640	706	807
PAC	2	42.5	7.8	383	783	95	311	1300	894	989
PAC	2	47.5	7.8	383	783	95	311	1300	894	989
PAC	2	52.5	7.8	377	350	207	411	1479	860	1068
PAC	2	57.5	7.8	377	350	207	411	1479	860	1068
PAC	3	2.5	7.8	222	450	139	431	752	182	321
PAC	3	7.5	7.8	295	217	142	43	429	245	386
PAC	3	12.5	7.9	351	400	146	47	440	247	393

	PAC	3	17.5	7.8	332	617	171	113	502	218	389
	PAC	3	22.5	7.7	366	617	176	189	576	212	387
	PAC	3	27.5	7.8	366	433	176	246	650	229	405
	PAC	3	32.5	7.8	368	433	157	228	650	265	422
	PAC	3	37.5	7.8	368	517	157	228	650	265	422
	PAC	3	42.5	7.8	395	583	177	477	900	246	423
	PAC	3	47.5	7.8	395	583	177	477	900	246	423
	PAC	3	52.5	7.8	379	517	181	504	909	225	405
	PAC	3	57.5	7.8	379	517	181	504	909	225	405
14-Jun-10	alum	1	2.5	7.5	412	345	97	623	832	112	209
	alum	1	7.5	7.4	346	376	71	582	805	152	223
	alum	1	12.5	7.4	343	396	68	520	761	173	241
	alum	1	17.5	7.3	347	385	65	701	926	160	225
	alum	1	22.5	7.3	392	313	77	504	768	187	264
	alum	1	27.5	7.3	361	754	48	319	755	388	436
	alum	1	32.5	7.3	385	386	63	204	449	182	245
	alum	1	37.5	7.3	387	359	57	477	694	160	216
	alum	1	42.5	7.3	415	327	58	229	442	155	213
	alum	1	47.5	7.3	372	426	52	229	444	163	216
	alum	1	52.5	7.3	392	460	70	220	416	126	196
	alum	1	57.5	7.3	367	368	67	208	406	132	199
	alum	2	2.5	7.4	337	215	46	142	359	170	216
	alum	2	7.5	7.4	358	270	54	243	410	112	166
	alum	2	12.5	7.4	380	251	50	177	333	105	156
	alum	2	17.5	7.4	367	261	148	127	314	39	187
	alum	2	22.5	7.4	374	232	47	225	410	138	185
	alum	2	27.5	7.4	400	244	48	179	315	87	136
	alum	2	32.5	7.4	370	226	73	142	286	71	144
	alum	2	37.5	7.4	387	242	47	179	312	86	133
	alum	2	42.5	7.4	386	248	60	266	388	62	122
	alum	2	47.5	7.4	448	183	112	313	434	9	121
	alum	2	52.5	7.4	343	200	39	269	381	73	112
	alum	2	57.5	7.4	366	209	42	217	333	74	116
	alum	3	2.5	7.5	343	256	60	271	374	44	104
	alum	3	7.5	7.5	285	337	72	154	328	101	174
	alum	3	12.5	7.5	366	301	69	189	341	83	152
	alum	3	17.5	7.5	373	306	69	353	483	61	130
	alum	3	22.5	7.5	393	357	62	297	433	73	136
	alum	3	27.5	7.5	428	453	61	149	235	25	86
	alum	3	32.5	7.5	356	325	56	70	191	66	122
	alum	3	37.5	7.5	402	255	66	491	645	87	153
	alum	3	42.5	7.5	380	354	51	33	152	67	118
	alum	3	47.5	7.5	387	219	47	212	328	69	116
	alum	3	52.5	7.5	391	514	55	139	296	102	157
	alum	3	57.5	7.5	456	277	66	254	374	53	120
	Grass	1	2.5	7.5	402	318	195	133	643	314	510
	Grass	1	7.5	7.5	406	237	231	107	623	285	516
	Grass	1	12.5	7.5	401	160	206	132	643	305	511
	Grass	1	17.5	7.5	449	133	236	91	654	327	563
	Grass	1	22.5	7.5	412	200	220	145	643	278	498
	Grass	1	27.5	7.6	451	197	227	81	590	283	509
	Grass	1	32.5	7.6	446	92	221	61	567	285	506
	Grass	1	37.5	7.6	422	204	215	37	543	291	506
	Grass	1	42.5	7.6	464	188	238	45	547	265	502
	Grass	1	47.5	7.6	449	168	326	93	564	145	471
	Grass	1	52.5	7.6	462	145	262	70	523	191	453
	Grass	1	57.5	7.6	434	280	273	23	543	246	520

	Grass	2	2.5	7.6	477	191	280	593	958	85	365
	Grass	2	7.5	7.5	376	183	267	502	931	161	429
	Grass	2	12.5	7.5	427	183	272	530	987	185	457
	Grass	2	17.5	7.5	436	174	256	476	955	223	479
	Grass	2	22.5	7.5	480	182	265	445	943	234	499
	Grass	2	27.5	7.6	550	61	261	411	888	216	477
	Grass	2	32.5	7.6	398	112	258	356	819	205	463
	Grass	2	37.5	7.6	421	110	267	421	841	153	420
	Grass	2	42.5	7.6	545	78	283	444	853	126	409
	Grass	2	47.5	7.6	407	166	289	389	796	118	408
	Grass	2	52.5	7.6	520	154	278	321	757	158	436
	Grass	2	57.5	7.6	539	103	279	394	812	139	418
	Grass	3	2.5	7.9	434	125	102	198	345	45	147
	Grass	3	7.5	7.6	566	99	166	109	322	47	213
	Grass	3	12.5	7.6	413	116	156	20	457	280	437
	Grass	3	17.5	7.6	267	74	261	96	567	210	471
	Grass	3	22.5	7.6	367	69	255	118	523	150	405
	Grass	3	27.5	7.6	340	84	266	138	546	142	408
	Grass	3	32.5	7.6	368	88	280	107	521	134	414
	Grass	3	37.5	7.6	343	48	237	89	476	150	387
	Grass	3	42.5	7.6	383	37	234	79	453	140	374
	Grass	3	47.5	7.6	315	108	236	35	432	161	397
	Grass	3	52.5	7.6	343	67	281	62	456	113	394
	Grass	3	57.5	7.6	356	71	281	49	432	102	383
28-Jun-10	lime	1	2.5	7.4	374	691	190	932	1964	842	1033
	lime	1	7.5	7.4	418	698	259	1080	2112	773	1032
	lime	1	12.5	7.4	460	696	270	1240	2255	745	1015
	lime	1	17.5	7.4	456	1000	286	1159	2081	637	922
	lime	1	22.5	7.4	532	794	334	965	1890	591	925
	lime	1	27.5	7.4	385	739	244	1037	1994	713	957
	lime	1	32.5	7.4	478	713	173	1171	2177	834	1007
	lime	1	37.5	7.4	453	826	293	1050	1922	578	871
	lime	1	42.5	7.4	466	747	326	909	1753	518	844
	lime	1	47.5	7.4	476	716	309	843	1524	373	681
	lime	1	52.5	7.4	463	778	360	602	1079	117	477
	lime	1	57.5	7.4	439	611	255	237	543	51	306
	lime	2	2.5	7.5	287	654	207	18	871	645	853
	lime	2	7.5	7.5	396	632	223	73	911	614	837
	lime	2	12.5	7.5	349	674	224	191	1040	625	849
	lime	2	17.5	7.5	358	558	286	126	974	562	848
	lime	2	22.5	7.5	370	711	287	1215	1891	389	676
	lime	2	27.5	7.5	360	293	328	1290	1957	338	666
	lime	2	32.5	7.5	414	429	278	1383	2023	363	640
	lime	2	37.5	7.5	392	667	241	1082	1862	539	780
	lime	2	42.5	7.5	323	607	295	1220	1666	151	446
	lime	2	47.5	7.5	362	767	324	183	1835	1328	1652
	lime	2	52.5	7.5	376	485	345	267	1634	1021	1367
	lime	2	57.5	7.5	265	520	388	80	1564	1096	1484
	lime	3	2.5	7.45	348	386	118	136	529	275	393
	lime	3	7.5	7.4	380	394	78	333	493	83	160
	lime	3	12.5	7.44	390	425	95	87	566	384	479
	lime	3	17.5	7.45	390	491	107	118	620	395	502
	lime	3	22.5	7.5	386	316	108	114	729	507	616
	lime	3	27.5	7.5	403	341	111	58	639	470	581
	lime	3	32.5	7.5	404	200	131	152	663	380	511
	lime	3	37.5	7.6	384	885	135	128	662	399	534
	lime	3	42.5	7.4	415	755	117	484	1081	480	597

	lime	3	47.5	7.4	414	586	133	680	1232	419	551
	lime	3	52.5	7.4	388	303	139	39	575	396	535
	lime	3	57.5	7.4	387	448	98	86	531	347	445
	lime	1	2.5	7.4	456	347	210	157	968	601	811
	lime	1	7.5	7.5	402	410	231	863	1425	331	562
	lime	1	12.5	7.5	520	571	242	751	1507	514	756
	lime	1	17.5	7.5	520	711	200	1014	1733	520	720
	lime	1	22.5	7.5	612	771	278	1080	1886	528	806
	lime	1	27.5	7.5	443	464	202	518	1930	1210	1412
	lime	1	32.5	7.5	538	690	304	1025	2156	828	1131
	lime	1	37.5	7.5	327	852	285	1101	2068	683	967
	lime	1	42.5	7.5	533	694	253	837	1995	905	1158
	lime	1	47.5	7.5	540	628	368	688	1959	902	1271
	lime	1	52.5	7.5	529	1044	297	1050	1930	583	880
	lime	1	57.5	7.5	510	439	282	905	1724	537	819
	lime	2	2.5	7.5	341	500	216	1041	1845	588	804
	lime	2	7.5	7.5	462	517	177	1216	1950	557	734
	lime	2	12.5	7.5	409	619	192	1200	1991	599	791
	lime	2	17.5	7.5	420	581	193	1224	1999	582	775
	lime	2	22.5	7.5	436	736	122	1072	1900	706	828
	lime	2	27.5	7.5	419	733	173	1180	1938	586	759
	lime	2	32.5	7.5	477	732	206	1149	1910	555	761
	lime	2	37.5	7.5	455	699	162	1080	1776	534	696
	lime	2	42.5	7.5	389	787	173	1103	1848	572	744
	lime	2	47.5	7.5	442	674	219	1075	1793	499	718
	lime	2	52.5	7.5	442	543	248	1042	1722	432	680
	lime	2	57.5	7.5	427	684	263	1112	1849	474	736
	lime	3	2.5	7.6	352	786	62	123	864	679	741
	lime	3	7.5	7.5	411	633	66	602	1022	354	420
	lime	3	12.5	7.53	425	435	81	683	1080	316	397
	lime	3	17.5	7.6	423	263	76	768	1220	376	451
	lime	3	22.5	7.6	420	468	80	719	1219	420	500
	lime	3	27.5	7.6	423	383	81	625	1074	368	449
	lime	3	32.5	7.6	443	588	80	670	1110	359	439
	lime	3	37.5	7.6	423	431	75	643	1163	445	520
	lime	3	42.5	7.6	458	404	83	488	870	299	382
	lime	3	47.5	7.6	445	229	89	655	1076	331	421
	lime	3	52.5	7.6	422	735	95	529	1066	443	538
	lime	3	57.5	7.6	417	667	145	641	1146	359	505
05-Jul-10	alum	1	2.5	7.47	248	478	58	453	643	133	191
	alum	1	7.5	7.46	272	485	46	443	646	156	202
	alum	1	12.5	7.4	258	580	79	413	648	156	235
	alum	1	17.5	7.4	347	554	48	451	654	155	202
	alum	1	22.5	7.4	373	625	46	349	548	153	199
	alum	1	27.5	7.4	397	531	43	350	574	181	224
	alum	1	32.5	7.4	388	553	58	372	602	172	231
	alum	1	37.5	7.4	435	523	47	371	567	149	196
	alum	1	42.5	7.4	362	575	43	342	543	158	201
	alum	1	47.5	7.4	382	543	52	379	563	133	185
	alum	1	52.5	7.4	396	500	56	344	531	131	187
	alum	1	57.5	7.4	368	476	59	415	520	46	105
	alum	2	2.5	7.5	331	333	126	400	628	102	228
	alum	2	7.5	7.5	359	556	66	643	875	167	233
	alum	2	12.5	7.5	320	722	74	323	526	128	202
	alum	2	17.5	7.5	365	505	69	256	553	228	297
	alum	2	22.5	7.5	379	427	84	217	496	194	278
	alum	2	27.5	7.5	392	727	80	202	488	206	286

	alum	2	32.5	7.5	361	529	81	216	480	183	264
	alum	2	37.5	7.5	387	500	85	204	484	195	280
	alum	2	42.5	7.5	404	660	89	248	453	117	205
	alum	2	47.5	7.5	336	254	91	253	476	132	223
	alum	2	52.5	7.5	384	551	94	291	526	141	235
	alum	2	57.5	7.5	385	446	105	301	525	119	224
	alum	3	2.5	7.5	392	309	73	85	391	234	306
	alum	3	7.5	7.5	250	371	89	31	393	273	362
	alum	3	12.5	7.5	338	624	84	147	388	157	241
	alum	3	17.5	7.5	387	467	83	145	383	155	237
	alum	3	22.5	7.5	386	378	84	160	436	192	276
	alum	3	27.5	7.5	413	544	86	78	378	215	300
	alum	3	32.5	7.5	404	167	115	101	400	184	299
	alum	3	37.5	7.5	380	212	99	146	402	157	256
	alum	3	42.5	7.5	447	143	97	37	367	232	330
	alum	3	47.5	7.5	375	486	90	107	377	180	270
	alum	3	52.5	7.5	389	638	97	182	394	115	212
	alum	3	57.5	7.5	405	420	87	248	425	90	177
	Grass	1	2.5	7.5	326	286	67	166	352	119	186
	Grass	1	7.5	7.5	384	213	71	187	372	114	185
	Grass	1	12.5	7.5	351	370	69	206	401	125	194
	Grass	1	17.5	7.5	390	240	75	228	424	121	196
	Grass	1	22.5	7.5	394	253	82	172	375	121	203
	Grass	1	27.5	7.5	392	267	77	144	347	126	203
	Grass	1	32.5	7.5	397	301	74	74	293	146	220
	Grass	1	37.5	7.5	400	302	76	59	281	146	222
	Grass	1	42.5	7.5	408	300	194	74	288	20	214
	Grass	1	47.5	7.5	364	433	102	56	223	65	167
	Grass	1	52.5	7.5	416	344	77	58	256	121	197
	Grass	1	57.5	7.5	389	256	81	93	265	91	172
	Grass	2	2.5	7.6	295	158	79	90	278	109	188
	Grass	2	7.5	7.6	433	88	72	91	271	108	180
	Grass	2	12.5	7.6	381	138	75	101	269	93	168
	Grass	2	17.5	7.6	382	45	77	85	246	83	161
	Grass	2	22.5	7.6	397	25	83	83	244	78	161
	Grass	2	27.5	7.6	412	76	84	86	227	57	141
	Grass	2	32.5	7.6	427	23	106	66	198	26	132
	Grass	2	37.5	7.6	398	42	100	63	206	44	144
	Grass	2	42.5	7.6	408	170	65	74	206	66	131
	Grass	2	47.5	7.6	404	100	109	60	192	24	133
	Grass	2	52.5	7.6	417	216	122	73	209	14	135
	Grass	2	57.5	7.6	411	48	130	45	177	2	132
	Grass	3	2.5	7.6	335	63	48	138	233	47	95
	Grass	3	7.5	7.6	393	85	44	88	176	44	88
	Grass	3	12.5	7.6	356	134	68	89	186	29	97
	Grass	3	17.5	7.6	409	50	75	46	168	47	122
	Grass	3	22.5	7.6	416	33	79	22	145	44	123
	Grass	3	27.5	7.6	362	95	113	11	156	32	145
	Grass	3	32.5	7.6	414	95	81	34	179	64	145
	Grass	3	37.5	7.6	394	115	96	31	187	60	156
	Grass	3	42.5	7.6	403	68	89	40	167	38	127
	Grass	3	47.5	7.6	408	85	82	54	165	29	111
	Grass	3	52.5	7.6	389	130	95	66	198	37	132
	Grass	3	57.5	7.6	409	43	145	8	166	13	158
07-Jul-10	lime	1	2.5	7.6	366	550	280	405	1095	410	690
	lime	1	7.5	7.6	295	367	105	304	1030	621	726
	lime	1	12.5	7.6	381	850	132	461	1084	491	624

lime	1	17.5	7.6	327	533	129	335	1139	674	803
lime	1	22.5	7.6	395	650	100	257	1097	740	840
lime	1	27.5	7.6	395	650	100	260	1055	694	794
lime	1	32.5	7.6	354	650	286	306	1055	463	749
lime	1	37.5	7.6	354	650	286	306	1055	463	749
lime	1	42.5	7.6	373	450	291	200	1000	509	800
lime	1	47.5	7.6	373	450	291	200	1000	509	800
lime	1	52.5	7.6	366	500	295	18	863	550	845
lime	1	57.5	7.6	366	500	295	18	863	550	845
lime	2	2.5	7.6	392	567	122	32	410	256	378
lime	2	7.5	7.6	295	467	86	28	790	676	762
lime	2	12.5	7.6	389	517	133	14	628	481	613
lime	2	17.5	7.6	377	400	98	38	566	430	528
lime	2	22.5	7.6	391	450	269	8	629	351	621
lime	2	27.5	7.6	391	450	269	50	713	393	662
lime	2	32.5	7.5	395	567	132	9	713	572	704
lime	2	37.5	7.6	395	567	132	9	713	572	704
lime	2	42.5	7.7	434	400	169	143	800	488	657
lime	2	47.5	7.6	434	400	169	177	834	488	657
lime	2	52.5	7.6	379	383	306	253	926	367	673
lime	2	57.5	7.6	379	383	306	253	926	367	673
lime	3	2.5	7.6	340	567	150	46	211	15	165
lime	3	7.5	7.6	380	500	145	402	929	382	526
lime	3	12.5	7.6	405	433	158	176	901	566	725
lime	3	17.5	7.6	382	450	186	501	873	186	372
lime	3	22.5	7.6	399	450	193	292	928	442	635
lime	3	27.5	7.6	399	500	193	306	983	484	677
lime	3	32.5	7.6	403	500	167	265	983	551	718
lime	3	37.5	7.6	403	450	167	265	983	551	718
lime	3	42.5	7.6	429	167	188	277	1000	535	723
lime	3	47.5	7.6	429	167	188	277	1000	535	723
lime	3	52.5	7.6	401	400	177	459	1186	550	727
lime	3	57.5	7.6	401	400	177	459	1186	550	727
slurry	1	2.5	7.8	153	1067	150	663	1219	406	556
slurry	1	7.5	7.8	216	1667	169	47	798	582	751
slurry	1	12.5	7.8	274	3000	177	672	1686	837	1014
slurry	1	17.5	7.8	304	2880	225	306	1974	1443	1668
slurry	1	22.5	7.8	326	2900	351	3892	5565	1322	1673
slurry	1	27.5	7.8	339	3933	363	5735	7519	1421	1784
slurry	1	32.5	7.8	358	4200	472	10434	12419	1514	1986
slurry	1	37.5	7.8	373	2400	384	11737	13855	1735	2119
slurry	1	42.5	7.8	378	3733	375	12089	14089	1625	2000
slurry	1	47.5	7.8	411	3600	512	10821	12982	1649	2161
slurry	1	52.5	7.8	393	3267	460	11021	13890	2410	2870
slurry	1	57.5	7.8	457	3800	373	10748	13330	2209	2582
slurry	2	2.5	7.8	276	1950	918	10786	12350	646	1564
slurry	2	7.5	7.8	268	3400	826	4776	6317	715	1541
slurry	2	12.5	7.7	348	3300	700	5785	8099	1614	2314
slurry	2	17.5	7.9	390	3350	541	8786	11029	1702	2243
slurry	2	22.5	7.9	357	3050	735	10025	12592	1832	2567
slurry	2	27.5	7.9	395	3333	709	9238	11764	1817	2526
slurry	2	32.5	7.9	406	3533	691	9341	11279	1248	1939
slurry	2	37.5	7.9	435	3600	714	9244	11031	1073	1787
slurry	2	42.5	7.9	439	3267	1166	9054	10603	383	1549
slurry	2	47.5	7.9	449	4067	867	6303	8857	1687	2554
slurry	2	52.5	7.9	436	2600	1134	9224	11022	665	1799
slurry	2	57.5	7.9	486	4667	800	6279	8878	1799	2599

	slurry	3	2.5	7.7	235	3000	868	4973	6049	208	1076
	slurry	3	7.5	7.8	334	1575	984	4168	5191	39	1023
	slurry	3	12.5	7.8	335	1000	1138	3806	4994	50	1188
	slurry	3	17.5	7.8	400	880	1077	2338	4060	645	1722
	slurry	3	22.5	7.8	312	5480	1093	2957	4692	642	1735
	slurry	3	27.5	7.8	384	2040	1057	3191	5098	850	1907
	slurry	3	32.5	7.8	399	2200	1050	4536	6247	661	1711
	slurry	3	37.5	7.8	426	2600	1134	5369	6896	393	1527
	slurry	3	42.5	7.8	409	1250	1125	3377	5324	822	1947
	slurry	3	47.5	7.8	480	1367	1130	4483	6061	448	1578
	slurry	3	52.5	7.8	446	1833	1224	4416	5858	218	1442
	slurry	3	57.5	7.8	488	1867	1309	3596	5469	564	1873
12-Jul-10	slurry	1	2.5	7.8	320	3050	574	11485	12084	25	599
	slurry	1	7.5	7.8	334	3200	529	8524	9125	72	601
	slurry	1	12.5	7.8	357	960	72	796	1528	660	732
	slurry	1	17.5	7.8	364	1080	40	1380	2141	721	761
	slurry	1	22.5	7.8	380	1360	166	2470	3287	651	817
	slurry	1	27.5	7.7	379	1233	430	3460	4588	698	1128
	slurry	1	32.5	7.7	385	1950	517	5202	6520	800	1317
	slurry	1	37.5	7.7	390	3550	557	6553	7995	885	1442
	slurry	1	42.5	7.7	384	2800	538	7400	8951	1013	1551
	slurry	1	47.5	7.7	438	3150	649	10152	11741	939	1588
	slurry	1	52.5	7.7	347	2600	758	10881	12506	867	1625
	slurry	1	57.5	7.7	398	3300	850	11207	12850	793	1643
	slurry	2	2.5	7.7	342	1550	256	7439	10819	3124	3380
	slurry	2	7.5	7.9	298	1257	340	8363	12188	3485	3825
	slurry	2	12.5	7.9	384	4200	271	4052	11596	7273	7544
	slurry	2	17.5	7.9	412	7333	280	5659	11883	5944	6224
	slurry	2	22.5	7.9	376	1550	491	7138	11550	3921	4412
	slurry	2	27.5	7.9	401	3150	368	7785	11701	3548	3916
	slurry	2	32.5	7.7	413	3700	390	8233	12245	3622	4012
	slurry	2	37.5	7.7	415	4867	448	7800	11784	3536	3984
	slurry	2	42.5	7.7	411	4867	517	7690	11642	3435	3952
	slurry	2	47.5	7.7	421	3800	609	6985	10977	3383	3992
	slurry	2	52.5	7.9	403	3200	777	6176	10100	3147	3924
	slurry	2	57.5	7.7	420	3400	682	8159	12347	3506	4188
	slurry	3	2.5	7.8	330	1525	410	307	2589	1872	2282
	slurry	3	7.5	7.6	381	1200	364	448	2566	1754	2118
	slurry	3	12.5	7.7	405	2367	369	677	3225	2179	2548
	slurry	3	17.5	7.7	434	1800	495	1992	4971	2484	2979
	slurry	3	22.5	7.7	345	2650	482	1344	4930	3104	3586
	slurry	3	27.5	7.7	405	1667	556	4779	6867	1533	2089
	slurry	3	32.5	7.7	411	1933	514	4282	6902	2106	2620
	slurry	3	37.5	7.7	413	1467	466	5711	7053	876	1342
	slurry	3	42.5	7.7	415	1500	619	4982	7209	1608	2227
	slurry	3	47.5	7.7	429	1833	558	4619	6699	1522	2080
	slurry	3	52.5	7.7	409	1367	543	4558	7076	1975	2518
	slurry	3	57.5	7.7	407	1400	334	4682	6206	1190	1524
	Fe	1	2.5	7.8	360	670	256	1154	1745	336	591
	Fe	1	7.5	7.8	323	670	95	1333	1993	564	659
	Fe	1	12.5	7.8	348	620	272	1336	2150	541	813
	Fe	1	17.5	7.8	345	660	272	1314	2150	563	836
	Fe	1	22.5	7.8	371	700	277	1827	2668	564	841
	Fe	1	27.5	7.8	371	700	280	1847	2668	541	821
	Fe	1	32.5	7.8	342	860	274	1834	2668	560	834
	Fe	1	37.5	7.8	342	860	274	1851	2668	543	817
	Fe	1	42.5	7.8	356	960	256	2563	3417	598	854

