Agricultural Catchments Programme

Phase 2 Report

February 2017

Editors: Ger Shortle and Phil Jordan

Teagasc

Crops, Environment and Land Use Programme

Johnstown Castle Environment Research Centre

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FOREWORD

FOREWORD

This is the Phase 2 report of the Agricultural Catchments Programme (ACP) and covers the second four year period from January 2012 to December 2015. The Department of Agriculture, Food and the Marine (DAFM) continues to fund the programme into Phase 3 which will run until the end of 2019.

The ACP was initiated to address needs brought about by the introduction of the Nitrates Directive and Water Framework Directive in Ireland. However, Ireland's agriculture and food landscape has evolved rapidly during the life of the project following the targets of the Food Harvest 2020 report in 2010, which proposed that Ireland could grow its exports of food and beverages by one-third and increase the value of primary food production by €1.5 billion, including a 50% increase in milk production. Food Wise 2025 followed in 2015 calling for an increase in the value of agri-food exports by 85%. The abolition of milk quotas has created the opportunity to achieve the ambitious milk production targets and it is likely that they will be achieved ahead of 2020.

Increasing farm output while meeting Nitrates and Water Framework Directive water quality targets poses substantial challenges for Irish farmers but also presents an opportunity. This opportunity lies in the potential to capitalise on Ireland's sustainable farming credentials as promoted by Bord Bia's Origin Green sustainability programme. The ACP is eager and well positioned to play an important part in providing the evidence to support the drive towards environmental and economic sustainability on Irish farms.

This report seeks to clearly communicate the scientific findings from Phase 2 of the ACP and their policy implications. To this end, each peer-reviewed output from Phase 2 is presented first as bullet point summaries which condense the studies into a few key messages (and highlighted policy implications). A synopsis then expands on these points and, for readers who wish to access the detail of the study, a journal reference and web link is supplied.

The ACP is built on a partnership with farmers and integrates research with advice to deliver excellent science. The trust that has been built between the ACP team and the farmers in the six catchments is the essential element of its success and we are very grateful to them for their continued support.

We wish to thank the DAFM, the catchment farmers, colleagues in Teagasc and all who have supported the programme through Phase 2. We look forward to continued collaboration and success during Phase 3.

Ger Shortle – Programme Manager   Phil Jordan – Principal Scientist

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EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

This report describes and explains the relevance of the outcomes from Phase 2 of the Agricultural Catchments Programme (2012-2015) and follows on from the Phase 1 report (2008-2011).

The Agricultural Catchments Programme (ACP) is funded by the Department of Agriculture, Food and the Marine and is operated by Teagasc. Its core objective is to measure the effectiveness of the Good Agricultural Practice (GAP) measures implemented under the Nitrates Directive, i.e. the Nitrates Regulations, at catchment scale while also evaluating the efficacy of the nitrates derogation.

The scientific findings from the ACP help fulfil Ireland's monitoring and reporting requirements under the EU Nitrates Directive and the EU Water Framework Directive. Furthermore, the findings support key agri-environmental policies and strategies, including:

- The review of Ireland's Nitrates Regulations, including the nitrates derogation in 2017.
- The 2nd cycle of River Basin District Planning under the Water Framework Directive.
- Food Wise 2025 and scientific verification that Irish farmers are producing milk, meat and crops in an environmentally and economically sustainable manner.
- Origin Green and water quality in the context of marketing the sustainability of Irish food production on world markets.

The overarching conclusion of the ACP's work to date is that the implementation of the Nitrates Regulations by Irish farmers has improved water protection against pollution caused by nitrogen (N) and phosphorus (P) from agricultural sources. Further improving nutrient management on Irish farms by supporting farmers' nutrient management decisions, is the single change that can do most to help farmers protect and improve water quality. Better nutrient management can also deliver improved economic returns to the farmer by increasing the efficiency with which farmers use nutrients, i.e. producing more output for the same, or less, nutrient input. Win-win mitigation measures, such as this, that reduce risk to the environment while also increasing economic returns are the most likely to be voluntarily taken up by farmers.

In fact, when farmers adopt innovations which increase nutrient use efficiency, the environment benefits because more product, e.g. meat, milk, grain, is exported from the farm for a given level of inputs. There are many existing practices and technologies that can be adopted by farmers, each of which can make a contribution to improved production efficiency and reduce pressure on the environment. In addition, new techniques are constantly being developed to further improve production efficiency. Some examples of relatively recent practice innovations at varying stages of adoption are:

- The Economic Breeding Index (EBI) is a technology that most Irish dairy farmers adopted quickly in recent years and which has delivered substantial efficiency increases through accelerated gains in the genetic merit of Irish dairy herds.
- The NMP Online package which has been developed to produce more easily understood nutrient management plans for farmers including maps of their farms to clearly show where to apply nutrients.
- Improved grassland management techniques based on grass measurement and budgeting supported by software packages such as Pasture Base which facilitate higher grass production and utilisation thus improving nutrient use efficiency.
- The €uro-Star system for beef cattle that guides farmers in selecting the most efficient and profitable animals to breed from.
- The Pasture Profit Index which can guide farmers in selecting grass varieties that best suit their needs.
- Better animal health management, as promoted by Animal Health Ireland, which improves animal performance.

When all these efficiency gains are accumulated they are likely to make a substantial and lasting difference to both economic and environmental performance.

The ACP approach, which uses high-resolution economic and environmental data gathered over successive years, is well suited to measuring changes in both these areas. These research outputs can be used to support Ireland's green credentials in the context of policy frameworks such as Food Wise 2025.

The strengths of the ACP approach

In the eight years since it started, the programme has continuously developed and established itself as a unique asset in meeting Irish farming's sustainable intensification challenge. Phase 1 (2008-2011) was concerned with project design, development and scientific assertion from the first years of data collection. Phase 2 (2012-2015) was mainly concerned with validation of assertions and policy impact. Phase 3 (2016-2019) will continue the approach established in the first two phases while developing the modelling area and expanding the dissemination effort.

The approach taken in the establishment and operation of the ACP has three key strengths which have served the programme well through Phase 1 and Phase 2.

First Key Strength

A single, common experimental design is used in all six agricultural catchments.

The bio-physical element of the design is based on the concept of a continuum from the source of farm nutrient to where that nutrient, if lost, would potentially cause an ecological impact. For N or P to impact on stream ecology (or downstream water bodies) it must pass through each stage of this continuum. Each stage is monitored and analysed to build up a better understanding of how the whole system works and to try to determine what conditions lead to increased risk of these nutrients impacting on water quality. This work entails high resolution monitoring, in both time and space, of the main physical parameters such as the N and P concentrations in the surface and groundwater, stream flow, weather data, soil nutrients levels and ecological status.

Second Key Strength

Integration of a strong socio-economic element with the biophysical component in the experimental design.

This integration enables the Programme to go beyond sophisticated monitoring and allows for the development of a deeper understanding of catchment processes related to changes in the agri-environment due to policy drivers. It also allows for key pressure and state expectations to be explained beyond just 'positive, negative or no change' over time. These are important considerations for Ireland's agri-environmental reviews and the support of the bio-economy and water resources.

Third Key Strength

Partnership with over 320 farmers across the six selected agricultural study catchments.

The active participation by these farmers and the goodwill that they have shown the ACP team has been essential in ensuring the success of the programme, in particular the socio-economic research. A high level engagement with the farmers is achieved mainly via the four ACP advisers who provide an advisory service and collect farm data on nutrient management and economic performance.

Phase 2 Key Findings and Implications

By the end of Phase 2 (December 2015) the ACP had published over 50 peer-reviewed papers in international journals and well over 200 communication outputs. Phase 2 findings make up the main part of this report, showing key messages and a short synopsis of each in-depth study with a reference for further information. Insofar as the ACP approach and key strengths have found evidence for improved water protection, the programme has also identified remaining challenges and also provided considerations for potential solutions. The main body of the report is, therefore, separated into these three areas: Effects of the Measures; Understanding the Challenges; and Potential Future Solutions. Some of the most important findings with their policy relevance are summarised:

1. Declining Soil Phosphorus Trends

The proportion of fields in phosphorus (P) index 4 (in excess of crop requirement and noted in the Nitrates Regulations as having an increased risk of loss to water) has declined in four out of the five catchments reported on. However, the decline in soil P has additionally occurred across less fertile fields with the number of fields at phosphorus index 1 and 2 (very low and low agronomic status and with low risk of phosphorus loss to water in the Regulations) increasing indicating an overall decline in soil P levels rather than just a correction of high P levels. This reflects national trends in soil phosphorus decline which have led to approximately 66% of soil samples being at Index 1 or 2.

Positive nutrient management results have emerged from the intensive dairying Timoleague catchment (in West Cork). Changes adopted by farmers in how they manage their nutrients have led to a convergence towards index 3 - the optimum index for production with a reduced risk to water quality. There was a significant reduction in numbers of P index 4 fields and increasing soil P levels in index 2 and 3 fields. Analysis of the water data showed that there were subtle improvements in the quality of water in surface and shallow subsurface (mostly quickflow) flow pathways. It is likely that these improvements have not occurred in deeper groundwater and in the stream because of natural lags in the system. This favourable outcome in surface and shallow subsurface flow pathways water has not occurred yet in the other catchments.

Policy Relevance

More widespread and effective use of nutrient management plans by farmers is likely to improve both environmental and economic performance on farms. This is likely to be achieved only with appropriate advisory support for farmers in the interpretation and implementation of the plans.

2. Low use of Nutrient Management Plans

Further to the above finding, in a survey of ACP and non-ACP farmers who had a Nutrient Management Plan (NMP), it was found that over half of them answered that they did not have one. A farmer focus group was set up to get their views on the use of soil analysis results, recommendations and nutrient management. The farmers said that they found their current plans, which use tables of figures, difficult to use and favoured a simpler, flexible NMP approach combining a durable map with a table. For example, this would allow the farmer to keep the plan in the tractor cab and increase the chances of it being implemented.

Policy Relevance

The new Online NMP package was developed by Teagasc to address the need for farmer-friendly plans that was identified by the ACP work. The package enables farm advisers and consultants to deliver easy-to-use plans to farmers and is an important step in improving the effectiveness and

impact of nutrient management on Irish farms.
However, it has been found through ACP surveys that the plans on their own will not meet the farmer's needs and to increase their effectiveness, advisory support is required to help with interpretation. To be most effective, this support should extend to decisions on manure and fertiliser spreading regarding timing, soil type, application method and location.

3. Improved nitrogen and phosphorus use efficiency

Analysis of National Farm Survey data from 150 nationally representative dairy farms over seven years since the introduction of the Nitrates Regulations (2006 to 2012) found that N and P surpluses have declined without reducing output. Between 2006 and 2012 N surpluses declined by approximately 25 kg/ha and P surpluses by approximately 6 kg/ha.

Policy Relevance
These research findings provide strong evidence of improving efficiency of nutrient use, as a greater proportion of nutrient inputs are exported from the farm in product and less nutrient is available for loss to the environment. This evidence supports the sector in achieving its twin goals of increased economic competitiveness and environmental protection, as set out in Food Wise 2025.

4. Soil type and geology override soil P level as a predictor of P loss risk

The type of soil and subsoil being farmed has a greater influence on the risk of phosphorus loss to water than soil P levels or the P applied by farmers. The more poorly drained the soil the greater the risk of loss to water through fast surface runoff (such as overland flow).

Policy Relevance
A 'one size fits all' approach to how land and nutrient inputs are managed, that does not take account of the soil type and underlying geology, may not adequately address either phosphorus loss risk mitigation or agronomic needs. Thus, for example, in some poorly drained fields, soil P levels that are low by agronomic standards may pose a risk to water through fast surface runoff while on some well drained fields agronomically high soil P levels may pose little risk to water. This may have further knock-on effects to implications in point 1, above.

5. P loss to groundwater through the soil can be important in some settings

On some free-draining soils over half of phosphorus loss can be leached down through the soil to groundwater, although overall losses are generally low in these settings. These types of losses are governed mainly by soil P chemistry. P is fixed by iron and aluminium in the soil, but iron-rich soils may produce higher water soluble P concentrations leading to higher groundwater P which can add to river baseflow concentrations.

Policy Relevance
Where groundwater contributes significantly to streams and rivers the likelihood of P entering these surface waters via the soil and groundwater should be considered in any risk assessment. This builds on the ACP phase 1 findings of understanding the specific P vulnerability of groundwater in karst areas.

6. Point sources have a disproportionately large summer influence

In some catchments phosphorus concentrations in stream water increase as baseflow reduces during summer. This indicates a predominantly point source influence, since during the summer, low rainfall and dry soil conditions rarely, if ever, lead to circumstances that cause diffuse nutrient losses from farmland. This is especially evident in catchments with lower summer stream water levels due to low groundwater contributions (and especially where groundwater P contributions are low).

Policy Relevance

Point sources may have a disproportionately large impact on year-round stream ecology. Consequently, focussing on the reduction in the phosphorus contributions from point sources (agricultural and non-agricultural) may have a significant, relatively quick and positive impact on river water quality in some catchments. This could allow time for slower-acting measures aimed at diffuse agricultural losses, such as the GAP measures, to have greater effect.

7. Closed period is effective but extension is not warranted

Concentrations of P in streams reduce during the closed slurry spreading period and don't show pulses of increased losses at the start of the open period as the open slurry spreading period begins. Pulses of high phosphorus concentrations in streams outside the closed period can be linked to losses from manure/slurry spreading due to high-rainfall summer storms.

Policy Relevance

Extending the existing closed period is unlikely to significantly reduce the risk of P loss to water. Additional support for farmers with more timely soil condition and weather information to enable better decisions about timing and location of organic nutrient applications could reduce the likelihood of these incidental losses all year round. In future it may be possible to have real-time updates for farmers based on weather forecasts to support their decision making.

8. Sediment losses are low and from a variety of sources

Irish sediment losses are low by international standards and sources differ between catchments. For example, stream bank and bed erosion and road losses made up most (75% in a poorly drained catchment) for the more common land uses, i.e. grassland in catchments with modified stream channels. Bare soils at vulnerable times of the year are also key sources in other catchments.

Policy Relevance

Targeting of mitigation measures at these specific sediment sources could reduce sediment losses more efficiently than blanket measures. Landscape variability (field sizes/shapes, hedgerows, riparian vegetation and ditches) are likely to offset sediment losses even in vulnerable catchments.

9. Critical Source Areas

Using high resolution digital maps, the ACP has developed a Geographic Information system (GIS) based method for pin-pointing areas in the landscape which are critical in facilitating the loss of nutrients from farmland to water. These electronic maps with a resolution (pixel size) of 1-2m were found to be optimum for capturing the influences of small-scale landscape features on the movement of water at the field scale and for identifying areas where overland flow is more likely, for example along river banks and further upslope. Targeting mitigation measures at these relatively small areas could be an alternative to implementing buffer strips along entire water courses. It was also found that the area of land deemed to be at risk based on soil at P index 4 was significantly reduced and the risky locations changed when compared with this new digital tool.

Policy Relevance

Ultimately, the development and use of a field scale Critical Source Area (CSA) identification package, based on pilot work undertaken by the ACP, could allow real precision in targeting mitigation measures to parts of the landscape where they can be most effective. This approach would minimise any possible impact on farm productivity and help target nutrients to where they will give the best return. The CSA package could be incorporated into nutrient management plans as required by farmers and farm advisors, for derogation and environmental schemes, clearly showing where to take specified actions. Thus it would facilitate sustainable intensification of farming and the operation of schemes in a clear and unambiguous way.

10. Main influencers on farmers' nutrient management practices

Extensive surveys found that the main influencers of farmers' nutrient management decisions, in descending order, were Teagasc advisers, family members, other farmers, the farming press, farm walks and discussion groups. Agencies whose main role is regulatory or commercial have the least influence.

Policy Relevance

This has implications for the dissemination of agri-environmental advice within the Nitrates Regulations and also in regulations where these principles have high importance (such as River Basin Management Plans).

11. Overriding climate and weather pressures on nutrient losses

It was found that measures to mitigate phosphorus and nitrogen losses from land to water are susceptible to influences by large-scale Atlantic weather systems which vary over decades. Excessively wet years and wet pulses following dry periods have become more common patterns during the time that the ACP has been monitoring the six catchments. Ireland may be particularly susceptible due to location, making the potential impact of mitigation measures hard to predict. This has implications for expectations of change and reviews of agri-environmental measures – these measures may be potentially more beneficial in some years and less so in others. These processes also have an overriding influence on water quality metrics such as chemical concentration and chemical load. The extreme variability between and within years, combined with other catchment pressures, means that trend analysis is difficult in the shorter term (and particularly within review periods) as concentration and load will be similarly impacted (with downstream ecological consequences). This is particularly important as source pressures at the other end of the nutrient continuum continue to decline.

Policy Relevance

A full appraisal of how measures are influencing agri-environmental management and impact from source to stream is required and these should not be assessed in isolation. This has implications, for example, for when considering the impacts of changes in the management of N and P source pressures (points 1 and 3 above) and also when considering the influence of transport factors such as soil type, geology, spreading practices and erosion (points 4, 5, 6, 7, 8 and 9 above).

12. Nitrate in groundwater

It was found that average groundwater nitrate levels in all six ACP catchments are well below the World Health Organisation standard of 11.3mg/l of nitrate-nitrogen. However, this threshold can be exceeded occasionally at individual wells in the ACP well network due to localised events but these recover to preceding levels over time.

Policy Relevance

Careful analysis of more coarse resolution groundwater data is important as short term events may provide an unsafe assessment of longer term trends. Short term landuse changes, such as reseeding, as part of normal management should be accounted for.

