Environmental RTDI Programme 2000–2006

Eutrophication from Agriculture Sources: Pathways for Nutrient Loss with Emphasis on Phosphorus

(2000-LS-2.1-M2)

Synthesis Report

(Main reports available for download on http://www.epa.ie/downloads/pubs/research/water/)

Prepared for the Environmental Protection Agency

by

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WATER QUALITY

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

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

This report is a synthesis report for the project LS-2.1: Pathways of Nutrient Loss to Water with Emphasis on Phosphorus Losses, which aimed at quantifying and ranking the magnitude of phosphorus loss from soil, grazed pastures, and the applications of slurry and fertiliser so as to identify effective mitigation strategies.

This project was one of the three main sub-projects from the project LS-2: Eutrophication from Agricultural Sources. The objective of this large-scale integrated research project, commissioned in 2000, was to supply scientific data to underpin appropriate actions and measures that might be used in the implementation of a national policy for reducing nutrient losses to waters from agricultural sources. The research, including desk, laboratory, field plot, farm and catchment studies, was conducted by teams in Teagasc, the National University of Ireland at Dublin, Cork and Galway; Trinity College Dublin; the University of Limerick and the University of Ulster, Coleraine.

It also included the following two sub-projects (see Figure 1):

- LS-2.2: Models and Risk Assessment Schemes for Predicting Phosphorus Loss to Water, which aimed at developing three modelling approaches that explored the sources of phosphorus and the hydrology that transports it from land to water.
- LS-2.3: Effects of Agricultural Practices on Nitrate Leaching, which aimed at measuring nitrate leaching from an intensively managed dairy farm on a soil type typical of a nitrate-vulnerable zone.

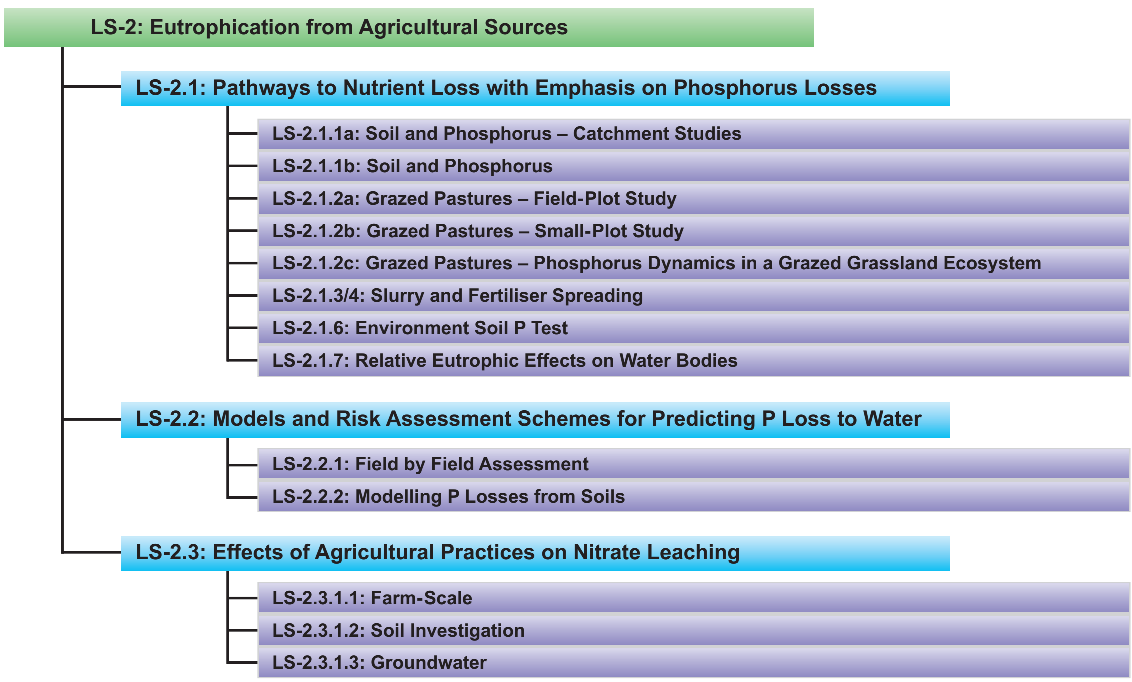

Figure 1: Overview of LS-2 projects

Individual reports from each sub-project are available for download on the EPA website:
http://www.epa.ie/downloads/pubs/research/water/

Executive Summary

The main objective of this project was to study phosphorus (P) loss from agricultural land under a range of conditions in Ireland, to quantify the main factors influencing losses and to make recommendations on ways to reduce these losses. This report is a synthesis of the main conclusions and recommendations from the results of the studies. The final reports from the nine individual sub-projects in this project are available from the EPA (www.epa.ie).