Fe	1	47.5	7.8	356	960	256	2553	3417	608	864
Fe	1	52.5	7.8	349	1020	152	2585	3417	680	832
Fe	1	57.5	7.8	349	1020	152	2541	3417	724	877
Fe	2	2.5	7.8	362	1100	312	1575	2452	565	877
Fe	2	7.5	7.8	334	1760	292	1879	2615	444	736
Fe	2	12.5	7.8	334	980	273	2266	2993	455	728
Fe	2	17.5	7.8	352	1320	271	2231	2993	491	762
Fe	2	22.5	7.8	355	1240	292	1835	2536	409	701
Fe	2	27.5	7.8	355	1240	300	1751	2536	485	785
Fe	2	32.5	7.8	361	1280	289	1785	2536	462	751
Fe	2	37.5	7.8	361	1280	289	1655	2536	592	882
Fe	2	42.5	7.8	373	1280	315	1838	2718	565	880
Fe	2	47.5	7.8	373	1280	315	1857	2718	546	861
Fe	2	52.5	7.8	342	1280	176	1968	2718	574	750
Fe	2	57.5	7.8	342	1280	176	1942	2718	601	777
Fe	3	2.5	7.8	324	960	319	586	1160	255	574
Fe	3	7.5	7.8	330	1420	333	912	1445	199	533
Fe	3	12.5	7.8	396	1540	332	570	1321	419	751
Fe	3	17.5	7.8	311	1080	342	650	1321	329	671
Fe	3	22.5	7.8	365	540	350	1241	1942	351	701
Fe	3	27.5	7.8	365	540	290	1261	1942	391	681
Fe	3	32.5	7.8	370	900	369	1582	2332	381	750
Fe	3	37.5	7.8	370	900	369	1552	2332	411	780
Fe	3	42.5	7.8	377	560	224	1594	2305	487	711
Fe	3	47.5	7.8	377	560	224	1704	2305	377	601
Fe	3	52.5	7.8	380	1000	182	1655	2305	468	650
Fe	3	57.5	7.8	380	1000	182	1710	2305	412	594

Appendix D Results from Chapter 5

Table D.1 Ammonia emissions data

			Cumulative runtime			mass N		NH$_3$-N loss kg/ha	
	Period	Run time (mins)	mins	hours	mg/l	mgN	mgN m-2	hourly KG HA-1	measurement period
Slurry	1	120	120	2	45.56	29	3699	18	18
	2	240	360	4	22.97	13	1703	4	4
	3	1080	1440	18	44.83	26	3325	2	2
	4	1440	2880	24	0.00	0	0	0	0
	5	2880	5760	48	16.76	9	1215	0	0
	6	4320	10080	72	0.00	0	0	0	0
Slurry	1	120	120	2	31.99	20	2570	13	13
	2	240	360	4	31.90	17	2234	6	6
	3	1080	1440	18	52.33	30	3881	2	2
	4	1440	2880	24	0.00	0	0	0	0
	5	2880	5760	48	22.00	12	1577	0	0
	6	4320	10080	72	0.00	0	0	0	0
Slurry	1	120	120	2	33.49	21	2732	14	14
	2	240	360	4	35.55	21	2637	7	7
	3	1080	1440	18	45.97	27	3429	2	2
	4	1440	2880	24	0.00	0	0	0	0
	5	2880	5760	48	15.34	9	1112	0	0
	6	4320	10080	72	0.00	0	0	0	0
Alum	1	120	120	2	0.41	0	33	0	0
	2	240	360	4	1.14	1	83	0	0
	3	1080	1440	18	3.22	2	236	0	0
	4	1440	2880	24	0.00	0	0	0	0
	5	2880	5760	48	7.40	4	549	0	0
	6	4320	10080	72	0.00	0	0	0	0
Alum	1	120	120	2	0.67	0	54	0	0
	2	240	360	4	2.42	1	156	0	0
	3	1080	1440	18	4.04	2	250	0	0
	4	1440	2880	24	0.00	0	0	0	0
	5	2880	5760	48	5.33	3	389	0	0
	6	4320	10080	72	0.00	0	0	0	0
Alum	1	120	120	2	0.39	0	32	0	0
	2	240	360	4	13.77	8	1021	3	3
	3	1080	1440	18	15.63	9	1159	1	1
	4	1440	2880	24	0.00	0	0	0	0
	5	2880	5760	48	6.59	4	473	0	0
	6	4320	10080	72	0.26	0	14	0	0
Ferrous	1	120	120	2	9.39	6	774	4	4
	2	240	360	4	16.64	11	1358	3	3
	3	1080	1440	18	26.66	17	2175	1	1

	4	1440	2880	24	35.60	21	2641	1	1
	5	2880	5760	48	24.40	13	1639	0	0
	6	4320	10080	72	3.55	2	226	0	0
Ferrous	1	120	120	2	7.00	4	574	3	3
	2	240	360	4	18.86	12	1531	4	4
	3	1080	1440	18	24.60	15	1895	1	1
	4	1440	2880	24	39.62	22	2775	1	1
	5	2880	5760	48	21.87	13	1649	0	0
	6	4320	10080	72	2.88	1	154	0	0
Ferrous	1	120	120	2	9.92	6	817	4	4
	2	240	360	4	23.51	15	1918	5	5
	3	1080	1440	18	25.98	16	1991	1	1
	4	1440	2880	24	36.88	22	2765	1	1
	5	2880	5760	48	15.60	10	1285	0	0
	6	4320	10080	72	2.51	1	149	0	0
Lime	1	120	120	2	115.47	73	9421	47	47
	2	240	360	4	30.75	19	2496	6	6
	3	1080	1440	18	18.58	11	1371	1	1
	4	1440	2880	24	4.47	2	313	0	0
	5	2880	5760	48	0.63	0	34	0	0
	6	4320	10080	72	0.66	0	42	0	0
Lime	1	120	120	2	112.20	71	9108	46	46
	2	240	360	4	33.94	22	2769	7	7
	3	1080	1440	18	11.84	7	927	1	1
	4	1440	2880	24	4.80	3	334	0	0
	5	2880	5760	48	0.47	0	33	0	0
	6	4320	10080	72	0.01	0	0	0	0
Lime	1	120	120	2	79.14	50	6457	32	32
	2	240	360	4	25.26	15	1977	5	5
	3	1080	1440	18	15.10	9	1182	1	1
	4	1440	2880	24	4.92	3	345	0	0
	5	2880	5760	48	0.17	0	12	0	0
	6	4320	10080	72	4.14	2	278	0	0
PAC	1	120	120	2	4.50	3	365	2	2
	2	240	360	4	9.07	6	732	2	2
	3	1080	1440	18	25.48	15	1963	1	1
	4	1440	2880	24	35.97	20	2609	1	1
	5	2880	5760	48	22.52	12	1596	0	0
	6	4320	10080	72	7.18	3	361	0	0
PAC	1	120	120	2	8.42	5	694	3	3
	2	240	360	4	14.97	10	1221	3	3
	3	1080	1440	18	27.44	16	2103	1	1
	4	1440	2880	24	41.35	24	3067	1	1

	5	2880	5760	48	25.71	16	2013	0	0
	6	4320	10080	72	7.29	4	453	0	0
Char	1	120	120	2	9.46	6	780	4	4
	2	240	360	4	13.55	9	1116	3	3
	3	1080	1440	18	14.69	9	1186	1	1
	4	1440	2880	24	11.07	7	894	0	0
	5	2880	5760	48	0.00	0	0	0	0
	6	4320	10080	72	3.89	2	288	0	0
Char	1	120	120	2	1.74	1	143	1	1
	2	240	360	4	10.05	6	820	2	2
	3	1080	1440	18	10.01	6	825	0	0
	4	1440	2880	24	5.44	3	440	0	0
	5	2880	5760	48	1.12	1	91	0	0
	6	4320	10080	72	4.23	3	342	0	0
Charcoal	1	120	120	2	2.93	2	241	1	1
	2	240	360	4	9.98	6	822	2	2
	3	1080	1440	18	19.55	12	1563	1	1
	4	1440	2880	24	11.74	6	813	0	0
	5	2880	5760	48	5.61	3	448	0	0
	6	4320	10080	72	0.76	0	52	0	0
Soil Only	1	120	120	2	0.00	0	0	0	0
	2	240	360	4	0.09	0	7	0	0
	3	1080	1440	18	0.00	0	0	0	0
	4	1440	2880	24	0.00	0	0	0	0
	5	2880	5760	48	0.00	0	0	0	0
	6	4320	10080	72	0.00	0	0	0	0
Soil Only	1	120	120	2	0.00	0	0	0	0
	2	240	360	4	0.01	0	1	0	0
	3	1080	1440	18	0.00	0	0	0	0
	4	1440	2880	24	0.00	0	0	0	0
	5	2880	5760	48	0.00	0	0	0	0
	6	4320	10080	72	0.00	0	0	0	0
Soil Only	1	120	120	2	0.92	1	76	0	0
	2	240	360	4	0.00	0	0	0	0
	3	1080	1440	18	0.06	0	5	0	0
	4	1440	2880	24	0.00	0	0	0	0
	5	2880	5760	48	0.00	0	0	0	0
	6	4320	10080	72	0.00	0	0	0	0

Table D.2 Nitrous oxide flux

Nitrous oxide						ppb							g N2O
Atmospheric pressure				1014.4									
	Time	Temp	RH	DewPt	0	1	2	3	4	ppm	R²	N_2O	g ha^{-1} hr^{-1}
	(hr)	°C	%	°C						h^{-1}		µg m^{-2}h^{-1}	
28	-1	23.1	32	5.7	0.53	0.56	0.55	0.62	0.52	0.25	0.03	22.8	0.23
Slurry	0	24.4	31	6.6	0.47	0.45	0.48	0.5	0.55	1.25	0.73	113.1	1.13
	6	22.3	35	6.5	0.58	0.7	0.74	0.81	0.79	3.14	0.84	285.1	2.85
	24	20.8	35	5	0.81	0.88	1.01	1.14	1.23	6.56	0.99	599.6	6
	48	22.3	42	8.9	0.54	0.58	0.56	0.65	0.66	1.84	0.83	167.4	1.67
	72	18.1	44	5.9	0.53	0.54	0.53	0.59	0.61	1.18	0.75	109	1.09
	96	22.7	38	8.1	0.58	0.51	0.53	0.59		0.45	0.06	40.8	0.41
	144	22.5	38	7.7	0.55	0.52	0.57	0.56	0.63	1.23	0.57	111.7	1.12
	168	17.7	41	4.4	0.53	0.54	0.59	0.56	0.59	0.8	0.65	74.2	0.74
	192	22	32	5	0.5	0.56	0.55	0.56	0.6	1.15	0.77	104.8	1.05
	216	20.9	32	3.8	0.53	0.58	0.55	0.6	0.58	0.77	0.54	70.1	0.7
	240	21.1	35	5.5	0.52	0.55	0.6	0.63	0.65	2.08	0.98	190	1.9
	264	24	37	8.9	0.5	0.51	0.53	0.52	0.54	0.57	0.75	51.5	0.52
	312	23.1	39	8.8	0.53	0.54	0.59	0.54	0.61	1.03	0.51	93.5	0.94
	336	23.8	34	7.3	0.59	0.66	0.75	0.82		4.64	1	419.9	4.2
	360	23.9	32	6.5	0.52	0.54	0.57	0.56	0.61	1.22	0.88	110.1	1.1
	384	24.1	33	7.1	0.49	0.51	0.55	0.64	0.58	1.87	0.69	168.5	1.69
	408	23.3	31	5.7	0.48	0.54	0.51	0.55		1.18	0.61	106.5	1.07
		0											
26	-1	23.1	32	5.7	0.54	0.49	0.55	0.53	0.53	0.11	0.02	10.3	0.1
Slurry	0	24.4	31	6.6	0.51	0.47	0.56	0.54	0.55	0.89	0.41	80.7	0.81
	6	22.3	35	6.5	0.58	0.62	0.66	0.73	0.75	2.69	0.98	244.3	2.44
	24	20.8	35	5	0.89	1.08	1.26	1.45	1.53	9.95	0.98	908.6	9.09
	48	22.3	42	8.9	0.46	0.46	0.49	0.44	0.43	-0.52	0.33	-46.9	-0.47
	72	18.1	44	5.9	0.46	0.58	0.58	0.75	0.68	3.65	0.77	336.3	3.36
	96	22.7	38	8.1	0.59	0.61	0.72	0.78	0.86	4.28	0.97	388.3	3.88
	144	22.5	38	7.7	0.48	0.44	0.5	0.53	0.51	1	0.53	90.5	0.9
	168	17.7	41	4.4	0.52	0.54	0.59	0.64	0.71	2.93	0.97	270.8	2.71
	192	22	32	5	0.6	0.58	0.67	0.79	0.79	3.58	0.87	325.3	3.25
	216	20.9	32	3.8	0.48	0.58	0.61	0.62		2.66	0.84	242.7	2.43
	240	21.1	35	5.5	0.49	0.49	0.51	0.59	0.58	1.69	0.84	154.4	1.54
	264	24	37	8.9	0.54	0.56	0.56	0.6	0.62	1.21	0.91	109.5	1.1
	312	23.1	39	8.8	0.5	0.53	0.61	0.62	0.55	1.15	0.34	103.9	1.04
	336	23.8	34	7.3	0.38	0.46	0.51	0.47		1.89	0.6	170.9	1.71
	360	23.9	32	6.5	0.5	0.51	0.56	0.56	0.55	0.95	0.62	85.7	0.86
	384	24.1	33	7.1	0.51	0.52	0.58	0.61	0.58	1.34	0.69	121.4	1.21
	408	23.3	31	5.7	0.48	0.48	0.5	0.54	0.56	1.3	0.9	117.9	1.18
		0											
27	-1	23.1	32	5.7	0.49	0.47	0.52	0.53	0.53	0.89	0.72	80.5	0.8
Slurry	0	24.4	31	6.6	0.44	0.45	0.5	0.46	0.41	-0.35	0.07	-31.4	-0.31
	6	22.3	35	6.5	0.54	0.56	0.57	0.6	0.65	1.6	0.93	145	1.45
	24	20.8	35	5	0.93	1.11	1.3	1.46	1.66	10.86	1	991.9	9.92
	48	22.3	42	8.9	0.62	0.66	0.82	0.9	0.98	5.74	0.97	521.3	5.21
	72	18.1	44	5.9	0.52	0.57	0.56	0.44	0.61	0.35	0.02	32.1	0.32
	96	22.7	38	8.1	0.54	0.58	0.62	0.52	0.6	0.29	0.04	26.7	0.27
	144	22.5	38	7.7	0.48	0.45	0.49	0.5	0.46	0.02	0	1.6	0.02
	168	17.7	41	4.4	0.48	0.5	0.51	0.5	0.51	0.4	0.55	37.1	0.37
	192	22	32	5	0.51	0.46	0.5	0.49	0.51	0.23	0.08	20.7	0.21
	216	20.9	32	3.8	0.48	0.52	0.49	0.54	0.51	0.4	0.21	36.7	0.37
	240	21.1	35	5.5	0.57	0.55	0.56	0.54	0.55	-0.25	0.44	-23	-0.23

	264	24	37	8.9	0.58	0.54	0.53	0.51	0.52	-0.85	0.7	-76.5	-0.76
	312	23.1	39	8.8	0.47	0.49	0.51	0.56	0.51	0.94	0.55	85.4	0.85
	336	23.8	34	7.3	0.52	0.51	0.5	0.54		0.39	0.18	35.3	0.35
	360	23.9	32	6.5	0.53	0.5	0.56	0.54	0.57	0.68	0.49	61.8	0.62
	384	24.1	33	7.1	0.47	0.46	0.48	0.49	0.51	0.66	0.87	59.6	0.6
	408	23.3	31	5.7	0.57	0.5	0.55	0.54	0.55	0.04	0	3.8	0.04
		0											
31	-1	23.1	32	5.7	0.51	0.58	0.58	0.52	0.51	-0.38	0.07	-34.3	-0.34
Alum	0	24.4	31	6.6	0.44	0.51	0.49	0.55	0.66	2.84	0.81	256	2.56
	6	22.3	35	6.5	0.66	0.69	0.83	0.85	0.93	4.26	0.96	387.1	3.87
	24	20.8	35	5	1.1	1.4	1.69	1.97	2.25	17.22	1	1572.9	15.73
	48	22.3	42	8.9	0.87	1.11	1.32	1.56	1.74	13.1	1	1191	11.91
	72	18.1	44	5.9	0.63	0.86	1.19	1.46	1.76	17.17	1	1582.7	15.83
	96	22.7	38	8.1	0.66	0.93	1.18	1.41	1.62	14.39	1	1306.5	13.06
	144	22.5	38	7.7	0.79	1.02	1.71	2.07	2.52	27.02	0.98	2454.4	24.54
	168	17.7	41	4.4	0.56	0.72	0.89	1.05	1.18	9.37	1	865.1	8.65
	192	22	32	5	0.68	0.8	0.9	1.04	1.08	6.23	0.98	567.1	5.67
	216	20.9	32	3.8	0.52	0.53	0.61	0.65	0.71	2.95	0.97	269	2.69
	240	21.1	35	5.5	0.58	0.62	0.64	0.7	0.71	2.11	0.96	192.7	1.93
	264	24	37	8.9	0.49	0.61	0.63	0.61	0.67	2.11	0.73	190.3	1.9
	312	23.1	39	8.8	0.49	0.55	0.58	0.61	0.69	2.77	0.97	251.2	2.51
	336	23.8	34	7.3	0.47	0.52	0.51	0.54	0.55	1.09	0.86	98.2	0.98
	360	23.9	32	6.5	0.58	0.54	0.53	0.6	0.61	0.66	0.25	59.6	0.6
	384	24.1	33	7.1	0.68	0.7	0.74	0.79	0.83	2.29	0.98	206.5	2.06
	408	23.3	31	5.7	0.69	0.81	0.83	0.9	0.71	0.75	0.05	67.9	0.68
		0											
30	-1	23.1	32	5.7	0.58	0.62	0.67	0.64	0.63	0.77	0.36	69.6	0.7
Alum	0	24.4	31	6.6	0.49	0.42	0.66	0.79	0.91	7.29	0.89	657.7	6.58
	6	22.3	35	6.5	0.73	0.82	0.83	0.91	0.92	2.84	0.93	257.9	2.58
	24	20.8	35	5	0.68	0.91	0.91	1.03	1.11	5.85	0.91	534.3	5.34
	48	22.3	42	8.9	0.65	0.72	0.77	0.81	0.88	3.29	0.99	299.4	2.99
	72	18.1	44	5.9	0.74	0.8	0.84	0.91	0.99	3.7	0.99	340.8	3.41
	96	22.7	38	8.1	0.61	0.74	0.81	0.87	0.9	4.18	0.94	379	3.79
	144	22.5	38	7.7	0.6	0.89	0.9	0.9		5.37	0.61	487.7	4.88
	168	17.7	41	4.4	0.51	0.6	0.59	0.69	0.71	2.96	0.91	273.1	2.73
	192	22	32	5	0.41	0.49	0.61	0.66	0.74	4.92	0.99	447.6	4.48
	216	20.9	32	3.8	0.55	0.6	0.6	0.62	0.6	0.7	0.6	64.1	0.64
	240	21.1	35	5.5	0.55	0.6	0.68	0.73	0.8	3.84	0.99	350.3	3.5
	264	24	37	8.9	0.51	0.62	0.62	0.7	0.77	3.65	0.95	330.2	3.3
	312	23.1	39	8.8	0.61	0.76	0.87	0.9	1.03	5.89	0.96	534	5.34
	336	23.8	34	7.3	0.71	0.99	1.28	1.42	0.8	3.67	0.1	332	3.32
	360	23.9	32	6.5	0.49	0.68	0.71	0.86	0.92	6.19	0.96	559.1	5.59
	384	24.1	33	7.1	0.57	0.64	0.74	0.82	0.81	3.98	0.91	359.3	3.59
	408	23.3	31	5.7	0.57	0.63	0.69	0.74	0.83	3.79	0.99	342.9	3.43
		0											
32	-1	23.1	32	5.7	0.72	0.85	0.95	0.97	1.01	4.24	0.91	383.9	3.84
Alum	0	24.4	31	6.6	0.72	0.8	0.99	0.99	1.14	6.15	0.95	554.9	5.55
	6	22.3	35	6.5	0.8	0.93	1.01	1.17	1.27	7.12	0.99	647.2	6.47
	24	20.8	35	5	0.73	0.77	0.93	0.9	0.94	3.31	0.8	302.5	3.03
	48	22.3	42	8.9	0.49	0.58	0.61	0.64	0.69	2.77	0.96	251.9	2.52
	72	18.1	44	5.9	0.59	0.64	0.67	0.7	0.69	1.59	0.83	146.6	1.47
	96	22.7	38	8.1	0.57	0.58	0.61	0.7	0.68	1.96	0.82	178.1	1.78
	144	22.5	38	7.7	0.53	0.52	0.65	0.64	0.69	2.62	0.83	237.6	2.38
	168	17.7	41	4.4	0.56	0.54	0.56	0.57	0.6	0.62	0.55	57.6	0.58
	192	22	32	5	0.61	0.64	0.64	0.65	0.65	0.51	0.78	46.4	0.46
	216	20.9	32	3.8	0.51	0.52	0.53	0.54	0.56	0.65	0.96	59.2	0.59
	240	21.1	35	5.5	0.44	0.47	0.5	0.51		1.4	0.99	127.5	1.28

	264	24	37	8.9	0.58	0.54	0.53	0.6	0.61	0.66	0.25	59.6	0.6
	312	23.1	39	8.8	0.55	0.65	0.68	0.72	0.75	2.74	0.91	248.5	2.48
	336	23.8	34	7.3	0.66	0.86	0.89	0.99		6.08	0.89	550.2	5.5
	360	23.9	32	6.5	0.48	0.5	0.57	0.52	0.6	1.55	0.71	139.9	1.4
	384	24.1	33	7.1	0.47	0.52	0.62	0.54	0.57	1.31	0.4	118.1	1.18
	408	23.3	31	5.7	0.5	0.53	0.56	0.54		0.75	0.46	67.9	0.68
		0											
23	-1	21.1	35	5.5	0.56	0.52	0.54	0.55	0.56	0.13	0.04	11.5	0.11
FeCl	0	19.7	40	6	0.57	0.6	0.64	0.71		2.7	0.95	247.6	2.48
	2	19.7	42	6.8	0.54	0.53	0.54	0.54	0.56	0.35	0.44	32.5	0.32
	8	24	37	8.9	0.47	0.52	0.52	0.5	0.55	0.97	0.62	87.8	0.88
	24	24.3	38	9.3	0.63	0.71	0.76	0.86	0.9	4.19	0.98	378	3.78
	48	23.8	34	7.3	0.64	0.78	0.88	1.01	1.14	7.37	1	666.3	6.66
	96	23.8	29	4.8	0.87	1.15	1.38	1.71	1.99	16.79	1	1517.7	15.18
	192	22.7	27	3	0.59	0.65	0.65	0.73		2.45	0.87	222.1	2.22
	216	21.6	27	2	0.47	0.51	0.57	0.58	1.14	8.43	0.66	768	7.68
	240	22.4	29	4	0.51	0.55	0.52	0.6	0.61	1.51	0.73	136.8	1.37
	312	23.2	33	6.5	0.53	0.58	0.56	0.57		0.7	0.39	63.1	0.63
	336	22.9	32	5.4	0.53	0.59	0.59	0.63	1.14	7.6	0.64	688.9	6.89
	360	23.4	30	5	0.47	0.54	0.51	0.52	0.57	1.1	0.62	99.9	1
	384	22.5	30	4.4	0.47	0.51	0.48	0.49	0.49	0.08	0.02	7.1	0.07
	408	22.5	30	4.5	0.47	0.47	0.51	0.53	0.49	0.59	0.42	53.4	0.53
	504	22.3	29	4.3	0.62	0.6	0.63	0.62		0.19	0.14	17.4	0.17
	528	22.1	28	4.4	0.46	0.49	0.49	0.5	0.49	0.43	0.57	39.3	0.39
	552	21.9	31	5.1	0.44	0.46	0.49	0.51	0.5	0.98	0.87	89.6	0.9
	576	22.9	27	3.9	0.48	0.46	0.54	0.5	0.49	0.29	0.07	26.1	0.26
		0											
24	-1	21.1	35	5.5	0.52	0.47	0.52	0.53	0.56	0.78	0.4	71.2	0.71
FeCl	0	19.7	40	6	0.62	0.59	0.58	0.69	0.77	2.35	0.61	215.7	2.16
	2	19.7	42	6.8	0.56	0.57	0.62	0.58	0.63	0.83	0.51	76.5	0.76
	8	24	37	8.9	0.5	0.53	0.56	0.53	0.56	0.72	0.53	65.1	0.65
	24	24.3	38	9.3	0.68	0.78	0.87	0.93	1.04	5.19	0.99	468.5	4.68
	48	23.8	34	7.3	0.79	0.97	1.06	1.26	1.38	8.76	0.99	792.1	7.92
	96	23.8	29	4.8	0.73	0.97	1.15	1.39	1.58	12.79	1	1156.5	11.56
	192	22.7	27	3	0.59	0.55	0.57	0.5		-1.45	0.67	-131.8	-1.32
	216	21.6	27	2	0.46	0.47	0.43	0.47	1.38	11.09	0.5	1010.7	10.11
	240	22.4	29	4	0.48	0.54	0.5	0.48	0.55	0.39	0.1	35.4	0.35
	312	23.2	33	6.5	0.45	0.53	0.48	0.51		0.94	0.28	85.3	0.85
	336	22.9	32	5.4	0.49	0.53	0.5	0.53	1.38	10.67	0.52	967.5	9.67
	360	23.4	30	5	0.46	0.51	0.46	0.47	0.52	0.46	0.21	41.8	0.42
	384	22.5	30	4.4	0.48	0.5	0.49	0.5	0.47	-0.12	0.07	-10.9	-0.11
	408	22.5	30	4.5	0.45	0.52	0.5	0.45	0.49	0.11	0.01	10.4	0.1
	504	22.3	29	4.3	0.58	0.56	0.55	0.57		-0.25	0.2	-22.9	-0.23
	528	22.1	28	4.4	0.51	0.46	0.52	0.52	0.53	0.65	0.4	58.9	0.59
	552	21.9	31	5.1	0.46	0.43	0.48	0.53	0.51	1.22	0.65	110.9	1.11
	576	22.9	27	3.9	0.44	0.47	0.49	0.49	0.43	0.04	0	3.8	0.04
		0											
18	-1	21.1	35	5.5	0.48	0.47	0.51	0.54	0.56	1.4	0.9	128.1	1.28
FeCl	0	19.7	40	6	0.6	0.64	0.6	0.63	0.65	0.52	0.43	47.9	0.48
	2	19.7	42	6.8	0.56	0.57	0.57	0.62		0.95	0.76	87.5	0.87
	8	24	37	8.9	0.52	0.56	0.57	0.57	0.61	1.24	0.85	111.7	1.12
	24	24.3	38	9.3	0.77	0.87	1.01	1.07	1.24	6.82	0.98	615.2	6.15
	48	23.8	34	7.3	0.63	0.85	1.12	1.29	1.52	13.36	1	1207.7	12.08
	96	23.8	29	4.8	0.42	0.62	0.8	0.95	1.18	11.14	1	1006.7	10.07
	192	22.7	27	3	0.54	0.55	0.59	0.58	0.68	1.9	0.79	172.6	1.73
	216	21.6	27	2	0.49	0.52	0.52	0.49	1.52	12.14	0.5	1106.3	11.06
	240	22.4	29	4	0.45	0.47	0.5	0.51	0.53	1.24	0.97	112.8	1.13