Phase 3 of the ACP

In Phase 3 of the ACP (2016 – 2019) the team will build on the data collected and the work undertaken in the previous two phases by continuing with the current scientific approach while developing a greater modelling competence. The challenge requires an integrated environmental-economic modelling approach to specifically address the challenges inherent in meeting the production and environmental targets set out for Irish agriculture in Food Wise 2025. The primary aim of the modelling work is to develop the capability to identify the risks to expansion and advise on the overall costs and benefits associated with sustainable intensification practices at field, farm and catchment scale. ACP data, together with appropriate data from other sources, will be used to best meet this challange.

In addition, building on the principle of peer-review for reporting ACP findings (and learnings), Phase 3 also aims to deliver an enhanced knowledge exchange (KE) and dissemination programme in collaboration with Teagasc colleagues. The programme will focus primarily on getting key messages from the ACP to farmers mainly via the existing Teagasc KE structures.In addition, it will include dissemination to a wider audience of policy makers, regulators, environmental scientists and the general public through popular media. Given the range and diversity of the audience and the resource constraints that exist an approach that uses all feasible channels will be used to deliver this enhanced dissemination programme.

CHAPTER 1

INTRODUCTION

INTRODUCTION

A full description of the establishment and operation of the ACP is provided in the Phase 1 report. This Chapter will, therefore, provide a summary of the main elements and background to the programme.

1.1 Overview

The combined and often competing need of food security within a strong agricultural economy whist sustaining environmental resources is a grand challenge in the 21st Century. A growing global population, competing markets, European Union and national legislations and the push to grow economies following the global economic crisis is as important in Ireland as any other state. These global pressures place particular focus on the need to sustain landscapes upon which agriculture depends, and also to sustain environmental quality (and quality of life) such as water quality and high biodiversity. The ACP was initially planned against this background but has evolved to evaluate the necessary adaptions to economic recovery and new national agricultural objectives for growth such as FoodHarvest 2020 and FoodWise 2025. Nevertheless, these objectives still remain within the EU policy drivers of the Nitrates Directive (ND) and Water Framework Directive (WFD).

The ACP was established on the basis that under Article 5.6 of the ND Member States (MS) are required to implement monitoring and evaluation programmes:

"MS shall draw up and implement suitable monitoring programmes to assess the effectiveness of action programmes …"

The Nitrates Action Programme (NAP) emphasises that the outputs of such a programme should include a "…valid and transparent evaluation of the efficacy of the NAP measures ….improved understanding of the links between sources, pathways and impact …long term monitoring and demonstration sites that can be used… as national focal points for technology transfer and education…elucidation of socio-economic and behavioural impediments that must be overcome …"

Against this background, Article 27 (1) of S.I. 31 of 2014 states "the Minister for Agriculture and Food shall carry out, or cause to be carried out, such monitoring and evaluation programmes in relation to farm practices as may be necessary to determine the effectiveness of measures being taken in accordance with these Regulations. "

Phase 1 ran from 2008 until 2011 and in planning for Phase 2 (2012 to 2015), DAFM defined the objectives:

1. To establish extended baseline information and comparative data on agriculture in relation to both the Nitrates and Water Framework Directives.
2. To provide a scientific evaluation of the NAP measures and the derogation in terms of water quality and farming practice.
3. To provide a basis for the scientific review of NAP measures with a view to adopting modifications where necessary.
4. To provide a greater understanding of the factors which determine farmers' understanding and implementation of the NAP.
5. To provide national focal points for technology transfer and education for all stakeholders in relation to diffuse nutrient loss from agriculture to water.
6. To advise on any specific monitoring requirements deemed necessary for the purposes of the WFD.

From the outset the integrated aims of profitable farming and good environmental stewardship were guiding principles and built into Phase 2 of the programme. Another important integration of the programme has been collaboration and exchanges between scientists, farmers and policy makers.

1.2 Experimental development

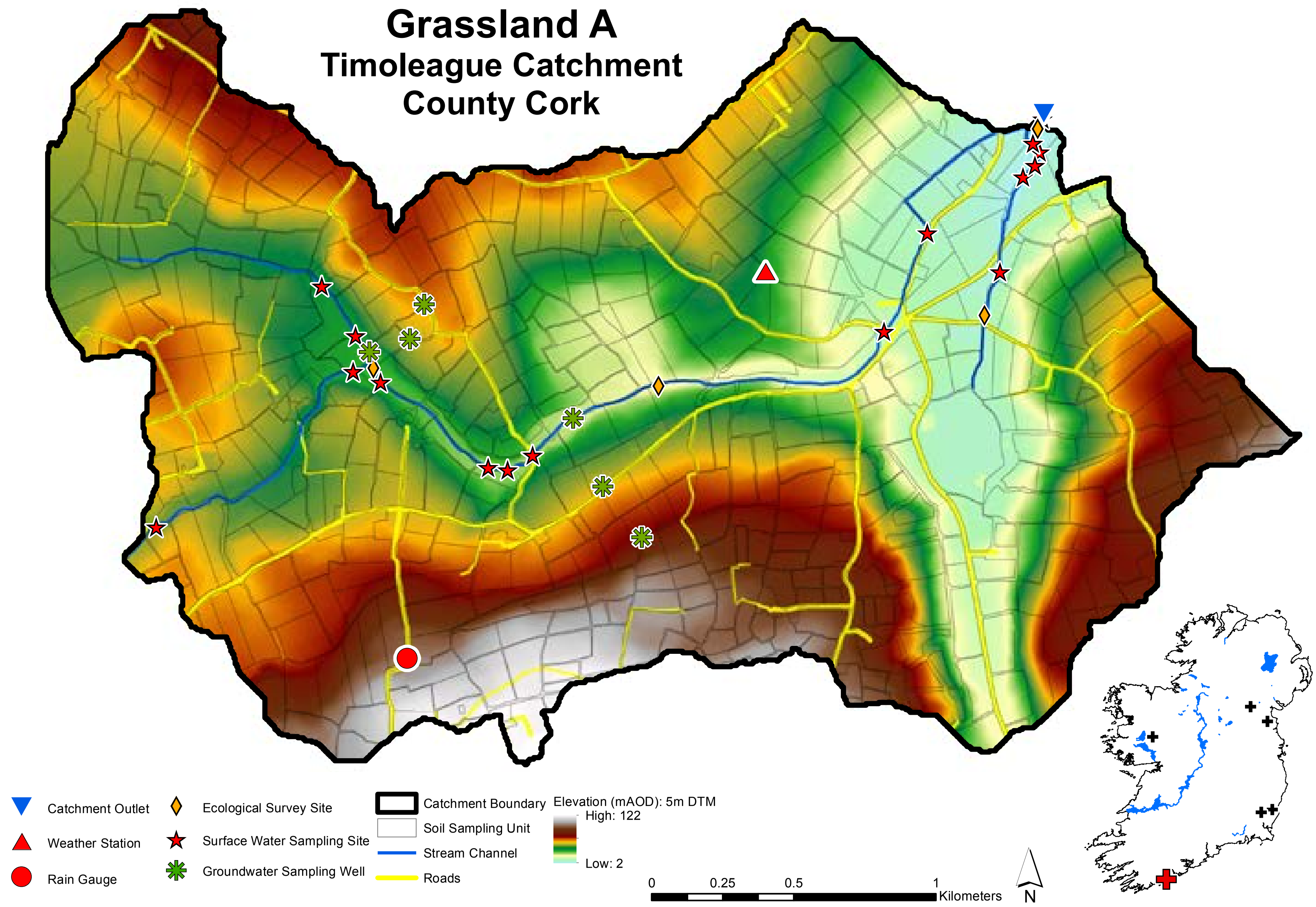
The scale of the ACP experiment is within the small agricultural catchment and which can encompass all aspects of the nutrient transfer continuum at a high spatial and temporal bio-physical and socio-economic resolution. But which also fully accounts for land management by incorporating the influence and feedback of all catchment farmers.

Phase 1 provided a baseline of information and a series of findings and assertions. Phase 2 was largely designed to extend this baseline, look for trends where these emerged, and validate assertions. Based on scientific investigation principles, much of the ACP work has been to look for barriers to water quality change following the introductions of agri-environmental regulations under the ND in 2006. These barriers may be behavioural (such as uptake), fit for purpose (sufficiently strong enough to cause a change), realistic (time expectations, all things being equal) or hindered (overriding influences between cause and effect – all thing not equal) – or combinations of all these factors. In addition to this, work has been developed on themes across the nutrient transfer continuum on issues such as soil N supply, soil erosion and sediment dynamics, point source pollution and meteorological considerations. This additional work provides context to evaluations, often missing from analysis of national datasets, and has been facilitated by a strong cohort of support from Walsh PhD Fellowships, competitively won and attached to universities and other centres of excellence.

This context is presented within the main body of this report as sections on understanding the challenges and also research into possible solutions. The context is also steered by world-wide convergent ideas on water quality pressures in agricultural catchments based on a scientific process of review and networking with national and international groups. It is no coincidence, for example, that many of the contextual themes being researched within the ACP evaluations and reported in Phase 2 have been highlighted as where further work is required by the recently published AgImpact project reviews on science needs and knowledge exchange needs. This is the space where ACP operates and the programme has developed a reputation around the world as an exemplar of catchment science and engagement platform.

1.3 Catchments

The ACP continues to operate in six catchments, established through spatial analysis and expert advice and in partnership with catchment farmers. This selection and establishment is described in detail in the Phase 1 report and highlights the range of combinations of farming systems and soil nutrient loss risk scenarios. In summary and for reference, the catchment details are presented here using catchment names and database codes (as presented in many previous publications and reports).


Grassland A
Timoleague Catchment
County Cork
Catchment Outlet
Weather Station
Rain Gauge
Ecological Survey Site
Surface Water Sampling Site
Groundwater Sampling Well
Catchment Boundary
Soil Sampling Unit
Stream Channel
Roads
Elevation (mAOD): 5m DTM
High: 122
Low: 2
0
0.25
0.5
1
Kilometers
N

Timoleague – Grassland A (Map 1)

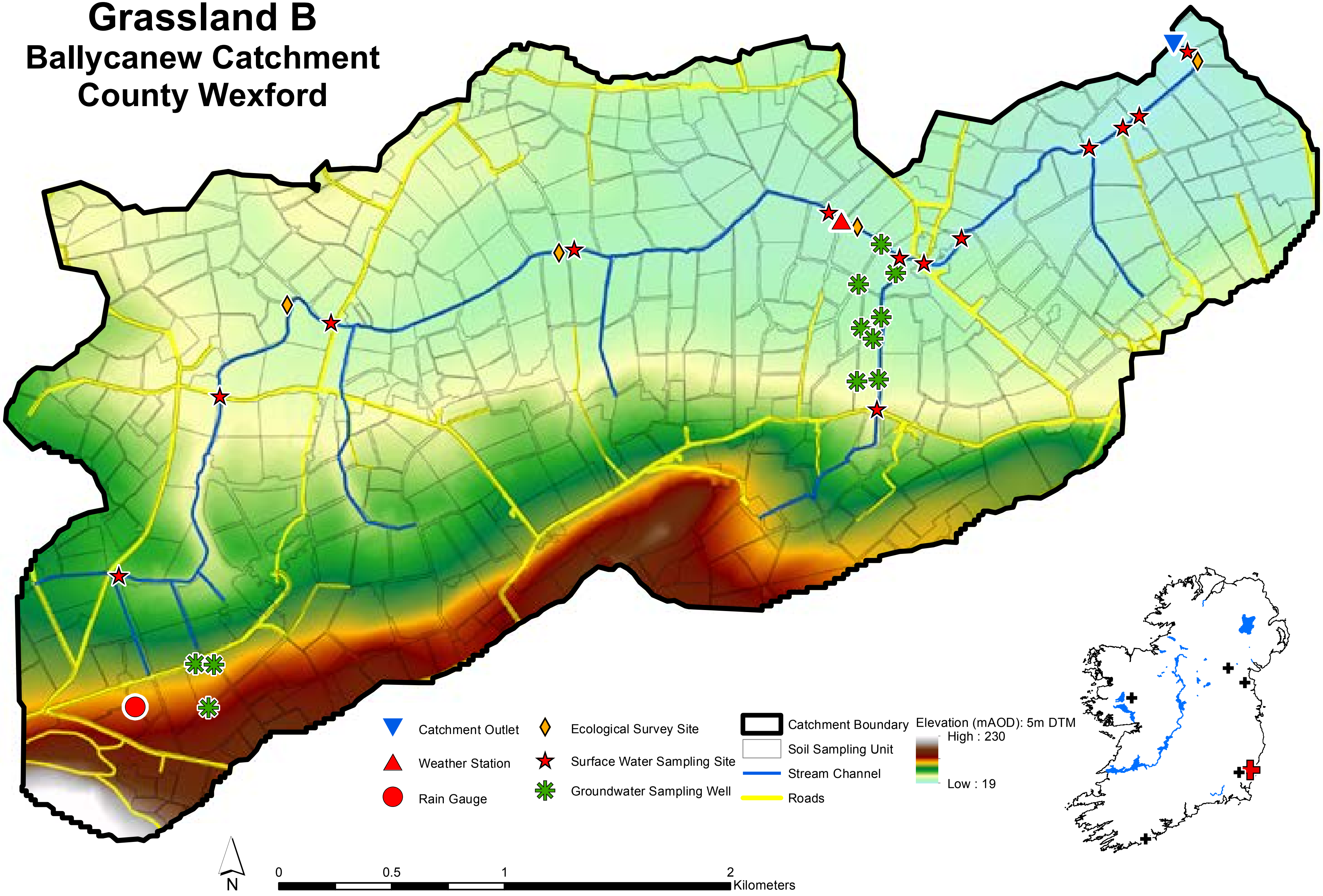
The Timoleague catchment is located south of the village of Timoleague near Clonakilty in Co. Cork. It is 758ha in area and 85% of the land is in grass with 4% tillage. The balance of the area is used for non-agricultural purposes. Dairying is the predominant land use in this catchment and the stocking rate is among the highest in the country (Fig. 1). The West Cork area where the catchment is located is representative of the most intensively farmed dairying areas in Ireland. It has the highest concentration of dairy farms in the country with large herds producing milk using an intensive, grass-based system.

The non-dairying farm area is used for beef and sheep production on the grassland and a variety of tillage crops including spring and winter barley and wheat, oil-seed rape and maize. The maize is used to produce silage mainly for winter fodder on the dairy farms. There is also a small area of fodder crops such as kale grown for grazing in the winter.

The soils in this catchment are brown earths over old red sandstone geology belonging mostly to the Clashmore and Ballyglass soil series. They are well drained with the exception of small areas of gleyic brown alluvial soils neighbouring the stream in the valley bottoms. These soils support a long growing season and early livestock turnout, and are generally well suited to the grassland dairy production that dominates in this catchment. Based on the free draining nature of the soils nitrogen would be considered the main nutrient at risk and the main loss pathway would be leaching through the soils to the groundwater. The stream that drains the catchment flows directly into Courtmacsherry Bay.

Fig. 1: Timoleague catchment – grass-based milk production

Grassland B
Ballycanew Catchment
County Wexford



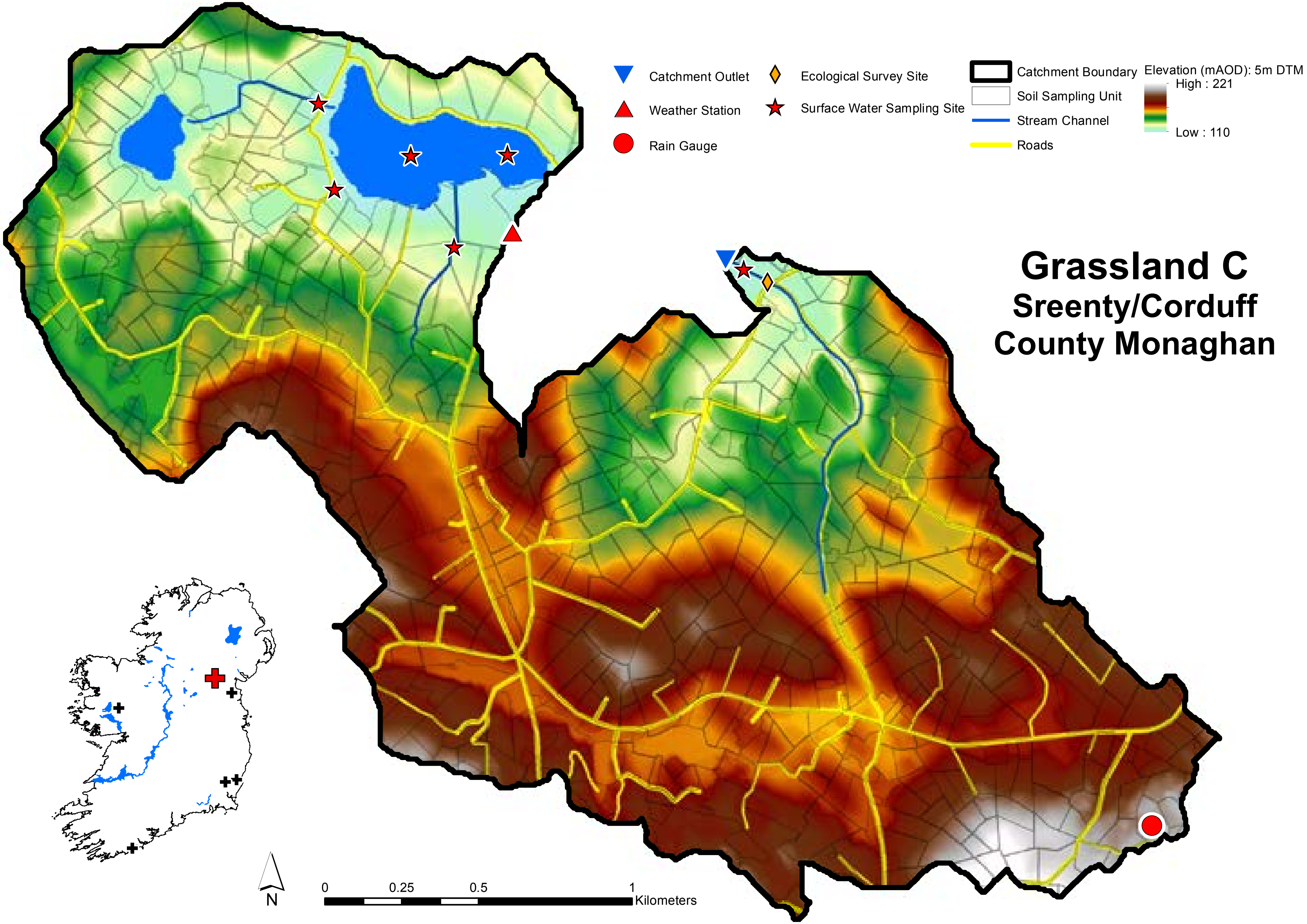
Ballycanew – Grassland B (Map 2)

The Ballycanew catchment is located just north of the village of Ballycanew, near Gorey in Co. Wexford. It is 1,191ha in area and grassland makes up approximately 78% of the landuse with 20% in tillage and the balance in woodland and other uses. The main grassland-based farm enterprises are beef production and dairying with some sheep production and sport horses (Fig. 2). Spring barley is the main tillage crop with small areas of other cereals.