Historically, Irish soils were low in P and much of the P that is presently in the topsoils on intensive farms was added directly in chemical fertiliser and indirectly in purchased feedstuffs, during the past forty years. This reservoir of P has a considerable influence on P losses from the land. Up to the 1960s, Irish soils had a low average soil-test P level and eutrophication of surface waters due to P loss from agricultural fields was not a matter for concern. Since then there has been a large input of P (about 3 million tonnes) in fertiliser and purchased feed to Irish agricultural land. The surpluses of inputs over outputs have been equivalent to doubling total P in agricultural topsoils, on average. However, the annual use of chemical fertiliser P in Ireland has decreased from about 62,000 tonnes P to about 42,000 tonnes over the last decade due to research advice and consequent changes in farming practice.

Diffuse P loss from agriculture occurs when P is mobilised from the land and transported to water bodies. Fields and farmyards are the main source of P from agriculture, and water from rainfall transports it to water bodies. Fertilising grassland with chemical fertilisers and organic manures can increase P losses by placing high concentrations of potentially mobile P at or near the soil surface, where it can easily be mobilised by water.

The conclusion of experimental investigations at the field-plot scale is that the build-up of soil P is the major factor determining the quantity of P lost from grassland fields to water. Thus, in these field-plot experiments where losses from grazing and cut grass were compared, loss rates were closely related to soil P levels, with relatively small and inconsistent effects associated with the grazing animals. The highest loads and concentrations of P from grassland occurred during autumn via overland flow. Summer losses of P were small as there was little or no overland flow in the summer during the experiment (2001–2003).

Exports of P from nested sub-catchments in three catchments were studied. Phosphorus losses to water from the Dripsey (Co. Cork) and Oona (Co. Tyrone) catchments were consistently high (greater than 2.0 kg/ha/yr total P in 2002) irrespective of position in the catchment, indicating that once P was lost from land, via overland flow or drainage, there was little net attenuation within streams. However, losses from the calcareous Clarianna (Co. Tipperary) catchment were only 10% of those in the Dripsey and Oona catchments and the lower loss rates were not a result of low soil-test P (STP) in the Clarianna catchment. The chemical and hydrological characteristics of soils in each catchment therefore play a major role in determining vulnerability to P losses. In particular, the free-draining soils in the Clarianna catchment ensure that surface run-off rarely occurs and the inherent capacity of the soil to absorb P prevents significant losses of P to the river. Laboratory studies indicated that the chemical characteristics of soils can influence land as a source of mobile P. For example, soils that have high amounts of aluminium will hold P more strongly and mineral soils with high organic matter will bind P more loosely.

Dung from grazing animals and soil microbial biomass play an important role in P cycling in Irish grassland soils. The STP concentrations in soil under dung-pats were shown to increase three- to four-fold compared to areas with no dung-pats. Uneven redistribution of nutrients within grazed grassland, due to livestock (dung-pats, feeding and drinking areas, near gates), may create areas of greater risk of P loss to water.

Calculations based on a US Department of Agriculture method showed that from 18 to 27 weeks' storage for slurry was required for different parts of Ireland, with significantly less safe spreading days in the north and west compared with the south and east of the country.

It is concluded that a reduction in P loss to water will be achieved when P inputs are approximately balanced with outputs for fields with optimum STP for grassland production and when soils with higher P levels adjust to suitable levels by non-application of P fertiliser or excess P inputs in animal feed. This reduction may take several years, or even decades for some soils with high STP and high P buffering capacity. It is necessary to identify the soils that are most at risk of P loss to water. Most effort could then be directed at reducing P loss from these soils in catchments sensitive to eutrophication due to P loss from agriculture. Observations from a limited number of farmyards indicate that nutrient losses may be significant and these need to be controlled as a priority. Sustainable agriculture and water quality is possible only if farmers, their advisers and other stakeholders know and adopt best management-practices.