	312	23.2	33	6.5	0.44	0.48	0.48	0.55		2.09	0.89	189.7	1.9
	336	22.9	32	5.4	0.54	0.51	0.57	0.55	1.52	11.95	0.52	1083.9	10.84
	360	23.4	30	5	0.48	0.51	0.47	0.51	0.55	0.78	0.45	70.6	0.71
	384	22.5	30	4.4	0.5	0.47	0.5	0.51	0.48	0.11	0.03	9.8	0.1
	408	22.5	30	4.5	0.45	0.49	0.48	0.49	0.5	0.52	0.74	47.4	0.47
	504	22.3	29	4.3	0.5	0.52	0.52	0.51		0.19	0.2	16.9	0.17
	528	22.1	28	4.4	0.44	0.49	0.48	0.51	0.51	0.91	0.75	82.9	0.83
	552	21.9	31	5.1	0.87	0.46	0.46	0.47	0.49	-4.4	0.42	-400.8	-4.01
	576	22.9	27	3.9	0.46	0.47	0.5	0.48	0.45	-0.15	0.04	-13.6	-0.14
		0											
17	-1	21.1	35	5.5	0.48	0.47	0.51	0.54	0.56	1.4	0.9	128.1	1.28
Lime	0	19.7	40	6	0.63	0.7	0.7	0.74		1.97	0.89	180.5	1.8
	2	19.7	42	6.8	0.58	0.58	0.59	0.64	0.65	1.18	0.85	108.4	1.08
	8	24	37	8.9	0.56	0.59	0.63	0.64	0.81	3.38	0.8	305.3	3.05
	24	24.3	38	9.3	0.87	0.95	1.07	1.24	1.33	7.34	0.99	662.4	6.62
	48	23.8	34	7.3	0.55	0.63	0.66	0.74	0.77	3.26	0.98	295.2	2.95
	96	23.8	29	4.8	0.42	0.49	0.54	0.51	0.52	1.24	0.53	112.3	1.12
	192	22.7	27	3	0.44	0.53	0.53	0.51	0.52	0.73	0.27	66.4	0.66
	216	21.6	27	2	0.46	0.56	0.49	0.54	0.54	0.71	0.22	64.5	0.65
	240	22.4	29	4	0.52	0.51	0.47	0.5	0.56	0.38	0.1	34.3	0.34
	264	23.2	33	6.5	0.48	0.46	0.48	0.47	0.47	-0.05	0.01	-4.3	-0.04
	336	22.9	32	5.4	0.51	0.47	0.47	0.51	0.51	0.25	0.1	22.9	0.23
	360	23.4	30	5	0.54	0.5	0.48	0.47	0.53	-0.34	0.09	-30.4	-0.3
	384	22.5	30	4.4	0.47	0.49	0.41	0.53	0.51	0.65	0.15	58.9	0.59
	432	22.5	30	4.5	0.49	0.46	0.53	0.5	0.52	0.54	0.23	49	0.49
	528	22.3	29	4.3	0.49	0.52	0.54	0.52		0.67	0.52	60.5	0.61
	552	22.1	28	4.4	0.47	0.51	0.53	0.47	0.56	0.79	0.31	72	0.72
	576	21.9	31	5.1	0.48	0.49	0.45	0.48	0.52	0.46	0.21	41.5	0.42
	600	22.9	27	3.9	0.47	0.46	0.51	0.46	0.48	0.2	0.06	18.5	0.19
		0											
21	-1	21.1	35	5.5	0.49	0.5	0.5	0.49	0.55	0.66	0.45	60.2	0.6
Lime	0	19.7	40	6	0.58	0.6	0.69	0.68	0.71	2.02	0.85	184.9	1.85
	2	19.7	42	6.8	0.54	0.52	0.57	0.59	0.64	1.53	0.81	140.3	1.4
	8	24	37	8.9	0.53	0.53	0.59	0.57	0.63	1.48	0.82	133.9	1.34
	24	24.3	38	9.3	0.75	0.77	0.86	0.98	1.03	4.57	0.95	412.7	4.13
	48	23.8	34	7.3	0.53	0.55	0.64	0.68	0.77	3.65	0.96	329.9	3.3
	96	23.8	29	4.8	0.42	0.51	0.5	0.51	0.47	0.62	0.19	56.4	0.56
	192	22.7	27	3	0.47	0.51	0.47	0.49	0.59	1.33	0.53	120.9	1.21
	216	21.6	27	2	0.43	0.47	0.45	0.48	0.48	0.71	0.65	64.5	0.65
	240	22.4	29	4	0.44	0.51	0.46	0.52	0.49	0.67	0.28	61	0.61
	264	23.2	33	6.5	0.45	0.5	0.49	0.55	0.48	0.64	0.24	57.6	0.58
	336	22.9	32	5.4	0.51	0.52	0.54	0.55	0.58	0.97	0.93	88.2	0.88
	360	23.4	30	5	0.5	0.49	0.54	0.54	0.53	0.65	0.52	58.7	0.59
	384	22.5	30	4.4	0.43	0.49	0.5	0.49	0.5	0.85	0.54	77.4	0.77
	432	22.5	30	4.5	0.45	0.46	0.47	0.52	0.53	1.37	0.92	124.2	1.24
	528	22.3	29	4.3	0.58	0.56	0.55	0.57		-0.25	0.2	-22.9	-0.23
	552	22.1	28	4.4	0.46	0.54	0.57	0.55	0.57	1.38	0.64	125.5	1.26
	576	21.9	31	5.1	0.53	0.5	0.5	0.51	0.53	-0.01	0	-1.1	-0.01
	600	22.9	27	3.9	0.44	0.52	0.44	0.48	0.46	-0.13	0.01	-11.4	-0.11
		0											
19	-1	21.1	35	5.5	0.52	0.52	0.48	0.51	0.48	-0.55	0.51	-49.8	-0.5
Lime	0	19.7	40	6	0.52	0.57	0.61	0.65	0.63	1.74	0.86	159.6	1.6
	2	19.7	42	6.8	0.53	0.57	0.6	0.63	0.64	1.67	0.98	152.9	1.53
	8	24	37	8.9	0.55	0.56	0.57	0.59	0.58	0.47	0.74	42.3	0.42
	24	24.3	38	9.3	0.68	0.66	0.74	0.75	0.79	1.86	0.8	167.9	1.68
	48	23.8	34	7.3	0.45	0.45	0.52	0.5	0.6	2.14	0.79	193.2	1.93
	96	23.8	29	4.8	0.37	0.49	0.5	0.47	0.52	1.75	0.58	158.4	1.58

	192	22.7	27	3	0.59	0.57	0.47	0.52	0.54	-0.86	0.23	-77.9	-0.78
	216	21.6	27	2	0.44	0.49	0.47	0.53	0.52	1.22	0.81	111.5	1.12
	240	22.4	29	4	0.48	0.53	0.52	0.48	0.49	-0.16	0.03	-14.2	-0.14
	264	23.2	33	6.5	0.49	0.54	0.54	0.47	0.51	-0.18	0.03	-16.3	-0.16
	336	22.9	32	5.4	0.55	0.49	0.53	0.53	0.57	0.5	0.19	45.7	0.46
	360	23.4	30	5	0.49	0.47	0.5	0.52	0.5	0.55	0.49	50	0.5
	384	22.5	30	4.4	0.51	0.49	0.47	0.48	0.47	-0.59	0.83	-53.9	-0.54
	432	22.5	30	4.5	0.46	0.47	0.5	0.46	0.48	0.25	0.16	22.9	0.23
	528	22.3	29	4.3	0.48	0.56	0.54	0.55		1.12	0.42	101.4	1.01
	552	22.1	28	4.4	0.43	0.49	0.54	0.52	0.49	0.78	0.29	70.9	0.71
	576	21.9	31	5.1	0.46	0.48	0.48	0.45	0.49	0.17	0.09	15.8	0.16
	600	22.9	27	3.9	0.47	0.46	0.49	0.46	0.47	0.05	0.01	4.4	0.04
		0											
PAC	-1	23.1	32	5.7	0.6	0.73	0.78	0.87	0.93	4.73	0.98	429.1	4.29
	0	24.4	31	6.6	0.54	0.54	0.58	0.58	0.58	0.74	0.68	66.6	0.67
	6	22.3	35	6.5	0.53	0.54	0.54	0.56	0.6	0.95	0.79	86.1	0.86
	24	20.8	35	5	0.78	0.9	1.01	1.2	1.3	8.05	0.99	735.5	7.35
	48	22.3	42	8.9	0.43	0.55	0.65	0.76	0.84	6.22	1	565	5.65
	72	18.1	44	5.9	0.36	0.5	0.54	0.63	0.73	5.2	0.98	479.6	4.8
	96	22.7	38	8.1	0.52	0.52	0.51	0.54	0.49	-0.25	0.16	-22.9	-0.23
	144	22.5	38	7.7	0.42	0.52	0.53	0.49	0.58	1.69	0.58	153.1	1.53
	168	17.7	41	4.4	0.52	0.51	0.47	0.5	0.56	0.34	0.08	31.6	0.32
	192	22	32	5	0.45	0.48	0.5	0.51	0.55	1.31	0.97	119	1.19
	216	20.9	32	3.8	0.52	0.48	0.53	0.54	0.58	1.12	0.66	102.4	1.02
	240	21.1	35	5.5	0.49	0.46	0.53	0.56	0.54	1.21	0.62	110	1.1
	264	24	37	8.9	0.49	0.49	0.5	0.51	0.51	0.34	0.86	30.4	0.3
	312	23.1	39	8.8	0.49	0.54	0.52	0.51	0.54	0.47	0.34	43	0.43
	336	23.8	34	7.3	0.49	0.52	0.54	0.52		0.67	0.52	60.2	0.6
	360	23.9	32	6.5	0.52	0.51	0.49	0.53	0.53	0.23	0.12	20.6	0.21
	384	24.1	33	7.1	0.53	0.5	0.5	0.51	0.53	-0.01	0	-1.1	-0.01
	408	23.3	31	5.7	0.48	0.48	0.48	0.44	0.51	0.1	0.01	9.2	0.09
		0											
PAC	-1	23.1	32	5.7	0.57	0.63	0.67	0.74	0.77	3.04	0.99	275.7	2.76
	0	24.4	31	6.6	0.5	0.54	0.53	0.54	0.58	0.95	0.74	86.1	0.86
	6	22.3	35	6.5	0.5	0.56	0.57	0.56	0.59	1.04	0.68	94.9	0.95
	24	20.8	35	5	0.7	0.77	0.84	0.94	0.97	4.37	0.98	399.5	4
	48	22.3	42	8.9	0.46	0.52	0.54	0.63	0.73	3.95	0.95	358.8	3.59
	72	18.1	44	5.9	0.39	0.59	0.57	0.61	0.67	3.43	0.76	316.4	3.16
	96	22.7	38	8.1	0.51	0.54	0.61	0.61	0.63	1.86	0.9	168.8	1.69
	144	22.5	38	7.7	0.53	0.53	0.53	0.51	0.52	-0.23	0.47	-20.7	-0.21
	168	17.7	41	4.4	0.5	0.49	0.53	0.6	0.62	2.13	0.9	196.6	1.97
	192	22	32	5	0.49	0.45	0.52	0.49	0.49	0.32	0.11	29.5	0.29
	216	20.9	32	3.8	0.46	0.5	0.46	0.51	0.53	0.88	0.57	80	0.8
	240	21.1	35	5.5	0.49	0.52	0.55	0.54	0.5	0.26	0.06	24.1	0.24
	264	24	37	8.9	0.46	0.49	0.48	0.49	0.48	0.29	0.43	26.6	0.27
	312	23.1	39	8.8	0.46	0.47	0.52	0.48	0.51	0.7	0.51	63.6	0.64
	336	23.8	34	7.3	0.5	0.52	0.52	0.51		0.19	0.2	16.8	0.17
	360	23.9	32	6.5	0.51	0.5	0.49	0.53	0.52	0.29	0.28	26.6	0.27
	384	24.1	33	7.1	0.4	0.45	0.48	0.49	0.45	0.86	0.44	77.5	0.77
	408	23.3	31	5.7	0.5	0.45	0.44	0.51	0.51	0.4	0.11	36.4	0.36
Char	-1	21.1	35	5.5	0.49	0.49	0.5	0.5	0.5	0.24	0.94	21.9	0.22
	0	19.7	40	6	0.48	0.48	0.49	0.49	0.49	0.17	0.57	16	0.16
	6	19.7	42	6.8	0.5	0.51	0.51	0.5	0.5	0.02	0.1	1.7	0.02
	24	24	37	8.9	0.49	0.5	0.5	0.5	0.5	0.06	0.93	5.4	0.05
	48	24.3	38	9.3	0.51	0.51	0.51	0.51	0.51	0.11	0.95	9.7	0.1
	72	23.8	34	7.3	0.48	0.49	0.49	0.49	0.5	0.23	1	21.2	0.21

	96	23.8	29	4.8	0.49	0.5	0.51	0.52	0.53	0.58	1	52.1	0.52
	144	22.7	27	3	0.48	0.5	0.51	0.53	0.55	1.04	0.99	94.2	0.94
	168	21.6	27	2	0.5	0.51	0.52	0.53	0.53	0.47	0.98	42.6	0.43
	192	22.4	29	4	0.49	0.49	0.49	0.5	0.5	0.16	0.93	14.2	0.14
	216	23.2	33	6.5	0.49	0.5	0.51	0.52	0.52	0.5	0.97	45.7	0.46
	240	22.9	32	5.4	0.48	0.48	0.49	0.49	0.49	0.13	0.98	11.4	0.11
	264	23.4	30	5	0.5	0.52	0.53	0.55	0.57	1.09	1	98.9	0.99
	312	22.5	30	4.4	0.49	0.51	0.52	0.54	0.55	0.86	0.99	78.5	0.78
	336	22.5	30	4.5	0.49	0.5	0.51	0.52	0.53	0.66	1	59.9	0.6
	360	22.3	29	4.3	0.5	0.51	0.51	0.52	0.53	0.37	0.98	33.8	0.34
	384	22.1	28	4.4	0.49	0.49	0.5	0.5	0.51	0.26	0.96	23.5	0.23
	408	21.9	31	5.1	0.48	0.49	0.49	0.5	0.5	0.36	0.97	32.8	0.33
Char	-1	21.1	35	5.5	0.42	0.42	0.43	0.43	0.44	0.28	0.99	25.7	0.26
	0	19.7	40	6	0.4	0.4	0.41	0.41	0.41	0.2	0.99	18.2	0.18
	6	19.7	42	6.8	0.38	0.39	0.4	0.4	0.41	0.43	0.99	39.6	0.4
	24	24	37	8.9	0.4	0.41	0.41	0.41		0.14	0.96	13	0.13
	48	24.3	38	9.3	0.43	0.44	0.45	0.45	0.46	0.41	0.98	36.8	0.37
	72	23.8	34	7.3	0.47	0.48	0.48	0.48	0.49	0.25	0.98	22.8	0.23
	96	23.8	29	4.8	0.5	0.5	0.51	0.51	0.51	0.2	0.96	17.9	0.18
	144	22.7	27	3	0.43	0.44	0.46	0.46	0.47	0.58	0.99	52.3	0.52
	168	21.6	27	2	0.4	0.4	0.41	0.42	0.41	0.25	0.61	23	0.23
	192	22.4	29	4	0.38	0.43	0.44	0.48	0.5	1.79	0.98	163	1.63
	216	23.2	33	6.5	0.4	0.44	0.46	0.46	0.48	0.98	0.82	89.1	0.89
	240	22.9	32	5.4	0.46	0.46	0.46	0.47	0.47	0.21	0.88	19	0.19
	264	23.4	30	5	0.5	0.5	0.51	0.52	0.54	0.61	0.96	54.9	0.55
	312	22.5	30	4.4	0.5	0.52	0.54	0.56	0.57	1.02	0.98	92.6	0.93
	336	22.5	30	4.5	0.47	0.49	0.53	0.56	0.56	1.46	0.96	132.4	1.32
	360	22.3	29	4.3	0.51	0.52	0.52	0.52	0.52	0.08	0.72	7.6	0.08
	384	22.1	28	4.4	0.41	0.42	0.44	0.44	0.44	0.45	0.9	40.9	0.41
	408	21.9	31	5.1	0.5	0.5	0.5	0.51	0.51	0.13	0.76	11.5	0.11
Soil	-1	21.1	35	5.5	0.48	0.48	0.48	0.48		0.04	0.3	3.3	0.03
	0	19.7	40	6	0.5	0.5	0.5	0.5	0.5	0.02	0.17	1.7	0.02
	6	19.7	42	6.8	0.42	0.43	0.43	0.43	0.43	0.17	0.81	15.4	0.15
	24	24	37	8.9	0.48	0.48	0.49	0.49	0.49	0.31	0.88	27.7	0.28
	48	24.3	38	9.3	0.5	0.51	0.52	0.53	0.54	0.53	0.99	48.2	0.48
	72	23.8	34	7.3	0.48	0.49	0.5	0.53	0.54	0.97	0.97	87.9	0.88
	96	23.8	29	4.8	0.48	0.52	0.56	0.59	0.62	2.01	0.99	181.7	1.82
	144	22.7	27	3	0.51	0.53	0.54	0.56	0.59	1.22	0.98	110.5	1.11
	168	21.6	27	2	0.42	0.43	0.46	0.46	0.47	0.76	0.94	68.9	0.69
	192	22.4	29	4	0.39	0.44	0.46	0.48	0.5	1.6	0.97	145.5	1.46
	216	23.2	33	6.5	0.43	0.44	0.46	0.46	0.46	0.53	0.81	48.4	0.48
	240	22.9	32	5.4	0.51	0.52	0.53	0.54		0.52	0.95	46.8	0.47
	264	23.4	30	5	0.49	0.49	0.5	0.5		0.21	0.95	19	0.19
	312	22.5	30	4.4	0.43	0.44	0.45	0.45		0.46	0.97	41.4	0.41
	336	22.5	30	4.5	0.47	0.48	0.48	0.49	0.49	0.26	0.92	24	0.24
	360	22.3	29	4.3	0.44	0.47	0.47	0.48	0.48	0.46	0.73	42	0.42
	384	22.1	28	4.4	0.46	0.46	0.46	0.46	0.47	0.1	0.63	9.3	0.09
	408	21.9	31	5.1	0.45	0.46	0.47	0.48	0.48	0.4	0.89	36.6	0.37

Table D 3 Methane flux

	Time (hr)	0	1	2	3	4	ppm h^{-1}	R²	ug ch4 m^{-2} h^{-1}	CH4 g ha^{-1} hr^{-1}	CH4-C g ha^{-1} hr^{-1}
28	-1	2.8	2.6	2.4	2.8	3.1	4.8	0.2	158.2	1.6	1.2
Slurry	0	27.4	38.1	48.5	57.5	66.1	580.8	1.0	19050.4	190.5	142.9
	6	0.4	0.8	0.9	1.0	2.8	29.6	0.7	976.8	9.8	7.3
	24	2.4	2.2	2.2	1.7	2.9	2.5	0.0	82.1	0.8	0.6
	48	1.1	1.2	1.6	1.3	1.3	3.0	0.2	99.1	1.0	0.7
	72	2.7	1.9	2.6	2.1	2.6	0.0	0.0	0.0	0.0	0.0
	96	1.7	1.6	1.6	1.2		-9.0	0.8	-297.0	-3.0	-2.2
	144	2.9	2.7	1.9	2.4		-13.8	0.5	-455.7	-4.6	-3.4
	168	2.0	3.2	3.0	3.9	5.0	39.5	0.9	1327.0	13.3	10.0
	192	2.1	2.5	1.6	2.2	2.0	-3.0	0.1	-99.2	-1.0	-0.7
	216	2.4	2.0	1.9	1.9	1.9	-6.6	0.6	-219.1	-2.2	-1.6
	240	2.4	2.0	1.8	2.3	2.6	4.2	0.1	139.3	1.4	1.0
	264	2.1	1.5	1.1	1.5	1.2	-10.8	0.5	-354.8	-3.5	-2.7
	312	2.2	1.6	0.7	1.2	1.2	-14.7	0.5	-485.9	-4.9	-3.6
	336	1.9	2.1	2.0	1.1		-15.0	0.5	-493.1	-4.9	-3.7
	360	3.3	2.8	2.6	3.0	3.1	-1.2	0.0	-39.4	-0.4	-0.3
	384	2.3	2.9	3.5	2.5	2.7	2.4	0.0	78.8	0.8	0.6
	408	1.9	1.7	2.1	2.5		13.2	0.7	434.7	4.3	3.3
26	-1	2.1	2.1	2.8	2.3	1.6	-4.8	0.1	-158.2	-1.6	-1.2
Slurry	0	29.3	37.8	45.7	52.6	59.1	446.4	1.0	14642.0	146.4	109.8
	6	2.0	3.1	2.8	4.4	3.7	28.7	0.7	949.4	9.5	7.1
	24	2.7	2.0	2.5	1.9	1.8	-11.8	0.6	-390.7	-3.9	-2.9
	48	2.1	1.9	2.8	4.6	4.8	48.4	0.9	1598.6	16.0	12.0
	72	1.5	2.8	2.2	1.9	6.0	48.0	0.5	1610.5	16.1	12.1
	96	0.7	2.4	2.4	5.5	8.3	109.6	0.9	3617.8	36.2	27.1
	144	1.8	2.7	2.4	5.1	7.2	79.4	0.8	2620.4	26.2	19.7
	168	0.7	2.4	3.2	4.3	5.5	68.5	1.0	2299.7	23.0	17.2
	192	2.3	5.0	6.5	7.0	7.8	77.7	0.9	2569.7	25.7	19.3
	216	1.8	2.9	3.2	4.0		40.4	1.0	1339.9	13.4	10.0
	240	2.8	3.3	3.3	4.1	5.4	36.0	0.9	1194.1	11.9	9.0
	264	2.4	3.5	3.8	4.1	4.3	26.4	0.9	867.3	8.7	6.5
	312	1.6	6.5	9.0	12.7	15.3	201.6	1.0	6642.1	66.4	49.8
	336	0.9	8.7	17.4	23.3		455.0	1.0	14959.3	149.6	112.2
	360	0.6	3.5	9.4	12.8	16.4	245.5	1.0	8065.2	80.7	60.5
	384	2.6	5.8	14.3	15.2	19.8	263.7	0.9	8659.3	86.6	64.9
	408	2.5	4.6	5.3	7.5	8.4	88.6	1.0	2916.9	29.2	21.9

27	-1	2.3	2.5	3.2	2.7	2.0	-2.4	0.0	-79.1	-0.8	-0.6
Slurry	0	27.0	36.8	44.5	52.6	60.4	495.6	1.0	16255.8	162.6	121.9
	6	1.2	1.9	2.9	4.2	4.4	52.6	1.0	1736.3	17.4	13.0
	24	2.6	3.3	3.6	4.4	4.1	24.0	0.9	798.0	8.0	6.0
	48	1.5	1.4	1.8	2.0	2.7	17.9	0.8	592.4	5.9	4.4
	72	1.6	1.6	2.5	2.7	2.9	23.0	0.9	770.9	7.7	5.8
	96	2.4	3.0	3.6	3.8	4.7	31.0	1.0	1021.8	10.2	7.7
	144	1.5	1.2	3.0	4.5	6.8	84.5	0.9	2791.0	27.9	20.9
	168	2.0	2.7	2.4	3.5	4.4	34.3	0.9	1152.2	11.5	8.6
	192	1.7	3.3	3.9	5.5	5.7	60.1	1.0	1987.3	19.9	14.9
	216	1.9	1.7	3.2	3.8	4.4	42.6	0.9	1414.1	14.1	10.6
	240	2.1	3.9	4.3	5.3	4.8	41.3	0.8	1369.6	13.7	10.3
	264	0.8	1.7	1.9	2.2	3.0	29.4	0.9	965.9	9.7	7.2
	312	1.1	2.4	2.6	2.2	4.5	40.4	0.7	1332.4	13.3	10.0
	336	1.5	1.2	0.6	0.6	4.2	-19.8	0.9	-650.9	-6.5	-4.9
	360	1.9	3.5	4.9	6.5	8.2	93.6	1.0	3073.8	30.7	23.1
	384	0.6	2.6	7.4	10.8	12.0	185.7	1.0	6099.1	61.0	45.7
	408	6.3	13.7	18.6	23.5	26.4	300.6	1.0	9899.0	99.0	74.2
31	-1	2.4	1.7	1.0	1.9	2.6	3.6	0.0	118.6	1.2	0.9
Alum	0	1.7	3.1	4.8	5.0	7.6	81.2	1.0	2662.7	26.6	20.0
	6	1.5	1.7	0.7	3.5	3.2	31.9	0.5	1052.5	10.5	7.9
	24	2.5	1.3	2.9	2.9	3.1	16.3	0.4	539.9	5.4	4.0
	48	2.6	3.1	3.6	3.7	4.5	26.8	1.0	886.8	8.9	6.7
	72	2.7	2.0	3.0	3.8	3.9	24.7	0.7	826.6	8.3	6.2
	96	0.6	1.1	0.6	1.2	1.8	15.0	0.6	495.0	4.9	3.7
	144	1.9	2.3	2.5	4.7	5.1	52.9	0.9	1745.6	17.5	13.1
	168	1.7	2.8	2.6	4.4	5.2	51.2	0.9	1717.8	17.2	12.9
	192	1.5	0.9	0.9	0.5	1.0	-8.4	0.4	-277.8	-2.8	-2.1
	216	2.3	2.6	4.4	7.3	9.5	115.4	0.9	3830.1	38.3	28.7
	240	2.3	2.8	3.1	3.3	3.9	22.2	1.0	736.4	7.4	5.5
	264	0.9	1.2	4.2	6.0	7.1	102.8	1.0	3378.6	33.8	25.3
	312	1.5	5.3	11.5	14.1	15.7	223.6	1.0	7367.6	73.7	55.3
	336	1.5	6.3	10.3	13.1	15.2	205.4	1.0	6751.8	67.5	50.6
	360	1.3	2.3	2.6	3.6	3.0	27.9	0.8	917.7	9.2	6.9
	384	1.5	2.7	4.1	5.5	6.7	78.5	1.0	2577.1	25.8	19.3
	408	1.7	0.5	1.2	1.9	2.3	15.6	0.4	513.7	5.1	3.9
30	-1	1.3	2.7	3.2	5.1	6.3	74.9	1.0	2468.4	24.7	18.5
Alum	0	7.8	11.0	13.6	19.6	22.6	228.7	1.0	7502.1	75.0	56.3
	6	0.3	0.8	2.4	2.8	3.3	47.3	0.9	1562.5	15.6	11.7
	24	2.2	2.6	3.7	3.5	5.0	39.0	0.9	1295.1	13.0	9.7
	48	1.3	2.0	2.6	3.1	3.7	35.3	1.0	1167.1	11.7	8.8