Fig. 2: Ballycanew catchment – mainly grassland with dairying and drystock

The dominant soils in the lowland of this catchment are surface water gleys, mostly belonging to the Kilrush and Macamore soil series. These soils are derived from end-morainic and marine deposits of heavy muds giving them poor drainage characteristics. The drainage in this area has been improved somewhat by the owners through tile and mole drainage. The soils on the elevated land to the southern catchment boundary are non-calcarious brown earths over slate and shale geology. Tillage in the catchment is limited to this area. With good management the heavy soils in the catchment are well suited to grassland farming and dairying is expanding in the area.

Based on the type of soil and subsoil in this catchment phosphorus would be considered to be the main nutrient at risk of loss to water in the heavy lowland soils. The main pathway for loss would be through overland flow during heavy rain events.


Grassland C
Sreenty/Corduff
County Monaghan
Catchment Outlet
Weather Station
Rain Gauge
Ecological Survey Site
Surface Water Sampling Site
Catchment Boundary
Soil Sampling Unit
Stream Channel
Roads
Elevation (mAOD): 5m DTM
High : 221
Low : 110
N
0
0.25
0.5
1
Kilometers

Sreenty/Corduff – Grassland C (Map 3)

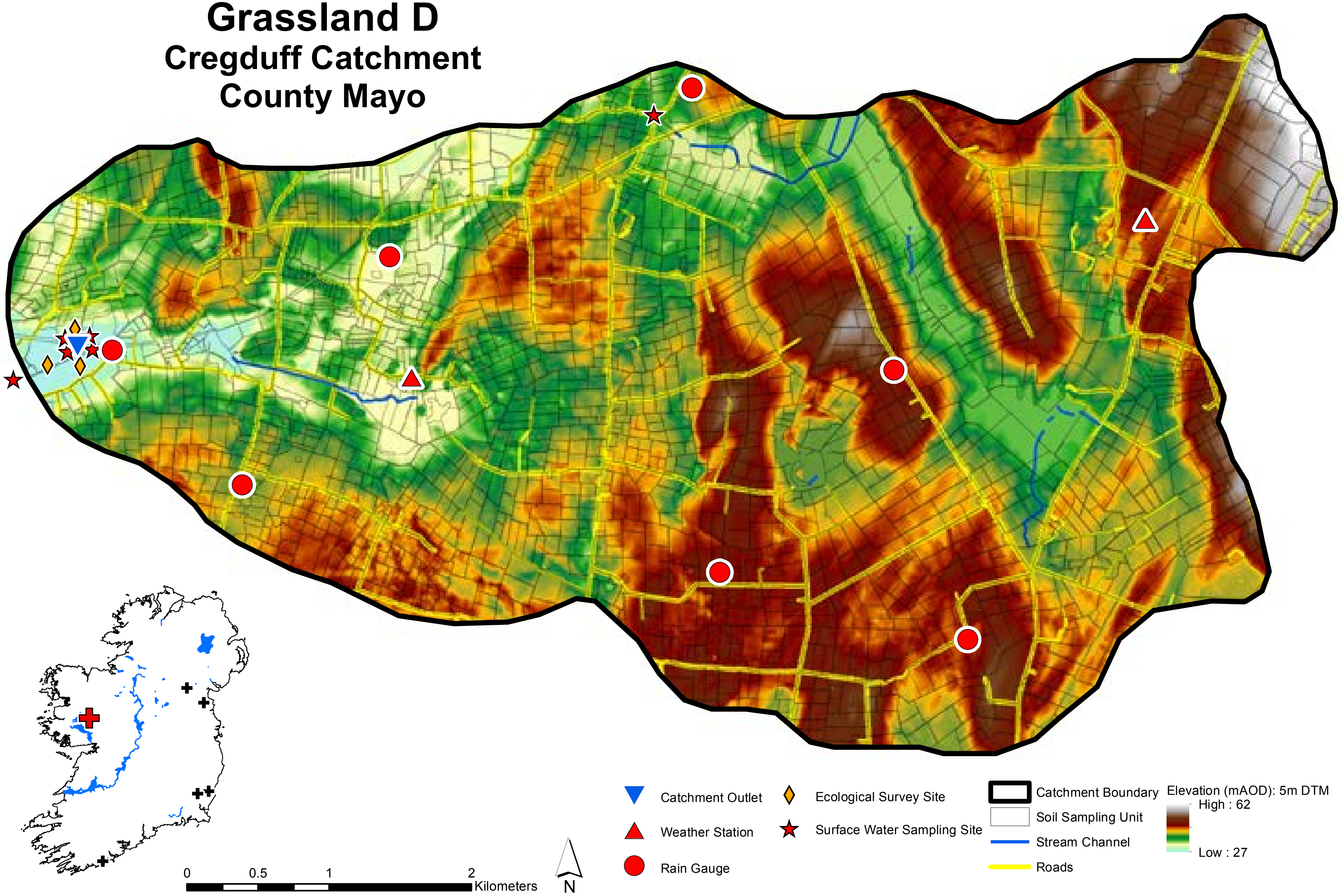
The Sreenty/Corduff site is comprised of two adjoining catchments and is located north-west of Carrickmacross in Co. Monaghan. The northern catchment drains into Sreenty Lake (also known as Lough Namachree (Fig. 3)) while the southern one is drained by a stream similar to the other stream catchments in the programme. The two catchments are 578ha in combined area and 89% of the area is grassland with the balance in non-agricultural uses. The main farming enterprise is beef production with some dairying and sheep production.

These catchments are in an area where the topography ranges from alluvial flatlands to variously shaped, recurrent drumlins with fairly steep slopes and with intervening U-shaped valleys. These drumlin features were formed when the advancing glacial ice sheet moved over this area compressing the till deposits into interlocking hump backed hills. There are often small lakes in the valleys and this catchment has two, the larger of which is Sreenty Lake.

The soils vary with the nature of the till deposits from drumlin to drumlin. The underlying rock is mainly sandstone in this catchment and the glacial till is relatively free draining and can be quite shallow. Acid brown earths dominate the hill tops, with stagnic luvisols and gleys on the hill slopes, foot slopes and valley bottoms. Given the soil type and topography, phosphorus is considered the main nutrient at risk of loss to water.
Sreenty Lake is the water source for the local group water scheme. The lake outflow and the stream join just downstream of the two catchments and flow into the Annaghlee/Erne system.

Fig. 3: Sreenty/Corduff catchment. All grassland, mainly beef production

Grassland D
Cregduff Catchment
County Mayo



Cregduff – Grassland D (Map 4)

The Cregduff catchment is estimated to be 2,998ha in area and is situated to the east of Ballinrobe in Co. Mayo. Grassland makes up 92% of the landuse with only 1% arable and the rest in non-agricultural use. It was chosen to represent areas of free-draining, shallow soils over karstified limestone. The karst landscape as found in Cregduff is typical of much of the area which contributes groundwater to the three large western lakes, Lough Corrib, Lough Mask and Lough Carra. Groundwater pathways predominate in this type of landscape and there is little or no surface drainage given the free-draining nature of the soils and the underlying karstified limestone with its network of fissures, and conduits. The Cregduff spring, which is used to supply water to the local community, was selected for monitoring based on water quality and discharge data collected by the EPA.

Dolines and swallow features are prevalent here, as dissolution of the underlying bedrock proceeds, leading to collapse and depressions at the soil surface. The area has many turloughs (Fig. 4) or seasonal lakes which fill up during the winter and recede each year in the spring as the water table falls.

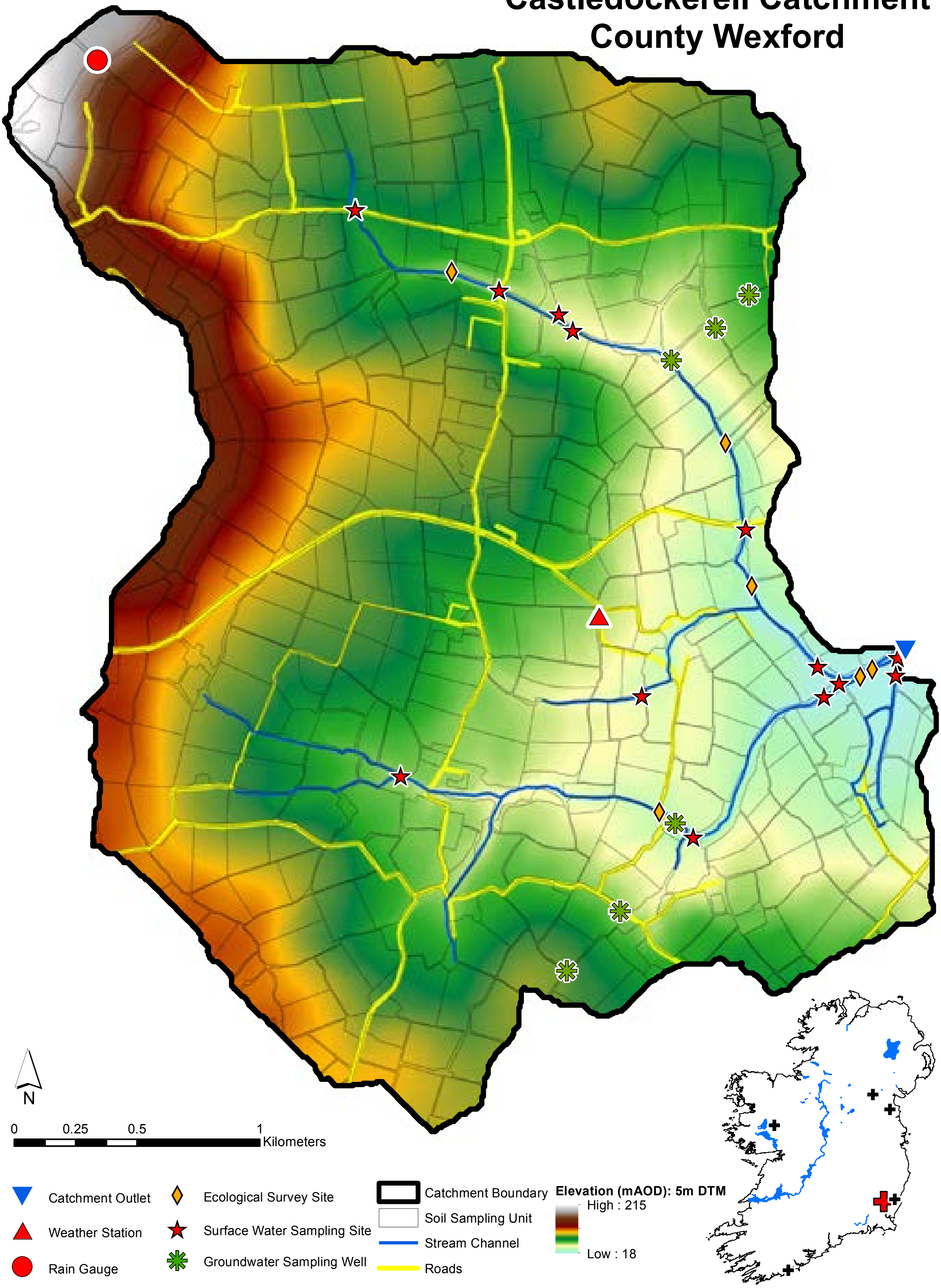
The western half of the catchment, closest to the spring, has shallow soil, mostly less than 3 m deep, where the epikarst is often exposed to the surface. The eastern half of the catchment has somewhat deeper soils with brown earths and brown podzolics on the head slopes and typical and humic rendzina soils on the hill slopes and foot slopes. In the turlough areas groundwater gleys and peat soils dominate due to the fluctuating groundwater. Based on the karst geology and connection to the surface through the exposed karst features, phosphorus would be considered the main nutrient at risk of loss. The main loss pathway would be through direct connection of the soil surface and runoff through the karst system to the groundwater.

Fig. 4: Cregduff catchment – grassland, mainly drystock with some dairying

Most of the farms in the catchment produce beef cattle and sheep at moderate stocking rates. There are a number of dairy farms which make up a significant area of the catchment and which are intensively farmed with high stocking rates and high inputs of nutrients from imported fertilisers and feedstuffs.

The spring at Cregduff flows into the Bulkaun River, a tributary of the Robe which flows into Lough Mask just to the west of Ballinrobe.

Arable A
Castledockerell Catchment
County Wexford



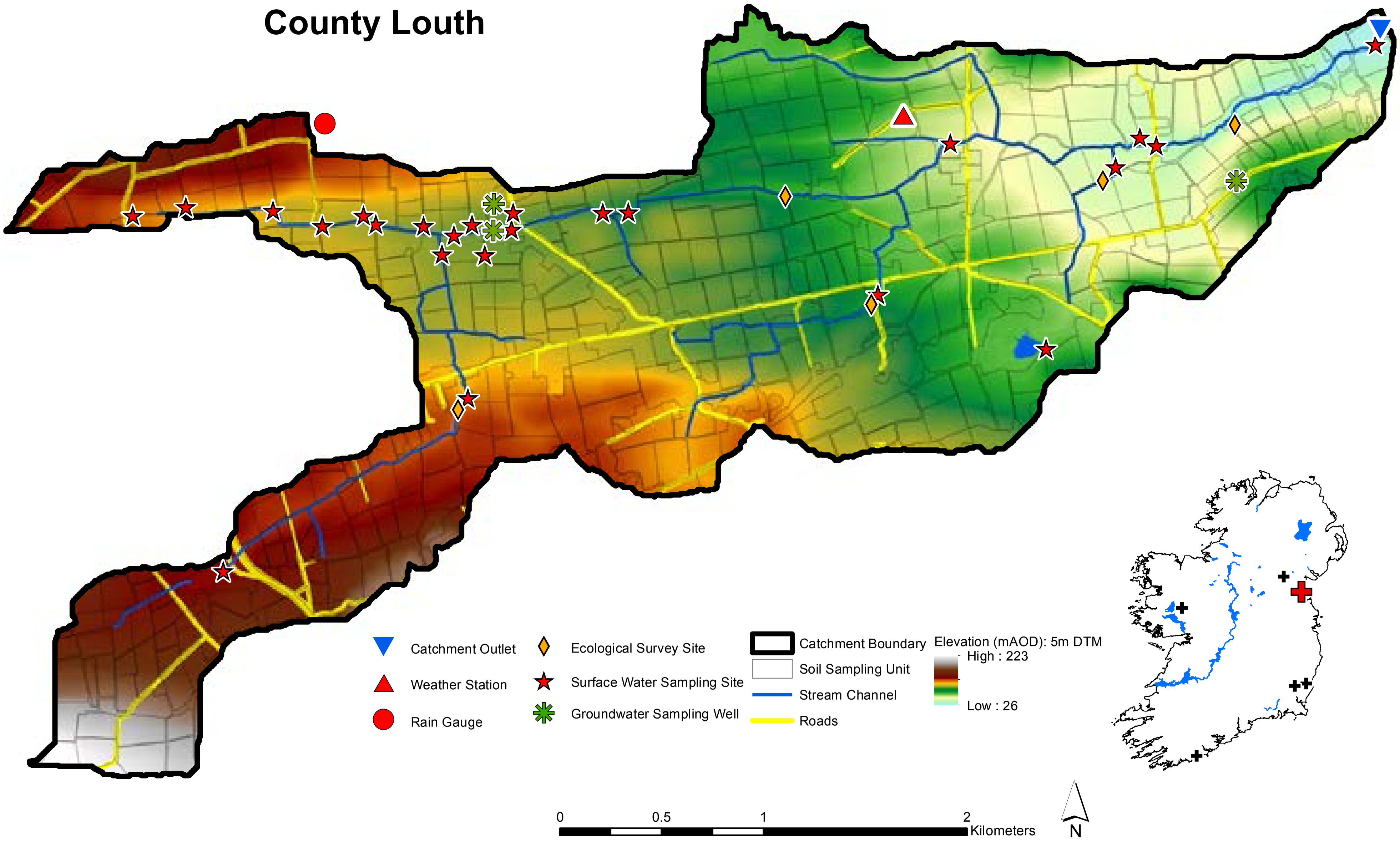
Castledockerell – Arable A (Map 5)

The Castledockerell catchment is situated between Enniscorthy and Bunclody in Co. Wexford. The stream that drains the catchment is a tributary of the Slaney River which drains much of the south-east region. It is 1,117ha in area and in a typical year 54% of the catchment area is used for tillage with 39% in grass and the balance in non-agricultural uses (Fig: 5). The type of farming in the catchment is typical of the tillage/drystock mix that is found in much of the south-east and south of Ireland on well-drained soils.