Some recommendations based on the studies are made to help reduce P loss from grassland, and proposals for future research are also included. It is recommended that the amount of available P in the soil as determined by the standard test should be maintained at the lowest level compatible with good agronomic production, to minimise loss to the environment and its threat to water quality. For grassland this will normally mean a STP level in Index 2 (3.1–5.0 mg/l P in soil) or Index 3 (5.1–8 mg/l P), and fertiliser P applications to soils in Index 4 (greater than 8 mg/l P) should be avoided. It is further recommended that the Teagasc soil P test (Morgan's P) and the soil sampling depth of 100 mm should continue to be used, as this approach provides a good indication of the relative potential for loss of P in overland flow.

A new initiative, including: (a) an awareness campaign for farmers on how to reduce P loss to water and (b) a national field soil-testing programme is recommended. Advice on P nutrient management plans (NMP) and P balances should be at farm scale and take account of slurry management and of risk in individual fields.

1 Introduction

The integrated research project Pathways for Nutrient Loss to Water with Emphasis on Phosphorus Losses (LS-2.1) was a sub-programme of the large-scale project Eutrophication from Agriculture Sources (2000-LS-2–M2) under the Environmental Research Technological Development and Innovation Programme 2000–2006.

Results of an earlier EPA study (Tunney et al, 2000) found that P loss from grassland can be higher than required to maintain good water quality. This project built on that earlier study.

The main objectives of this project were to study P loss from agricultural land under a range of conditions in Ireland, to quantify the main factors influencing losses and to make recommendations on possible options to reduce these losses. This project studied grassland only and was based on the research studies on the selected catchments and soils listed below. The application of the results to other situations (e.g. soil type, topography, climatic conditions and management regimes) requires some caution. However, the principles governing P transfer from agricultural land to water will be the same.

There were six individual sub-project (SP) contracts as follows.

- SP1: Soil and Phosphorus: Catchment Studies (LS-2.1.1a)
- SP2: Soil and Phosphorus (LS-2.1.1b)
  - Soil and phosphorus
  - Phosphorus concentration and flow
- SP3: The Impact of the Grazing Animal on Phosphorus, Nitrogen, Potassium and Suspended Solids Loss from Grazed Pastures (LS-2.1.2)
  - Field plot study (LS-2.1.2a)
  - Small plot study (LS-2.1.2b)
  - Phosphorus dynamics in grazed grassland (LS-2.1.2c)
- SP4: Slurry Spreading (LS-2.1.3) and Fertiliser Spreading (LS-2.1.4)
- SP5: Environmental Soil Phosphorus Test (LS-2.1.6)
- SP6: Relative Eutrophic Effects on Water Bodies (LS-2.1.7)

An additional study (LS-2.1.5) on farmyards did not proceed.

The project was coordinated by Teagasc, Johnstown Castle and the individual project leaders were: (SP1) G. Kiely, University College Cork; (SP2) H. Tunney, Teagasc; (SP3) H. Tunney, Teagasc; (SP4) D. Ryan, Teagasc; (SP5) K. Daly, Teagasc; (SP6) E. Jennings, Trinity College Dublin.

This report is a synthesis of the main conclusions and recommendations from the results of all the sub-projects that made up the LS-2.1 project. In addition, recommendations for future research are provided in the Appendix. Reports (Table 1) on the individual sub-projects in the LS-2.1 project are published and accessible on the EPA website (www.epa.ie) and can be consulted there for the detailed objectives, methods, results, conclusions, recommendations and references. Sub-project LS-2.1.7 was a literature and desk study, while the others also included field and laboratory experiments or measurements. Sub-project LS-2.1.7 was a six-month study, LS-2.1.3/LS-2.1.4 a two-year study, while the others were for periods of three to four years.

Table 1: 2000-LS-2.1 Projects and Reports: Eutrophication from Agricultural Sources