	72	1.9	2.3	3.1	3.3	4.1	32.3	1.0	1082.6	10.8	8.1
	96	2.5	2.7	2.3	3.0	4.3	22.8	0.6	752.7	7.5	5.6
	144	1.7	1.2	1.0	1.5		-4.8	0.1	-158.5	-1.6	-1.2
	168	2.4	3.0	4.1	4.2	4.9	37.5	1.0	1257.7	12.6	9.4
	192	2.0	2.2	2.4	2.5	2.8	11.4	1.0	377.0	3.8	2.8
	216	1.8	1.9	1.8	2.0	1.5	-3.0	0.2	-99.6	-1.0	-0.7
	240	1.3	5.4	6.6	6.9	7.4	82.7	0.8	2742.4	27.4	20.6
	264	1.8	4.5	5.9	7.4	8.6	99.7	1.0	3275.7	32.8	24.6
	312	1.6	2.0	3.3	3.9	4.3	43.8	1.0	1443.1	14.4	10.8
	336	2.0	1.5	1.2	0.3	7.9	63.7	0.3	2094.8	20.9	15.7
	360	1.1	3.5	6.3	8.4	10.5	141.6	1.0	4653.6	46.5	34.9
	384	1.8	1.9	1.6	1.7	2.2	3.1	0.1	102.8	1.0	0.8
	408	1.1	5.2	8.0	10.1	12.7	169.1	1.0	5567.9	55.7	41.8
32	-1	3.2	3.3	3.6	4.3	4.4	20.4	0.9	672.2	6.7	5.0
Alum	0	4.0	5.5	5.6	7.3	8.6	65.2	1.0	2139.2	21.4	16.0
	6		0.3	3.3	3.9	3.5	62.3	0.6	2057.4	20.6	15.4
	24	2.4	4.3	4.5	4.5	4.8	30.3	0.7	1006.2	10.1	7.5
	48	2.1	3.0	3.1	3.2	3.8	21.0	0.9	694.7	6.9	5.2
	72	2.7	4.3	5.2	5.3	6.5	51.1	0.9	1711.9	17.1	12.8
	96	1.9	2.7	4.0	2.7	7.9	71.5	0.6	2358.0	23.6	17.7
	144	1.3	1.7	2.2	2.5	3.1	26.4	1.0	873.3	8.7	6.5
	168	0.5	1.1	2.4	3.4	4.2	58.4	1.0	1960.8	19.6	14.7
	192	0.9	0.9	0.8	0.7	1.0	0.0	0.0	0.0	0.0	0.0
	216	1.3	1.3	1.5	2.1	2.3	16.8	0.9	557.7	5.6	4.2
	240	1.9	2.7	4.4	5.1	4.9	68.2	1.0	2261.6	22.6	17.0
	264	1.8	2.3	2.0	1.9	2.7	8.4	0.4	276.0	2.8	2.1
	312	1.7	2.2	3.3	4.3	4.5	47.1	1.0	1551.8	15.5	11.6
	336	1.8	2.4	3.9	5.0		66.8	1.0	2197.2	22.0	16.5
	360	1.1	1.8	4.5	6.1	7.2	100.0	1.0	3285.3	32.9	24.6
	384	1.4	3.2	4.2	6.8	8.2	102.9	1.0	3378.0	33.8	25.3
	408	2.3	2.9	3.9	4.8	7.0	51.0	1.0	1679.5	16.8	12.6
23	-1	1.1	1.5	1.7	1.0		-0.6	0.0	-19.9	-0.2	-0.1
FeCl	0	5.1	7.8	11.2	13.9		179.1	1.0	5970.5	59.7	44.8
	2	1.7	2.3	3.2	3.9	5.0	50.1	1.0	1668.7	16.7	12.5
	8	2.1	6.2	2.6	2.8	3.1	-8.4	0.0	-276.0	-2.8	-2.1
	24	2.0	2.7	2.3	3.2	2.8	12.6	0.5	413.5	4.1	3.1
	48	2.3	2.6	1.9	2.1	3.0	5.0	0.1	163.7	1.6	1.2
	96	2.0	1.3	1.0	1.1	0.5	-19.2	0.9	-631.0	-6.3	-4.7
	192	1.7	2.3	2.6	1.8		3.0	0.0	100.0	1.0	0.7
	216	4.4	3.8	3.0	3.6		-18.5	0.5	-612.1	-6.1	-4.6
	240	1.8	2.2	2.3	1.5	1.7	-5.4	0.2	-178.3	-1.8	-1.3

	312	1.9	2.0	2.3	2.4	6.6	10.8	1.0	355.7	3.6	2.7
	336	1.6	0.9	0.7	0.5	5.6	46.4	0.3	1529.2	15.3	11.5
	360	1.8	1.8	1.6	0.8	0.2	-25.2	0.9	-829.4	-8.3	-6.2
	384	1.7	1.8	1.4	0.7	1.1	-13.8	0.7	-455.7	-4.6	-3.4
	408	1.9	3.2	2.4	2.3	2.0	-4.2	0.0	-138.7	-1.4	-1.0
	504	1.1	2.9	2.3	1.8	5.7	9.0	0.1	297.4	3.0	2.2
	528	2.5	2.2	2.0	2.4	1.6	-9.6	0.5	-317.4	-3.2	-2.4
	552	1.2	0.9	0.9	0.8	1.6	4.2	0.1	139.0	1.4	1.0
	576	1.5	1.5	1.6	1.3	1.6	0.0	0.0	0.0	0.0	0.0
24	-1	2.5	2.4	1.5	2.4	2.1	-4.8	0.1	-159.2	-1.6	-1.2
FeCl	0	3.4	6.7	9.1	11.6	14.9	167.4	1.0	5580.5	55.8	41.9
	2	1.5	2.2	3.2	4.7	5.3	61.2	1.0	2039.7	20.4	15.3
	8	1.3	1.2	1.9	2.4	2.3	19.2	0.8	630.8	6.3	4.7
	24	1.8	1.7	2.4	2.4	2.1	7.8	0.4	256.0	2.6	1.9
	48	1.3	1.5	1.4	1.3	1.8	4.8	0.4	157.8	1.6	1.2
	96	1.9	0.1	0.2	0.0	0.3	-19.8	0.4	-650.8	-6.5	-4.9
	192	1.5	1.1	1.7	1.8		10.4	0.5	343.0	3.4	2.6
	216	3.7	3.8	3.1	3.1	1.4	-31.9	0.8	-1055.4	-10.6	-7.9
	240	4.0	1.1	1.2	0.4	0.4	-46.3	0.7	-1527.7	-15.3	-11.5
	312	1.1	0.4	0.4	0.6		-9.0	0.3	-296.4	-3.0	-2.2
	336	1.8	1.9	2.5	2.2	5.7	48.6	0.6	1602.4	16.0	12.0
	360	1.5	1.4	1.4	1.0	1.3	-4.8	0.4	-158.0	-1.6	-1.2
	384	2.0	1.0	0.8	0.2	0.2	-26.4	0.9	-871.7	-8.7	-6.5
	408	1.4	1.1	1.1	1.1	1.5	1.2	0.0	39.6	0.4	0.3
	504	1.9	1.7	1.7	2.3		7.2	0.3	237.9	2.4	1.8
	528	1.9	3.1	2.4	3.6	3.0	16.2	0.4	535.6	5.4	4.0
	552	2.5	3.0	3.1	3.0	2.7	2.4	0.1	79.4	0.8	0.6
	576	2.2	2.1	1.6	1.9	2.5	2.4	0.0	79.1	0.8	0.6
18	-1	1.6	1.6	1.0	1.0	0.7	-14.4	0.9	-477.6	-4.8	-3.6
FeCl	0	3.2	5.8	8.0	10.6	12.2	136.4	1.0	4548.4	45.5	34.1
	2	2.5	1.8	4.7	5.0		62.5	0.7	2083.3	20.8	15.6
	8	1.7	2.3	1.6	2.1	2.0	2.4	0.0	78.8	0.8	0.6
	24	1.8	2.2	1.4	1.5	1.6	-6.6	0.3	-216.6	-2.2	-1.6
	48	2.2	1.6	2.0	2.1	2.2	3.0	0.1	98.6	1.0	0.7
	96	2.8	1.4	0.7			-62.7	1.0	-2059.8	-20.6	-15.4
	192	2.5	2.7	1.3	2.3	1.9	-10.5	0.3	-346.6	-3.5	-2.6
	216	2.3	1.1	1.4	1.3		-17.3	0.5	-572.3	-5.7	-4.3
	240	2.9	2.5	1.5	1.4	0.9	-30.9	0.9	-1020.5	-10.2	-7.7
	312	1.4	0.9	1.3	1.7		7.8	0.3	256.9	2.6	1.9
	336	1.8	2.4	2.0	1.6		-6.0	0.1	-197.8	-2.0	-1.5
	360	1.5	0.4	0.3	0.0		-27.6	0.8	-908.4	-9.1	-6.8

	384	2.0	2.3	1.9	1.7	1.2	-13.2	0.7	-435.8	-4.4	-3.3
	408	3.1	2.8	2.9	2.5	2.7	-6.6	0.6	-217.9	-2.2	-1.6
	504	1.2	1.6	1.4	0.8		-8.4	0.3	-277.5	-2.8	-2.1
	528	1.5	1.3	1.3	0.8	1.3	-5.4	0.3	-178.5	-1.8	-1.3
	552	2.3	1.8	1.7	2.4	2.0	0.0	0.0	0.0	0.0	0.0
	576	1.1	0.7	1.4	1.3	1.1	3.6	0.1	118.7	1.2	0.9
17	-1	2.6	2.6	2.0	2.0	1.7	-14.4	0.9	-477.6	-4.8	-3.6
Lime	0	43.4	47.7	51.6	55.3		237.6	1.0	7920.7	79.2	59.4
	2	1.4	1.6	2.1	2.6	2.8	22.6	1.0	753.3	7.5	5.6
	8	2.2	2.1	2.0	1.8	1.9	-5.4	0.8	-177.4	-1.8	-1.3
	24	1.9	2.1	1.8	1.8	1.7	-4.2	0.5	-137.8	-1.4	-1.0
	48	1.9	1.4	1.6	1.6	1.5	-3.6	0.3	-118.3	-1.2	-0.9
	96	2.7	0.9	0.2	0.0	1.1	-24.5	0.4	-806.6	-8.1	-6.0
	192	1.5	2.1	1.1	0.9	0.5	-19.1	0.7	-631.0	-6.3	-4.7
	216	3.5	1.8	2.5	0.9	0.7	-38.6	0.8	-1279.8	-12.8	-9.6
	240	2.2	1.8	1.9	1.3	0.7	-21.1	0.9	-696.3	-7.0	-5.2
	264	3.0	3.2	0.9	1.6	1.1	-31.2	0.6	-1028.4	-10.3	-7.7
	336	1.7	2.1	1.5	1.8	1.5	-4.2	0.2	-138.5	-1.4	-1.0
	360	3.0	2.3	2.3	1.5	2.2	-14.4	0.5	-473.9	-4.7	-3.6
	384	1.7	1.2	1.5	0.3	1.3	-10.2	0.2	-336.8	-3.4	-2.5
	432	1.9	0.6	0.8	0.0	0.4	-21.8	0.6	-719.1	-7.2	-5.4
	528	1.6	1.8	1.5	0.9	1.6	-5.4	0.2	-178.4	-1.8	-1.3
	552	2.6	1.6	0.9	1.6		-22.2	0.5	-734.0	-7.3	-5.5
	576	1.7	1.6	2.1	2.0	2.3	9.6	0.8	317.6	3.2	2.4
	600	2.4	1.8	2.2	2.2	2.7	6.0	0.2	197.8	2.0	1.5
21	-1	1.5	1.6	1.6	1.6	1.4	-1.2	0.1	-39.8	-0.4	-0.3
Lime	0	14.8	18.1	22.7	25.5	27.8	200.4	1.0	6680.6	66.8	50.1
	2	2.3	2.2	3.2	3.3	3.2	17.4	0.7	579.9	5.8	4.3
	8	1.6	0.8	1.3	1.5	1.6	4.2	0.1	138.0	1.4	1.0
	24	2.1	2.4	2.5	2.3	2.3	1.8	0.1	59.1	0.6	0.4
	48	1.7	0.9	1.0	1.3	0.7	-9.6	0.4	-315.6	-3.2	-2.4
	96	2.8	2.2	1.7	1.4	1.8	-16.8	0.7	-552.2	-5.5	-4.1
	192	2.7	1.7	1.6	1.5	1.8	-12.4	0.4	-410.5	-4.1	-3.1
	216	2.7	2.5	2.2	1.8	1.3	-21.0	1.0	-695.5	-7.0	-5.2
	240	2.5	1.7	0.6	0.7	1.2	-21.6	0.5	-712.5	-7.1	-5.3
	264	2.5	1.7	0.6	0.7	1.2	-21.6	0.5	-710.6	-7.1	-5.3
	336	3.5	3.6	2.4	2.0	1.9	-28.8	0.9	-949.6	-9.5	-7.1
	360	1.9	0.9	0.9	0.3	-0.1	-27.6	0.9	-908.4	-9.1	-6.8
	384	1.8	1.7	0.3	0.8	0.9	-16.2	0.5	-534.9	-5.3	-4.0
	432	2.1	1.7	1.7	0.8	0.6	-23.4	0.9	-772.6	-7.7	-5.8
	528	1.8	0.7	0.5	0.4	0.3	-19.8	0.7	-654.2	-6.5	-4.9

	552	1.9	1.7	1.7	2.3	7.2	7.2	0.3	238.1	2.4	1.8
	576	1.9	1.7	3.4	2.2	1.1	-6.6	0.0	-218.4	-2.2	-1.6
	600	2.4	2.7	2.7	2.4	1.4	-12.9	0.4	-426.9	-4.3	-3.2
19	-1	3.1	3.0	2.6	3.4	2.9	0.0	0.0	0.0	0.0	0.0
Lime	0	13.9	16.1	18.4	20.5	22.6	130.8	1.0	4360.4	43.6	32.7
	2	2.0	1.8	2.5	3.1	2.9	19.0	0.7	632.1	6.3	4.7
	8	1.7	1.2	1.9	1.3	1.7	0.6	0.0	19.7	0.2	0.1
	24	1.9	2.5	1.6	1.7	1.7	-7.2	0.3	-236.3	-2.4	-1.8
	48	1.7	1.2	0.5	0.5	0.3	-20.6	0.9	-677.7	-6.8	-5.1
	96	2.7	1.1	0.2			-76.1	1.0	-2501.5	-25.0	-18.8
	192	2.8	2.1	2.2	1.5	1.9	-14.2	0.6	-469.3	-4.7	-3.5
	216	2.1	0.7	1.0	0.2		-33.1	0.7	-1097.0	-11.0	-8.2
	240	2.5	1.8	1.1	0.4		-42.0	1.0	-1387.0	-13.9	-10.4
	264	2.4	1.7	1.0	0.3	0.8	-27.6	0.8	-909.0	-9.1	-6.8
	336	1.5	0.8	0.5	0.2	0.3	-18.0	0.8	-593.5	-5.9	-4.5
	360	2.0	1.5	0.8	0.8		-25.8	0.9	-849.1	-8.5	-6.4
	384	2.8	2.3	1.0	0.7		-45.6	0.9	-1505.7	-15.1	-11.3
	432	2.0	1.0	0.7	0.9	1.2	-10.2	0.3	-336.8	-3.4	-2.5
	528	1.8	1.3	0.4	0.2	0.2	-25.8	0.9	-852.4	-8.5	-6.4
	552	1.9	1.2	0.6	0.5		-28.8	0.9	-952.2	-9.5	-7.1
	576	2.0	0.8	0.9	1.4	0.3	-16.8	0.5	-555.9	-5.6	-4.2
	600	2.2	1.0	1.7	1.5	1.6	-4.2	0.1	-138.5	-1.4	-1.0
PAC	-1	1.6	3.4	5.1	6.6	8.2	98.8	1.0	3256.1	32.6	24.4
	0	1.9	1.7	2.0	2.3	2.2	7.2	0.6	236.2	2.4	1.8
	6	1.9	1.9	1.9	1.7	1.7	-3.6	0.8	-118.9	-1.2	-0.9
	24	1.3	1.0	1.6	1.0	1.3	0.0	0.0	0.0	0.0	0.0
	48	2.8	2.4	1.2	2.0	1.8	-13.0	0.4	-430.6	-4.3	-3.2
	72	2.5	0.8	0.1			-70.9	0.9	-2376.1	-23.8	-17.8
	96	3.2	2.5	2.6	3.0	1.8	-13.3	0.4	-440.3	-4.4	-3.3
	144	1.1	1.1	0.8	1.1	1.3	1.9	0.1	61.4	0.6	0.5
	168	2.2	1.8	1.9	1.3	0.7	-21.1	0.9	-707.6	-7.1	-5.3
	192	1.9	0.9	0.0	0.0	0.8	-18.7	0.4	-619.1	-6.2	-4.6
	216	2.0	1.4	0.9	1.1	1.1	-12.6	0.6	-418.3	-4.2	-3.1
	240	1.2	0.0	1.0	0.8	0.7	-1.2	0.0	-39.8	-0.4	-0.3
	264	1.7	2.0	1.3	1.9	1.8	0.6	0.0	19.7	0.2	0.1
	312	1.4	0.6	1.0	1.1	0.7	-5.4	0.2	-177.9	-1.8	-1.3
	336	2.2	1.2	0.5	1.2		-22.2	0.5	-729.8	-7.3	-5.5
	360	1.5	1.2	1.4	1.4	1.3	-1.2	0.1	-39.4	-0.4	-0.3
	384	1.2	1.6	1.6	1.3	0.3	-12.9	0.4	-425.2	-4.3	-3.2
	408	1.9	1.8	1.2	1.5	1.3	-9.0	0.6	-296.4	-3.0	-2.2

PAC	-1	0.6	3.3	4.9	5.6	6.6	86.2	0.9	2838.9	28.4	21.3
	0	1.4	1.7	1.8	1.7	2.3	10.8	0.8	354.2	3.5	2.7
	6	1.8	1.5	1.4	1.8	1.6	-0.6	0.0	-19.8	-0.2	-0.1
	24	1.6	1.5	2.2	1.9	2.1	8.4	0.5	278.9	2.8	2.1
	48	4.3	2.8	1.6	2.4	2.2	-26.3	0.5	-868.2	-8.7	-6.5
	72	4.9	0.0	0.6			-127.5	0.6	-4273.6	-42.7	-32.1
	96	4.3	2.4	2.6	1.8	2.2	-28.3	0.6	-932.9	-9.3	-7.0
	144	0.9	1.0	0.5	0.5	0.3	-10.1	0.8	-335.0	-3.4	-2.5
	168	1.8	1.1	0.9	0.5	0.9	-14.4	0.6	-483.9	-4.8	-3.6
	192	1.7	1.5	1.8	0.9	1.4	-7.2	0.3	-238.1	-2.4	-1.8
	216	2.1	1.5	0.4	0.8		-30.0	0.7	-995.9	-10.0	-7.5
	240	1.6	0.8	0.6	0.9	0.6	-11.4	0.5	-378.1	-3.8	-2.8
	264	1.8	0.2	0.4	0.0	0.3	-19.2	0.5	-630.8	-6.3	-4.7
	312	1.9	2.3	1.7	1.8	1.8	-4.2	0.2	-138.4	-1.4	-1.0
	336	1.9	2.3	2.1	1.5		-8.4	0.3	-276.1	-2.8	-2.1
	360	1.1	1.6	2.5	1.6	2.2	13.2	0.4	433.7	4.3	3.3
	384	2.2	1.4	1.4	1.5	2.1	-0.6	0.0	-19.7	-0.2	-0.1
	408	1.3	1.0	1.6	1.4	1.2	1.2	0.0	39.5	0.4	0.3
Char	-1	1.6	1.7	1.7	1.7	1.7	1.2	0.5	39.8	0.4	0.3
	0	8.4	10.2	13.0	16.0	16.9	136.8	1.0	4560.4	45.6	34.2
	6	2.9	3.3	4.0	5.1	5.8	45.6	1.0	1519.8	15.2	11.4
	24	2.0	2.0	2.1	2.2	2.1	2.4	0.6	78.8	0.8	0.6
	48	1.7	1.6	1.6	1.6	1.7	0.0	0.0	0.0	0.0	0.0
	72	2.8	2.6	2.5	2.5	2.5	-9.0	0.7	-295.9	-3.0	-2.2
	96	2.1	2.0	1.9	1.9	1.9	-3.0	0.8	-98.6	-1.0	-0.7
	144	3.3	2.8	1.6	2.4	2.2	-14.3	0.4	-470.9	-4.7	-3.5
	168	1.7	2.0	2.1	2.2	2.2	7.2	0.8	238.5	2.4	1.8
	192	2.0	2.1	2.2	2.3	2.5	7.2	1.0	237.8	2.4	1.8
	216	2.5	3.0	3.5	3.6	3.6	23.0	0.8	756.9	7.6	5.7
	240	1.6	1.7	1.7	1.8	1.9	4.2	0.9	138.5	1.4	1.0
	264	2.0	1.6	1.8	1.9	2.1	3.0	0.2	98.7	1.0	0.7
	312	1.9	2.0	2.1	2.2	2.2	4.4	0.9	146.6	1.5	1.1
	336	1.9	1.9	2.0	2.1	2.1	3.8	0.9	124.8	1.2	0.9
	360	1.9	1.9	1.7	1.6	1.5	-6.6	0.9	-218.1	-2.2	-1.6
	384	2.0	2.1	2.1	2.2	2.2	3.0	0.9	99.2	1.0	0.7
	408	1.9	2.1	1.9	1.8	1.8	-3.0	0.4	-99.3	-1.0	-0.7
Char	-1	1.6	1.8	2.2	2.0	1.9	4.8	0.3	159.2	1.6	1.2
	0	4.9	5.9	8.1	9.3	11.2	96.2	1.0	3208.3	32.1	24.1
	6	2.1	3.1	4.5	5.2	5.7	55.8	1.0	1859.7	18.6	13.9
	24	2.1	1.1	1.6	1.7	1.9	1.2	0.0	39.4	0.4	0.3
	48	1.7	1.7	1.8	1.8	1.9	3.0	0.9	98.4	1.0	0.7

	72	1.3	1.3	1.3	1.3	1.4	1.2	0.5	39.4	0.4	0.3
	96	2.0	2.1	2.2	2.2	2.3	4.2	0.9	138.0	1.4	1.0
	144	2.0	2.0	2.0	2.1	2.1	1.8	0.8	59.4	0.6	0.4
	168	1.8	1.7	1.6	1.6	1.5	-4.2	0.9	-139.1	-1.4	-1.0
	192	1.3	1.0	0.6	1.1	0.9	-4.2	0.2	-138.7	-1.4	-1.0
	216	2.2	1.2	1.4	1.2	0.9	-15.6	0.7	-513.8	-5.1	-3.9
	240	2.3	2.4	2.4	2.2	2.1	-3.6	0.5	-118.7	-1.2	-0.9
	264	2.0	2.0	1.7	1.6	1.5	-8.4	0.9	-276.5	-2.8	-2.1
	312	2.1	2.1	2.2	2.2	2.3	3.0	0.9	99.1	1.0	0.7
	336	2.4	2.5	2.2	1.8	1.7	-12.6	0.9	-416.0	-4.2	-3.1
	360	2.6	2.6	2.5	2.6	2.4	-2.4	0.5	-79.3	-0.8	-0.6
	384	2.1	2.1	2.0	2.1	2.2	1.2	0.2	39.7	0.4	0.3
	408	1.8	1.8	1.7	1.8	1.6	-2.4	0.5	-79.4	-0.8	-0.6
Soil	-1	2.4	2.4	2.5	2.6	2.6	3.6	0.9	119.4	1.2	0.9
	0	1.8	3.2	4.1	7.2	8.4	103.2	1.0	3440.3	34.4	25.8
	6	2.1	2.3	2.6	2.9	3.1	15.6	1.0	519.9	5.2	3.9
	24	2.2	2.3	2.3	2.1	1.9	-4.8	0.6	-157.7	-1.6	-1.2
	48	2.2	2.3	2.3	2.2	2.2	-0.6	0.1	-19.7	-0.2	-0.1
	72	1.2	1.2	1.2	1.3	1.2	0.6	0.1	19.7	0.2	0.1
	96	1.8	1.7	1.6	1.4	1.5	-5.4	0.8	-177.5	-1.8	-1.3
	144	2.0	2.1	2.1	2.2	2.0	0.6	0.0	19.8	0.2	0.1
	168	2.0	2.2	2.3	2.3	2.4	5.4	0.9	178.9	1.8	1.3
	192	1.6	1.3	1.2	1.4	1.7	1.8	0.1	59.4	0.6	0.4
	216	1.3	1.3	1.1	1.1	1.1	-3.6	0.8	-118.6	-1.2	-0.9
	240	1.9	2.0	2.3	2.1	1.8	-0.6	0.0	-19.8	-0.2	-0.1
	264	2.0	2.0	2.1	2.1	2.3	4.2	0.8	138.2	1.4	1.0
	312	2.1	2.2	2.4	2.4	2.5	6.0	0.9	198.1	2.0	1.5
	336	2.4	2.4	2.1	2.2	2.3	-2.4	0.2	-79.2	-0.8	-0.6
	360	2.0	2.0	2.0	1.9	1.8	-3.0	0.8	-99.1	-1.0	-0.7
	384	2.1	2.2	2.2	2.3	2.5	5.4	0.9	178.5	1.8	1.3
	408	1.8	1.8	1.9	2.1	2.1	5.4	0.9	178.7	1.8	1.3