Fig. 5: Castledockerell catchment – mainly tillage with drystock and some dairying

Spring barley production is the main tillage enterprise with some other cereals such as winter barley as well as some oil-seed rape and potatoes. Sheep production is traditional in the area and is still carried on by many farmers as well as beef production. The majority of the land in the catchment has free draining typical brown earth soils, belonging to the Ballylanders and Clonroche Soil Series. These soils which are underlain by slate and shale geology are ideal for spring barley growing. In the low lying areas near the stream there are some poorly-drained groundwater gleys soils most of which are artificially drained. Based on the type of soil and subsoil in this catchment nitrogen is considered to be the main nutrient at risk of loss to water and the main pathway for loss is considered to be leaching through the soil to the groundwater.

Arable B
Dunleer Catchment
County Louth



Dunleer – Arable B (Map 6)

The Dunleer catchment lies west of the village of Dunleer, in Co. Louth. It is just over 948ha in area and in a typical year half of the land is in grass with a third in tillage (Fig. 6), The balance of the land is in woodland and other uses. Winter wheat is the main tillage enterprise in the catchment but with considerable areas of other crops such as winter and spring barley, oil seed rape and potatoes. A substantial area of the land is rented on the 11-month conacre rental system and much of the tillage, especially potato production, is carried out on this land. The use of the conacre system means that management responsibility of a significant proportion of the land changes from one farmer to another from year to year making the collection of farm management records more of a challenge. The grassland area of the catchment is mainly used for dairying and beef production with some sheep, goat-dairying and horses.

In this catchment the influence of past glacial movement is apparent with its undulating landscape dissected by ditches and streams and many different deep soil types derived from glacial drift underlain by greywacke, mudstone and limestone geology. The dominant soils in this catchment are typical and stagnic luvisols. In the better drained areas on the head slopes well drained luvisols belonging to the Dunboyne soil series dominate, however, these are often interspersed by smaller areas of brown earths. On the hill slope and foot slope areas, stagnic luvisols belonging to the Fethard soil series, are more prevalent. These soils exhibit impeded subsoil drainage. In many of these soils, artificial drainage has improved water flow making them suitable for both grass and crop production. Pockets of gleyic brown alluvial soils adjoin the stream in the valley, 70% of the catchment is classified as poorly drained and so phosphorus is considered the main nutrient at risk of loss from this site through overland flow. There is a much smaller risk of nitrogen loss through leaching on the more freely drained soils mainly in the east of the catchment.

Fig. 6: Dunleer catchment – tillage and grassland with dairying and drystock

1.4 Experimental facilities

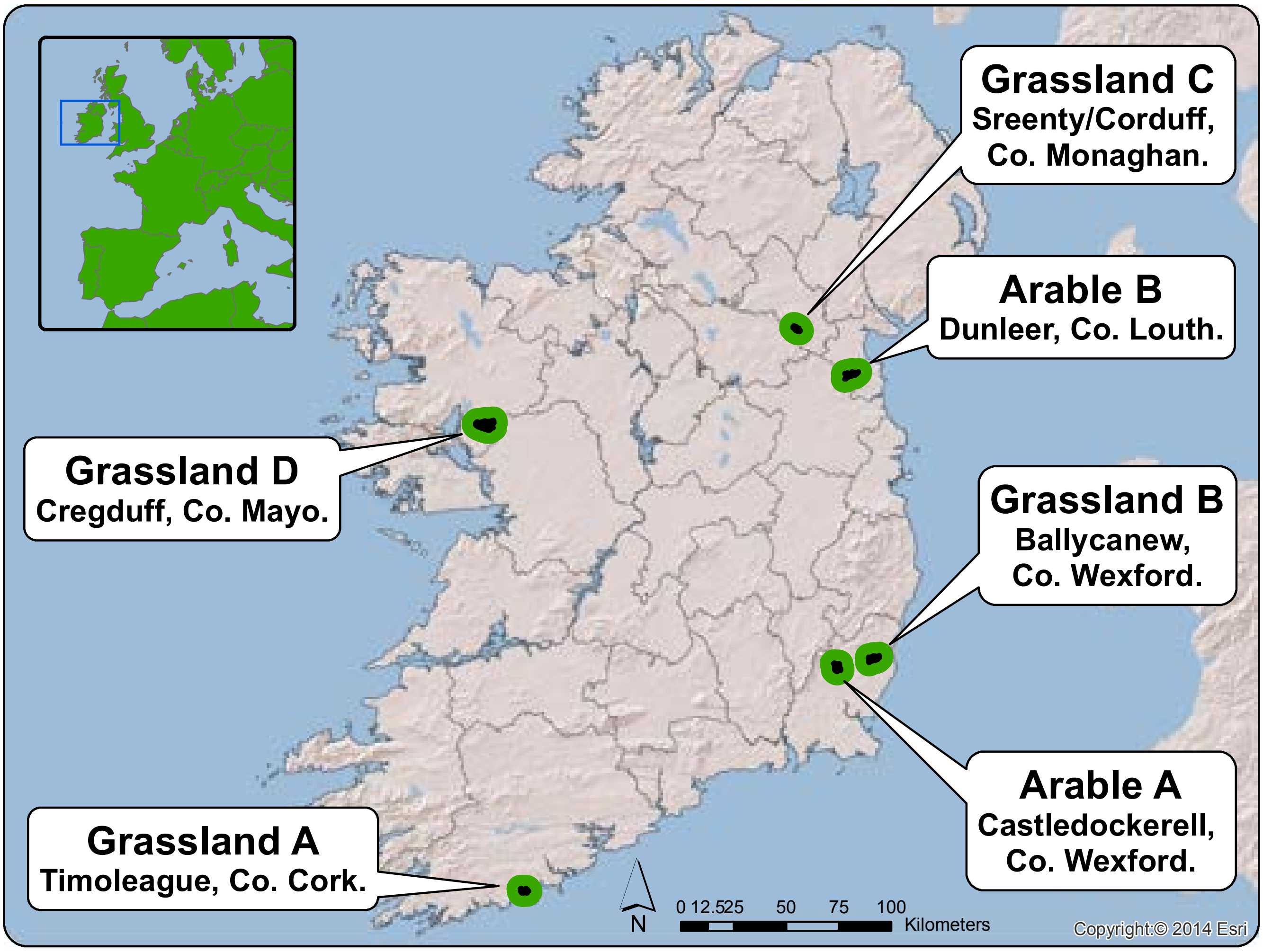
The scale of the working catchment remains the principle management, economic, behavioural and biophysical backdrop to the ACP experimental design. As these catchments are places of work and of habitude, care and respect are needed and exercised at all times. In terms of scientific protocols, catchment scale work differs somewhat from conventional experimental designs at, for example, the plot or field scale. In the latter scales, replications and controls are used to gauge the significance in differences caused by and between interventions. This is not as straightforward in working catchments due to i) all catchments being different in large or small ways to an almost indeterminate degree making replication impractical and ii) with evaluations based on policies implemented on a national scale, controls are mostly redundant. Instead, catchment scale experiments rely on time series trends and, in the timescale of policy reviews (generally 3-6 year cycles), subtle changes in the spectrum of biophysical and socio-economic outcomes to policies need to be detected.

These trends are monitored and have been reported in Phase 1 outputs and in this Phase 2 report using a sophisticated set of equipment and survey principles, common to each catchment.

Based on the nutrient transfer continuum outlined in the Phase 1 report, source pressures are monitored and evaluated at farm and field scale for elements such as nutrient use, balance and soil nutrient (P, K, pH) status. The resolution at this end of the continuum is, as far as possible, linked to the farming scale of management – either the field or the farm depending on the parameter – and set, at the field scale, at 2ha.

At the river end of the continuum, the passage of nutrients out of the catchments is monitored by bankside analysers (measuring P fractions, N [as TON], turbidity and conductivity) situated alongside river discharge stations. Careful rating of these discharge stations has been and continues to be conducted to ensure that chemistry patterns are contextualised within discharge ranges (low to high flow) and that chemical loads (concentrations multiplied by discharge) can be recorded with reduced uncertainty. This monitoring takes account of the rapid changes experienced in river water level and discharge in many Irish rivers and especially in small catchments. Data is collected sub-hourly according to equipment settings and generally collated to hourly averages or longer periods for reporting.

One of the key advantages with this monitoring approach is that coverage is provided during those storm conditions that influence diffuse transfer of nutrients from land to water – crucial for trend evaluation of diffuse pollution policies. Evaluations using coarser datasets in river systems can be highly uncertain due to the probability burden of the samples occurring during lower flows – i.e. missing diffuse events – and this is widely known. Between farms and soils and the river export of nutrients, the ACP also studies pathways in specific hydrological pathways and surface and sub-surface zones, including groundwater. These studies are for recording water quality conditions and trends (in the case of groundwater) but more often the analysis, supported by measured groundwater data, is based on the numerical separation of river discharge and concentration patterns moni-



tored with the bankside stations. This load analysis, or 'Loadograph Recession Analysis' has been developed by ACP based on the rich river datasets and is able to show when and where the subtle shifts in flow pathway chemical concentrations (undertaken for P up to now) are likely to have occurred. This is an independent analysis of annual chemical load comparisons which are highly influenced by the timing and magnitude of annual rainfall and discharge – even when expressed as concentration on a flow-weighted basis (due to other export factors such as soil chemical exhaustion and channel scouring). Annual load, can therefore, be a climate/weather related signal and, over the shorter term, may buffer any subtle changes that could have occurred due to smaller shifts in land-management. One of the catchments, Sreenty/Corduff, has a lake (Sreenty Lake, or Lough Namachree) that was instrumented and monitored for water quality parameters during parts of Phase 1 and 2 and reported in each Phase.

Socio-economic studies have also been undertaken, to investigate behaviour and attitude with regard to agri-environmental management and the cost implications (generating or incurring) of regulations to manage water quality in a working landscape. In these studies, replication and experimental control are able to be used – replicating with numbers of respondents and controls by using respondents outside of ACP catchment areas, for example. These methods have been used to good effect and utilising professional survey companies to ensure independence.

One of the most useful aspects of the experiment design is the ability to look at higher resolution data either over time or over repeated surveys. As the ACP continues into a Phase 3, these datasets become more important and more insightful for their primary policy evaluation aims in catchments that are adapting to growth and environmental objectives.

1.5 Management

The management structure and the operational programme have remained the same with two external structures providing steer and operational quality control to the internal Teagasc structure. These two structures are the Consultation and Implementation Group (CIG) and the Expert Steering Group (ESG). The former group was established to facilitate dissemination best practise to the farming organisations regarding the aims, implementation strategy and on-going progress of the ACP and to elicit their views. The group consists of farmers, industry representatives and policy people. The latter ESG group was established to provide expert advice on scientific and operational aspects of the programme and to ensure that its outputs meet the highest international scientific standards and those required in the draft EU guidelines for monitoring the effectiveness of the Action Programme including the derogation. The group consisted of science and policy experts from Ireland, the UK, the Netherlands and the USA. The necessity to meet regularly during Phase 2 was largely overridden by the experimental base of the programme remaining unchanged and the dissemination routes and quality being established. However, groups were consulted and appraised of developments and operations throughout Phase 2. Nevertheless, with a small but significant change of focus towards the end of Phase 2 and into Phase 3 (see below), these groups have been realigned for further input.

The Programme Manager (PM), reporting to Teagasc Head of Crops, Environment and Land Use Programme (CELUP) is responsible for the development, implementation and delivery of the programme. As with Phase 1, the Phase 2 programme consists of six specific Tasks each of which is the responsibility of the Task Leaders (TL) who report to the PM and Principal Scientist (PS). The PM, PS and TLs are supported by a Data Manager (DM) and Data Technologist (who comprise the Data Management Team - DMT), an Instrumentation Technologist and an Administrative Assistant. The DMT is central to ensuring the collection, management, analysis and interpretation of the large datasets is cost effective and at an appropriate level to provide the scientific evidence for the monitoring and evaluation programme. The Instrumentation Technologist's role is to manage the water quality data stream by ensuring the efficient operation of field and laboratory protocols, analytical field equipment, Laboratory Information Management System protocols and facilitating data quality control protocols with the Programme team prior to final data storage. An overview of the Teagasc management structure for the project team of 16 staff is shown in Fig. 7.

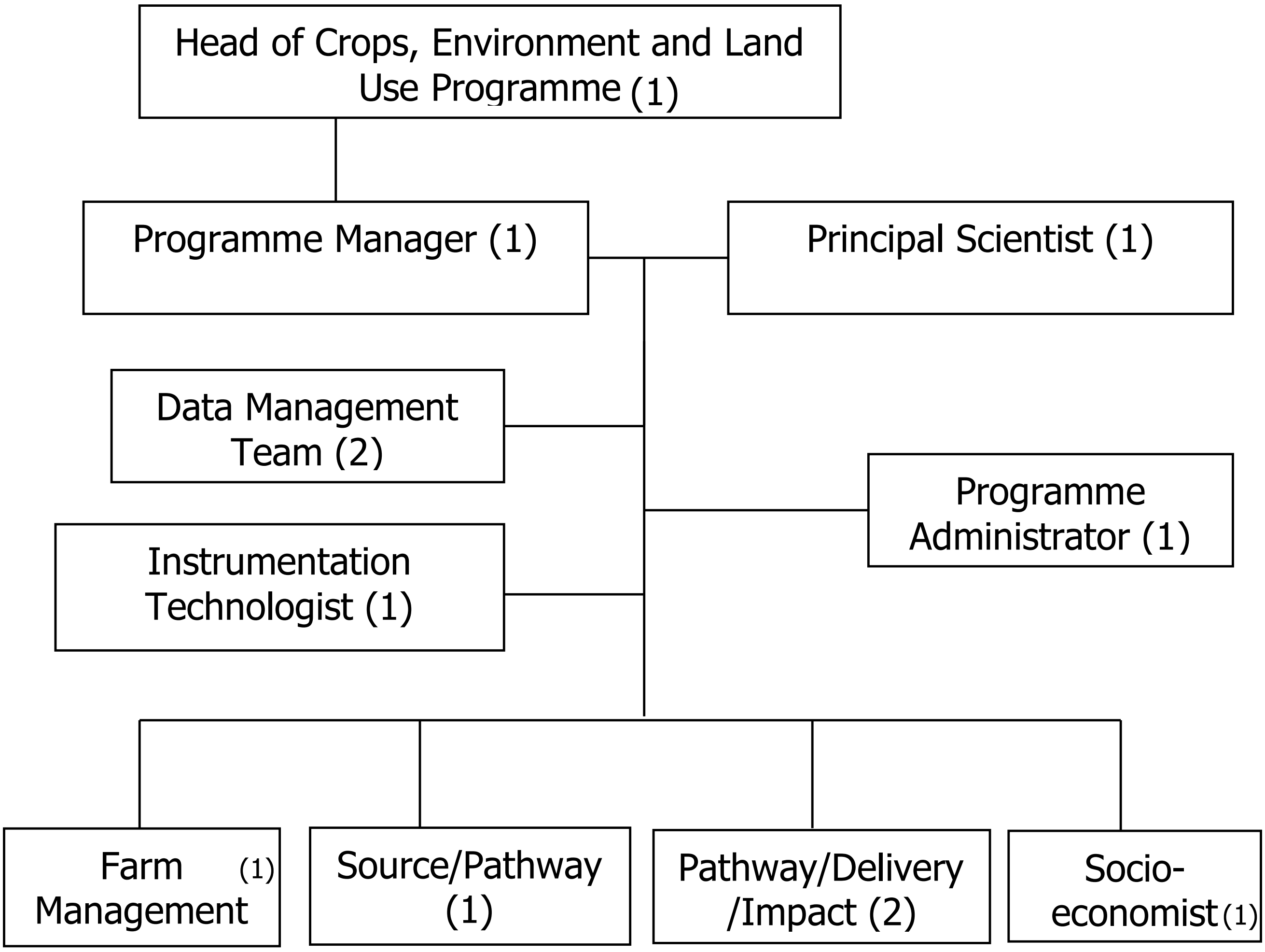


Fig. 7. The ACP management structure - the number in brackets represents the number of staff associated with each task.

Task 1- Programme Management

The PM has responsibility for the overall management of the programme and delivery of its outputs. The Administrative Assistant supports the PM and the project team. The objective of the PM post is the development, implementation and delivery of the work programme required to ensure the proposal objectives and any other tasks mandated by the ESG are met within the agreed timeframe. The PS works with the PM to ensure scientific rigour in operating the experimental design and scientific quality of outputs.

Task 2 – Farm Management

Advisory and technical services are delivered in the catchments by teams consisting of an Agricultural Adviser and Technician except for Timoleague which has a Technologist who provides both technical and advisory support. Overall there are three Agricultural Advisers, three Technicians and one Technologist carrying out these roles in the catchments; they report to the PM. The Task 1 objectives are :

- To encourage, foster and develop local farmer and stakeholder participation in the project.
- To provide participating farmers with detailed development and management advice and planning to ensure farm profitability and environmental sustainability in conjunction with the appropriate Teagasc advisory services.
- To provide detailed baseline data on nutrient inputs and management on participating farms as well as financial records on a representative group of farms.

In addition ongoing farm management data is collected to quantify the nutrient inputs from farm yards (point sources) and field sources (diffuse losses). This data is used to quantify their respective contribution to the pool that forms the source of the field/farm nutrient loss.