Reference	Title	Lead organisation	Project leader	Report and lead report author
2000-LS-2.1-M2	Pathways for Nutrient Loss with Emphasis on Phosphorus	Teagasc	H. Tunney	Synthesis report Kiely et al.
2000-LS-2.1.1a	Soil and Phosphorus (Catchment Studies)	University College Cork	G. Kiely	Final and synthesis reports Kiely et al.
2000-LS-2.1.1b	Phosphorus Chemistry of Mineral and Peat Soils in Ireland	Teagasc	H. Tunney	Final report Daly and Styles (2005) ERTDI Report 38
2000-LS-2.1.1b	Phosphorus Concentration and Flow	Teagasc	H. Tunney	Final report Doody et al. (2006) ERTDI Report 40
2000-LS-2.1.2	Grazed Pastures	Teagasc	H. Tunney	Final synthesis report Tunney et al. ERTDI Report 66
2000-LS-2.1.2a	Field Plot Study on the Impact of the Grazing Animal on P, N, K and SS Loss from Grazed Pastures	Teagasc	H. Tunney	Final report Tunney et al. ERTDI Report 68
2000-LS-2.1.2b	Small Plot Study on the Impact of Grazing Animals on Nutrient Losses to Water	Teagasc	I. Kurz	Final report Kurz et al. (2006) ERTDI Report 41
2000-LS-2.1.2.c	Phosphorus Dynamics in a Grazed Grassland Ecosystem	Trinity College Dublin	D. Bourke	Final report Bourke et al.
2000-LS-2.1.3/ 2000-LS-2.1.4	Slurry and Fertiliser Spreading	Teagasc	D. Ryan	Final and synthesis reports Ryan et al.
2000-LS-2.1.6	Environmental Soil P test	Teagasc	K. Daly	Final report Daly and Casey (2003) ERTDI Report 14
2000-LS-2.1.7	Relative Eutrophic Effects on Water Bodies	Trinity College Dublin	K. Irvine	Final report Jennings et al. (2003) ERTDI Report 13

2 Main Results and Conclusions: Agricultural Land as a P Source

The main results and conclusions from the nine reports are grouped under two headings: (1) environment (soil, water, pathways, catchment, and weather), largely outside human control, and (2) management practices, where action may be taken to reduce loss. Diffuse P loss from agriculture occurs when P is mobilised from the land and transported to water bodies. Fields and farmyards are the main source of P from agriculture, and water from precipitation transports it to water bodies. Thus, the environment and management practices affect both P source and transport pathways (from land to water body). Sources and transport mechanisms determine the amount of P delivered to a water body, while processes within streams, rivers and lakes may alter the chemical forms of the P lost from land.

In free-draining soils, losses of nutrients are generally associated with leaching down through the profile. These soils are characterised by a light texture or a well-defined structure and are easy to manage from a grassland perspective as they afford a long grazing season and are generally accessible by farm machinery for most of the year. In wet, poorly drained soils, nutrient losses are usually associated with overland flow. These soils are characterised by a heavy texture or a poor structure and are more difficult to manage because field access for animals and farm machinery must be restricted during wet periods if soil structural damage is to be avoided.

2.1 Environment (Soil, Water, Pathways, Catchment and Climate)

Exports of P from nested sub-catchments in three catchments were studied (SP1). Total P losses from the Dripsey (Co. Cork) and Oona (Co. Tyrone) were high (greater than 2.0 kg P/ha/yr in 2002) and were ten times higher than from the calcareous Clarianna (Co. Tipperary) catchment. The results demonstrate that the chemical characteristics of soils have a large influence on land as a source of mobile P. Agricultural catchments with fertilised non-calcareous soils can be at greater risk of P transfer from soil to water than other catchments. This is particularly likely when the soils have a small P sorption capacity, are high in organic matter and when the catchment has a rapid hydrological response to rainfall. Losses occur by desorption (amount of P moving from solid to liquid state per unit time) and detachment (physical erosion of particles with bound P), particularly during high-rainfall events.

One of the three catchments studied (Oona) lost more P per unit area at the larger catchment scale than at the smaller sub-catchment scale, while another (Dripsey) lost more at the smaller sub-catchment scale. Scaling up or down from one catchment level to another requires a study of the accuracy of this approach for the individual catchment. Extrapolation of P loss rate measured at a particular point in a catchment to others further upstream or downstream must be made with caution in view of the findings. Smaller catchments will tend to be more uniform and larger catchments will tend to be more variable in relation to P export, because the latter have increased ranges of land use, soils and management.

Loss of P from agricultural land occurs in two phases. Firstly there is the annual cycle of overland flow beginning in autumn (normally September/October) after low flows (low net rainfall) and little or no overland flow during the summer. These initial flows have a washout effect on P, nitrogen (N) and potassium (K), leading to the highest concentrations and loads of the nutrients occurring at this time. The concentrations decrease and stabilise over the winter months (SP1 and SP3). The second phase is centered on individual events when P is typically exported from catchments in pulses related to episodes of high flow and which can be further influenced by recent applications of manures or fertilisers to the land. A review of the literature (Jennings et al., 2001) indicated that pulses of nutrients in late autumn and early winter may have little effect on eutrophication in lakes with short retention times as the nutrients may have been flushed from the lake before strong algal growth recommences in the following spring; the particulate component of these intermittent flows may contribute to the sediment P pool (SP6). However, in lakes with a longer retention time the dissolved P load entering over the winter period can provide increased levels of P for algal growth in the following spring.