Table D 4 Carbon dioxide flux

		ppm							ug CO2 m^{-2} h^{-1}	kg CO_2-C ha^{-1} hr^{-1}
		0	1	2	3	4	ppm h-1	R²		
28	-1	889	1010	1120	1190	1280	5772	0.99	523126	1.4
Slurry	0	2950	3840	4580	5250	5840	43140	0.99	3892138	10.6
	6	1330	1630	1900	2140	2360	15420	1.00	1401168	3.8
	24	882	1010	1120	1230	1320	6576	1.00	600647	1.6
	48	654	728	797	858	912	3876	1.00	352285	1.0
	72	669	734	792	846	901	3456	1.00	318634	0.9
	96	575	642	698	748	841	3828	0.99	347443	0.9
	144	668	734	791	846	897	3420	1.00	310613	0.8
	168	819	871	916	962	1010	2838	1.00	261977	0.7
	192	756	851	913	972	1100	4854	0.98	441567	1.2
	216	672	738	771	858	849	2844	0.92	259684	0.7
	240	775	946	1010	1060	1120	4824	0.92	440120	1.2
	264	606	678	732	780	819	3168	0.99	286284	0.8
	312	795	896	986	1050	1110	4704	0.99	426297	1.2
	336	942	1060	1160	1240		5964	0.99	539302	1.5
	360	792	869	926	973	1010	3240	0.98	292814	0.8
	384	760	867	931	993	1050	4236	0.98	382611	1.0
	408	637	729	749	791		2892	0.92	261958	0.7
									0	0.0
26	-1	833	956	1060	1140	1230	5868	0.99	531826	1.5
Slurry	0	2750	3490	4110	4670	5100	35280	0.99	3183000	8.7
	6	1210	1460	1690	1900	2100	13320	1.00	1210347	3.3
	24	846	972	1080	1180	1270	6336	1.00	578726	1.6
	48	636	711	786	861	933	4464	1.00	405727	1.1
	72	614	739	830	914	999	5670	0.99	522759	1.4
	96	625	725	804	887	963	5028	1.00	456360	1.2
	144	614	705	778	846	913	4434	1.00	402708	1.1
	168	686	808	895	978	1060	5508	0.99	508445	1.4
	192	850	955	1050	1120	1190	5070	0.99	461217	1.3
	216	832	855	928	969		2904	0.97	265163	0.7
	240	635	749	835	907	969	4956	0.99	452164	1.2
	264	704	777	831	882	928	3318	0.99	299839	0.8
	312	767	887	937	999	1070	4308	0.98	390409	1.1
	336	1480	1380	1420	1450		-300	0.02	-27128	-0.1
	360	786	896	977	1040	1100	4632	0.98	418616	1.1
	384	798	895	969	1040	1090	4374	0.99	395076	1.1
	408	665	731	787	835	880	3204	0.99	290219	0.8

									0	0.0
27	-1	627	773	849	923	987	5220	0.97	473097	1.3
Slurry	0	2900	3730	4410	5010	5560	39600	0.99	3572755	9.7
	6	1300	1580	1820	2040	2250	14160	1.00	1286675	3.5
	24	868	987	1090	1180	1280	6102	1.00	557352	1.5
	48	700	790	864	939	1000	4494	1.00	408454	1.1
	72	657	771	850	927	996	5004	0.99	461356	1.3
	96	579	694	779	858	932	5220	0.99	473786	1.3
	144	591	732	812	893	967	5478	0.98	497526	1.4
	168	654	792	866	934	998	4980	0.97	459705	1.3
	192	766	852	919	978	1030	3924	0.99	356965	1.0
	216	674	750	806	848	889	3168	0.98	289268	0.8
	240	709	790	843	887	929	3222	0.98	293961	0.8
	264	653	712	759	798	833	2676	0.99	241823	0.7
	312	731	803	866	907	952	3276	0.99	296885	0.8
	336	872	970	1030	1120		4824	0.99	436216	1.2
	360	875	939	990	1030	1070	2886	0.99	260822	0.7
	384	734	803	855	898	930	2922	0.98	263926	0.7
	408	752	801	836	865	881	1932	0.97	175001	0.5
									0	0.0
31	-1	735	877	963	1050	1120	5658	0.98	512794	1.4
Alum	0	1480	2920	3920	4670	5380	57300	0.98	5169669	14.1
	6	845	1000	1160	1310	1460	9240	1.00	839610	2.3
	24	877	1030	1180	1320	1460	8736	1.00	797940	2.2
	48	739	856	970	1070	1180	6576	1.00	597684	1.6
	72	545	678	809	937	1060	7734	1.00	713055	1.9
	96	569	678	791	898	1000	6492	1.00	589238	1.6
	144	637	778	882	976	1070	6384	0.99	579812	1.6
	168	637	750	856	966	1060	6372	1.00	588201	1.6
	192	882	946	1000	1060	1120	3540	1.00	322033	0.9
	216	596	669	726	785	832	3528	0.99	322140	0.9
	240	770	845	912	976	1040	4026	1.00	367314	1.0
	264	937	982	1030	1080	1130	2904	1.00	262427	0.7
	312	727	789	913	969	1030	4716	0.98	427384	1.2
	336	978	986	1010	1040	1060	1308	0.97	118277	0.3
	360	716	791	845	899	948	3432	0.99	310166	0.8
	384	782	867	946	1020	1090	4614	1.00	416753	1.1
	408	807	876	953	1020	1040	3660	0.97	331524	0.9
									0	0.0
30	-1	1040	1220	1370	1500	1610	8520	0.99	772182	2.1
Alum	0	2900	3890	4770	5590	6210	49920	0.99	4503837	12.3
	6	960	1130	1290	1440	1580	9300	1.00	845062	2.3
	24	851	991	1110	1230	1340	7302	1.00	666959	1.8

	48	781	874	953	1030	1110	4884	1.00	443901	1.2
	72	794	906	1020	1110	1210	6216	1.00	573099	1.6
	96	623	737	842	927	1000	5664	0.99	514086	1.4
	144	640	881	917	1020		7056	0.89	640845	1.7
	168	758	891	980	1060	1140	5598	0.99	516753	1.4
	192	678	801	890	981	1050	5544	0.99	504336	1.4
	216	773	739	805	859	879	1992	0.81	181888	0.5
	240	725	831	904	973	1030	4512	0.99	411655	1.1
	264	722	822	880	958	1020	4392	0.99	396894	1.1
	312	859	952	1030	1100	1150	4380	0.99	396934	1.1
	336	843	977	1088	1140	1030	3222	0.55	291353	0.8
	360	741	872	965	1040	1110	5436	0.98	491277	1.3
	384	779	867	928	980	1020	3570	0.98	322456	0.9
	408	706	780	844	897	946	3582	0.99	324459	0.9
									0	0.0
32	-1	843	970	1070	1150	1220	5604	0.99	507900	1.4
Alum	0	2000	2530	2990	3410	3780	26640	1.00	2403490	6.6
	6	870	1010	1140	1260	1380	7620	1.00	692406	1.9
	24	934	1050	1150	1260	1360	6372	1.00	582014	1.6
	48	719	813	901	984	1060	5118	1.00	465169	1.3
	72	804	911	1010	1110	1200	5946	1.00	548206	1.5
	96	624	740	838	928	1010	5760	1.00	522799	1.4
	144	651	722	864	948	1030	5904	0.99	536217	1.5
	168	896	991	1080	1150	1230	4962	1.00	458044	1.2
	192	841	949	1030	1100	1170	4854	0.99	441567	1.2
	216	709	777	828	872	911	2994	0.99	273380	0.7
	240	642	764	838	909		5250	0.98	478987	1.3
	264	703	786	851	908	961	3828	0.99	345927	0.9
	312	803	944	1050	1140	1210	6060	0.98	549183	1.5
	336	944	1090	1190	1280		6648	0.99	601153	1.6
	360	708	795	871	930	982	4098	0.99	370356	1.0
	384	669	795	860	939	1000	4836	0.98	436805	1.2
	408	671	763	806	846		3408	0.95	308698	0.8
									0	0.0
23	-1	846	992	1060	1120	1160	4536	0.94	413845	1.1
FeCl	0	2870	3650	4350	4970	5530	39840	1.00	3653149	10.0
	2	1110	1280	1440	1590	1730	9300	1.00	852561	2.3
	8	620	700	767	833	894	4086	1.00	369241	1.0
	24	954	1090	1210	1330	1440	7272	1.00	656408	1.8
	48	746	845	927	1000	1080	4938	1.00	446525	1.2
	96	697	800	872	949	1020	4770	0.99	431228	1.2
	192	960	1030	1090	1130		3420	0.99	310336	0.8
	216	747	861	918	1000	1080	4830	0.99	440025	1.2

	240	740	836	909	971	1020	4170	0.98	378792	1.0
	312	966	1020	1070	1110		2892	1.00	262001	0.7
	336	955	1020	1070	1120	1080	2100	0.76	190450	0.5
	360	714	805	877	940	985	4062	0.98	367729	1.0
	384	699	742	779	811	839	2094	0.99	190183	0.5
	408	841	887	945	971	997	2376	0.97	215771	0.6
	504	823	930	993	1050		4464	0.98	405684	1.1
	528	873	909	949	985	1020	2220	1.00	201899	0.6
	552	738	805	851	889	924	2736	0.98	249008	0.7
	576	682	762	799	836	867	2664	0.96	241623	0.7
									0	0.0
24	-1	647	807	862	903	965	4392	0.92	400707	1.1
FeCl	0	2810	3245	4250	4870	5450	41430	0.99	3798945	10.4
	2	1600	1780	1950	2100	2220	9360	0.99	858062	2.3
	8	658	747	832	908	982	4854	1.00	438644	1.2
	24	1290	1470	1630	1780	1930	9540	1.00	861129	2.3
	48	825	941	1040	1140	1230	6054	1.00	547440	1.5
	96	666	809	949	1080	1190	7914	1.00	715459	2.0
	192	1070	1150	1220	1300		4560	1.00	413782	1.1
	216	895	976	1040	1110	1230	4824	0.99	439478	1.2
	240	776	861	955	1050	1130	5382	1.00	488887	1.3
	312	902	969	1020	1070		3330	0.99	301681	0.8
	336	964	1030	1090	1150	1230	3912	1.00	354781	1.0
	360	822	903	974	1040	1100	4158	1.00	376419	1.0
	384	588	681	749	801	837	3708	0.97	336770	0.9
	408	769	817	872	915	951	2772	0.99	251733	0.7
	504	866	974	1050	1130		5208	0.99	473298	1.3
	528	740	819	883	954	998	3906	0.99	355232	1.0
	552	713	779	827	865	897	2724	0.98	247916	0.7
	576	701	746	790	827	865	2454	1.00	222576	0.6
									0	0.0
18	-1	605	732	798	856	907	4368	0.96	398517	1.1
FeCl	0	2130	2670	3160	3620	4030	28500	1.00	2613322	7.1
	2	1270	1420	1560	1700		8580	1.00	786557	2.1
	8	629	698	766	829	889	3906	1.00	352975	1.0
	24	1060	1220	1360	1490	1620	8340	1.00	752811	2.1
	48	769	864	950	1030	1010	3888	0.89	351577	1.0
	96	573	694	790	886	971	5928	1.00	535917	1.5
	192	961	1070	1170	1260	1340	5688	1.00	516138	1.4
	216	860	953	1040	1120	1010	2802	0.58	255269	0.7
	240	701	885	992	1100	1190	7158	0.98	650214	1.8
	312	814	972	1040	1100		5556	0.94	503345	1.4
	336	991	1060	1120	1180	1210	3348	0.98	303632	0.8

	360	760	825	893	951	1010	3756	1.00	340027	0.9
	384	904	937	962	990	1020	1710	1.00	155307	0.4
	408	719	778	873	916	954	3648	0.97	331285	0.9
	504	829	927	997	1060		4578	0.99	416044	1.1
	528	702	792	848	903	954	3690	0.99	335588	0.9
	552	705	760	816	864	909	3072	1.00	279588	0.8
	576	790	816	847	876	898	1656	1.00	150198	0.4
									0	0.0
17	-1	638	701	760	806	847	3138	0.99	286297	0.8
Lime	0	350	311	287	273		-1530	0.95	-140294	-0.4
	2	483	479	477	473	469	-204	0.99	-18701	-0.1
	8	419	416	413	410	407	-180	1.00	-16266	0.0
	24	778	831	875	918	959	2694	1.00	243174	0.7
	48	758	872	950	1020	1096	4944	0.99	447067	1.2
	96	713	845	952	1050	1150	6474	1.00	585277	1.6
	192	818	907	982	1050	1110	4362	0.99	395815	1.1
	216	813	948	1040	1120	1190	5556	0.98	506165	1.4
	240	794	843	893	941	980	2820	1.00	256161	0.7
	264	807	856	897	950	1030	3240	0.98	293528	0.8
	336	698	801	860	910	953	3714	0.97	336824	0.9
	360	770	824	875	918	954	2772	0.99	250946	0.7
	384	666	709	751	774	805	2058	0.99	186913	0.5
	432	700	782	787	819	872	2286	0.92	207598	0.6
	528	811	920	979	1030		4296	0.97	390416	1.1
	552	786	839	880	918	944	2370	0.99	215540	0.6
	576	720	781	823	863	893	2568	0.98	233718	0.6
	600	709	731	752	791	807	1536	0.98	139314	0.4
									0	0.0
21	-1	644	803	861	918	964	4530	0.92	413297	1.1
Lime	0	379	324	261	241	228	-2310	0.92	-211817	-0.6
	2	437	435	425	419	410	-420	0.97	-38503	-0.1
	8	392	382	374	380	361	-384	0.79	-34701	-0.1
	24	767	826	892	937	976	3174	0.99	286501	0.8
	48	717	826	1010	1090	1070	5820	0.88	526281	1.4
	96	711	869	996	1110	1220	7554	0.99	682914	1.9
	192	761	905	1010	1090	1160	5898	0.98	535194	1.5
	216	848	937	989	1060	1120	4002	0.99	364592	1.0
	240	790	921	1010	1090	1160	5454	0.98	495427	1.4
	264	739	827	880	939	985	3624	0.99	328316	0.9
	336	776	891	940	1060	1130	5262	0.99	477213	1.3
	360	751	829	899	956	1010	3870	0.99	350347	1.0
	384	688	757	810	852	882	2898	0.98	263204	0.7
	432	794	835	878	911	944	2256	1.00	204873	0.6

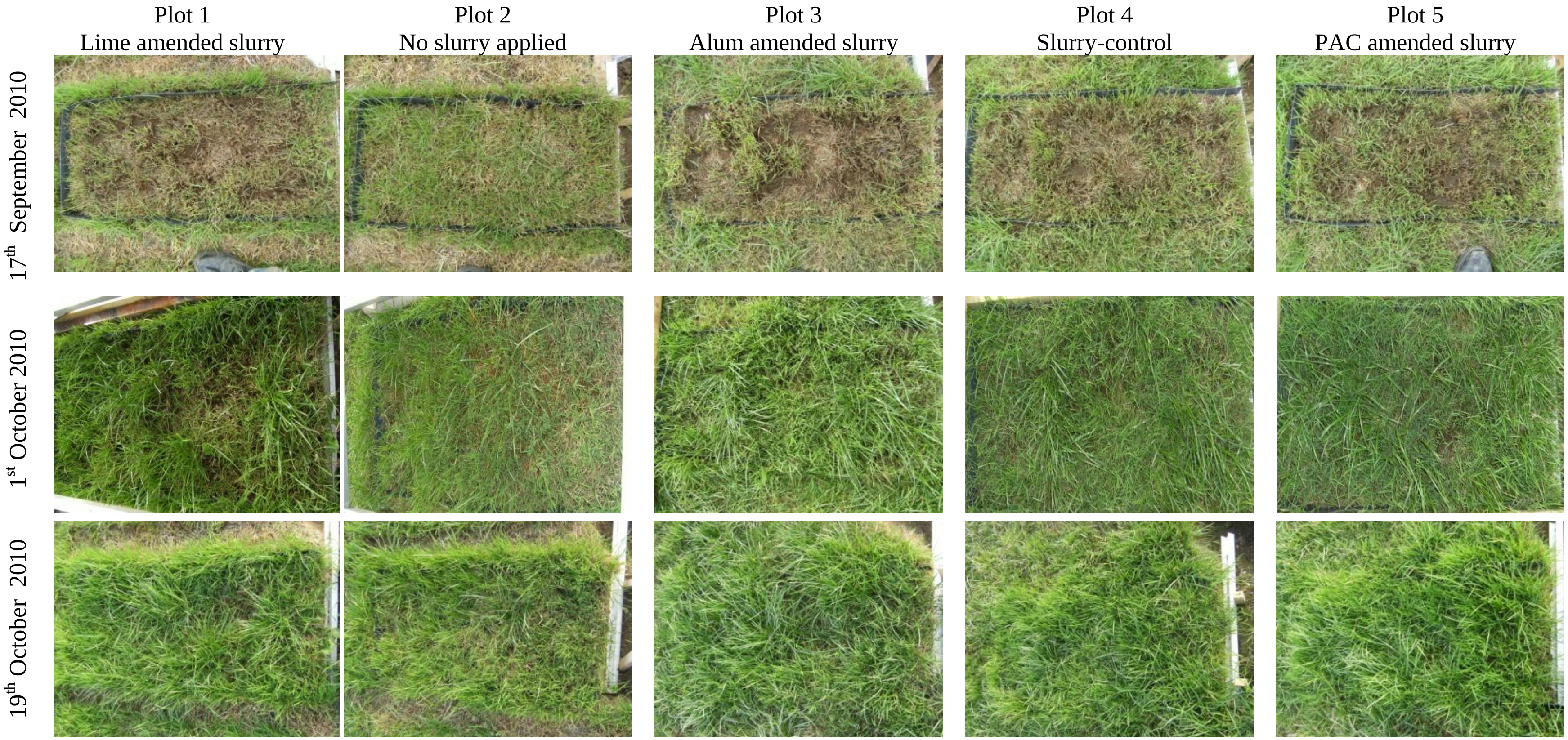
	528	866	974	1050	1130		5208	0.99	473298	1.3
	552	856	955	981	1030	1070	3018	0.95	274473	0.7
	576	821	870	915	955	980	2418	0.99	220066	0.6
	600	639	675	710	742	771	1986	1.00	180129	0.5
									0	0.0
19	-1	872	953	1020	1070	1110	3558	0.98	324616	0.9
Lime	0	480	455	432	417	406	-1116	0.97	-102332	-0.3
	2	443	435	424	421	414	-432	0.97	-39603	-0.1
	8	374	361	351	343	337	-552	0.98	-49883	-0.1
	24	713	751	787	820	847	2022	1.00	182516	0.5
	48	646	700	789	862	927	4344	1.00	392811	1.1
	96	525	688	793	898	995	6900	0.99	623790	1.7
	192	820	931	1030	1120	1200	5694	1.00	516683	1.4
	216	751	892	1060	1130	1190	6696	0.96	610022	1.7
	240	860	1000	1100	1180	1260	5880	0.98	534124	1.5
	264	937	1020	1090	1160	1200	3996	0.99	362017	1.0
	336	798	915	1000	1080	1150	5214	0.99	472860	1.3
	360	711	865	944	1020	1060	5118	0.95	463327	1.3
	384	792	849	893	932	968	2610	0.99	237047	0.6
	432	611	790	848	899	941	4614	0.89	419010	1.1
	528	773	903	997	1070		5910	0.98	537095	1.5
	552	754	860	931	987	1040	4194	0.98	381425	1.0
	576	687	789	847	899	947	3780	0.97	344024	0.9
	600	675	716	764	784	802	1932	0.96	175231	0.5
									0	0.0
PAC	-1	3310	4150	4840	5500	6070	41220	0.99	3735836	10.2
	0	833	1050	1200	1330	1460	9204	0.99	830395	2.3
	6	681	765	845	917	987	4584	1.00	416534	1.1
	24	1140	1310	1470	1620	1760	9300	1.00	849455	2.3
	48	627	735	860	973	1080	6864	1.00	623860	1.7
	72	464	586	737	868	993	8040	1.00	741267	2.0
	96	781	889	982	1060	1130	5214	0.99	473242	1.3
	144	760	882	982	1070	1150	5808	0.99	527498	1.4
	168	802	948	1060	1160	1250	6648	0.99	613679	1.7
	192	693	795	881	955	1020	4884	0.99	444296	1.2
	216	767	863	937	981	1050	4104	0.98	374734	1.0
	240	835	930	997	1060	1110	4080	0.99	372241	1.0
	264	734	798	844	888	925	2832	0.99	255921	0.7
	312	736	813	882	928	975	3558	0.99	322441	0.9
	336	811	920	979	1030		4296	0.97	388471	1.1
	360	836	910	961	1010	1050	3168	0.99	286307	0.8
	384	821	870	915	955	980	2418	0.99	218403	0.6
	408	678	738	792	839	887	3114	1.00	282067	0.8

										0.0
PAC	-1	2010	2234	3430	3820	4200	35796	0.94	3244250	8.8
	0	836	962	1080	1190	1300	6936	1.00	625774	1.7
	6	612	676	734	842		4488	0.98	407811	1.1
	24	886	1010	1120	1220	1320	6468	1.00	590782	1.6
	48	617	716	806	889	967	5238	1.00	476075	1.3
	72	561	622	697	765	831	4098	1.00	377825	1.0
	96	898	1100	1230	1330	1430	7764	0.97	704689	1.9
	144	742	858	937	1010	1070	4848	0.98	440308	1.2
	168	1150	1240	1280	1320	1360	3000	0.96	276931	0.8
	192	960	1040	1060	1090	1120	2220	0.93	201953	0.6
	216	758	896	974	1040	1100	4968	0.97	453625	1.2
	240	942	994	1040	1080	1110	2532	0.99	231009	0.6
	264	663	779	849	907	959	4320	0.97	390387	1.1
	312	885	954	1000	1040	1080	2856	0.98	258823	0.7
	336	829	827	997	1022	1060	3942	0.84	356460	1.0
	360	982	1050	1100	1150	1190	3096	0.99	279800	0.8
	384	836	874	914	953	999	2430	1.00	219487	0.6
	408	708	744	783	815	851	2142	1.00	194023	0.5
										0.0
Char	-1	1012	1022	1038	1044	1052	612	0.97	55836	0.2
	0	678	681	688	693	698	312	0.99	28609	0.1
	6	552	555	562	568	573	330	0.99	30252	0.1
	24	704	706	708	709	710	102	0.98	9217	0.0
	48	783	789	793	803	812	432	0.97	38995	0.1
	72	722	717	724	731	729	204	0.57	18447	0.1
	96	691	702	704	707	708	300	0.86	27121	0.1
	144	829	832	844	847	851	354	0.94	32123	0.1
	168	449	452	467	473	488	594	0.96	54115	0.1
	192	594	596	598	604	609	228	0.95	20711	0.1
	216	560	652	655	656	661	1236	0.57	111975	0.3
	240	723	726	732	738	741	288	0.98	26119	0.1
	264	890	902	917	926	943	780	0.99	70613	0.2
	312	882	886	892	899	903	330	0.99	29971	0.1
	336	1001	1004	1012	1014	1019	276	0.97	25064	0.1
	360	702	708	714	723	736	498	0.97	45258	0.1
	384	722	723	723	725	729	96	0.82	8731	0.0
	408	511	524	555	571	579	1098	0.96	99931	0.3
										0.0
Char	-1	736	754	777	823	896	2334	0.92	212944	0.6
	0	1003	1021	1134	1146	1204	3162	0.93	289941	0.8
	6	823	879	933	972	1011	2814	0.99	257969	0.7
	24	742	890	1023	1085		6972	0.97	630042	1.7

	48	825	922	1057	1108	1239	6084	0.99	549173	1.5
	72	552	627	645	674	681	2304	0.91	208342	0.6
	96	716	724	748	776	779	1224	0.95	110655	0.3
	144	713	735	746	772	783	1062	0.98	96368	0.3
	168	924	926	931	937	946	330	0.95	30064	0.1
	192	801	810	814	823	834	474	0.98	43057	0.1
	216	649	652	655	656	661	168	0.97	15220	0.0
	240	702	702	705	709	710	138	0.92	12515	0.0
	264	714	712	715	717	721	114	0.77	10320	0.0
	312	783	786	792	793	796	198	0.96	17983	0.0
	336	802	813	813	809	812	96	0.29	8718	0.0
	360	853	870	876	891	902	714	0.99	64888	0.2
	384	739	741	745	751	759	300	0.95	27284	0.1
	408	795	801	803	809	810	228	0.96	20751	0.1
										0.0
Soil	-1	488	499	502	509		396	0.95	36129	0.1
	0	566	571	577	579	581	228	0.95	20907	0.1
	6	362	367	371	376	378	246	0.98	22552	0.1
	24	466	469	478	493	505	612	0.95	55305	0.2
	48	593	594	597	602	611	264	0.89	23830	0.1
	72	738	741	750	757	762	384	0.98	34724	0.1
	96	711	713	713	716	718	102	0.94	9221	0.0
	144	892	903	926	951	973	1260	0.99	114334	0.3
	168	764	777	781	789	795	444	0.97	40449	0.1
	192	721	730	734	742	748	396	0.99	35972	0.1
	216	692	703	717	728	751	858	0.98	77730	0.2
	240	503	510	513	518		288	0.98	26119	0.1
	264	901	903	908	911		210	0.98	19011	0.1
	312	873	875	878	880		144	0.99	13078	0.0
	336	772	784	801	819	837	990	0.99	89905	0.2
	360	813	820	822	825	832	258	0.96	23447	0.1
	384	845	850	852	857	859	210	0.98	19099	0.1
	408	703	708	719	725	740	546	0.97	49692	0.1

Appendix E Photographs of slurry and amended slurry applied to plots (Chapter 6)

Figure E Photographs of slurry and amended slurry applied to plots (Chapter 6)



Appendix F Results of plot study

Notation used in Table F.1

Plot: plot identification number
ttorun1: time from start of rain to runoff event 1
pHe1: pH of runoff water (average for each event)
ttorun2: time from start of rain to runoff event 2
ttorun3: time from start of rain to runoff event 3
intensity1: average rainfall intensity during rainfall event 1
intensity2: average rainfall intensity during rainfall event 1
intensity3: average rainfall intensity during rainfall event 1
slope%: slope of plot

Table F.1. Volume of runoff, concentrations of Cl (chlorine), NH_4 (ammonium), NO_2 (nitrite), DRP (dissolved reactive phosphorus), total dissolved phosphorus (TDP), TP (total phosphorus) and TON (total oxidized nitrogen).