The critical role of the Agricultural Advisers in the programme is to encourage active farmer participation and to facilitate access by the programme to their lands for data collection, sampling, equipment installation, etc. This task also involves the mainstreaming of the programmes activities with Teagasc Knowledge Transfer programmes and other local/national water quality initiatives to develop the catchments as national focal points for technology transfer.

Task 3 - Source/Pathway

This task is delivered by the programme's Soil Scientist. The task objective is to link the nutrient sources from the field and farm with the supply of nutrients available for transport and loss to water. The soil scientist works collaboratively with Teagasc's Nutrient Efficiency research sub-programme. The output contributes to the delivery of the scientific evaluation of the effectiveness of the NAP measures through a greater understanding of how farm nutrient decisions determine the supply of nutrients for transport from the farm systems and assist in the identification of possible changes required in the measures to improve their efficacy.

Task 4 - Pathways/Delivery

A Hydrogeochemist and Environmental Hydrologist make up the Pathways/Delivery team and their objective is to link the nutrient sources identified in the Source/Pathway task with the movement of water through the pathways from field/farm to streams leaving the catchment. The Hydrogeochemist investigates the changes in stream water quality in each of the catchments identifying the physical and chemical processes contributing to the nutrient export from the catchments as well as the fate and impact of the nutrients entering the stream. The Environmental Hydrologist works on determining the contributions of water and nutrient that reach the stream via the various surface and subsurface pathways. The approach involves monitoring, data analysis and modelling.

The challenges are the complexities of scale involved. These arise from the spatial variability of soil physical/chemical properties that determine the pathway, the temporal variability of rainfall and the nutrient transformations that occur in the soil. The output from this task contributes to the scientific evaluation of the effectiveness of the measures through an improved understanding of the pathways and will also provide a basis for any modifications to the measures.

Task 5 - Socio-economic studies

The Socio-economist provides the socio-economic information in relation to the attitudes and awareness of the farming community to water quality issues, the measures used to address them and the potential economic farm level impact of changed agricultural practises arising from compliance with the measures. The Socio-economist also oversees a financial assessment of the farming system. This is undertaken in conjunction with the Agricultural Advisers.

The approach taken is to collect data in relation to socio-economic activity on the farms in the catchments. It involves the establishment of a baseline in Phase 1 followed by a review survey of farmers' attitudes in Phase 2. When combined, the output from these surveys will be used to identify important issues regarding the farmer's attitudes to nutrient management and water quality protection measures and will seek to identify improved methods of bringing about changes in farm practice. The output from the surveys will also be used to compare the degree to which improved management practices are taken up by farmers involved with the programme versus non-participant farmers.

The task also involves the collection and examination of detailed farm financial records to determine the financial impact, if any, of the implementation of the measures and to model potential impacts of the introduction of new or modified measures. The collection and analysis of the main attitudinal survey was sub-contracted to a survey company whose recorders did not have any pre survey contact with the farmers as this is best practice in the conduct of attitudinal surveys.

The output from this task will contribute to the monitoring and evaluation report by identifying the socio-economic factors that affect the implementation of the measures on farms, the cost implications of implementation and the relative cost effectiveness in terms of reducing nutrient loss.

Task 6 - Data Management, Modelling and Statistics

The objective of this task is to provide the project team with the necessary data management and modelling/statistical support. This ensures that the design and analysis of each task can deliver on its objectives, that the management and sharing of all data sets generated is efficient and effective and to integrate and address the scaling up of the catchment results to catchment and river basin district level.

The programme generates very large quantities of agricultural management, soil, weather, water quality/quantity, and attitudinal, spatial and cost data from each of the catchments. These very large data volumes from disparate sources require careful collection, quality control and storage. This task poses substantial challenges in areas such as tracking and using existing data; collection and integration of new data which is often captured and stored in hardcopy and other inflexible formats and limited data sharing and linkages due to both technical issues involving the inflexibility of storage/retrieval systems and organization cultural issues.

To meet these challenges an information management system has been built for the ACP on the following key guiding principles:

- Most efficient data capture and integration from multiple sources retaining the spatial component of collected data
- Industry standard data storage and management
- Flexible and timely distribution of data to all identified users for analysis and reporting
- Seamless integration into existing corporate-wide geospatial and database systems

While the DMT provides modelling and statistical support for the team, a collaborative approach will be used to ensure that the ACP gains access to the most appropriate models and modellers internationally. Links have already been established in Phase 1 with key researchers at a number of universities and institutes and these will be further developed to ensure that the large amounts of high-quality data held by the ACP is exploited as fully and as expertly as possible.

The publication of the results in peer reviewed journals is the most effective QC on the programme outputs to underpin DAFM reporting requirements to the EU Commission. The high resolution water quality monitoring programme combined with the detailed sources and pathway data requires new statistical and modelling techniques to be developed to assess the effectiveness of the measures, to advise on possible changes necessary to improve their efficacy and cost effectiveness and to extrapolate the results to other areas. Modelling will also be used to develop conceptual frameworks that can be used to integrate productivity data with the wider environmental impacts. These will include not only water quality but gaseous emissions. This integration will contribute to the knowledge that will deliver the crucial but delicate balance between farm profitability and society's environmental objectives required for a sustainable rural environment.

CHAPTER 2

EFFECTS OF THE MEASURES

Paper 1: Developing the EU Farm Accountancy Data Network to derive indicators around the sustainable use of nitrogen and phosphorus at farm level

Buckley et al. (2015)

KEY MESSAGES

- This study developed a methodology for indicators of nitrogen (N) and phosphorus (P) use across a range of farm systems.
- The data used are from the Teagasc National Farm Survey (NFS) and consisted of 827 farms weighted to be representative of 71,480 farms nationally.
- Results indicated an average N balance of 71.0 kg ha^{-1} and P balance of 4.7 kg ha^{-1} across the sample.
- Mean and median N use efficiency was 79.6 % and 57.4% across all farm systems.
- Mean and median P use efficiency was 36.7 % and 23.3% across all farm systems.
- This work will provide a template for assessing Ireland's sustainability performance over time as the sector strives to meet the Food Wise 2025 challenge of increasing competitiveness while at the same time providing environmental protection.

SYNOPSIS

This study used the Teagasc National Farm Survey (NFS) in the Republic of Ireland which is part of the European Union Farm Accountancy Data Network to develop sustainability indicators in the use of N and P across a range of farm systems. The NFS data in 2012 (collected annually) was employed in this analysis. Detailed farm accounts and enterprise level transactions are recorded on a random representative sample of farms throughout the Republic of Ireland. The final data set consisted of 827 farms weighted to be representative of 71,480 farms nationally. Results are reported according to 6 different farm systems; these included specialist dairying, cattle rearing, cattle other, sheep, tillage and mixed livestock.

Two indicators were derived in this study. Farm gate N and P balances are an indicator of source pressure on environmental quality and are calculated by subtracting the total quantities of N or P (kg ha^{-1}) exported from the total quantities imported.

The second indicator, nutrient use efficiency is calculated by dividing total N or P exported (kg) by total imported (kg), expressed as a percentage. This is a more a measure of agronomic efficiency. Both indicators require a full audit of imported and exported nutrients across the farm gate to be established. The main imports that crossed the farm gate in this analysis were chemical fertilisers, concentrate feeds, forage feeds, milk replacer (for feeding calves) and purchased livestock. The principle farm-gate exports were milk, livestock, cereal crops, forage crops and wool. Each import and export is converted to N and P mass (kg).

Results indicated an average N balance of 71.0 kg ha^{-1} across the nationally representative sample. Nitrogen balances were between two to four times higher across dairy orientated systems (105.9–145.5 kg ha^{-1}) compared to livestock rearing (38.2–55.9 kg ha^{-1}) and specialist tillage systems (52.5 kg ha^{-1}) as shown in Figure 1.

Nitrogen use efficiency was generally lowest across milk producing systems compared to livestock rearing and tillage systems.   Dairying systems had mean-median nitrogen use efficiency (NUE) of circa 23-25%. Specialist sheep systems had the highest mean NUE of the livestock based systems at 67.1 %; however, the median value was significantly lower at 28.5 %. Cattle rearing systems had average NUE of 26.5-34.3 % and median values of 15.6-23.4% as illustrated in Figure 2.

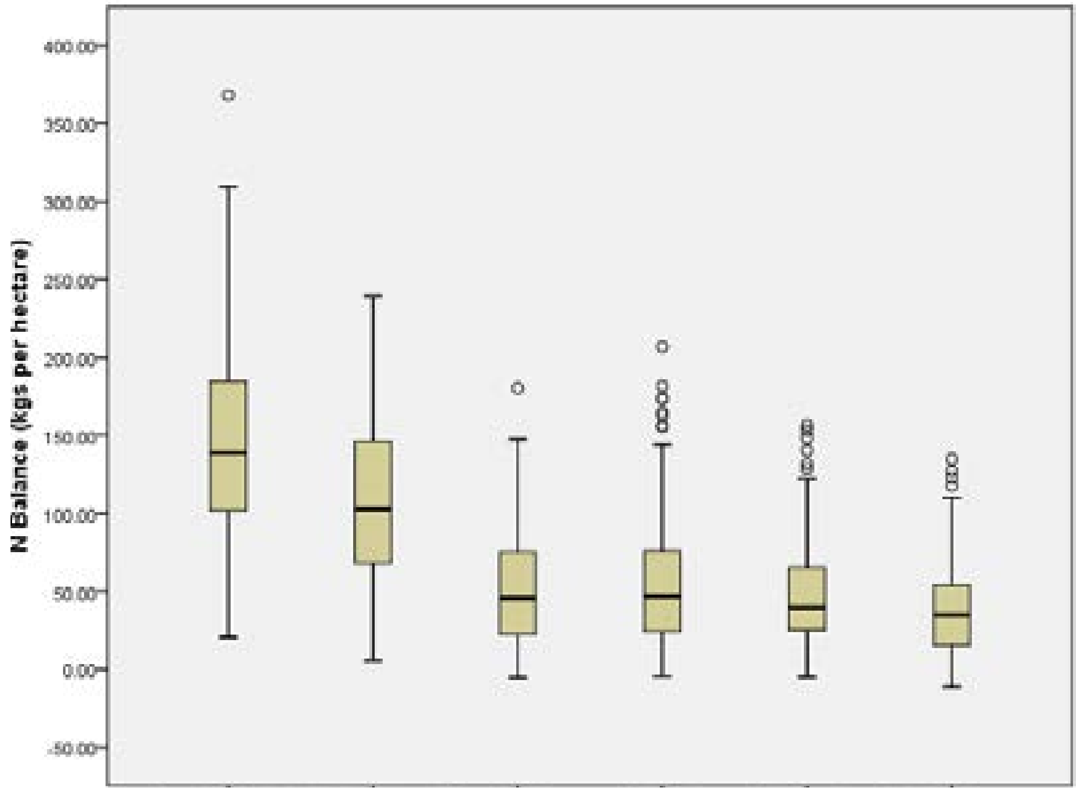


Figure 1: N balance kg ha^{-1} by farm system

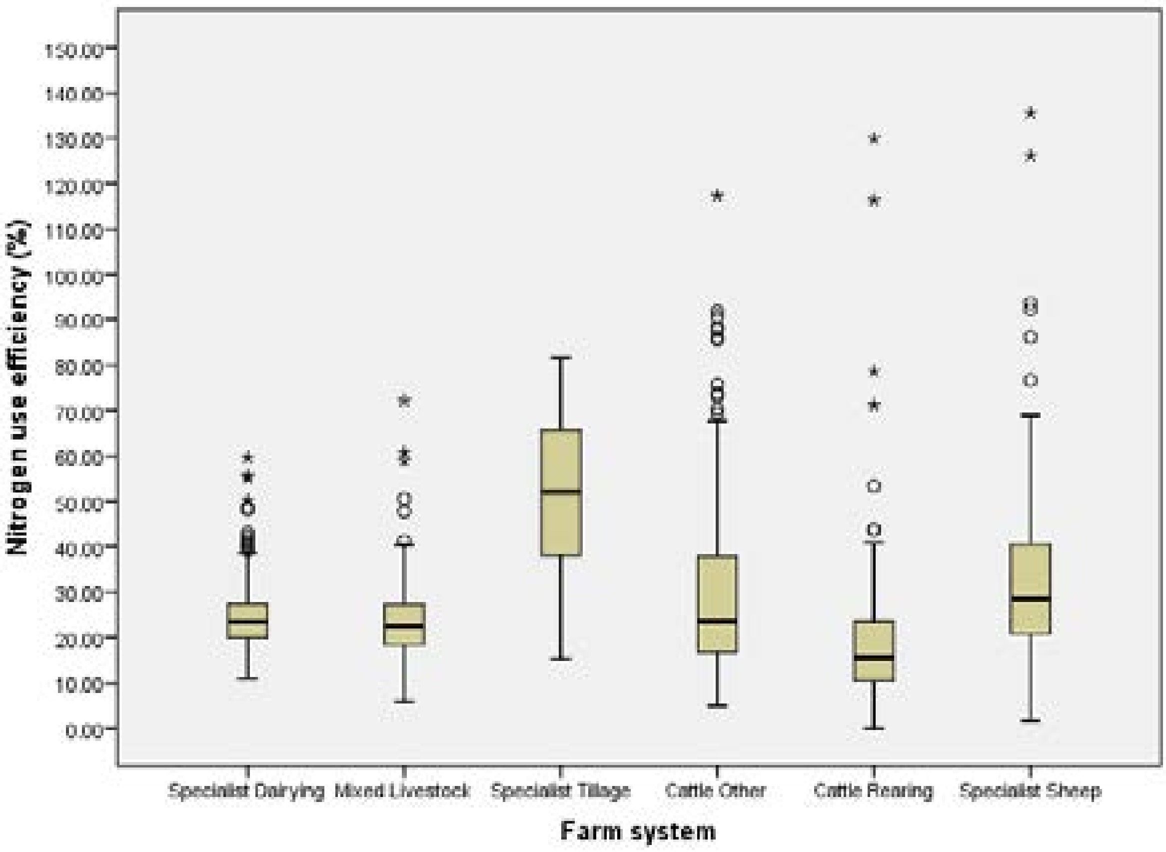


Figure 2: Nitrogen use efficiency by farm system.

Phosphorus balance averaged 4.7 kg ha^{-1} across the sample. Specialist tillage farms had higher average P balances (6.3 kg ha^{-1}) compared to dairying (6.2–5.2 kg ha^{-1}) and livestock based systems (3.5–4.7 kg ha^{-1}) as seen in Figure 3.

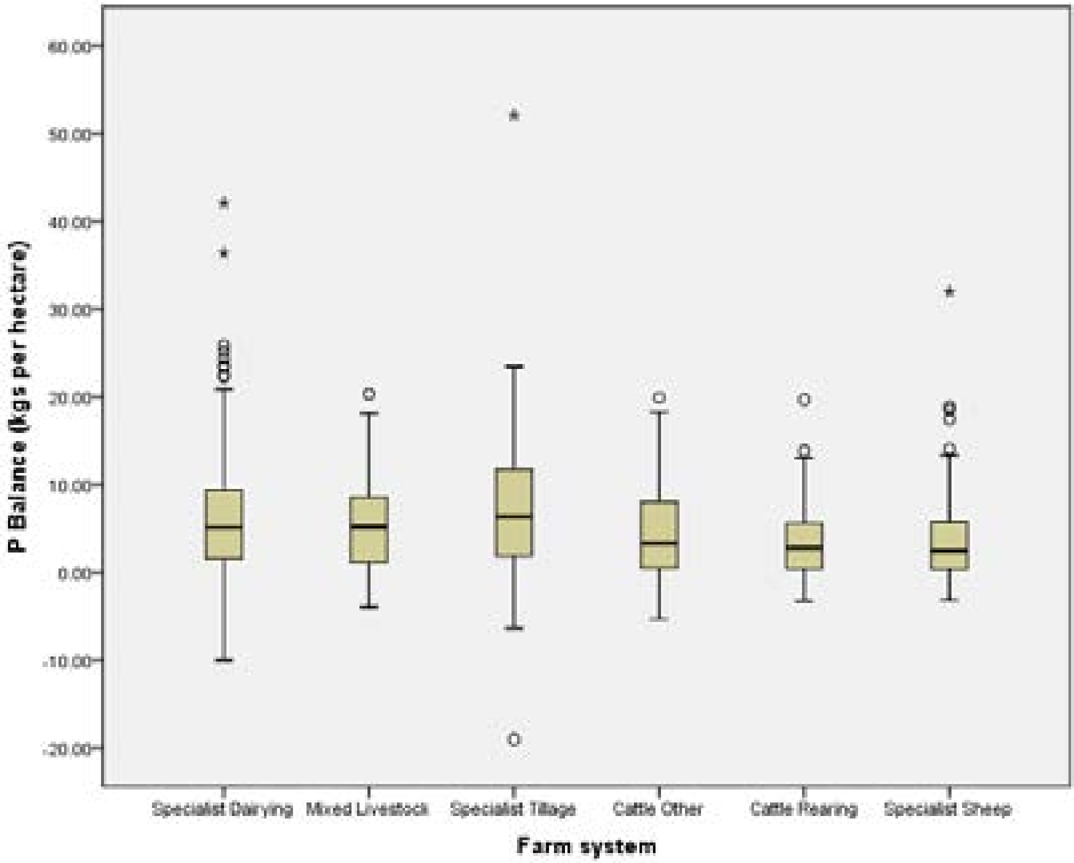


Figure 3: Distribution of P balance (kg ha^{-1}) by farm system.