In laboratory studies, mineral soils with high soil-test P STP (Morgan's P) were shown to have relatively high rates of P desorption to water, reflecting the higher degree of P saturation in the soil (SP2). Soil P desorption is affected by soil pH in non-calcareous mineral soils, and soils that are neutral in status desorb more P (maintain higher concentrations of soluble P) than soils that are more acidic. Phosphorus binding is affected by factors such as aluminium and organic-matter contents through their contrasting influences (the former increases and the latter decreases). Phosphorus sorption data collected from calcareous soils could not explain the low P loss in the Clarianna catchment. Peat soils with high organic matter (greater than 20% and particularly with much higher organic matter contents) have low cation content and do not chemically adsorb P as mineral soils do. Thus, applied manure and fertiliser P will be more easily lost from peat soils because it is not adsorbed due to low cation (e.g. aluminium, iron, calcium and magnesium) content.

Dung from grazing animals and soil microbial biomass plays an important role in P cycling in Irish grassland soils. An annual turnover through the microbial biomass of 50 kg P/ha/yr was calculated (SP3). The (STP) concentrations in soil under dung-pats were shown to increase three- to four-fold compared to areas with no dung-pats. The grazing animal and the associated dung deposition increase the rate of P recycling in grazed compared to cut grassland. Uneven redistribution of nutrients within grazed grassland, due to livestock (dung-pats, feeding and drinking areas, near gates), may create areas of greater risk of P loss to water.

Suspended solids concentrations (November 2003 to March 2004) averaged 45 mg/l in overland flow from six field plots at Johnstown Castle; only a small number of samples were over 100 mg/l and most of these were associated with two storm events on two experimental plots (not grazed in 2003 and 2004) in spring 2004 (SP3). This was lower than the maximum levels found in river water in the Oona catchment but higher than such levels in the Dripsey (SP1).

The area of water-saturated soil increases during heavy rainfall and contracts when rain stops; saturated soil enhances the risk of overland flow. This leads to the expansion and contraction of the areas contributing to overland flow (variable source areas). In other words the area of saturated land increases over time during heavy rainfall (SP2). These areas lead to transport of potentially mobile P from soil when overland flow occurs. The interaction of overland flow, generated by rainfall, with the pool of freely desorbable P in the soil is the main reason for high P loss and the increase in P concentration that sometimes occurs with an increase in the rate of overland flow. Soil drying and wetting cycles increase the quantity and change the forms of P present as potentially mobile P. In addition, significant quantities of particulate P can be mobilised and transported by water over short distances on the soil surface of grassland during overland flow after heavy rain.

There was a highly significant correlation between the concentrations of the three P fractions (dissolved reactive P, total dissolved P and total P) measured in overland flow water (SP3). On average, total P in overland flow water samples contained over 80% total dissolved P and over 70% dissolved reactive P. There was also a significant correlation of total nitrogen with total dissolved nitrogen concentrations. Total nitrogen contained more than 70% of the total dissolved nitrogen on average. There was also a significant correlation between total P and total nitrogen concentrations, the latter being about five times higher than that of the former.

The results indicate that Morgan's P, the standard agronomic STP used in Ireland, normally with 20 cores taken to 100 mm depth, provided the best indicator of P loss for two sites at the Johnstown Castle Research Centre (SP5).

2.2 Management Practices

Historically, Irish soils were low in P. Much of the P that is presently in the topsoils on intensive farms was added in chemical fertiliser and purchased feedstuffs, mostly during the past half-century. This reservoir of P has a considerable influence on P losses from the land. Fertilising grassland with chemical fertiliser and organic manure P can increase losses by placing high concentrations of potentially mobile P at or near the soil surface, where it can easily be mobilised by water. Most P loss occurs in the autumn and winter period. In the region of 80% of P export was in the period October to February in the three catchments studied, Clarianna, Dripsey and Oona (SP1). The catchments had a mean STP of 10–12 mg/l (Index 4).