					Volume	Cl	NH4	NO2	DRP	TDP	TP	TON
Plot	Event	Treatment	Start	End	Vol runoff	mg/l	mg/l	mg/l	mg/l	mg/L	mg/L	mg/l
1	1	lime	-60	0	97.0	53.2	0.5	0.0	0.8	1.1	1.7	4.1
1	1	lime	0	5	140.1	72.2	1.4	0.1	2.1	3.1	5.4	4.8
1	1	lime	5	10	197.1	81.1	2.0	0.1	3.2	4.0	6.8	4.1
1	1	lime	10	15	217.4	83.5	2.4	0.1	3.7	4.7	8.4	3.9
1	1	lime	15	20	98.7	85.6	2.6	0.1	3.9	5.3	9.4	4.4
1	1	lime	20	25	149.8	83.2	2.2	0.1	4.1	5.3	9.5	4.3
1	1	lime	25	30	287.6	82.2	3.1	0.1	4.2	5.5	9.3	4.3
1	1	lime			1187.6							
1	2	lime	t	0	51.1	48.7	0.0	0.0	0.3	0.5		3.2
1	2	lime	0	10	19.0	55.2	0.0	0.0	0.3		0.3	2.6
1	2	lime	10	20	17.2	57.0	0.1	0.0	0.2		0.3	3.0
1	2	lime	20	30	40.7	57.3	0.2	0.0	0.2		1.4	2.8
1	2	lime			127.9							
1	3	lime	t	0	150.2	45.7	0.0	0.0	0.1	0.1	0.2	4.4
1	3	lime	0	10	200.0	43.5	0.0	0.0	0.1	0.1	0.2	4.4
1	3	lime	10	20	74.7	42.4	0.0	0.0	0.1	0.2	0.3	4.3
1	3	lime	20	30	112.2	40.8	0.0	0.0	0.1	0.2	0.3	4.1
1	3	lime			537.0							
2	1	soil	-19	0	47.4	28.8	1.2	0.0	0.0	0.0	0.1	5.0
2	1	soil	0	5	52.9	28.5	1.0	0.0	0.0	0.0	0.1	4.5
2	1	soil	5	10	36.9	26.2	1.2	0.0	0.0	0.0	0.0	4.5
2	1	soil	10	15	42.4	26.4	1.3	0.0	0.0	0.0	0.0	4.6
2	1	soil	15	20	45.0	26.0	1.1	0.0	0.0	0.0	0.1	4.4
2	1	soil	20	25	35.5	26.4	1.0	0.0	0.0		0.0	4.5
2	1	soil	25	30	42.9	26.1	0.9	0.0	0.0		0.1	4.5
2	1	soil			302.9							
2	2	soil	t	0	19.1	45.8	0.2	0.2	1.3	1.6	2.1	5.3
2	2	soil	0	10	18.4	51.1	0.1	0.3	1.9	2.3	2.9	5.7
2	2	soil	10	20	39.3	48.8	0.1	0.2	1.4		2.0	5.3

2	2	soil	20	30	31.0	47.9	0.1	0.1	1.5		0.4	5.0
2	2	soil			107.7							
2	3	soil	t	0	95.7	49.0	0.2	0.0	0.0	0.0	0.2	3.9
2	3	soil	0	10	84.5	46.9	0.0	0.0	0.0	0.1	0.2	3.8
2	3	soil	10	20	97.2	46.1	0.0	0.0	0.0	0.1	0.1	3.8
2	3	soil	20	30	52.3	45.8	0.0	0.0	0.0	0.0	0.1	3.7
2	3	soil			329.7							
3	1	alum	-30	0	50.0	84.0	2.1	0.1	1.6	3.2	5.3	4.5
3	1	alum	0	5	34.0	82.8	2.3	0.0	2.3	7.7	9.2	4.9
3	1	alum	5	10	54.0	169.9	5.2	0.2	5.0	8.0	15.1	2.9
3	1	alum	10	15	23.0	181.2	5.8	0.1	5.1		12.6	2.8
3	1	alum	15	20	45.0	175.6	10.0	0.0	6.2	7.1	14.7	4.2
3	1	alum	20	25	32.0	174.7	7.7	0.2	5.9		15.2	3.0
3	1	alum	25	30	35.0	160.9	5.6	0.1	6.0		15.4	2.0
3	1	alum			273.0							
3	2	alum	t	0	106.0	63.6	0.2	0.1	0.1	0.3	0.4	6.8
3	2	alum	0	10	61.8	61.0	0.2	0.0	0.1	0.3	0.4	6.6
3	2	alum	10	20	76.4	57.9	0.1	0.0	0.2	0.3	0.5	6.1
3	2	alum	20	30	66.1	58.4	0.0	0.0	0.2	0.3	0.4	5.9
3	2	alum			310.3							
3	3	alum	t	0	48.6	38.3	0.0	0.0	0.0	0.2	0.2	3.0
3	3	alum	0	10	15.9	36.6	0.0	0.0	0.1		0.2	3.0
3	3	alum	20	30	17.6	35.6	0.0	0.0	0.1			3.3
3	3	alum			82.2							
4	1	slurry	0	5	17.0	29.6	0.9	0.0	0.0	0.1	0.2	5.0
4	1	slurry	5	10	23.1	48.1	2.3	0.0	0.0	0.1	0.3	5.5
4	1	slurry	15	20	37.2	40.2	2.1	0.0	0.0		0.2	5.6
4	1	slurry	20	25	29.2	42.2	2.6	0.0	0.0	2.0		5.2
4	1	slurry	25	30	36.1	40.2	2.5	0.0	0.0		0.3	5.1
4	1	slurry			142.5							
4	2	slurry	t	0	104.0	32.9	0.1	0.0	0.1	0.1	0.3	4.0
4	2	slurry	0	10	67.0	29.6	0.2	0.0	0.1		0.3	3.2
4	2	slurry	10	20	66.5	30.0	0.1	0.0	0.2		0.3	3.2
4	2	slurry	20	30	59.0	30.1	0.0	0.0	0.0		0.2	3.2
4	2	slurry			296.5							
4	3	slurry	t	0	58.8	36.6	0.0	0.0	0.0	0.0	0.1	3.7
4	3	slurry	0	10	43.8	36.0	0.0	0.0	0.0	0.0	0.1	3.8
4	3	slurry	10	20	37.7	35.9	0.0	0.0	0.0		0.1	3.8
4	3	slurry	20	30	33.8	36.2	0.0	0.0	0.0		0.1	3.9
4	3	slurry			174.1							
5	1	pac	t	0	59.1	96.2	0.7	0.0	0.0		0.2	4.7
5	1	pac	0	5	17.9	153.2	0.9	0.1	0.0			4.8
5	1	pac	15	20	14.8	152.0	0.7	0.1	0.0			4.7

5	1	pac	20	25	23.0	240.2	0.3	0.1	0.0		0.3	3.9
5	1	pac	5	10	12.6	159.4	0.6	0.1	0.0			4.7
5	1	pac	10	15	14.7	163.8	0.5	0.1	0.0			5.2
5	1	pac	25	30	6.9	326.3	1.5	0.1	0.0			4.0
5	1	pac			149.0							
5	2	pac	t	0	106.2	35.6	0.0	0.0	0.1	0.1	0.1	3.5
5	2	pac	0	10	33.9	34.4	0.1	0.0	0.0		0.1	3.2
5	2	pac	10	20	70.1	34.3	0.1	0.0	0.1		0.2	3.0
5	2	pac	20	30	67.4	35.0	0.0	0.0	0.0	0.1	0.6	3.3
5	2	pac			277.7							
5	3	pac	t	0	86.8	41.0	0.0	0.0	0.1	0.3	0.5	3.2
5	3	pac	0	10	174.2	39.5	0.0	0.0	0.2	0.3	0.5	3.2
5	3	pac	10	20	130.4	39.0	0.0	0.0	0.1	0.2	0.6	3.3
5	3	pac	20	30	157.4	38.8	0.0	0.0	0.2	0.2	0.4	3.4
5	3	pac			548.6							
6	1	slurry	-57	0	53.1	94.8	1.0	0.0	0.7	4.7		3.8
6	1	slurry	0	5	27.3	155.8	1.6	0.0	1.0		6.4	3.7
6	1	slurry	5	10	39.5	232.0	2.4	0.1	2.5		7.0	3.5
6	1	slurry	10	15	43.5	220.3	3.9	0.1	3.1	0.4		4.1
6	1	slurry	15	20	54.5	199.4	3.6	0.1	3.5		8.6	3.6
6	1	slurry	20	25	53.3	190.2	3.6	0.1	3.3		8.1	3.9
6	1	slurry	25	30	65.8	184.8	4.2	0.1	3.5	4.5	7.9	3.7
6	1	slurry			337.0							
6	2	slurry	t	0	44.7	48.6	0.1	0.0	0.1	0.4	0.8	2.8
6	2	slurry	0	10	18.8	48.3	0.2	0.0	0.3		0.8	3.3
6	2	slurry	10	20	24.5	46.4	0.2	0.0	0.3	0.5	0.8	3.5
6	2	slurry	20	30	26.6	46.6	0.1	0.0	0.3	0.5	0.0	3.7
6	2	slurry			114.5							
6	3	slurry	t	0	35.7	35.3	0.0	0.0	0.3		0.7	1.7
6	3	slurry	0	10	50.5	32.7	0.0	0.0	0.4	0.6	0.7	1.4
6	3	slurry	10	20	28.7	33.8	0.0	0.0	0.5		0.8	1.4
6	3	slurry	20	30	60.6	34.3	0.0	0.0	0.6	0.8	0.9	1.4
6	3	slurry			175.4							
7	1	alum	t	0	288.6	207.4	4.3	0.0	0.0	0.4	0.9	5.9
7	1	alum	0	5	79.9	168.1	6.8	0.1	0.1	0.3	1.3	6.3
7	1	alum	5	10	142.1	84.8	5.5	0.1	0.1	0.3	1.0	5.7
7	1	alum	10	15	164.2	77.1	4.5	0.1	0.0	0.4	1.0	5.6
7	1	alum	15	20	165.2	65.6	4.1	0.1	0.1	0.5	0.7	5.5
7	1	alum	20	25	157.8	65.4	4.5	0.1	0.1	0.2	0.8	5.3
7	1	alum	25	30	118.1	70.8	5.7	0.1	0.1	0.2	3.0	5.2
7	1	alum			1115.7							
7	2	alum	t	0	25.2	36.5	0.0	0.0	0.0	0.6		4.6
7	2	alum	0	10	28.4	46.6	1.2	0.9	1.1	2.0	2.3	3.2

7	2	alum	10	20	18.2	47.6	0.4	0.1	2.9	3.6	3.7	4.9
7	2	alum	20	30	52.6	48.1	0.5	0.1	2.9	3.5	3.6	4.9
7	2	alum			99.2							
7	3	alum	t	0	213.5	34.7	0.0	0.0	0.2	0.3	0.5	2.7
7	3	alum	0	10	204.0	34.8	0.0	0.0	0.1	0.3	0.4	2.7
7	3	alum	10	20	148.9	35.6	0.0	0.0	0.1	0.2	0.4	2.6
7	3	alum	20	30	111.0	36.4	0.0	0.0	0.2	0.2	0.5	2.7
7	3	alum			677.4							
8	1	soil	t	0	67.3	27.0	0.7	0.0	0.1	0.2	0.4	4.1
8	1	soil	0	5	15.0	25.2	0.2	0.0	0.0			3.9
8	1	soil	5	10	14.9	25.1	0.2	0.0	0.0			4.0
8	1	soil	10	15	14.8	25.5	0.2	0.0	0.0			4.0
8	1	soil	15	20	15.6	26.6	0.2	0.0	0.0			4.1
8	1	soil	20	25	15.7	25.0	0.2	0.0	0.0			3.7
8	1	soil	25	30	27.6	30.9	0.9	0.0	0.0	3.3	4.2	5.2
8	1	soil	25	30	27.6	42.1	0.1	0.0	0.2			4.3
8	1	soil			198.5							
8	2	soil	t	0	195.4	68.5	0.2	0.0	0.3	0.4	1.6	4.6
8	2	soil	0	10	151.6	66.1	0.1	0.0	0.3	0.5	0.9	4.9
8	2	soil	10	20	113.7	87.1	0.1	0.0	0.3	0.4	0.5	4.3
8	2	soil	20	30	91.1	93.1	0.1	0.0	0.2	0.4	0.4	4.1
8	2	soil			551.8							
8	3	soil	t	0	64.0	36.9	0.0	0.0	0.2	0.3	0.4	3.4
8	3	soil	0	10	93.8	36.3	0.0	0.0	0.2	0.3	0.4	3.1
8	3	soil	10	20	23.8	35.1	0.1	0.0	0.2		0.4	2.4
8	3	soil	20	30	9.7	34.9	0.0	0.0	0.2			2.0
8	3	soil			191.3							
9	1	pac	t	0	52.2	27.3	0.1	0.0	0.0	3.3		4.6
9	1	pac	0	10	43.3	37.1	0.1	0.0	0.0			4.5
9	1	pac	10	20	163.7	42.0	0.2	0.0	0.0			5.2
9	1	pac	20	30	163.7	40.8	0.1	0.0	0.0			5.3
9	1	pac			422.9							
9	2	pac	t	0	10.2	48.4	0.5	0.1	3.0	3.5	3.8	4.9
9	2	pac	0	10	107.7	37.1	0.0	0.0	0.1	3.6	4.2	4.1
9	2	pac	10	20	52.2	36.3	0.0	0.0	0.2	0.2	0.5	4.2
9	2	pac	20	30	132.7	36.4	0.0	0.0	0.1	0.2	0.2	4.2
9	2	pac			302.7							
9	3	pac	t	0	57.6	39.7	0.1	0.0	0.1	0.1	0.3	3.8
9	3	pac	0	10	30.7	39.1	0.0	0.0	0.1		0.2	3.8
9	3	pac	10	20	17.6	40.0	0.0	0.0	0.1		0.2	3.7
9	3	pac	20	30	36.3	39.3	0.0	0.0	0.1		0.2	3.7
9	3	pac			142.1							
10	1	lime	t	0	72.2	72.1	1.0	0.0	0.7	0.9	2.4	4.7

10	1	lime	0	5	33.0	92.0	0.7	0.0	1.3		4.0	4.6
10	1	lime	5	10	56.0	94.4	1.6	0.1	2.1		8.4	4.5
10	1	lime	10	15	53.8	94.6	1.4	0.1	2.5		10.2	4.8
10	1	lime	15	20	64.0	135.3	2.6	0.2	3.7		9.2	5.8
10	1	lime	20	25	78.3	87.8	1.7	0.2	2.8	3.3	7.7	4.4
10	1	lime	25	30	81.8	84.3	1.8	0.1	2.8	3.3	8.6	4.7
10	1	lime			439.0							
10	2	lime	t	0	57.8	41.6	0.1	0.0	0.0		0.2	5.1
10	2	lime	0	10	145.0	38.3	0.0	0.0	0.0	0.1	0.1	4.5
10	2	lime	10	20	153.8	38.1	0.1	0.0	0.1	0.1	0.7	4.5
10	2	lime	20	30	133.6	51.2	0.2	0.0	0.3	0.5	1.0	4.8
10	2	lime			490.1							
10	3	lime	t	0	61.4	37.7	0.2	0.0	1.1	1.2	1.3	3.6
10	3	lime	0	10	51.5	36.9	0.1	0.0	1.4	1.5	1.6	3.4
10	3	lime	10	20	23.0	36.6	0.1	0.0	1.2		1.4	3.1
10	3	lime	20	30	42.7	36.7	0.1	0.0	1.3		1.5	3.3
10	3	lime			178.6							
11	1	pac	t	0	82.4	92.8	0.5	0.0	0.2	0.3	2.1	4.4
11	1	pac	0	5	66.6	161.6	0.8	0.0	0.1	2.3	1.7	4.7
11	1	pac	5	10	40.1	190.4	0.9	0.0	0.1	3.1	4.7	4.8
11	1	pac	10	15	54.8	190.5	0.8	0.0	0.1	3.0	1.3	4.7
11	1	pac	15	20	52.5	191.7	0.6	0.0	0.1	1.4	1.8	4.5
11	1	pac	20	25	59.3	181.2	0.2	0.0	0.0		0.9	4.4
11	1	pac	25	30	43.1	195.9	0.5	0.0	0.1		0.9	4.2
11	1	pac			398.7							
11	2	pac	t	0	59.5	36.6	0.0	0.0	0.1	0.2	0.2	4.2
11	2	pac	0	10	93.0	38.5	0.0	0.0	0.1	0.2	0.2	3.1
11	2	pac	10	20	80.0	38.5	0.1	0.0	0.0		0.2	3.3
11	2	pac	20	30	52.0	37.2	0.0	0.0	0.0		0.2	2.9
11	2	pac			284.5							
11	3	pac	t	0	76.5	37.1	0.0	0.0	0.1	0.2	0.2	4.3
11	3	pac	0	10	98.5	37.3	0.0	0.0	0.1	0.2	0.2	4.3
11	3	pac	10	20	94.3	37.0	0.0	0.0	0.2	0.2	0.4	4.1
11	3	pac	20	30	62.4	34.4	0.0	0.0	0.2	0.2	0.5	4.2
11	3	pac			331.7							
12	2	lime	t	0	50.4	39.0	0.0	0.0	0.0		0.2	3.0
12	2	lime	0	10	24.1	36.4	0.1	0.0	0.0		0.1	4.3
12	2	lime	10	20	22.0	36.1	0.0	0.0	0.0		0.0	4.2
12	2	lime	20	30	16.9	33.4	0.0	0.0	0.0		0.3	3.7
12	3	lime	t	0	55.5	34.9	0.0	0.0	0.0	0.2	0.2	3.4
12	2	lime			113.4							
12	3	lime	0	10	13.4	30.1	0.0	0.0	0.1			3.1
12	3	lime	10	20	16.1	32.5	0.0	0.0	0.1			3.2

12	3	lime	20	30	9.3	33.5	0.0	0.0	0.1			3.1
12	3	lime			38.7							
13	1	slurry	t	0	35.0	147.8	1.1	0.1	2.4	2.6	6.3	4.0
13	1	slurry	0	5	34.0	162.0	1.1	0.0	2.8		7.0	4.1
13	1	slurry	5	10	43.0	141.0	1.3	0.0	2.7		6.8	4.5
13	1	slurry	10	15	39.0	133.3	0.9	0.0	2.4		6.1	4.4
13	1	slurry	15	20	43.0	138.1	0.8	0.1	2.0		6.4	4.2
13	1	slurry	20	25	14.8	137.5	0.8	0.0	2.1			4.3
13	1	slurry			208.8							
13	2	slurry	t	0	251.7	32.1	0.0	0.0	0.0		0.1	3.7
13	2	slurry	0	10	101.4	37.1	0.0	0.0	0.3	0.6	0.7	4.0
13	2	slurry	10	20	40.2	37.2	0.0	0.0	0.3	0.5	0.6	3.5
13	2	slurry	20	30	42.2	36.9	0.0	0.0	0.3	0.5	0.7	3.7
13	2	slurry			435.5							
13	3	slurry	t	0	70.4	31.5	0.1	0.0	0.7	0.8	1.0	3.9
13	3	slurry	0	10	42.8	33.3	0.0	0.0	0.6	0.8	0.9	4.0
13	3	slurry	10	20	70.3	33.5	0.0	0.0	0.6	0.7	0.9	4.1
13	3	slurry	20	30	44.2	34.9	0.0	0.0	0.5	0.6	0.6	4.1
13	3	slurry			227.7							
14	2	alum	t	0	114.7	37.1	0.0	0.0	0.4	0.5	0.7	3.6
14	2	alum	0	10	60.2	44.7	0.4	0.0	0.1	0.6	0.9	4.6
14	2	alum	10	20	56.2	44.8	0.4	0.0	0.1		0.8	4.6
14	2	alum	20	30	42.2	44.9	0.2	0.0	0.1	0.2	0.8	4.6
14	2	alum			273.3							
14	3	alum	t	0	43.4	29.7	0.0	0.0	0.1	0.1	0.2	2.1
14	3	alum	0	10	9.6	34.7	0.0	0.0	0.1			2.6
14	3	alum	10	20	12.6	34.5	0.0	0.0	0.1			2.3
14	3	alum	20	30	14.4	34.6	0.0	0.0	0.1			2.5
14	3	alum			80.0							
15	2	alum	t	0	46.4	44.6	0.2	0.0	0.1	0.2	0.6	4.5
15	2	alum	0	10	18.0	37.0	0.0	0.0	0.1	0.2	0.3	4.2
15	2	alum	10	20	41.4	38.5	0.0	0.0	0.1	0.1	0.3	4.1
15	2	alum	20	30	29.3	47.8	0.2	0.0	0.3		3.2	4.4
15	2	alum			135.1							
15	3	alum	t	0	52.1	34.6	0.0	0.0	0.1	0.1	0.3	4.1
15	3	alum	0	10	21.6	34.7	0.0	0.0	0.1		0.3	4.0
15	3	alum	10	20	52.7	35.6	0.0	0.0	0.1	0.1	0.3	4.1
15	3	alum	20	30	45.4	36.3	0.0	0.0	0.0	0.1	0.2	4.1
15	3	alum			171.7							
16	1	slurry	t	0	87.4	55.2	0.9	0.0	0.4			5.4
16	1	slurry	5	10	30.0	70.9	0.3	0.0	1.3			4.7
16	1	slurry	15	20	12.3	68.4	0.6	0.0	1.4			5.0
16	1	slurry	20	25	18.6	68.4	0.3	0.0	1.6			4.8

16	1	slurry	10	15	18.6	68.7	0.2	0.0	1.6		5.0	4.7
16	1	slurry	0	5	30.0	62.7	0.6	0.0	0.8			4.7
16	1	slurry	25	30	19.1	66.3	0.1	0.1	1.5		4.4	4.6
16	1	slurry			215.9				0.0		0.0	
16	2	slurry	t	0	44.0	43.5	0.0	0.0	0.1	0.2	0.2	4.5
16	2	slurry	0	10	2.5	38.1	0.0	0.0	0.1			4.5
16	2	slurry	10	20	2.6	38.1	0.0	0.0	0.1			4.4
16	2	slurry	20	30	1.9	42.3	0.0	0.0	0.0			4.5
16	2	slurry			50.9							
16	3	slurry	t	0	44.8	29.3	0.1	0.0	0.2	0.3	0.5	2.6
16	3	slurry	0	10	77.0	33.3	0.0	0.0	0.3	0.4	0.5	3.1
16	3	slurry	10	20	62.3	33.6	0.0	0.0	0.3	0.4	0.5	3.4
16	3	slurry	20	30	87.4	33.6	0.0	0.0	0.3	0.4	0.7	3.4
16	3	slurry			271.4							
17	1	alum	t	0	39.5	37.2	0.0	0.0	0.0		1.8	4.9
17	1	alum	0	5	36.1	51.8	1.1	0.0	0.7	0.3		5.1
17	1	alum	5	10	44.5	51.5	0.9	0.1	1.2		0.3	4.9
17	1	alum	10	15	51.0	52.9	0.6	0.0	0.1		0.4	5.0
17	1	alum	15	20	54.4	53.3	0.7	0.0	0.1		0.3	5.1
17	1	alum	20	25	52.9	52.5	0.5	0.0	0.0		0.3	4.9
17	1	alum	25	30	48.4	55.5	0.7	0.0	0.0		0.4	5.1
17	1	alum			326.7							
17	2	alum	t	0	35.7	42.8	0.0	0.0	0.2		0.4	3.0
17	2	alum	0	10	13.7	39.6	0.0	0.0	0.2			3.1
17	2	alum	10	20	13.4	38.3	0.0	0.0	0.2			3.1
17	2	alum	20	30	16.5	39.2	0.0	0.0	0.2			3.0
17	2	alum			79.3							
17	3	alum	t	0	41.3	39.3	0.3	0.0	0.1		0.2	4.2
17	3	alum	0	10	15.4	37.7	0.2	0.0	0.1			3.8
17	3	alum	10	20	10.9	37.4	0.1	0.0	0.1			2.8
17	3	alum	20	30	42.8	30.6	0.0	0.0	0.1	0.3	0.4	1.7
17	3	alum			110.4							
18	1	soil	t	0	105.5	59.9	1.3	0.1	0.1	0.3	1.0	5.3
18	1	soil	0	5	19.9	49.0	1.4	0.1	0.5			4.9
18	1	soil	5	10	16.2	42.4	0.5	0.0	0.0			4.5
18	1	soil	10	15	24.2	42.2	0.5	0.1	0.1		0.7	4.4
18	1	soil	15	20	28.6	40.5	0.2	0.0	0.0			4.4
18	1	soil	20	25	34.5	40.2	0.3	0.0	0.0			4.4
18	1	soil	25	30	66.7	61.0	0.5	0.1	0.2	0.6	0.8	5.4
18	1	soil	25	30	31.2	40.2	0.2	0.0	0.0			4.5
18	1	soil	t	0	105.5	49.8	1.8	0.2	0.3			4.7
18	1	soil	15	20	24.2	40.5	0.4	0.1	0.2			4.7
18	1	soil	0	5	19.9	43.4	0.6	0.1	0.3			4.9