Phosphorus use efficiency (PUE) averaged 79.6 % across all farm systems, with a median value of 57.4 kg ha^{-1}. Specialist sheep had the highest mean PUE at 97.7 %, however the median value for specialist sheep was the second lowest at 57.9 %. Cattle other (non-suckling) had the second highest mean PUE at 79.2 %, however median value was second lowest at 56.8%. Specialist dairying, mixed livestock, cattle rearing and specialist tillage systems averaged PUE's between circa 70–74 %. Cattle rearing (suckler cow based) had the lowest median PUE at 46.1% (Figure 4).

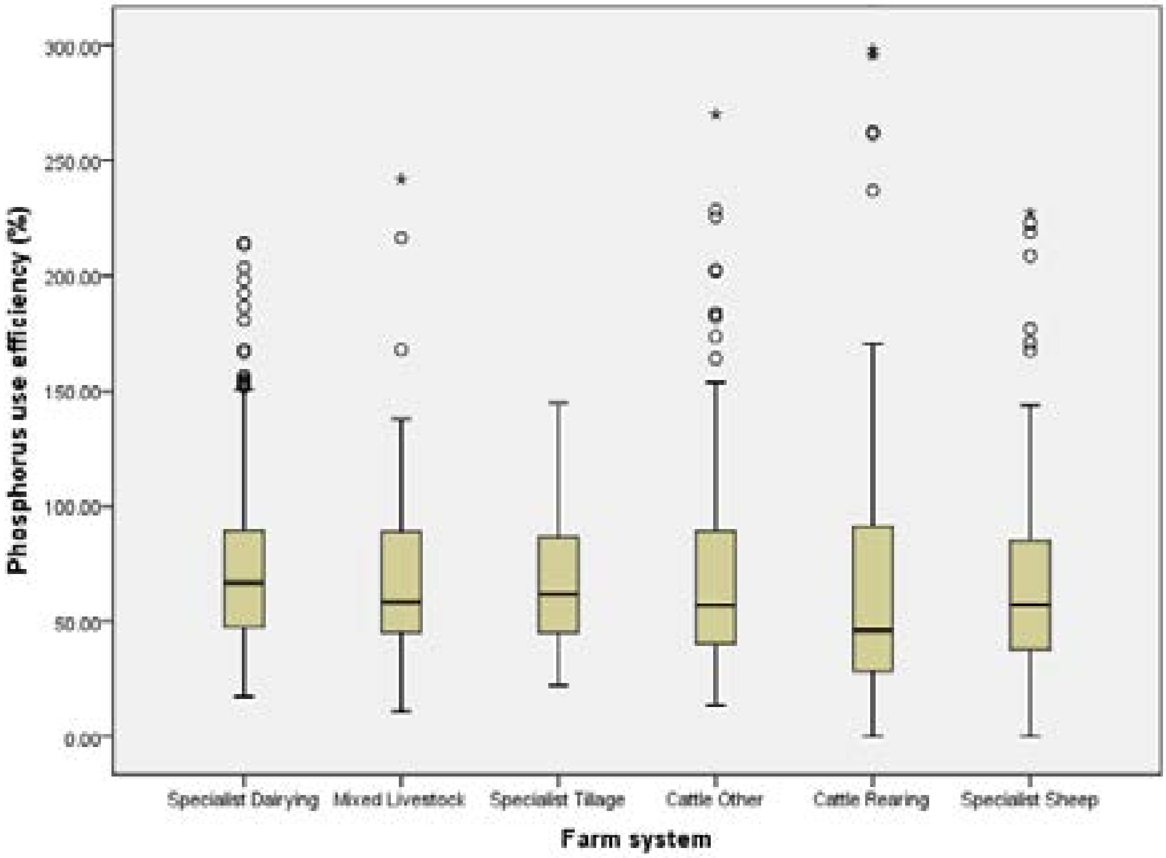


Figure 4: Distribution of phosphorus use efficiency by farm system.

Results from this study can provide a template and benchmark for temporal analysis nutrient use across these efficiency indicators for the Republic of Ireland and particularly in the sustainability context of intensification initiatives such as FoodWise 2025. Additionally, the template developed in this study could assist other members of the EU FADN to develop similar nationally representative indicators and allow overall EU assessments to be made for more global comparisons. This work is described in detail in Buckley et al., (2015).

Reference: Buckley, C., Wall, D.P., Moran, B., and Murphy, P.N.C., 2015. Developing the EU Farm Accountancy Data Network to derive indicators around the sustainable use of nitrogen and phosphorus at farm level. Nutrient Cycling in Agrosystems, 102, 319–333.

http://rd.springer.com/article/10.1007/s10705-015-9702-9

Paper 2:

Phosphorus management on Irish dairy farms post controls introduced under the EU Nitrates Directive.

Buckley et al. (2016)

KEY MESSAGES

- This study estimated farm-gate P balance and use efficiency across 150 dairy farms in the Teagasc National Farm Survey (NFS) over the period 2006-12.
- P balance declined by 50% from 11.9 to 6.0 kg ha^{-1} between 2006-2012.
- Decline can be attributed to reduced chemical P fertiliser inputs of 6.5 kg ha^{-1}.
- Phosphorus use efficiency improved by 18% over the study period from 60 to 78%.
- P balance and use efficiency were found to be significantly influenced by contact with extension services.
- P balance and use efficiency were also significantly influenced by factors such as fertiliser prices, stocking rates, land use potential, use of milk recording technology and rainfall patterns

SYNOPSIS

This study investigated changes in the use of P on specialist dairy farms since the introduction of controls through the EU Nitrates Directive based GAP regulations in 2006. This analysis was based on data from the Teagasc National Farm Survey (NFS). The analysis focused on a balanced panel of 150 specialist dairy farms that remained in this NFS over a 7 year period from 2006 to 2012. Average population weights over the period were employed and the sample was hence representative of 8,668 dairy farms nationally over the study period. Two indicators were developed in the study. Firstly, farm gate balance is an indicator of source pressure and was calculated by subtracting the total quantities of P (kg ha^{-1}) exported from the total quantities imported on a per hectare basis. Secondly, P use efficiency is a measure of agronomic efficiency and was calculated by dividing total P exported (kg) by total imported (kg), expressed as a percentage. The main farm gate P imports included chemical fertilisers, concentrate feeds, forage feeds, and purchased livestock.

Exports of P included milk, livestock, cereal crops, forage crops and wool as many farms had a second farm enterprise (beef, sheep, tillage) in conjunction with the main dairy enterprise. All import and exports were converted into kg P and indicators were derived on this basis. A number of farm level and environmental variables were expected to influence P balance and use efficiency. Hence, a random effects panel data model was used to explore the effect of these variables on P balance and use efficiency over the study period.

Results indicated that total P imports declined over the study period by 6.6 kg ha^{-1} (from 21.7 kg ha^{-1} in 2006 to 15.1 kg ha^{-1} in 2012). This was almost exclusively driven by a decline in chemical P fertiliser imports which fell by 6.5 kg ha^{-1} during the period from 13.3 kg ha^{-1} to 6.8 kg ha^{-1}. All other P imports remained relatively stable. Total P exports declined slightly by 0.7 kg ha^{-1} over the period (from 9.8 kg ha^{-1} in 2006 to 9.1 kg ha^{-1} in 2012). Milk was the dominant P export and accounted for approximately 60% of total P farm gate exports. Phosphorus based milk exports remained static over the period and was the same in 2012 as 2006 at 5.5 kg ha^{-1}. Results show that P balances declined by 50% over the study period (from 11.9 kg ha^{-1} in 2006 to 6.0 kg ha^{-1} in 2012 - Table 1). This decline was driven by a reduction in chemical fertiliser imports of 6.5 kg ha^{-1}. This is equivalent to a reduction of 281 kg of P and represents a cost saving of €812 per annum across the average farm as put remained relatively stable over the period.

Table 1: Phosphorus balance and use efficiency 2006-2012

Imports	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
P Fertilisers kg ha^{-1}	13.3	8.8	7.4	6.5	7.0	6.7	6.8
P Concentrates kg ha^{-1}	7.2	6.4	7.8	6.3	6.6	5.8	6.9
P Forage Feeds kg ha^{-1}	0.8	0.8	0.7	0.9	0.9	0.9	0.9
P Livestock Imports kg ha^{-1}	0.4	0.3	0.3	0.3	0.3	0.4	0.3
P Other Imports kg ha^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total P Imports kg ha^{-1}	21.7	16.3	16.2	14.0	14.8	13.8	15.1
Exports							
P Milk kg ha^{-1}	5.5	5.6	5.4	5.2	5.5	5.7	5.5
P Livestock Exports kg ha^{-1}	4.0	3.8	3.5	3.3	3.4	3.3	3.4
P Crops kg ha^{-1}	0.3	0.2	0.2	0.2	0.2	0.2	0.2
P Wool kg ha^{-1}	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total P Exports kg ha^{-1}	9.8	9.6	9.2	8.7	9.1	9.2	9.1
P Balance kg ha^{-1}	**11.9**	**6.7**	**6.9**	**5.3**	**5.7**	**4.6**	**6.0**
P use efficiency	**59.6**	**73.5**	**77.8**	**80.0**	**80.2**	**88.4**	**78.0**

Phosphorus use efficiency also improved over the period from 60% in 2006 to 78% in 2012, peaking in 2011 at 88.4% (Table 1). This was achieved while increasing milk solids output per hectare (increased from 44 kg ha^{-1} to 58 kg ha^{-1} over the period) and per cow (increased from 23 kg to 35 kg per cow 2006-2012).

An inverse relationship was found between fertiliser price and P balance (significant at the 1% level). Results indicated that a 1 unit increase in fertiliser price (€1/kg) leads to an estimated 1.736 kg ha^{-1} decline in P balance. However, it should be noted that such an increase would have the effect of increasing the average price of P fertiliser by 40%. Fertiliser price was found to have a positive and significant effect (also at the 1% level) on P use efficiency. Results show a 1 unit increase in fertiliser price predicting a 6.4% increase in P use efficiency. A positive and significant relationship was found between stocking rate as measured by organic P based stocking rate and P balance (significant at the 5% level). Results indicated a 1 unit increase in organic P kg ha^{-1} leads to a 0.192 P kg ha^{-1} increase in P balance. There was no statistically significant relationship found between P use efficiency and organic P based stocking rate. Off-farm employment was associated with a lower P balance and lower P use efficiency but again the effect was not found to be significant. Farmers who were in contact with an agricultural advisor or had contact with an advisor and a discussion group had significantly lower P balances (1% level) and higher P use efficiencies (5% level). Farmers with these extension contacts tended to have a P balance of approximately 4.2-4.7 kg ha^{-1} lower than the base category of no extension contact. Conversely, farmers in contact with the aforementioned extension contacts had 13-14% higher P use efficiency.

Table 2: Results of regression analysis on factors influencing P balance and P use efficiency

Variables	**P Balance Ha^{-1}**	**P Use Efficiency**
Fertiliser price	-1.736***	6.441***
	(0.435)	(2.373)
Organic P kg ha^{-1}	0.192**	0.077
	(0.089)	(0.385)
Farm Size	-0.043	0.070
	(0.041)	(0.249)
Mundlak – Farm Size	0.064	-0.258
	(0.0458)	(0.242)
Off farm-employment	-0.422	2.863
	(1.255)	(5.810)
Contact with farm Advisor	-4.171***	13.01**
	(1.191)	(5.459)
Contact with farm advisor & discussion group	-4.651***	14.258**
	(1.236)	(6.708)
Milk recording	-1.901***	13.64***
	(0.673)	(4.382)
Average land use potential	1.521*	-17.241***
	(0.882)	(4.781)
Poor land use potential	0.537	-21.629***
	(1.569)	(7.484)
Rainfall	0.0034***	-0.0187***
	(0.001)	(0.0065)
Temperature	0.160	1.005
	(0.335)	(2.244)
Constant	3.339	69.53***

*** p<0.01, ** p<0.05, * p<0.1 (robust standard errors in parentheses)

Additionally, farmers who engaged with milk recording had also significantly lower P balances and higher P use efficiencies (both at 1% level). Farmers using this technology were associated with a P balance that was 1.9 kg ha^{-1} lower and a P use efficiency that was 13.6% higher. Farmers operating on land of average (significant at the 10% level) and poor use potential were associated with higher P balances than those on better soils (good land use potential). A statistically significant relationship (1% level) was found between P use efficiency and land use potential. Phosphorus use efficiency was 17.2% lower for farms of average land use potential and 21.6% lower for farms of poor land use potential compared to the base category of good land use potential farms. Rainfall was found to have a significant effect on both P balance and use efficiency at the 1% level. Higher annual rainfall was associated with higher P balances and lower use efficiencies. No significant effect was found between temperature and P balance or use efficiency (Table 2).

Reference: Buckley, C., Wall, D.P., Moran, B., O'Neill, S., and Murphy, P.N.C., 2016. Phosphorus management on Irish dairy farms post controls introduced under the EU Nitrates Directive. Agricultural Systems, 142, 1-8.

http://www.sciencedirect.com/science/article/pii/S0308521X1530038X

Paper 3:

Farm gate level nitrogen balance and use efficiency changes post implementation of the EU Nitrates Directive

Buckley et al. (2016)

KEY MESSAGES

- This study estimated farm-gate N balance and use efficiency across 150 dairy farms in the Teagasc National Farm Survey (NFS) over the period 2006-12.
- N balance declined by 25.1 kg ha^{-1} from 180.4 to 155.3 kg ha^{-1} over the study period, this was attributable to reduced chemical N fertiliser imports of 23.1 kg ha^{-1}.
- N use efficiency improved by 2.1% over the 2006-12 period from 20.8 to 22.9%.
- N balance and use efficiency were significantly influenced by contact with extension services.
- N balance and use efficiency were also significantly influenced by other factors such as fertiliser prices, stocking rates, land use potential and climatic variables.

SYNOPSIS

The aim of this study was to estimate the farm-gate N balance and use efficiency across 150 dairy farms in the Teagasc National Farm Survey (NFS) over the first 7 years post implementation of the EU Nitrates Directive in the Republic of Ireland from 2006 to 2012. Average population weights over the period were employed and the sample was hence representative of 8,668 dairy farms nationally over the study period. Additionally, a panel data model analysis was used to explore environmental and managerial factors which influenced farm-gate N balance and use efficiency indicators over the study period. Two indicators were developed in this study on an annual basis. Firstly, farm gate N balance is an indicator of source pressure and was calculated by subtracting the total quantities of N (kg) exported from the total quantities imported on a per hectare basis. Secondly, nutrient use efficiency was calculated by dividing total N exported (kg) by total imported (kg), expressed as a percentage.

The main farm gate exports of N included milk, livestock, cereal and forage crops, as many farms had a second farm enterprise (beef, sheep, tillage) in conjunction with the main dairy enterprise. Imports principally included chemical fertilisers, concentrate feeds, forage feeds, and purchased livestock. All import and exports were converted into kg N and indicators were derived on this basis.

Results indicated that chemical fertiliser was the dominant N import; this accounted for 76-80% of total N imports over the period 2006-12. Total N imports declined from 221.3 kg N ha^{-1} in 2006 to approximately 197 kg N ha^{-1} in 2011-12. This decline (approximately 24 kg N ha^{-1}) was almost exclusively driven by a reduction in chemical N fertiliser use of 23 kg N ha^{-1} over the period from 177 kg N ha^{-1} in 2006 to 154 kg N ha^{-1} in 2012. Concentrate feedstuff accounted for the majority of the remaining N imports, averaging 16 to 21% of total N imports between 2006 and 2012. The main N export was via milk; this accounted for 73-78% of total N exports over the study period. Within a milk quota environment, milk based N exports from these farms were relatively stable over the period ranging from 29.9 kg N ha^{-1} to 33.7 kg N ha^{-1}. Livestock N based exports were the next major class of exports accounting for 19-24% of total N exports. The weighted average farm gate N surplus per hectare declined by approximately 16% over the period from 180.4 kg N ha^{-1} in 2006 to 155.3 kg N ha^{-1} in 2012 (Table 1). As output remained relatively stable over the period, this decline (of 25.1 kg N ha^{-1}) can almost entirely be attributed to reduced chemical N fertiliser inputs of 23.1 kg ha^{-1} over the period, equivalent to 1,247 kg N, or a cost saving of €1,347 per annum across the average dairy farm. Average farm gate nitrogen use efficiency also improved over the period from 20.8% in 2006 to 23.7% in 2011 and 22.9% in 2012. This was achieved while increasing milk solids output per hectare (increased by 44-58 kg ha^{-1} over the period) and per cow (increased by 23-35 kg per cow 2006-2012) in the context of a declining stocking rate (1.86 to 1.84 livestock units ha^{-1}).

Table 1: N Balance and use efficiency results 2006-12

Imports	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
N Fertiliser kg ha^{-1}	177.0	163.0	147.7	159.2	163.7	159.1	153.9
N Concentrates kg ha^{-1}	38.0	34.0	41.4	33.4	35.9	31.4	36.8
N Forage Feeds kg ha^{-1}	5.4	5.1	4.2	5.5	5.7	5.3	6.0
N Livestock Imports kg ha^{-1}	0.9	0.9	0.8	0.7	0.6	0.9	0.7
Total N Imports kg ha^{-1*}	221.3	203.0	194.1	198.8	205.9	196.7	197.4
Exports							
N Milk Exports kg ha^{-1}	29.9	30.5	29.8	28.6	32.8	33.7	32.6
N Crops Exports kg ha^{-1}	1.2	1.2	1.5	0.9	1.1	1.2	1.1
N Livestock Exports kg ha^{-1}	9.8	9.4	8.7	8.2	8.3	8.2	8.4
Total N Exports kg ha^{-1*}	40.9	41.1	40	37.7	42.2	43.1	42.1
N Balance kg ha^{-1}	**180.4**	**161.9**	**154.1**	**161.1**	**163.7**	**153.6**	**155.3**
Nitrogen use efficiency %	**20.8**	**22.4**	**22.7**	**20.8**	**21.8**	**23.7**	**22.9**

Following regression analysis a negative relationship (significant at the 1% level) was found between fertiliser price and N balance. Results indicated that a 1 unit increase in fertiliser price (€1 per kg of N) leads to an estimated 49.89 kg ha^{-1} decline in N balance. However, it should be noted that such an increase would be an effective doubling of the average price of N fertiliser. Conversely, fertiliser price was found to have a positive and significant effect (1% level) on N use efficiency with results indicating that a 1 unit increase in fertiliser price leads to a 5.619 percentage point increase in N use efficiency.