In field-plot experiments, the presence of grazing animals did lead to significant short-term increases in total P, but not in water-soluble P concentrations for some overland flow events, although the relative effect of these on average annual concentrations was not large (SP3). This effect was also evident in the quality of rainfall-simulated overland flow studied on small plots after the first grazing cycle in spring 2004. The presence of cattle led to physical changes in the topsoil and to increased concentrations of total P, particulate P, particulate N and particulate K in rainfall-simulated overland flow. However, at the field-plot scale the impact of grazing animals was small compared with the other factors such as surplus added P and high STP. A comparison of P forms in rainfall simulated overland flow revealed that although inorganic orthophosphate was the principal form of P found in samples collected from grazed and non-grazed plots, the main differences between plot treatments were found in the organic P (SP3).

Dung-pat decomposition was affected by the seasonality and amount of rainfall over a 90-day decomposition period. The principal mechanism of dung-pat incorporation into the soil was physical incorporation, relying on soil fauna and physical degradation (SP3). The STP concentrations in soil under dung-pats were shown to increase three- to four-fold over a 90-day decomposition period.

Literature describing the effect of slurry and fertiliser spreading was reviewed (SP4). This showed that higher loss was generally associated with higher nutrient application rates, especially where over 50 m^3/ha of slurry is applied. However, where application rates (slurry and fertiliser) are balanced with (do not exceed) nutrient demand, nutrient loss is likely to be small.

The likelihood of safe slurry-spreading days occurring was determined using a database of 30 years' rainfall for 151 rainfall stations (SP4). A method was developed that could identify the number of safe slurry-spreading days for each month of the year. The output showed fewer days suitable for slurry spreading in the north and west compared with the south and east of the country. This is also true for fertiliser spreading. A further analysis using this method suggested that between 8 and 24 weeks of slurry storage is required, depending on the region. However, calculations based on a US method showed that from 18 to 27 weeks of storage was required for different regions (Stettler, 2003). Further soil and rainfall data would improve the reliability of these projections.

3 Overall Conclusions

Agriculture is a significant contributor of P loss to water. Up to the 1960s, Irish soils had a low average STP level and eutrophication due to P loss from agricultural fields was not a matter for concern. Since then there has been a large input of P (about 3 million tonnes) in fertiliser and purchased feed to Irish agricultural land. The surpluses of inputs over outputs (exports in meat, milk, crops and water) have been equivalent to a doubling of total P in agricultural topsoils (0–15 cm) on average. The increase of P in Irish soils has not been uniform as some soils have received excess P, while others have received little or no P inputs. Some of the P added to soil is contributing to P loss to water. There has been an increase in animal numbers and thus of excreted P, most of which is added to the soil surface (as with chemical P fertiliser) where it is more at risk of loss in overland flow.

1. The consensus of the LS-2.1 projects is that the build-up of soil P is a major factor contributing to P loss from agricultural fields to water. The average STP increased ten-fold in the past 50 years. Part of this build-up in soil P was necessary for crop and animal production and health. However, there has been an excess build-up of P on some areas of farm land. In the region of 20% of soil samples analysed for P are now in Index 4 (STP greater than 8 mg/l for grassland and 10 mg/l for tillage land).
2. It is further concluded that a reduction in P loss to water will be achieved when P inputs are approximately balanced with outputs for fields with optimum STP for crop production, and when soils with higher P levels adjust to suitable levels by non-application of P fertiliser or excess P inputs in animal feed. These changes may take several years, or even decades for some soils with high STP and high P buffering capacity (retention). In the meantime there is an urgent need to study methods that could reduce the loss of P to water from these soils.
3. For given STP levels, not all fields are at equal risk of P loss to water. For example, free-draining, deep calcareous soils, where soil P is in Index 3 or lower (P below 8 mg/l soil on grassland) and where overland flow is rare in most years, appear to pose relatively less risk of contributing to eutrophication due to P loss, in the short-term at least. However, fields with high soil P, poor retention of P by soil (depending on soil chemistry), and with good connectivity to water courses and with frequent overland flow events, are likely to be most at risk of contributing P loss to water in a catchment.
4. It is necessary to identify the soils that are most at risk of P loss to water. Most effort could then be directed at reducing P loss from these soils in catchments sensitive to eutrophication due to P loss from agriculture.
5. The P loss from farmyards needs to be controlled as a priority.