18	1	soil	20	25	28.6	40.4	0.1	0.1	0.1			4.7
18	1	soil	25	30	27.8	39.1	0.3	0.1	0.2			4.7
18	1	soil	10	15	16.2	40.2	0.3	0.1	0.2			4.8
18	1	soil			295.6							
18	2	soil	t	0	49.2	37.4	0.0	0.0	0.0	0.1	0.1	3.8
18	2	soil	0	10	6.8	37.4	0.0	0.0	0.0			3.7
18	2	soil	10	20	9.3	36.9	0.0	0.0	0.0			3.6
18	2	soil	20	30	8.7	37.2	0.0	0.0	0.1			3.5
18	2	soil			73.9							
18	3	soil	t	0	38.5	43.3	0.0	0.0	0.0		0.2	3.9
18	3	soil	0	10	8.0	40.4	0.0	0.0	0.0			3.3
18	3	soil	10	20	14.7	39.4	0.0	0.0	0.1			2.7
18	3	soil	20	30	14.9	38.3	0.0	0.0	0.1			2.6
18	3	soil			76.2							
19	1	pac	0	5	34.7	54.0	0.4	0.0	0.1	0.1	1.2	5.2
19	1	pac	5	10	56.9	53.6	0.2	0.1	0.0	0.2	0.6	5.1
19	1	pac	10	15	50.9	56.0	0.3	0.1	0.1	0.2	0.4	5.2
19	1	pac	15	20	48.9	56.6	0.4	0.1	0.2	0.2	0.5	5.1
19	1	pac	20	25	65.6	59.6	0.4	0.1	0.1	0.2	0.4	5.1
19	1	pac	25	30	54.5	63.2	0.6	0.1	0.2	0.3	0.4	5.2
19	1	pac			311.5							
19	2	pac	t	0	41.2	47.8	0.0	0.0	0.2	0.3	0.4	3.6
19	2	pac	0	10	3.1	41.0	0.0	0.0	0.2			3.8
19	2	pac	10	20	3.8	42.6	0.0	0.0	0.2			3.7
19	2	pac	20	30	11.1	41.3	0.0	0.0	0.2			3.7
19	2	pac			59.0							
19	3	pac	t	0	54.7	40.0	0.0	0.0	0.1	0.2	0.4	3.1
19	3	pac	0	10	48.5	37.4	0.0	0.0	0.2	0.3	0.5	2.8
19	3	pac	10	20	56.7	37.8	0.0	0.0	0.2	0.3	0.5	2.8
19	3	pac	20	30	39.6	37.8	0.0	0.0	0.2		0.7	2.9
19	3	pac			199.5							
20	1	lime	t	0	59.3	129.6	3.4	0.2	5.1	7.2	9.6	2.1
20	1	lime	0	5	49.5	150.7	3.9	0.2	6.0		10.8	3.4
20	1	lime	5	10	80.3				0.1		15.4	
20	1	lime	10	15	96.7	178.2	4.4	0.1	6.2		14.2	2.3
20	1	lime	15	20	110.7				2.4		12.6	
20	1	lime	20	25	276.5	172.7	4.2	0.1	5.3			3.5
20	1	lime	25	30	123.0	179.4	4.1	0.1	4.7			6.4
20	1	lime			796.0							
20	2	lime	t	0	108.5	45.4	0.0	0.0	2.8	3.0	3.4	4.1
20	2	lime	0	10	21.5	45.3	0.0	0.0	2.8		3.3	4.2
20	2	lime	10	20	19.1	45.4	0.0	0.0	2.8			4.1
20	2	lime	20	30	17.0	43.4	0.0	0.0	3.0			4.1

20	2	lime			166.0							
20	3	lime	t	0	38.0	36.7	0.0	0.0	1.0		1.5	3.3
20	3	lime	0	10	11.9	33.7	0.0	0.0	1.6			2.9
20	3	lime	20	30	14.3	34.2	0.0	0.0	1.5			2.9
20	3	lime			64.3							
21	1	alum	t	0	47.4	48.1	0.7	0.0	0.0	0.2	0.7	5.2
21	1	alum	0	5	52.9	58.6	0.6	0.0	0.0		0.6	5.1
21	1	alum	5	10	36.9	112.1	6.6	0.1	0.1		1.7	6.6
21	1	alum	10	15	42.4	133.5	11.0	0.1	0.2		3.1	7.1
21	1	alum	15	20	45.0	141.2	12.7	0.2	0.2		3.2	7.1
21	1	alum	20	25	35.5	138.6	12.7	0.2	0.2		2.7	6.9
21	1	alum	25	30	42.9	127.9	14.0	0.2	0.2		2.9	7.0
21	1	alum			302.9							
21	2	alum	t	0	44.1	43.6	0.0	0.0	0.0	0.1	0.1	4.4
21	2	alum	0	10	7.7	43.2	0.0	0.0	0.0			4.3
21	2	alum	10	20	8.3	42.6	0.0	0.0	0.1			4.3
21	2	alum	20	30	1.0	42.0	0.0	0.0	0.1			4.4
21	2	alum			61.2							
21	3	alum	t	0	45.7	36.6	0.0	0.0	0.1	0.1	0.3	3.8
21	3	alum	0	10	24.3	35.8	0.0	0.0	0.1		0.1	3.6
21	3	alum	10	20	29.5	36.0	0.0	0.0	0.1		0.1	3.6
21	3	alum	20	30	34.4	35.8	0.0	0.0	0.0		0.1	3.8
21	3	alum			133.8							
22	1	soil	t	0	46.3	48.7	1.5	0.0	0.2		0.2	4.5
22	1	soil	0	10	3.7	40.5	0.4	0.0	0.0			4.0
22	1	soil	10	20	14.1	39.9	0.4	0.0	0.0			4.2
22	1	soil	20	30	14.5	39.1	0.3	0.0	0.0			4.1
22	1	soil			78.6							
22	2	soil	t	0	51.1	44.7	0.0	0.0	1.0	2.8	3.4	4.2
22	2	soil	0	10	25.3	46.6	0.2	0.0	0.1		0.4	3.9
22	2	soil	10	20	34.0	50.9	0.0	0.0	0.1		0.7	3.4
22	2	soil	20	30	66.3	51.0	0.3	0.0	0.2		0.6	3.4
22	2	soil			176.7							
22	3	soil	t	0	221.5	38.1	0.0	0.0	0.1	0.1	0.1	3.1
22	3	soil	0	10	211.1	37.6	0.0	0.0	0.1	0.1	0.1	3.4
22	3	soil	10	20	208.0	37.6	0.0	0.0	0.1	0.1	0.2	3.1
22	3	soil	20	30	230.0	37.7	0.0	0.0	0.1	0.1	0.1	3.1
22	3	soil			870.5							
23	1	slurry	t	0	57.7	62.4	0.5	0.0	0.3	0.6	1.4	4.4
23	1	slurry	0	5	31.2	88.4	0.5	0.0	0.7	0.9	2.8	4.7
23	1	slurry	5	10	25.5	86.5	1.0	0.0	1.1		1.6	4.7
23	1	slurry	10	15	37.3	92.1	0.7	0.1	1.6		2.8	4.7
23	1	slurry	15	20	41.4	108.2	1.6	0.1	2.2		3.7	4.8

23	1	slurry	20	25	59.8	105.9	1.7	0.0	2.0		4.8	4.7
23	1	slurry	25	30	39.9	92.3	1.5	0.1	2.0		4.1	4.9

23	1	slurry			292.8							
23	2	slurry	t	0	100.2	55.2	1.4	0.1	8.3	9.8	10.5	4.4
23	2	slurry	0	10	73.3	56.7	1.2	0.1	8.0	9.4	10.4	4.4
23	2	slurry	10	20	68.9	59.3	0.8	0.1	7.4	8.9	9.9	4.3
23	2	slurry	20	30	52.6	52.8	0.4	0.1	4.6	5.3	5.9	3.7
23	2	slurry			295.1							
23	3	slurry	t	0	103.7	35.1	0.0	0.0	1.0	1.1	1.2	2.2
23	3	slurry	0	10	72.0	36.6	0.0	0.0	1.2	1.4	1.5	2.5
23	3	slurry	10	20	139.8	36.4	0.0	0.0	0.9	1.0	1.2	2.9
23	3	slurry	20	30	146.3	36.5	0.0	0.0	0.5		0.6	3.5
23	3	slurry			461.7							
24	1	lime	t	0	50.1	50.7	0.2	0.0	0.0		0.5	4.7
24	1	lime	0	10	15.5	116.8	0.4	0.0	0.3	0.6		3.2
24	1	lime	10	20	19.4	133.4	0.5	0.0	1.2	2.2		3.7
24	1	lime	20	30	43.5	146.3	1.3	0.0	3.3		6.3	4.3
24	1	lime			128.4							
24	3	lime	t	0	64.3	37.5	0.0	0.0	0.3	0.6	0.6	3.5
24	3	lime	0	10	145.4	35.5	0.0	0.0	1.2	2.5	2.6	2.7
24	3	lime	10	20	220.0	35.8	0.0	0.0	1.4	2.4	2.8	2.6
24	3	lime	20	30	117.0	35.8	0.0	0.0	1.4	1.6	1.7	2.6
24	3	lime			546.7							
25	1	pac	t	0	64.3	87.2	0.2	0.0	0.0		0.4	4.1
25	1	pac	0	5	44.9	127.2	0.4	0.0	0.0		0.5	3.8
25	1	pac	5	10	56.5	122.0	0.4	0.0	0.0		0.5	3.8
25	1	pac	10	15	49.5	117.2	0.2	0.0	0.0		0.4	4.0
25	1	pac	15	20	57.1	118.7	0.2	0.0	0.0	0.2	0.5	4.1
25	1	pac	20	25	64.9	99.8	0.2	0.0	0.0	0.2	0.6	4.3
25	1	pac	25	30	68.5	97.1	0.4	0.0	0.0	0.2	0.8	4.4
25	1	pac			405.7							
25	2	pac	t	0	83.2	50.1	0.0	0.0	0.2		0.7	3.4
25	2	pac	0	10	221.4	80.6	0.3	0.1	0.1		0.7	3.5
25	2	pac	10	20	286.7	55.8	0.1	0.0	0.1		1.3	3.6
25	2	pac	20	30	295.7	48.6	0.1	0.0	0.0	1.4	2.2	3.9
25	2	pac			887.0							
25	3	pac	t	0	46.0	39.1	0.0	0.0	0.0	0.3	2.2	4.0
25	3	pac	0	10	41.0	38.9	0.0	0.0	0.1		0.3	3.5
25	3	pac	10	20	32.5	39.3	0.0	0.0	0.1		0.3	3.2
25	3	pac	20	30	41.5	37.6	0.0	0.0	0.1		0.4	3.0
25	3	pac			161							

Table F.2 Plot physical characteristics

Plot	ttorun1	pH e 1	ttorun2	ttorun3	intensity1	intensity2	intensity3	slope%
1	60	7.73	50	20	14.25	9.5	8.5	5.125
2	19	6.96	70	50	13.5	9.5	8.5	3.625
3	30	8	40	25	14	10	7.8	7.25
4	35	8	114	30	14.5	10	10.5	3.75
5	40	8.2	120	40	10.5	7	9.5	3.875
6	62	7.83	57	60	14.6	10	9.25	2.375
7	60	6.97	105	40	13.01	9.5	8.9	4.125
8	72	8.8	90	35	10.98	10	10.6	4.375
9	48	8.8	62	20	13.01	9	9.25	4.5
10	35	7	111	35	10.12	8	7.98	0.375
11	74	7.4	120	50	15.01	10	8.72	0.5
12	140	7.7	75	50	12.98	9	9.5	4.875
13	130	7.8	71	30	10.5	9.5	10	1.75
14	145	7.9	115	25	13.5	9.5	9.5	3.5
15	135	7.7	54	36	12.45	11.54	9.4	0.625
16	78	7.65	121	54	11.5	9.04	8.7	0.625
17	40	8	74	34	9.5	13.12	12	3.875
18	43	7.6	90	25	9.21	8.34	10	2.875
19	45	7.5	80	50	14.25	8.35	8.76	5
20	72	7.8	75	35	10.88	8.9	10.25	4
21	47	7.66	105	42	13.23	11	10.75	3.125
22	50	7.8	95	31	8.12	11	11.22	3.75
23	120	7.8	45	25	10.5	9.75	9.23	6
24	43	7.9	32	34	10.12	8.56	8.32	4.375
25	35	7.9	25	27	12.3	8.97	9.51	4.5

Table F 3 Rainfall simulator allocation, blocking and treatments

Application sequence	plot	block	treat	Sequence of rainfall simulations	Allocation of simulators during events 1,2,3			
					sime1	sime2	sime3	treatment
3	1	1	5	6	2	1	2	lime
3	2	1	1	6	1	2	1	soil
3	3	1	3	7	2	1	2	alum
3	4	1	2	7	1	2	1	slurry
3	5	1	4	8	2	1	2	pac
2	6	2	2	3	2	1	2	slurry
2	7	2	3	4	1	2	1	alum
2	8	2	1	4	2	1	2	soil
2	9	2	4	5	2	1	1	pac
2	10	2	5	5	1	2	2	lime
5	11	3	4	11	1	2	2	pac
5	12	3	5	11	2	1	1	lime
5	13	3	2	12	1	2	2	slurry
5	14	3	3	12	2	1	1	alum
5	15	3	1	13	1	2	1	soil
1	16	4	2	1	2	1	1	slurry
1	17	4	3	1	1	2	2	alum
1	18	4	1	2	1	2	2	soil
1	19	4	4	2	2	1	1	pac
1	20	4	5	3	1	2	1	lime
4	21	5	3	8	1	2	1	alum
4	22	5	1	9	1	2	2	soil
4	23	5	5	9	2	1	1	lime
4	24	5	2	10	1	2	1	slurry
4	25	5	4	10	2	1	2	pac

Table F 4 Soil analysis results for the 25 plots potassium (K), lime requirement (LR), Mg (magnesium) and pH at times t=0 days (before slurry application) and t=30 days after the last rainfall simulation event.

plot	K0	LR0	Mg0	P0	pH0	K30	LR30	Mg30	P30	pH30
1	59.35	4	130.2	3.72	6.14	49.75	3	150.06	2.26	6.08
2	49.86	3.5	143.44	2.48	6.34	124.65	4	141.24	3.39	5.89
3	45.12	3.5	122.48	2.37	6.24	95.97	5	129.1	4.18	5.73
4	46.22	5.5	108.13	3.39	5.81	79.86	3.5	126.89	3.72	6.15
5	47.66	4.5	113.65	4.29	5.93	102.26	4	129.1	4.4	5.89
6	64.53	5.5	124.68	3.61	5.96	80.2	6.5	116.96	4.29	5.58
7	44.46	5	191.99	2.48	5.81	56.59	6	135.72	4.06	5.63
8	62.11	6	126.89	5.76	5.64	74.57	5	148.96	6.89	5.9
9	51.52	6	143.44	5.76	5.97	81.74	4.5	167.72	8.69	6.09
10	53.61	5.5	161.1	7.11	5.93	92.77	4.5	159.99	8.13	5.98
11	57.14	6.5	168.82	5.98	5.75	111.85	0.5	208.54	9.6	6.73
12	66.74	3	174.34	7.68	6.46	99.72	3.5	168.82	5.19	6.13
13	56.26	5	165.51	6.1	6	134.13	4	220.68	6.89	6.09
14	56.15	5.5	190.89	7.11	6	67.62	3.5	221.79	8.24	6.01
15	62.44	5	221.79	7.68	6.08	92.44	4.5	217.37	8.13	6.06
16	63.54	8	227.3	6.21	5.68	99.17	3	239.44	8.35	6.29
17	62.11	6	226.2	4.97	5.97	57.58	4.5	248.27	6.21	6.03
18	57.14	5	237.23	5.98	6.14	81.96	4	211.86	6.32	6.07
19	47.32	4.5	212.96	5.87	6.03	99.5	3.5	244.96	6.57	6.2
20	61.66	3.5	247.17	7.34	6.27	84.61	3.5	290.2	5.76	6.15
21	56.48	6.5	239.44	4.63	5.73	56.48	6	226.2	4.97	5.9
22	51.19	7	222.89	2.6	5.57					
23	53.28	6	239.44	3.39	5.74	96.85	4	226.2	7.23	6.17
24	54.16	5	226.2	3.61	5.79	73.14	4.5	227.3	5.53	5.91
25	89.13	4	161.1	3.72	6.01	72.92	4	212.96	4.29	6

Table F 5 Slurry characterisation for plot study

Plot no.	WEP mg kg^{-1}	Dry matter %	pH	TN mg L^{-1}	TP mg L^{-1}	TK mg L^{-1}	TAN mg L^{-1}
1	3.572	9.2	9.9	4359	1319	5421	1311
2	0.000						
3	0.002	10.3	6.6	3881	1306	5560	1319
4	3.509	9.4	7.2	2781	1188	4875	1368
5	0.022	10.1	6.8	2155	799	3317	1284
6	3.004	9.4	7.2	4671	1280	5640	1320
7	0.005	9.8	6.3	4979	1502	6052	1343
8	0.000						
9	0.003	9.5	6.8	4810	1350	5823	1307
10	1.802	9.6	6.8	5000	1478	6304	1419
11	0.004	9.7	7.7	5360	1400	5480	1320
12	3.003	9.1	7.1	5142	1417	6032	1238
13	3.169	9.2	6.7	4488	1237	4700	1225
14	0.002	9.8	6.2	4019	1061	4502	1307
15							
16	3.567	9.5	6.2	4032	1048	4222	1364
17	0.002	9.2	7.3	4035	1066	4669	1136
18	0.000						
19	0.006	9.4	6.5	3245	897	4169	1315
20	1.125	10.0	9.8	4399	1168	4227	1404
21	0.003	8.8	6.4	5118	1378	5276	690
22	0.000						
23	2.909	9.3	10.3	6147	1558	6061	690
24	2.683	8.2	7.9	3830	1447	6426	743
25	0.002	8.4	6.8	4324	1051	2883	661

Table F 6 Climate data from a weather station located in Johnstown close to study site.

date_captured	Total rainfall	Natural rainfall	Mean windspeed	Solar radiance	humidity	Atmospheric pressure
01-Jul-10	12.5	12.5	9.6	1322	88.9	999.9
02-Jul-10	0	0	9.5	2660.2	83.5	1002.9
03-Jul-10	0	0	7.4	2535	79.5	1012
04-Jul-10	1.6	1.6	10.4	1892.7	79	1009.7
05-Jul-10	0.4	0.4	5.1	2040.3	71.5	1017.7
06-Jul-10	1	1	8.5	1133.3	84.5	1016.3
07-Jul-10	2.9	2.9	10.6	2291.5	84.9	1009.1
08-Jul-10	7.6	7.6	6.4	1273.8	86.1	1010.1
09-Jul-10	7.5	7.5	9.5	937.8	96.1	1007.3
10-Jul-10	6.7	6.7	10.2	445.7	97.9	1005.4
11-Jul-10	0	0	5.6	1941	80.2	1008.2
12-Jul-10	0	0	4.7	2177.6	80.2	1006.9
13-Jul-10	10.8	10.8	5.6	327.1	95.1	999
14-Jul-10	2.7	2.7	7.6	1855	90.5	988.4
15-Jul-10	31.4	31.4	9.2	1419.3	91.8	989.7
16-Jul-10	6.9	6.9	7.1	1550.9	86.6	999
17-Jul-10	2.9	2.9	8.4	1969.7	81.7	1012.1
18-Jul-10	18.7	18.7	12	625.8	98.2	1012.8
19-Jul-10	19.5	19.5	8.1	695.1	97.8	1009.4
20-Jul-10	0	0	5.5	1788.8	86.7	1002.6
21-Jul-10	0.8	0.8	3.7	1750.7	86.7	998.2
22-Jul-10	7.7	7.7	5.3	1171.7	88.6	1007.1
23-Jul-10	0	0	5	1924.2	81.9	1015.6
24-Jul-10	1.9	1.9	6.6	678.5	98.1	1014.2
25-Jul-10	0	0	4.3	1248.7	83.7	1013.4
26-Jul-10	0	0	5.9	2288	84	1013.2
27-Jul-10	0	0	4.8	1567.8	78.1	1012.2
28-Jul-10	0	0	4.4	1158	78	1013.3
29-Jul-10	0	0	4.9	1293.8	81.2	1012.8
30-Jul-10	0.5	0.5	7.1	792.5	92.6	1006.7
31-Jul-10	0.9	0.9	6.2	1549.2	83.9	1006.1
01-Aug-10	0	0	3.8	998.1	83.5	1008.7
02-Aug-10	0	0	4.3	1009.5	84.1	1013.4
03-Aug-10	0.8	0.8	4.6	1669.1	80.6	1009.4
04-Aug-10	0.1	0.1	6.6	1919.7	75.5	1004.8
05-Aug-10	0.3	0.3	5.3	1190.9	80.2	1007.9
06-Aug-10	2.3	2.3	7.4	885.2	94.9	1003.7
07-Aug-10	0	0	5.1	1337.2	80.6	1010.5
08-Aug-10	0	0	5.9	2099.7	73.9	1014.7
09-Aug-10	0.9	0.9	7.2	2113.5	83.3	1005.9
10-Aug-10	0	0	5	2144.1	68.2	1003.8
11-Aug-10	0	0	4.5	1490	74.3	1009.6
12-Aug-10	0	0	5.5	1051.8	72.6	1014.9
13-Aug-10	0	0	7.6	2150.4	67	1017.1
14-Aug-10	0	0	6.7	1910.2	75.1	1015.9
15-Aug-10	0	0	5.1	1955	81.3	1018.3
16-Aug-10	1.8	1.8	6.2	1071	80.2	1013.2
17-Aug-10	0.2	0.2	5.7	1647	74.3	1005.8

18-Aug-10	0.1	0.1	6.4	1717.4	80.2	1001.6
19-Aug-10	11	11	7.1	546	94.9	999.6
20-Aug-10	2.5	2.5	10.8	1459.5	94	1001.8
21-Aug-10	0.1	0.1	6.3	1657.3	88.1	1009.2
22-Aug-10	1.7	1.7	5.6	1988.1	87.4	1005.6
23-Aug-10	2.8	2.8	5.8	1855.6	78.4	995.9
24-Aug-10	0	0	7.6	1775	72.7	1003.1
25-Aug-10	5.1	5.1	6.7	920	86.9	1004.4
26-Aug-10	0	0	7	867.7	83	1001.7
27-Aug-10	0	0	5.2	1552.6	70.1	1009.4
28-Aug-10	0	0	5.4	1642.1	71.8	1017
29-Aug-10	0	0	6.2	1306.9	68.4	1015.8
30-Aug-10	0	0	4	1886.5	73.6	1020.9
31-Aug-10	0	0	3.8	1625.8	81.5	1018.3
01-Sep-10	0.1	0.1	4.4	1643.8	85.6	1014.4
02-Sep-10	0.3	0.3	4.6	1667.4	82.4	1013.9
03-Sep-10 plots isolated	**0**	**0**	**4.6**	**1467.5**	**89.2**	**1013.2**
04-Sep-10	1.8	1.8	6	214.1	98.9	1010.8
05-Sep-10	11.5	11.5	8.6	383.8	99.7	1005.5
06-Sep-10	60.5	60.5	8.1	154.7	99.8	993.2
07-Sep-10	1.3	1.3	5	1365.9	91.8	990.8
08-Sep-10	6.5	6.5	4.4	1161.9	92.7	996.3
09-Sep-10	5.5	5.5	7.2	1498.7	91.4	1008.2
10-Sep-10	10.4	10.4	10	481.2	99.6	1005.1
11-Sep-10	4.3	4.3	5.8	1438.7	83.3	1007
12-Sep-10	0.7	0.7	4.8	1168.8	84.9	1019.1
13-Sep-10	0.3	0.3	11.8	609.7	98.3	1015.3
14-Sep-10	1.8	1.8	9	1072.8	84	1009.3
15-Sep-10	0	0	7.2	1347.8	77.3	1007.9
16-Sep-10	0	0	3.8	702.2	80.3	1009.6
17-Sep-10 RS 1	**19.42**	**0**	**5**	**1238.6**	**73.7**	**1014.3**
18-Sep-10	0	0	7.2	874.8	84.9	1012.9
19-Sep-10	0	0	10.3	394.7	96	1004.9
20-Sep-10	0	0	6.9	1108	96.5	1005.9
21-Sep-10	0.1	0.1	7.4	929.7	96.2	1009.3
22-Sep-10	3	3	8.9	412.1	99.9	1004.3
23-Sep-10	0.7	0.7	5.8	980.6	89.9	999.3
24-Sep-10	0.1	0.1	6.7	706.9	77.3	1008.2
25-Sep-10	0	0	5.7	1195.6	71.2	1015.2
26-Sep-10 RS 2	**17.5**	**0**	**3.1**	**929.4**	**71**	**1012.5**
27-Sep-10	0	0	2.5	1224.4	80.6	1009.3
28-Sep-10	8.2	8.2	5.4	425.7	97.5	1006.8
29-Sep-10	0.1	0.1	4.4	1149.9	88.9	1007.1
30-Sep-10	2	2	6.5	841.2	95	1002.7
01-Oct-10	7.7	7.7	7.9	1112	83.1	989.5
02-Oct-10	8	8	7.3	581.8	87	991.2
03-Oct-10	5.2	5.2	3.8	1040.1	90.8	987.2
04-Oct-10	3.6	3.6	8.2	829.6	91.5	989.3
05-Oct-10	4.6	4.6	8.7	994.5	81.5	988.7