A positive and significant relationship (1% level) was found between organic N loading (stocking rate) and N balance. Results indicated that a 1 unit increase in organic N (1 kg ON ha^{-1}) leads to a 0.922 kg ha^{-1} increase in N balance kg ha^{-1}. Conversely, the stocking rate has a very small negative effect (significant at the 1% level) on N use efficiency with a 1 unit increase in organic N kg ha^{-1} indicating a 0.026 percentage point decline in N use efficiency. The small decline in N use efficiency per unit increase in intensity indicates that there is a relatively small change in use efficiency at higher stocking rates; an increase of 100 kg N ha^{-1} would be associated with a 2.6 percentage point decrease in N use efficiency.

Table 2: Results of regression analysis for factors influencing N balance and N use efficiency

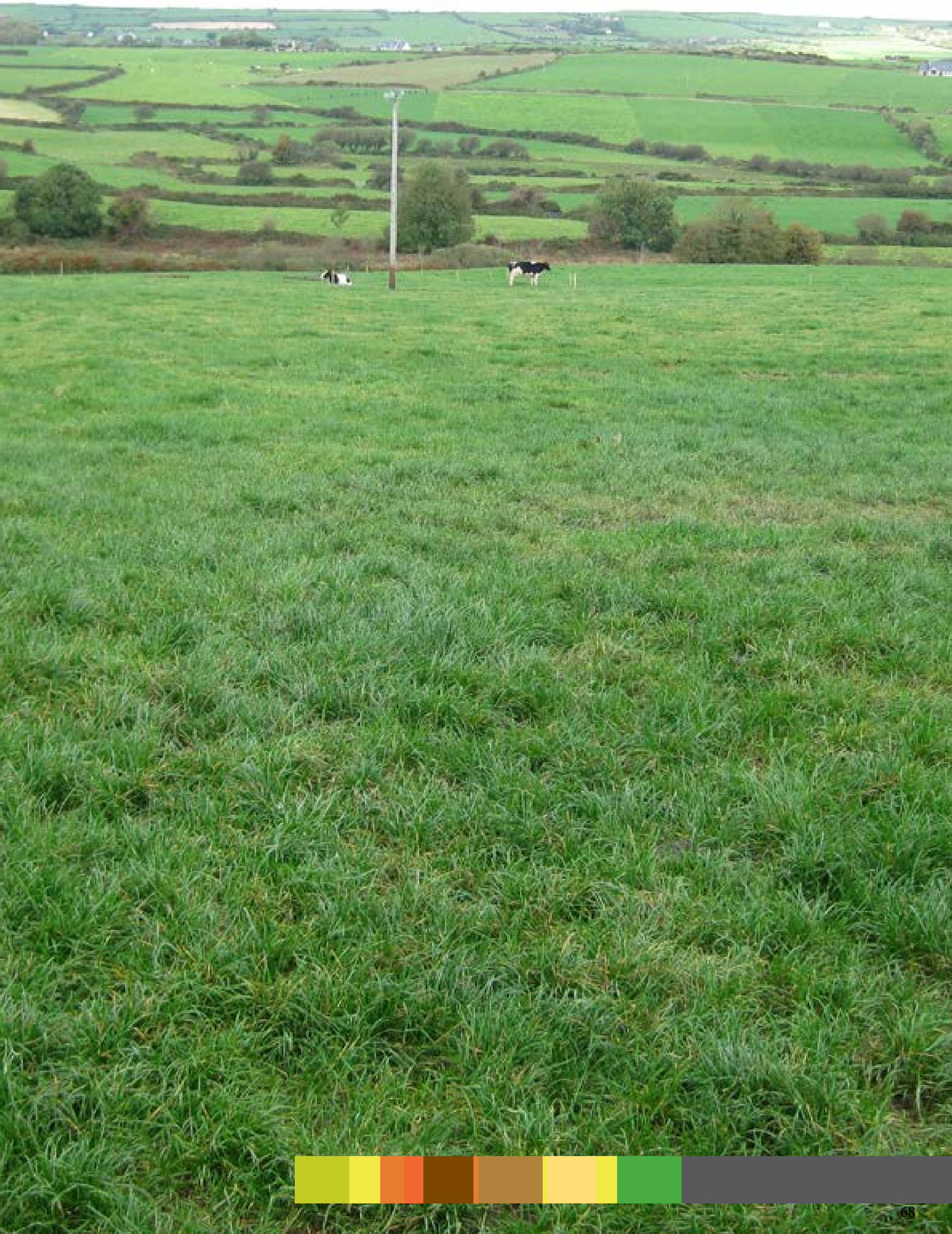
Variables	*N Balance kg ha^{-1}*	*N Use Efficiency (%)*
Fertiliser price	-49.89***	5.619***
	(9.82)†	(1.295)
Organic N kg ha^{-1}	0.922***	-0.026***
	(0.0831)	(0.0099)
Farm Size	-0.226	-0.0382
	(0.268)	(0.0381)
Mundlak – Farm Size	0.590**	-0.0001
	(0.268)	(0.0422)
Off farm-employment	5.741	-0.153
	(8.225)	(0.999)
Contact with farm Advisor	-7.11	1.36*
	(6.161)	(0.801)
Contact with farm advisor & discussion group	-3.87	1.625*
	(6.51)	(0.857)
Average land use potential	-9.88	-1.27
	(6.893)	(0.804)
Poor land use potential	-8.11	-4.74*
	(9.33)	(1.321)
Rainfall	0.0099	-0.003***
	(0.007)	(0.001)
Temperature	-2.947	0.726**
	(2.337)	(0.305)
Constant	61.15**	18.27***
	(29.27)	(3.807)

*** p<0.01, ** p<0.05, * p<0.1 (robust standard errors in parentheses)

Contact with extension services (contact with farm advisor and/or discussion group membership) was found to have a negative effect on N balance (surplus) but the effect was not significant. However, contact with an agricultural advisor and/or discussion group membership was found to have a significant positive effect on N use efficiency (both at 10% level). Compared to dairy farms operating on land with good use potential, those farmers operating on land with average or poor use potential had lower N balances but the effect was not significant. Conversely, farms of good land use potential had higher N use efficiency compared to the average and poor land use potential groups. This effect was significant (10% level) compared to the poor land use potential cohort with N use efficiency 4.74 percentage points higher on farms of good land use potential. Finally, higher annual rainfall was associated with higher N balances and lower N use efficiency. The effect was significant for N use efficiency at the 1% level. Conversely higher mean annual temperatures were associated with lower N balances and higher N use efficiency. However, again the effect was significant only for N use efficiency (5% level) as outlined in Table 2.

Reference: Buckley, C., Wall, D.P., Moran, B., O'Neill, S., and Murphy, P.N.C. 2016. Farm gate level nitrogen balance and use efficiency changes post implementation of the EU Nitrates Directive. Nutrient Cycling in Agroecosystems, 104, 1-13.

http://rd.springer.com/article/10.1007/s10705-015-9753-y



Paper 4:

Responses to phosphorus mitigation measures across the nutrient transfer continuum in a dairy grassland catchment

Murphy et al. (2015)

KEY MESSAGES

- Environmental and economic performance was monitored in an intensive dairy catchment over several years with an emphasis on phosphorus.
- Farmers were found to have improved their nutrient management resulting in a decrease in P index 4 (excessive) soils and an increase in P index 3.
- Output and gross margins on dairy farms in the catchment have remained on a par with the top 10% of Irish dairy farms.
- There was some evidence of reduced P concentrations in stream water but only in that contribution from near surface quickflow pathways.
- There was no clear evidence of changes in stream biological quality.
- These results point to a clear potential to reduce excessively high soil P concentrations in the most intensive dairy catchments in line with Nitrates Directive regulations and without economic penalty; water quality benefits are emerging at a slower pace.

SYNOPSIS

Very precise monitoring is needed to tease out what happens to nutrients following applications to soil. Nationally, P is the nutrient that causes the most difficulty with water quality. The Nitrates Regulations (GAP Measures) limit how much N and P can be applied, for P the objective is to reduce soil P levels where they are high (P Index 4) to reduce risk to water. However the effects of reducing P can't be predicted exactly - it could reduce the P transferred into in rivers during rainfall but could also reduce soil P levels below what is best for grass growth, with possible knock-on reductions in farm profitability. This trail from P use and soil P level, through losses from soil during rainfall, subsequent ecological impacts in water and possible economic impacts is known as the nutrient continuum or 'cascade'. This is what the

ACP has set measured with high precision over successive years. Some of the emerging research on trends in the nutrient cascade over a 3-4 year period in the intensive dairy Timoleague catchment (Grassland A) has been reported.

Soil and water trends

Soils were intensively sampled in 2009/2010 and again in 2013. During this time, water quality in the stream was monitored, spring and autumn ecological surveys were conducted and nutrient use and production were monitored. This catchment had the highest numbers of soil P index 4 fields of the six monitored, 32% in 2009/2010. By 2013 this figure had fallen to 24% and the proportion of fields at index 3 (the recommended level for good grass growth and cow health) had increased from 27 to 36% (Fig. 1). There was little change in the number of index 1 and 2 fields but these fields did show an increase in the average P test level indicating that farmers were building them up gradually. Overall there was a small P surplus of 2.4 kg/ha per year across the catchment – low by comparison with other intensive milk production areas internationally. The equivalent of 89% of the P that was spread left the farms in products (mostly meat and milk) giving a very high level of P use efficiency.

In other parts of the cascade, despite wetter years which provided more water to carry off P from the land to the water, the results of the water monitoring showed some reductions in concentrations of P. These decreases occurred in near surface quickflow hydrological pathways, where contact with soil P would be greatest (Fig. 2). Over time, it can be expected that decreases in P index 4 fields will lead to improvements in water quality but the ecological recovery is still not possible to predict.

Production and gross margins maintained

Expansion occurred on the catchment dairy farms between 2010 and 2012 with more land and increased numbers of dairy cows. The farms remained on a par with the top 10% of specialist dairy farmers nationally; the stocking rate was 2.48 LU/ha (2.47 LU/ha - top 10%), 1125 kg milk solids/ha (1045 kg milk solids /ha top - 10%) and, importantly, gross margin from dairying was maintained at a high level being just slightly lower than the average for the top 10% (€3,130/ha versus €3,261/ha).

This study is described in detail in Murphy et al. (2015).

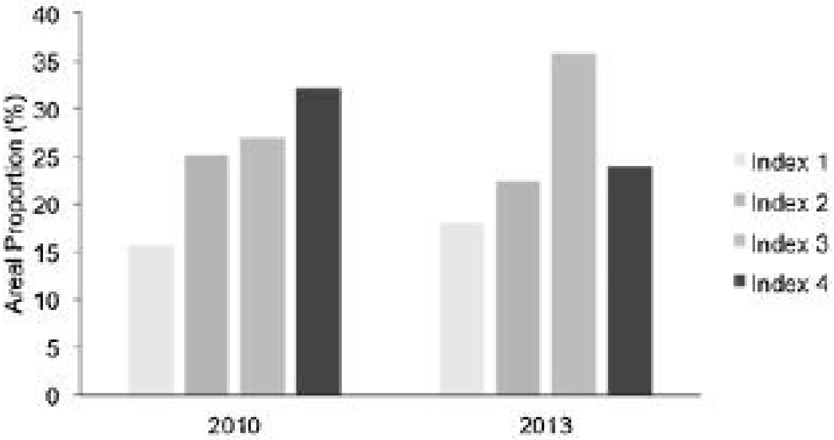


Figure 1: The areal proportion of soils in each soil P index in 2010 and 2013.

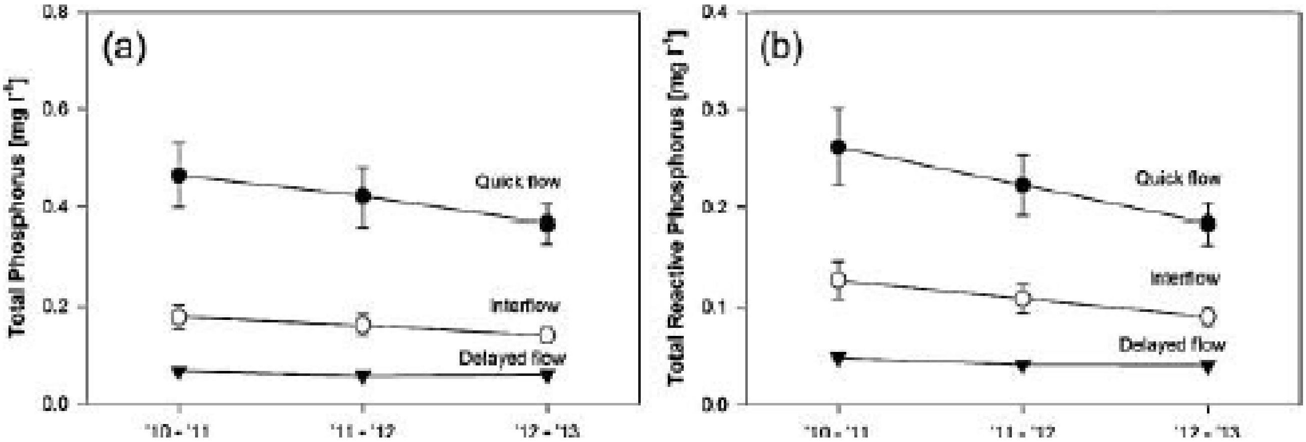


Figure 2: Flow-weighted mean TP (a) and TRP (b) concentrations based on daily transfer pathways over three closed periods. Error bars indicate standard error.

Reference: Murphy, P.N.C., Mellander, P.-E., Melland, A.R., Buckley, C., Shore, M., Shortle, G., Wall, D.P., Treacy, M., Shine, O., Mechan, S. and Jordan, P. 2015. Variable response to phosphorus mitigation measures across the nutrient transfer continuum in a dairy grassland catchment. Agriculture, Ecosystems and Environment. 207, 192-202.

http://www.sciencedirect.com/science/article/pii/S0167880915001401

Paper 5:

Incidental nutrient transfers: assessing critical times in agricultural catchments using high-resolution data

Shore et al. (2016)

KEY MESSAGES

- This study investigated links between slurry spreading restrictions during 'closed' (and adjacent) periods and water quality.
- Nutrient losses were disproportionately high during the closed period and likely derived from soil stores using a suspended phosphorus to sediment ratio in river water.
- Using the same ratio, some of the early closed period losses were also associated with slurry/manure.
- In the four weeks following the end of the closed period, despite continued soil moisture vulnerability, the ratio found no signals of slurry/manure transfer.
- This implies that farmers were either not spreading slurry during these four weeks or were choosing to spread on soils where nutrient transfer risk was low.
- Promoting these practices among farmers (i.e. focusing spreading to the best places and times) through knowledge transfer will be important to avoid storm driven incidental nutrient transfers.

SYNOPSIS

Closed periods for nutrient application were introduced across the Republic of Ireland in 2006 under the Nitrates Directive National Action Programme (NAP) (SI 378, 2006). The slurry closed-period starts on the 15th October and finishes between 12th and 31st of January, depending on climatic zones. An evaluation of the critical times for nutrient transfer to catchment streams forms a necessary part of NAP reviews and was provided in this study.

Soil moisture deficits (SMDs) were modelled in five agricultural catchments during (i) the closed period, (ii) the adjacent 'shoulder periods' and (iii) the open period (i.e. the rest of the year) to identify when nutrients were most susceptible to mobilisation and transfer in runoff.

High resolution measurements of nutrient concentrations and loads were analysed at catchment outlets during these three distinct periods (i – iii above) to identify:

1. The timing of greatest nutrient losses from the catchments.
2. Signals of elevated nutrient source pressures (e.g. slurry spreading) - as detected by increased nutrient concentrations in similar storm discharges.
3. When signals of elevated nutrient source pressures were not associated with soil erosion processes - as detected by increased ratios of total phosphorus (TP) to suspended sediment (SS) in similar storm discharges - and were therefore indicative of slurry/manure sources.

Closed-period

- Average annual TP and nitrate-N loads were disproportionately high during the slurry closed period supporting the notion of restricting nutrient applications during this time, as any additional source pressures may exacerbate the existing losses.
- Nutrient losses during the closed period appeared to be predominantly derived from soil stores. However, there was evidence that some of the nutrient transfers in the early closed period were associated with slurry/manure (rather than soil) which may have been applied just prior to the start of the closed-period in preparation for winter housing of animals.

Shoulder periods (4 weeks before and 4 weeks after closed-period)

- Nutrient loads were higher during the four weeks after the end of closed period compared to the two weeks before the start of the closed period.
- Modelled SMDs indicated a continued vulnerability to nutrient mobilisation during the four weeks after the end of the closed period (e.g. Fig. 1 - one Grassland catchment used to illustrate the main findings).