Sustainable agriculture and water quality is possible only if farmers, their advisers and other stakeholders are informed, through education and effective targeted advisory programmes, on the impact of management practices on nutrient loss to water and the best management practices to minimise losses.

4 Recommendations on Reducing P Loss from Agricultural Land

4.1 Background

The main factor controlling the transport of P is high intensity rainfall, which cannot be regulated by human activity. Factors that increase the amount of mobile P available for transport include the occurrence of prolonged dry periods, previous land management (through its influence on the capacity of soil to retain P within the soil matrix), and current management practices, in particular timing of grazing, fertiliser use and slurry spreading. Land-use management offers the best potential for control of diffuse P export.

Identification of areas vulnerable to P loss in a catchment can aid in the control of P export. Soils vary in their capacity to retain P, with most risk of P loss associated with artificial drainage, overland flow and preferential flow (cracks or large pores that allow water to move more freely).

4.2 Management Practices

1 Soil-test P should be maintained at the lowest level compatible with agronomic production, to minimise loss to the environment and the threat to water quality. This will mean a STP level in Index 2 (3.1–5.0 mg/l P in soil) or Index 3 (5.1–8 mg/l P for grassland; where it is necessary for agronomic production and is unlikely to cause pollution due to diffuse P loss from agriculture) as provided for in the implementation of the Nitrate Directive in Ireland (Statutory Instrument 378 of 2006). Chemical fertiliser P applications to grassland soils in Index 4 (greater than 8 mg/l P) should be avoided and manure P inputs should be minimised.

2 It is recommended that the Teagasc soil P test (Morgan’s P) should continue to be used to test for soil P as it provides a good indication of the relative potential for loss of dissolved P in overland flow from soils. The current standard of taking soil-core samples to a depth of 100 mm should continue to be used.

3 Where necessary (on soils with risk of high P loss in catchments vulnerable to eutrophication from agricultural sources), fields should be assessed on an individual farm basis. Fields with a high risk of P loss to water should receive priority attention to reduce risk.

4 It is recommended that the Teagasc P advice for peat soils should be reviewed and revised. The LS-2.1 projects and a previous study (Jennings et al., 2001) indicate that there is a need for more tailored guidelines for intensively managed grassland on peat soils and on high organic-matter (over 20%) soils. Phosphorus application to these soils should be managed (minimum P inputs and correct timing) with special care to avoid P loss.

5 Adequate animal manure storage facilities should be available on all livestock farms so that the manure can be spread at the most appropriate rates and times to meet crop needs. It is recommended that a decision-support system based on soil conditions and weather forecasting be developed to aid in the timing of manure spreading.

6 A new initiative, including: (a) an awareness campaign for farmers on how to reduce P loss to water and (b) a national field soil-testing programme, is recommended. Advice on P nutrient management plans (NMP) and P balances should be at farm scale and take account of slurry management and of risk in individual fields. This could be provided under the EU Nitrate and Water Framework Directives.

7 Design of water-quality monitoring programmes should take account of catchment scale effects and consideration should be given to groundwater in management plans for sensitive catchments (e.g. Clarianna). This could be provided for under the EU Water Framework Directive. Differences in soil types should be considered in all catchment and river basin district studies when P loss to surface waters is under investigation.

Appendix Research Recommendations

A. Soil Type (Soil and Water or Source and Hydrology)

1 Research is needed on the fate of agriculture-derived P in the soils of calcareous catchments with connectivity to groundwater, to develop a P model for these soils as they account for approximately 40% of Irish farmland. The potential for groundwater P transfer to surface waters requires further research.

2 The use of measurements of total reactive P (also know as molybdate reactive P or MRP) on unfiltered samples, as used by the EPA to measure biologically available P in rivers and lakes, merits further consideration, research and debate, and comparison with P fractions measured in other countries. Further studies, in addition to work in this project (SP5), on the Irish soil P test and how it relates to tests in other countries merits further research.

3 The extent of artificial drainage systems in Ireland and the impact of these systems on P losses need to be assessed. The effects of a soil moisture deficit on P availability and mobility in Irish soils are poorly understood and require research. Phosphorus loss to water during a river dredging event was measured in the Clarianna, and losses were markedly increased during and immediately after dredging; there is an absence of information in the literature on this and it should be researched further.