06-Oct-10	1.1	1.1	7.3	1070.3	89.1	995.9
07-Oct-10	1	1	9.5	1008.1	88.9	1005.2
08-Oct-10	0	0	8.7	732.5	95.5	1003.6
09-Oct-10	0	0	8.9	501.5	96.1	1006.1
10-Oct-10	0	0	7.5	337.2	93.9	1007.5
11-Oct-10	0.3	0.3	7	934.9	87.1	1013.7
12-Oct-10	0.4	0.4	6.1	831.9	94.2	1015.8
13-Oct-10	0.3	0.3	4.3	486.2	92.6	1016.6
14-Oct-10 RS 3	**10.45**	**0**	**5.5**	**268.8**	**79.7**	**1017.2**
15-Oct-10	0	0	6.4	743	78	1016.4
16-Oct-10	0	0	5.9	727.5	81.9	1018.2
17-Oct-10	0	0	4.4	840.4	81.6	1019.6
18-Oct-10	0	0	5.7	491.8	85.7	1014.8
19-Oct-10	0.5	0.5	5.5	620.5	85.1	1010.7
21-Oct-10	0	0	4.7	813.5	76.6	1016.3
22-Oct-10	7.3	7.3	7.8	362.9	90.1	1006.8
24-Oct-10	0	0	6	861	76.7	1013.6
25-Oct-10	1.1	1.1	7.7	710.3	75.8	1019.6
26-Oct-10	10.8	10.8	13	213.9	98.2	1008.2
28-Oct-10	3.5	3.5	11	199.8	95.2	1000.7
29-Oct-10	8.8	8.8	11.7	163.3	94.7	983.4
30-Oct-10	3	3	5	484.1	91.9	985.5
31-Oct-10	17.8	17.8	7.7	220.6	93.6	995.1
01-Nov-10	3.7	3.7	7.2	143.5	95.7	1005.2
02-Nov-10	2.9	2.9	11.8	134.5	91.3	999.4
03-Nov-10	4.4	4.4	7.6	202.7	95	1003.3
04-Nov-10	0.1	0.1	14.5	113.6	97.6	1007.4
05-Nov-10	2.2	2.2	3.5	177.5	91.6	1012.7
06-Nov-10	1.7	1.7	5	530.6	89.9	1011.2
07-Nov-10	16.3	16.3	10.2	468.5	85.6	998.6
08-Nov-10	5.2	5.2	6	418.8	90.6	960.3
09-Nov-10	3.3	3.3	10.3	250.1	82.8	977.4
10-Nov-10	1.2	1.2	6.8	610.5	77.2	993.9
11-Nov-10	9.7	9.7	14	513.1	81	977.4
12-Nov-10	0.2	0.2	8	270.3	84.1	985.5
13-Nov-10	2.9	2.9	5	340.3	89.9	984.5
14-Nov-10	0.1	0.1	2.9	550.1	88.2	990.2
15-Nov-10	2.4	2.4	2.7	431.5	93	1006
16-Nov-10	12.9	12.9	9.4	282.1	86.7	1006.2
17-Nov-10	20.2	20.2	10.4	425.8	87.5	988.2
18-Nov-10	0.6	0.6	6.9	444.5	87.7	992.5
19-Nov-10	6.8	6.8	3.8	235.4	94.9	1001.6
20-Nov-10	0.2	0.2	7.3	83.9	89.6	1006.8
21-Nov-10	3	3	6.7	190.7	90.4	1009.1
22-Nov-10	1.7	1.7	6.5	221.9	91.8	1007.3
23-Nov-10	0.5	0.5	5.9	418.8	89.2	1009.6
24-Nov-10	0.4	0.4	6.1	340.1	90.4	1007.6
25-Nov-10	0.4	0.4	8.5	440.7	83.6	1008.9
26-Nov-10	0	0	8.1	386.3	84.9	1003.5
27-Nov-10	9.5	9.5	7.9	111.3	90.4	1001.4

28-Nov-10	2.7	2.7	6	138.2	94.9	1000.5
29-Nov-10	4.4	4.4	6.1	315.1	79.1	1006.2
09-Dec-10	0	0	4.6	367	86.4	1027.6
10-Dec-10	0	0	3.4	270.6	92.4	1028.3
11-Dec-10	0	0	3.8	150.5	94.7	1022.5
12-Dec-10	0	0	5.8	322	86	1018.6
13-Dec-10	0.1	0.1	4.1	73.1	81.2	1022
14-Dec-10	0	0	6.1	321.6	81.3	1030.4
15-Dec-10	0	0	5.8	129.5	86.2	1033.3
16-Dec-10	1	1	7.6	149.4	85.2	1010.7
17-Dec-10	0	0	6.3	358.1	87.7	995.8
18-Dec-10	0	0	4.3	331.8	86.1	986.3
19-Dec-10	0	0	6.4	214.4	74.6	988.8
20-Dec-10	0	0	6.2	261.8	81.3	994
21-Dec-10	3	3	7.6	306.4	90.8	997.3
22-Dec-10	0.6	0.6	7.1	270	87.6	1003.5
23-Dec-10	2	2	7.5	187.2	90.4	1011
24-Dec-10	0.1	0.1	8.4	352.6	82.4	1017.9
25-Dec-10	0	0	4.2	274.8	84.3	1022.4
26-Dec-10	3.6	3.6	10.7	78.7	76.2	1014.5
27-Dec-10	38.1	38.1	11.4	27	98.7	999.4
28-Dec-10	0.8	0.8	7.1	134.3	98.8	1001.7
29-Dec-10	1.8	1.8	4.2	111.7	100	1009.8
30-Dec-10	0.6	0.6	4.1	104.4	99.9	1016.7
31-Dec-10	0	0	3.3	62.6	87.5	1020.5

Appendix G Incubation study results

Notation used in appendix G

Soils

A	Cork	Sandy loam
B	Wexford	Clay loam
C	Wexford	Clay loam
D	Galway	Silty loam
E	Sligo	Peat

Treatment

1. Soil only
2. Slurry only
3. Alum
4. Lime
5. PAC
6. FeCl

Table G. 1 Incubation study analysis results:

Month	Sample	Soil type	Treatment	Perecent moisture lost	pH	WEP	Phos
1	1	A	1		5.36	2.21	5.8
1	2	A	1	1.56	5.39	2.16	5.9
1	3	A	1	1.54	5.37	2.62	6.1
1	4	A	2		5.51	2.57	12.6
1	5	A	2	1.70	5.48	5.52	10.9
1	6	A	2	2.07	5.42	3.97	12.3
1	7	A	3	2.17	5.06	2.53	5.8
1	8	A	3	3.08	5.08	2.28	6.8
1	9	A	3	1.94	5.09	2.52	5.7
1	10	A	4		5.38	2.71	6.7
1	11	A	4	1.23	5.43	0.89	6.5
1	12	A	4	1.31	6.63	1.27	11.4
1	13	A	5	0.77	5.49	6.27	8.3
1	14	A	5	0.70	5.47	4.76	7.7
1	15	A	5	0.71	5.47	2.28	7.2
1	16	A	6	0.54	6.83	7.83	14.1
1	17	A	6	0.62	5.38	1.77	6.3
1	18	A	6	0.70	6.57	5.50	12.4
3	91	A	1	1.86		3.87	2.6
3	92	A	1	5.05		4.06	2.45
3	93	A	1	1.57	5.48	5.85	2.71
3	94	A	2	1.04	5.62	22.94	5.38
3	95	A	2	1.04	6.02	16.17	5.41
3	96	A	2	2.59	6.92	20.61	6.38

3	97	A	3	0.99		4.47	
3	98	A	3	7.18	5.71	5.44	3.41
3	99	A	3	6.46	5.58	4.55	4.68
3	100	A	4	2.06	6.66	5.79	5.55
3	101	A	4	1.54	7.11	8.13	3.76
3	102	A	4	0.85	5.51	8.60	7.81
3	103	A	5	2.30	6.03	9.70	2.95
3	104	A	5	1.46	5.32	9.25	5.61
3	105	A	5	1.09	5.7	7.61	8.96
3	106	A	6	2.60	5.69	2.24	8.73
3	107	A	6	0.54	7.49	3.81	13.12
3	108	A	6	1.17	5.54	0.67	8.5
6	181	A	1	5.33	5.22	3.81	6.55
6	182	A	1	4.41	5.21	3.17	6.09
6	183	A	1	13.28	5.17	3.30	5.97
6	184	A	2	4.14	5.1	8.63	12.17
6	185	A	2	0.39	5.14	8.61	12.64
6	186	A	2	0.24	5.1	8.09	11.7
6	187	A	3	2.41	4.71	3.89	6.32
6	188	A	3	3.91	4.67	4.33	7.14
6	189	A	3	4.91	4.71	3.92	6.79
6	190	A	4	4.65	4.95	3.84	7.02
6	191	A	4	3.05	4.97	4.38	6.67
6	192	A	4	4.89	4.96	3.98	6.67
6	193	A	5	0.82	4.97	5.86	8.43
6	194	A	5	2.33	4.99	7.01	8.43
6	195	A	5	1.56	4.99	5.87	8.9
6	196	A	6	3.08	6.4	10.19	25.87
6	197	A	6	8.46	6.92	10.89	22.3
6	198	A	6	5.67	4.84	3.37	16.32
9	271	A	1	5.59	5.4	2.59	6.09
9	272	A	1	5.63	5.28	2.61	6.32
9	273	A	1	3.49	5.32	4.58	6.32
9	274	A	2	3.07	5.25	4.92	12.31
9	275	A	2	3.28	5.2	6.35	12.07
9	276	A	2	6.40	5.15	6.88	12.31
9	277	A	3	3.34	4.82	3.25	8.36
9	278	A	3	4.58	4.7	3.54	8.36
9	279	A	3	2.26	4.72	3.21	8.12
9	280	A	4	5.61	4.94	3.49	7.28
9	281	A	4	-0.24	4.94	4.25	7.64
9	282	A	4	1.23	5.01	4.27	6.8
9	283	A	5	3.50	4.98	4.81	8.72

9	284	A	5	9.49	5.01	5.56	10.15
9	285	A	5	4.71	5.01	5.23	8.84
9	286	A	6	2.72	7.05	9.89	24.16
9	287	A	6	8.88	6.77	10.41	29.06
9	288	A	6	3.50	6.9	10.55	27.27
1	19	B	1	2.02	5.05	5.03	6.4
1	20	B	1	2.45	5.03	3.86	6.2
1	21	B	1	1.56	5.04	5.18	6.2
1	22	B	2	1.99	5.18	7.43	9
1	23	B	2	1.93	5.22	7.72	10.3
1	24	B	2	1.71	5.17	12.18	12
1	25	B	3	2.35	5.05	2.62	6.7
1	26	B	3	2.33	5.04	0.25	7.1
1	27	B	3	2.36	5.02	0.12	6.7
1	28	B	4	0.78	5.41	0.63	7
1	29	B	4	0.79	5.43	0.13	7.1
1	30	B	4	0.78	5.44	0.75	7.2
1	31	B	5	0.40	5.59	4.41	7.7
1	32	B	5	0.32	5.64	2.85	7.7
1	33	B	5		5.68	1.25	7.5
1	34	B	6	1.09	6.34	6.23	14.4
1	35	B	6	0.93	6.34	4.77	11.8
1	36	B	6	0.87	6.06	2.50	10.1
3	109	B	1	2.32	6.36	4.29	7.11
3	110	B	1	0.76	6.29	6.07	7.34
3	111	B	1	4.82	5.19	7.04	6.65
3	112	B	2	1.69	5.13	16.48	12.31
3	113	B	2	0.20	6.79	12.97	17.63
3	114	B	2	1.68		11.79	
3	115	B	3	1.16		8.17	
3	116	B	3	2.66	5.47	10.59	8.73
3	117	B	3	2.63	6.41	6.55	7.12
3	118	B	4	2.38	6.86	11.16	8.88
3	119	B	4	0.63	5.39	12.37	7.11
3	120	B	4	0.94	5.18	7.28	8.76
3	121	B	5	2.28	5.74	10.40	7.34
3	122	B	5	5.10	5.54	10.84	8.5
3	123	B	5	5.63	5.09	8.45	8.04
3	124	B	6	1.97	5.32	12.52	5.96
3	125	B	6	2.58	5.71	16.79	12.3
3	126	B	6	0.63	5.55	16.43	8.5
6	199	B	1	4.45	5.4	3.43	4.9
6	200	B	1	6.08	5.3	9.19	4.73

6	201	B	1				
6	202	B	2	6.20	4.72	8.73	11.12
6	203	B	2	3.17	4.84	8.60	11.12
6	204	B	2	3.65			
6	205	B	3	6.02	4.51	5.01	7.84
6	206	B	3	5.43	4.54	4.40	7.96
6	207	B	3	4.21	4.57	5.06	7.14
6	208	B	4	6.30	4.8	5.11	7.84
6	209	B	4	2.14	4.81	4.72	7.96
6	210	B	4	5.85	4.78		7.72
6	211	B	5	7.03	4.83	10.91	8.54
6	212	B	5	6.43	4.83	11.16	8.08
6	213	B	5				
6	214	B	6	2.52	6.25		20.48
6	215	B	6	7.83	6.24		26.92
6	216	B	6		6.25	1.31	22.11
9	289	B	1	3.57	5.03	2.77	6.09
9	290	B	1	2.95	4.96	2.96	5.97
9	291	B	1	1.39	4.91	3.34	5.97
9	292	B	2	3.09	4.82	9.36	12.31
9	293	B	2	3.04	4.8	7.47	11.71
9	294	B	2	2.71	4.84	7.00	11.59
9	295	B	3	3.16	4.58	4.09	8.96
9	296	B	3	3.82	4.51	3.78	8.72
9	297	B	3	2.99	4.47	2.44	9.32
9	298	B	4	2.01	4.77	4.17	8
9	299	B	4	3.76	4.79	4.22	8.84
9	300	B	4	1.57	4.76	6.18	8.6
9	301	B	5	3.94	4.81	5.53	8.96
9	302	B	5	3.40	4.78	6.22	9.44
9	303	B	5			5.63	
9	304	B	6	4.72	6.34	13.72	20.45
9	305	B	6	3.74	6.8	13.37	28.46
9	306	B	6	2.99	6.61	13.25	31.34
1	37	C	1	1.89	6.3	0.12	2.4
1	38	C	1	1.96	6.25	0.13	2.2
1	39	C	1	2.37	6.28	0.12	2.1
1	40	C	2	3.47	6.18	7.90	5.5
1	41	C	2	2.46	6.25	8.12	7.7
1	42	C	2	2.20	6.21	5.91	6.6
1	43	C	3	4.84	5.58	0.19	3.2
1	44	C	3	5.31	5.57	0.12	2.4
1	45	C	3	4.88	5.59	0.12	2.6

1	46	C	4	0.82	6.08	0.12	2.7
1	47	C	4	0.82	6.08	0.12	2.6
1	48	C	4	1.21	6.08	0.12	2.2
1	49	C	5	0.81	6.28	0.12	4.7
1	50	C	5	0.81	6.34	0.13	3
1	51	C	5	1.23	6.36	0.12	2.8
1	52	C	6	1.64	7.34	3.92	13.1
1	53	C	6	4.72	7.26	0.12	5.7
1	54	C	6	0.15	7.35	0.12	7.1
3	127	C	1	2.18	5.55	0.63	2.34
3	128	C	1	1.51	6.36	0.51	2.37
3	129	C	1	2.43	6.28	0.68	2.49
3	130	C	2	2.29	5.51	6.63	6.88
3	131	C	2	0.46	5.63	4.06	5.38
3	132	C	2	1.73	5.94	5.52	6.18
3	133	C	3	1.27	5.27	3.72	10.7
3	134	C	3	1.21		2.52	
3	135	C	3	1.36	6.01	3.08	3.76
3	136	C	4	1.47		0.47	
3	137	C	4	1.46	7.54	0.86	4.97
3	138	C	4	0.82	5.96	0.50	2.83
3	139	C	5	1.70	5.31	3.70	5.96
3	140	C	5	1.94	5.66	3.60	4.1
3	141	C	5	1.37	6.34	0.40	7
3	142	C	6	1.34	6.74	9.72	15.9
3	143	C	6	1.48	5.43	10.94	13.24
3	144	C	6	2.25			
6	217	C	1	5.85	5.22	5.39	2.11
6	218	C	1	9.02	5.17	6.00	2.22
6	219	C	1	9.76	6.07	5.01	3.02
6	220	C	2	5.61	6.08	10.75	6.55
6	221	C	2	3.23	6.08	7.12	6.32
6	222	C	2	4.07	5.47	8.62	7.39
6	223	C	3	11.07	5.47	1.21	2.57
6	224	C	3	5.74	5.52	1.59	2.93
6	225	C	3	4.88	5.74	1.49	2.69
6	226	C	4	0.83	5.71	2.62	2.34
6	227	C	4	5.45	5.7	2.35	2.46
6	228	C	4	1.64	5.81	1.85	3.51
6	229	C	5	6.30	5.76	5.04	3.75
6	230	C	5	4.32	5.78	4.72	3.39
6	231	C	5	3.49	7.25	7.28	13.34
6	232	C	6	4.80	7.35	2.67	9.71

6	233	C	6	2.83	7.44	2.34	12.99
6	234	C	6	9.05	5.03		4.56
9	307	C	1	3.84	6.28	1.45	2.5
9	308	C	1	2.54	6.23	1.41	2.14
9	309	C	1	4.10	6.25	1.18	2.02
9	310	C	2		6.07	5.91	6.44
9	311	C	2	3.20	6.03	5.89	7.04
9	312	C	2	2.20		5.38	
9	313	C	3	-4.44	5.4	2.78	3.69
9	314	C	3	4.06	5.46	2.27	3.57
9	315	C	3	2.63	5.41	1.52	3.57
9	316	C	4	2.50	5.6	1.46	3.33
9	317	C	4	2.59	5.61	2.07	2.85
9	318	C	4	3.53	5.65	1.18	2.61
9	319	C	5	3.29	5.68	1.19	4.41
9	320	C	5	2.30	5.72	2.14	3.81
9	321	C	5	3.60		1.83	
9	322	C	6	3.48	7.28	5.60	16.02
9	323	C	6	2.04	7.43	6.04	15.54
9	324	C	6	2.18	7.28	6.21	11.83
1	55	D	1	1.98	5.33	0.24	5.2
1	56	D	1	2.07	5.3	0.14	4.5
1	57	D	1	2.19	5.34	0.28	4.5
1	58	D	2	4.08	5.6	6.07	9.6
1	59	D	2	3.16	5.56	8.16	9.4
1	60	D	2	1.48	5.51	3.85	8
1	61	D	3	4.31	5.58	0.54	5.8
1	62	D	3	4.24	5.51	0.30	5.5
1	63	D	3	3.80	5.47	0.13	5
1	64	D	4	0.75	6.12	0.23	6.1
1	65	D	4	0.80	6.07	0.14	5.6
1	66	D	4	0.95	6.11	0.14	6.2
1	67	D	5	1.24	6.34	0.32	9
1	68	D	5	1.10	6.27	0.95	7.2
1	69	D	5	1.03	6.23	0.14	7.2
1	70	D	6	1.02	6.85	4.30	16.1
1	71	D	6	1.26	6.76	0.68	11.2
1	72	D	6	0.80	6.62	3.36	10.9
3	145	D	1	2.30	5.64	5.05	5.05
3	146	D	1	1.13	5.57	4.88	4.89
3	147	D	1	2.22		4.34	
3	148	D	2	0.76		10.58	
3	149	D	2	1.59	5.72	9.91	16.81

3	150	D	2	2.82	7.22	11.25	23.01
3	151	D	3	0.51	5.52	0.60	5.61
3	152	D	3	1.43	5.5	0.56	5.61
3	153	D	3	1.09		0.56	
3	154	D	4	1.16	6.87	0.55	7.82
3	155	D	4	0.44	5.68	0.55	3.64
3	156	D	4	0.74	5.71	5.89	8.73
3	157	D	5	3.43	5.72	11.37	5.96
3	158	D	5	-0.51	6.27	7.19	6.65
3	159	D	5	2.14	5.78	6.13	7.57
3	160	D	6	1.81	5.7	0.56	10.58
3	161	D	6	2.04	5.49	0.52	7.81
3	162	D	6	0.86	6.61	0.56	16.94
6	235	D	1	8.82	5.02	2.74	4.21
6	236	D	1	3.80	5.04	2.87	4.21
6	237	D	1	8.89	5.26	3.19	5.36
6	238	D	2	20.52	5.35	11.34	8.9
6	239	D	2	7.82	5.08	10.55	8.19
6	240	D	2	43.82	4.69	9.50	5.38
6	241	D	3	4.88	4.77	3.95	5.03
6	242	D	3	5.15	4.86	3.53	4.92
6	243	D	3	2.64	5.23	2.99	5.38
6	244	D	4	2.87	5.27	8.06	
6	245	D	4	8.47	5.03	4.98	
6	246	D	4	1.97	5.2	4.79	6.09
6	247	D	5	5.71	5.15	8.23	5.97
6	248	D	5	4.70	5.31	6.85	6.91
6	249	D	5	22.84	6.14		15.92
6	250	D	6	3.37	6.26	6.44	12.76
6	251	D	6	3.13	6.56	8.39	14.51
6	252	D	6	3.93	5.18		12.74
9	325	D	1	2.33	5.03	2.41	5.25
9	326	D	1	3.36	4.95	2.16	5.25
9	327	D	1	3.90	4.93	2.45	5.37
9	328	D	2	3.07	5.06	6.85	7.52
9	329	D	2	1.98	5.09	6.08	8.48
9	330	D	2	3.04	4.91	5.75	8.24
9	331	D	3	3.32	5.01	1.70	4.29
9	332	D	3	5.33	4.74	2.71	5.37
9	333	D	3	0.64	4.78	4.12	6.21
9	334	D	4	1.92	5.08	3.38	5.61
9	335	D	4	2.46	5.01	3.10	4.65
9	336	D	4	46.89	4.95	3.59	5.61

9	337	D	5	3.08	5.01	3.72	5.85
9	338	D	5	4.03	5.09	3.09	6.09
9	339	D	5	4.26	5.24	2.41	6.56
9	340	D	6	3.45	6.39	6.42	16.38
9	341	D	6	3.69	6.51	5.97	14.34
9	342	D	6	3.65	6.43	5.33	16.98
1	73	E	1	0.59	5.65	52.45	35.2
1	74	E	1	0.49	6.05	51.37	30.3
1	75	E	1	0.63	5.62	37.17	38.5
1	76	E	2	0.75	5.81	70.88	42.4
1	77	E	2	0.52	5.68	53.76	43.7
1	78	E	2	0.11	5.71	66.83	45.3
1	79	E	3	0.26	5.57	63.82	37.1
1	80	E	3	0.32	5.62	39.95	37.8
1	81	E	3	0.05	5.61	48.86	39.4
1	82	E	4	0.54	5.74	63.13	44.4
1	83	E	4	0.74	5.72	58.83	45
1	84	E	4	0.54	5.71	48.81	43.1
1	85	E	5	0.69	5.99	44.45	52.4
1	86	E	5	0.59	5.95	46.16	49.1
1	87	E	5	1.09	5.9	44.03	45.3
1	88	E	6		5.4		45
1	89	E	6		5.4		54
1	90	E	6				
3	163	E	1	1.32	5.21	58.60	39.13
3	164	E	1	1.29	5.48	71.43	37.46
3	165	E	1	0.10		55.47	
3	166	E	2	0.79	5.41	106.98	34.34
3	167	E	2	1.36	5.252	96.67	36.19
3	168	E	2	0.86		108.57	
3	169	E	3	0.92	5.21	95.78	49.13
3	170	E	3	0.95	5.18	74.59	34.37
3	171	E	3	1.21	5.51	106.13	37
3	172	E	4	0.50	5.52	84.53	38.5
3	173	E	4	1.41	5.26	78.82	37.17
3	174	E	4	1.58		60.24	
3	175	E	5	1.02	5.62	53.56	46.66
3	176	E	5	1.18		72.94	
3	177	E	5	1.26	5.22	80.56	44.02
3	178	E	6	6.91	5.67	72.58	34.463
3	179	E	6	4.86	5.66	91.15	44.378
3	180	E	6	3.78		67.53	
6	253	E	1	0.53	5.2	58.42	33.36

6	254	E	1	6.12	5.23	66.64	29.49
6	255	E	1	2.58	5.16	64.46	36.28
6	256	E	2	2.20	5.21	97.99	35.35
6	257	E	2	1.14	5.1	80.22	39.33
6	258	E	2	6.24	5.05	87.67	36.4
6	259	E	3	5.08	5.12	84.57	28.79
6	260	E	3	7.72	5.04	67.75	31.72
6	261	E	3	3.07	5.12	83.54	29.38
6	262	E	4	6.14	5.13	120.30	27.39
6	263	E	4	8.03	5.14	96.88	28.21
6	264	E	4	2.39	5.57	84.25	29.96
6	265	E	5	7.02	5.56	66.21	33.01
6	266	E	5	7.50	5.53	63.82	30.78
6	267	E	5	7.94	5.26	63.00	32
6	268	E	6	7.25	5.21	69.33	35
6	269	E	6	5.19	5.23	72.39	35
6	270	E	6	7.10	5.23	66.12	36
9	343	E	1	2.86	5.38	44.65	25.59
9	344	E	1	0.14	5.31	48.03	25.83
9	345	E	1	5.48	5.14	51.37	35.05
9	346	E	2	2.68	5.13	64.75	42.35
9	347	E	2	3.98	5.15	65.02	37.92
9	348	E	2	1.56	5.14	64.98	40.07
9	349	E	3	3.13	5.04	61.70	36.6
9	350	E	3	0.68	5.08	51.03	36.6
9	351	E	3	3.21	5.17	46.31	34.57
9	352	E	4	2.62	5.06	63.81	35.65
9	353	E	4	2.12	5.11	67.83	41.87
9	354	E	4	4.23	5.15	61.23	41.39
9	355	E	5	2.12	5.91	43.36	33.37
9	356	E	5	1.60	5.59	53.20	39.24
9	357	E	5	3.14	5.62	68.55	47.97
9	358	E	6	1.00	5.13	71.14	45.435
9	359	E	6	2.00	5.21	52.24	43.433
9	360	E	6	3.00	5.14	54.22	38.352