B. Management

1 Develop a pilot scale (~10 farms) real-time, web-based meteorological and hydrological forecasting system (including soil moisture status) to aid farmers with selecting the best timing for spreading fertiliser and slurry. Investigate the development and use of a simple model based on antecedent rainfall, soil moisture and rain forecast as an aid in identifying suitable slurry-spreading times. In consultation with Met Eireann and EPA (hydrometric section), investigate the possibility of a real-time weather station for installation at approximately 1000 km^2 catchment scale.

2 Develop a slurry storage requirement prediction tool (e.g. the USA's) for use at farm level. This could support nutrient management planning (NMP) on many farms and give a more accurate estimate for slurry storage than is available from an assessment at regional level.

3 There is a need for research to establish if practices such as ploughing down the P enriched layer on high STP soils or other approaches can be used in the medium term to reduce the P loss in overland flow water from P enriched soils.

4 Compaction by grazing animals decreases macroporosity of the topsoil but this may be remedied by closing pastures for cutting for hay or silage production. The possibility of this approach to reduce P loss to water should be researched further, taking account of the economic implications. The observation of increased occurrence of overland flow due to the presence of grazing animals was made at small-plot scale using rainfall simulation and this should be further researched at field scale.

5 Occasional high N levels, including high ammonium and nitrate concentrations, were found in overland flow water from field plots. Some of these were related to overland flow after fertiliser spreading and should be studied further. In addition, there were indications from small-plot study (SP3) rainfall simulation that P concentration in overland flow increased after fertiliser N application in spring and further work is necessary to confirm this trend.

6 The resistance to penetration (RP) at high soil moisture (SM) is largely affected by bulk density (BD) and soil texture. Developing soil texture specific relationships between BD and RP at high SM may therefore allow BD to be estimated with the much less time-consuming measurement of RP at high SM and merits further study. Similarly, the use of one P or N fraction as an adequate estimate for other fractions merits further study.

7 The risk from out-wintering animals on sacrifice paddocks for winter feeding is a potential source of high nutrient and sediment loss to water and merits further research.

8 There is a continuum from P sources and mobilisation processes to the delivery of P to receiving waters. Most research to date has been on sources and levels of P loss and there is now a need for research and for tools to find the optimal set of mitigation measures to reduce losses. The impact of proposed mitigation options in different soils, topography and hydrologic settings needs to be tested to ensure that they are practical and effective.

9 Experience in many countries shows that recommended measures and awareness campaigns are often not effective in changing farming practices; as a result, policy interventions such as monetary incentives, levies and other measures have been adopted. Socio-economic and policy research is recommended to determine the most appropriate approaches to enhance the adoption of good agricultural practice within farming systems, and to find the best societal measures and interventions for solving the problem of P loss from agriculture to water in a cost effective and practical way.

10 The implementation of the EU Water Framework Directive has important implications for the reduction of the loss of P from agriculture to water in Ireland and should be linked to an evaluation of the best management plans to reduce such loss. In order to achieve reliable plans, research on nutrient management practices should be linked to chemical and ecological research in surface waters. When sufficient data is available, management models should be linked to ecological dose–response models. This research will require considerable resources and skills, and it is recommended that experts in Ireland should be familiar with and involved in international research in this area in order to be able to adopt the most appropriate approaches to solve the problems in Ireland.

C. Catchment Scale

1 Catchment scale studies should be developed as a means of monitoring the impact of measures to address nutrient loss such as the Nitrates Directive Action Programme (AP), Water Framework Directive and the Rural Environment Protection Scheme. These studies should include the collection of agronomic data (e.g. stocking rates, fertiliser inputs and spreading dates) for correlation with water quality. In addition, these catchment studies will perform an important technology transfer function between the stakeholders in rural water quality.

2 The Dripsey, Clarianna and Oona Water catchments should be considered as demonstration/monitoring catchments for monitoring the effectiveness of the Nitrate Directive Action Programme under the Nitrates Directive, based on their P and/or N transfer rates and the established infrastructure (including baseline data). In addition, selected catchments, including those with high inputs of fertiliser and with intensive pig and poultry production, require detailed study.

3 A review of P loss control (e.g. buffer strips, wetlands and reed beds) at both farm and catchment scale should be undertaken for Irish conditions. Potentially viable systems should be evaluated in flashy (rapid stream flow response to heavy rainfall) catchments to determine their efficacy in reducing soil erosion.

4 Research facilities using large plots (1 ha or more each) or catchment scale are recommended for nutrient loss studies, based on the literature reviewed as part of this study.

References

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