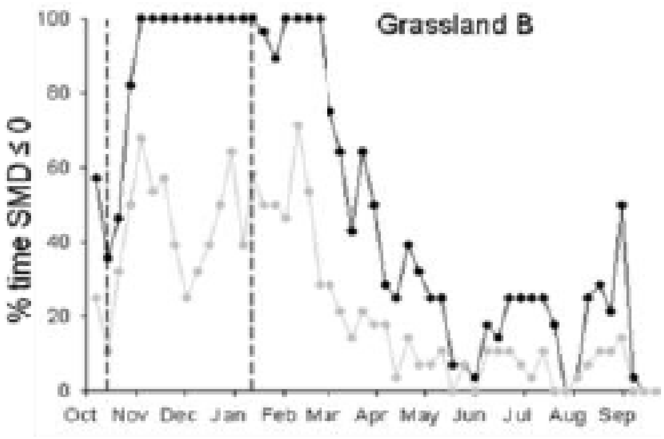


Figure 1: Weekly, the average time over four years (October 2010 –2014) that SMDs were ≤ 0, (assumed to represent critical times for nutrient mobilisation) in Grassland B for both well and poorly drained soil drainage scenarios. Black vertical lines represent the regular closed period beginning and end dates.

There was no evidence of any slurry/manure transfers during the four weeks after the end of the closed period (no increase in nutrient source signals, e.g. Fig. 2, or storm TP/SS ratios, e.g. Fig. 3)

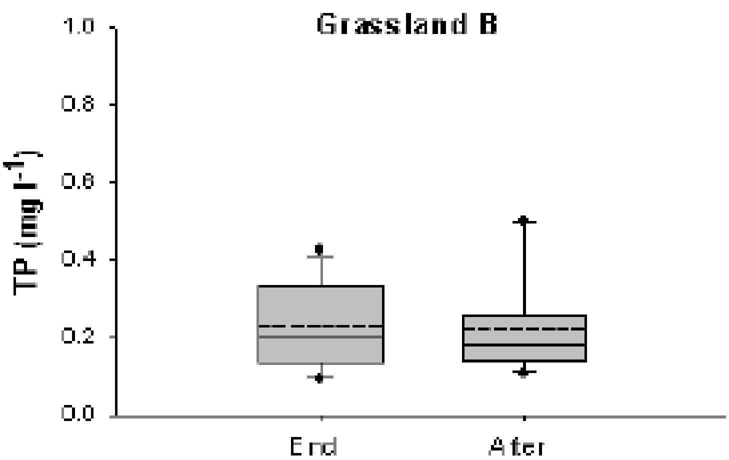


Figure 2: Storm TP concentrations for the four week periods at the end of (End) and after (After), the regular closed period, for four years (October 2010 –2014) in Grassland B.

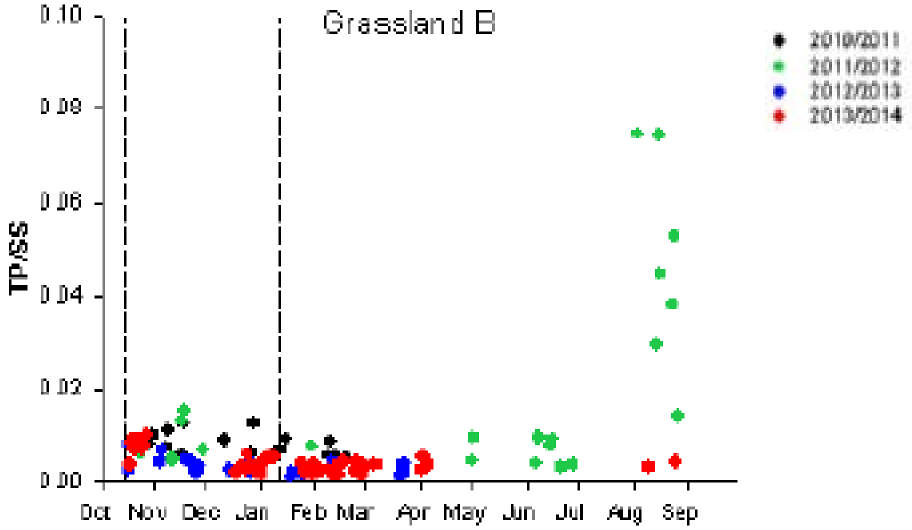


Figure 3: Ratio of TP load to suspended sediment (SS) load during 'storms' over four years (October 2010 - 2014) in Grassland B. Black vertical lines represent the regular closed period beginning and end dates.

This implies that slurry either wasn't spread during these four weeks (and subsequently not lost as incidental transfers in storms) or that slurry was spread on more freely draining soils where the risk of mobilisation and transfer to the stream was low. The signals of slurry/manure transfers used in the present study will require some other validation from one or more emerging hydro-biochemical tracing tools.

Open-period (remainder of year)
The data in this study showed sporadic occurrences of storm nutrient losses during the spring/summer time, with evidence of increased source pressures, attributed to transfer of soils and slurry/manure (e.g. elevated TP/SS ratios in August 2012, Fig. 3).
This is a concern considering this is the period when the ecological risk is greatest.

It is inferred from this study that farmers are implementing practices that reduce the risk of nutrient transfers from manure applications in the weeks after the end of the closed-period. These practices are likely to be focussing slurry applications at those times (higher SMDs) and/or those places (freer-draining soils) when potential for nutrient mobilisation and transfer is low. Such practices could be promoted among farmers through appropriate knowledge transfer methods to mitigate the risk associated with storm driven slurry transfers during the early closed-period, derogated periods and more importantly, during sensitive summer periods.

Reference: Shore, M., Jordan, P., Melland, A.R., Mellander, P.-E., McDonald, N., Shortle, G. 2016 Incidental nutrient transfers: assessing critical times in agricultural catchments using high-resolution data. Science of the Total Environment, 553, 404-415.

http://www.sciencedirect.com/science/article/pii/S0048969716302959

Paper 6:

Investigating trajectories of change in ecology quality in agricultural stream catchments – impediments and implications

Subject to peer-review

KEY MESSAGES

- This study investigated stream flow dependence on biology (diatoms and macroinvertebrates) and signals of faecal pollution across the flow range.
- In five catchments with variable biological quality, the records in May following high flow periods were generally of higher quality than in September following low flow periods.
- The seasonal trends of better biological quality in May were stronger than any other identifiable inter-annual trends over the five years.
- In one case study catchment, low flows had faecal signals associated with human and ruminant sources – and long durations of high P concentrations. These faecal signals (but not P) were diluted at higher flows.
- Summer ecological surveys will require benchmarking against the effects of chronic, multiple and seasonal pressures in order to be used as metrics of agricultural diffuse pressure changes in the ACP and similar catchments.

SYNOPSIS

The ACP is assessing all stages of the nutrient transfer continuum to evaluate whether changes in source pressures from the Nitrates Directive measures will be detectable in the ecological status of catchment waters. This will enable the agricultural sector to gauge whether it can sufficiently contribute to the achievement of at least 'Good status' river water quality nationally, as required by the Water Framework Directive (WFD).

This study focused primarily on the biological/ecological impacts component of this continuum, describing the baseline biological quality of stream water in six agricultural catchments, investigating trajectories of change and exploring the impediments to achieving a positive trajectory and therefore achieving WFD objectives in these catchments. Stream benthic diatom and macro-invertebrate quality was measured in September (post summer) from 2009 to 2015 and in May (post winter) from 2010 to 2015 using standard methods, at multiple (3-5) sites within five surface water catchments (Grassland A, B, C; Arable A, B). Diatoms only were measured over the same period, at the same frequency, in the emergence channel of a karst spring (Grassland D). Macro-invertebrate Q-values and diatom TDIs were calculated and expressed as ecological quality ratios (EQRs).

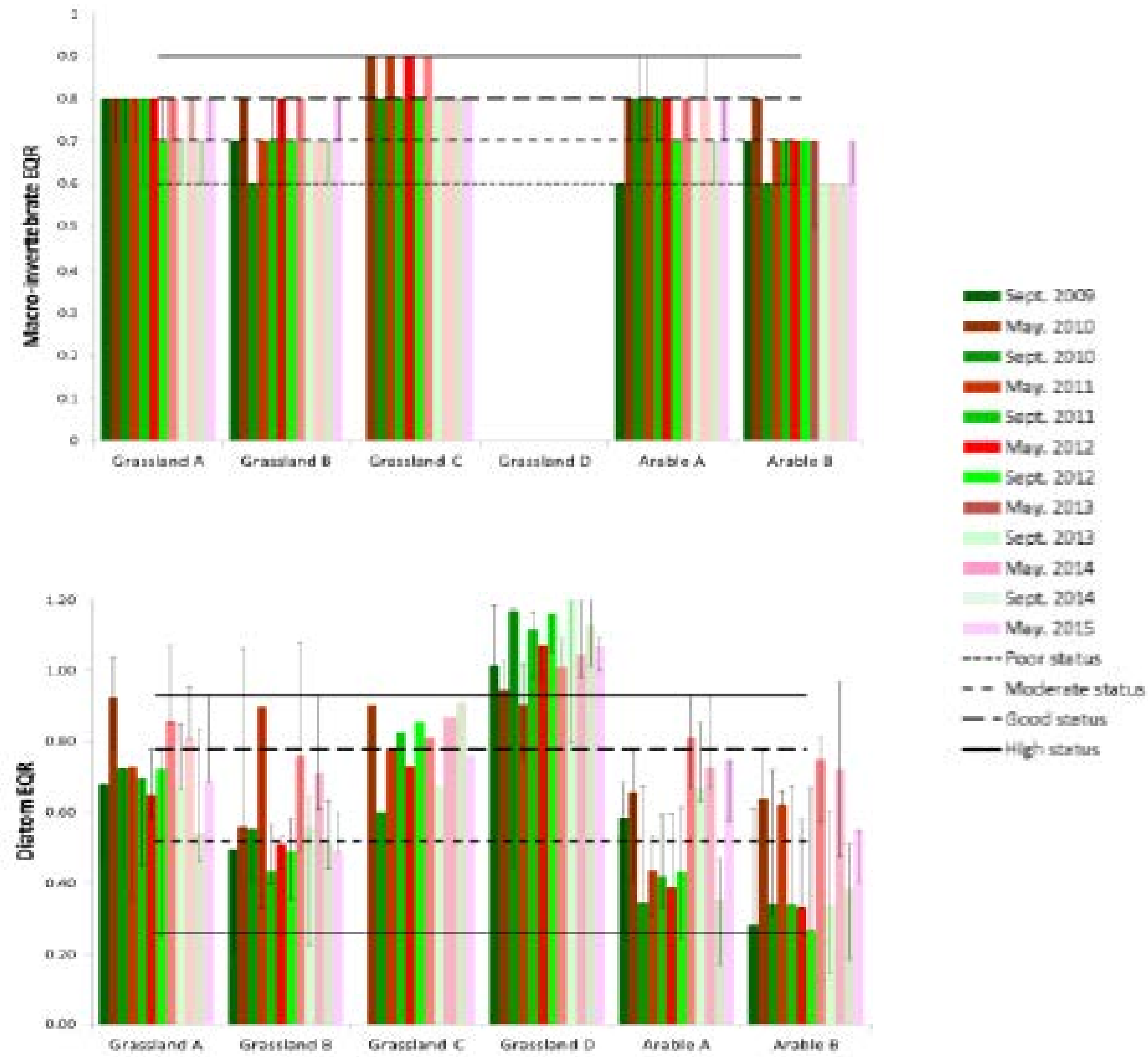
Sub-hourly unfiltered total phosphorus (TP), total reactive phosphorus (TRP) and nitrate-N concentrations were measured at each catchment outlet. These were analysed for 'spring' (the 3 months prior to the May ecology survey) and 'summer' (the 3 months prior to the September ecology survey) periods. The chemical water-quality in 'spring' was then compared to the ecological quality in May and the chemical water-quality in 'summer' was compared to the ecological quality in September.

Genetic markers of the Bacteroidales environmental bacteria were catalogued from a range of faecal sources (human and animal) in one case study catchment (Arable B). Assays were then applied to stream water samples collected across the flow range (from low to high) to detect the presence of host associated faecal matter. E. coli bacterial numbers were also measured in water samples.

Baseline ecological status and temporal trends

The Grassland C drumlin catchment was the only catchment to consistently present Good macro-invertebrate status required by the WFD (Fig. 1a). Grassland A and Arable A catchments consistently presented Good status in May but have not presented Good status in September since 2011. Grassland B and Arable B have achieved Good status in May at least once, but have never achieved Good status in September. These seasonal trends of better macro-invertebrate quality in May compared to September were stronger than any inter-annual trends. Whilst there are early indications of a decline in the September macro-invertebrate quality in Grassland A and Arable A, longer-term data-sets are required to discern if these emerge into real trends. The Grassland D karst catchment was the only catchment that consistently presented Good diatom status or higher (Fig. 1b).

A



B

Figure 1: a) Benthic macro-invertebrate EQR and b) Diatom EQR for each catchment outlet over 11 surveys a) Error bars denote the range across all survey sites. Horizontal line shows WFD status boundaries

In the Grassland C drumlin catchment, Good status was achieved for 6 of the 11 surveys and no seasonal trends were apparent. For the other 4 catchments, Good diatom status was never achieved in September and very rarely achieved (1 to 3 occasions) if at all (never in Arable B) in May. These seasonal trends of better diatom quality in May compared to September were stronger than any inter-annual trends. There are early indications of an improvement in the May diatom quality in the Arable A catchment - however, longer-term data-sets are required to discern if these emerge into real trends.

Baseline nutrient status and temporal trends

The Grassland D karst catchment was the only catchment with P concentrations consistently below the EQS of 0.035mg/l and the only catchment where P concentrations did not exhibit marked seasonal trends (Fig. 2). In all other catchments TRP concentrations were almost always higher in summer than spring, and often exceeded the EQS (summer only in Grassland C and Arable A). These summer seasons (except 2012) were characterised by low flows when agriculture soils are least hydrologically connected. The higher P concentrations during 'summer' were frequently followed by a decline in the ecological quality in September, particularly the diatoms, with a subsequent recovery evident the following May.

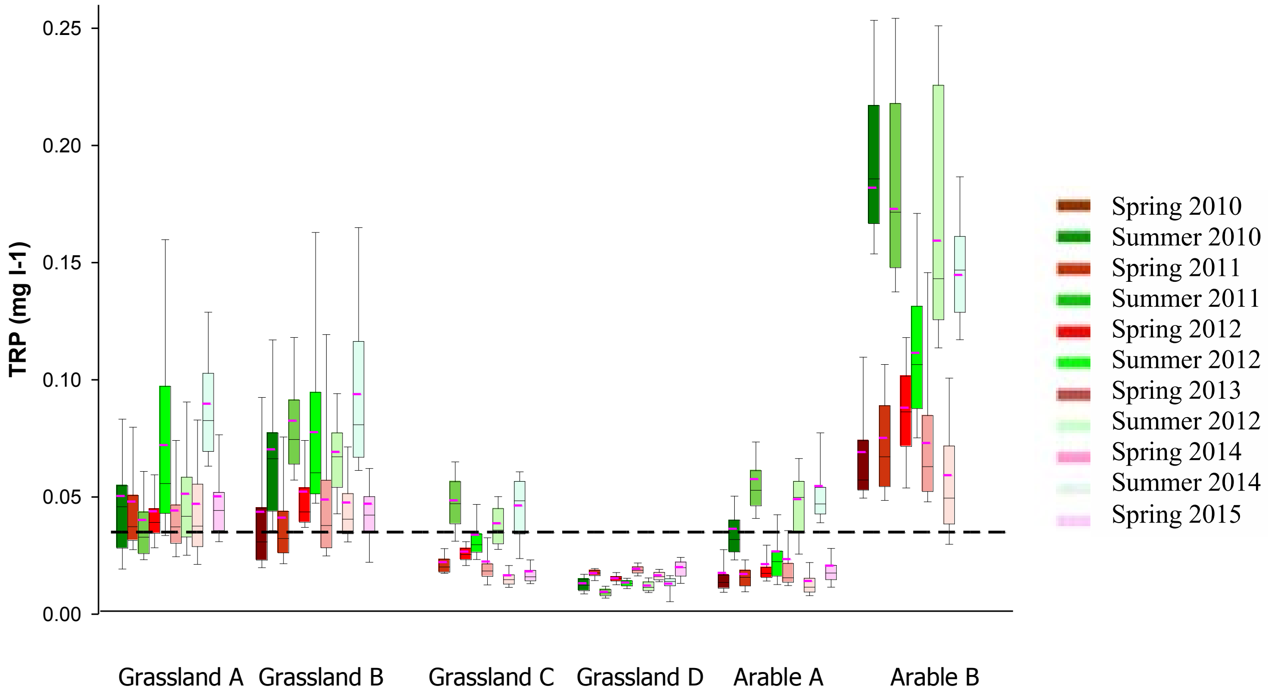


Figure 2: Distribution of stream TRP concentrations (hourly means) during spring (February-April) and summer (June-August) over the survey period.

Comparison of P concentrations with ecological quality

A broad relationship existed between TRP and diatom EQR, showing a positive response to nutrient concentration reduction at TRP < 0.035 mg/l and a negative response to nutrient concentrations above this threshold (Fig. 3). This indicates that the current stream P standard was a suitable threshold to describe good diatom quality in these rural headwater streams – albeit with chemistry collected at a very high resolution and collated to monthly averages. The relationship between TRP and macroinvertebrate EQR was less clear, but still showed a positive response to nutrient concentrations below 0.035 mg/l (data not shown). Cases of good chemistry and poor ecology occurred and may be due to specific hydro-morphology pressures and episodic pollution. Cases of good ecology and bad chemistry also occurred, but mostly for the macro-invertebrates and indicate that other factors (such as sediment and oxygen levels) may be more important drivers of macro-invertebrate quality than stream P levels.

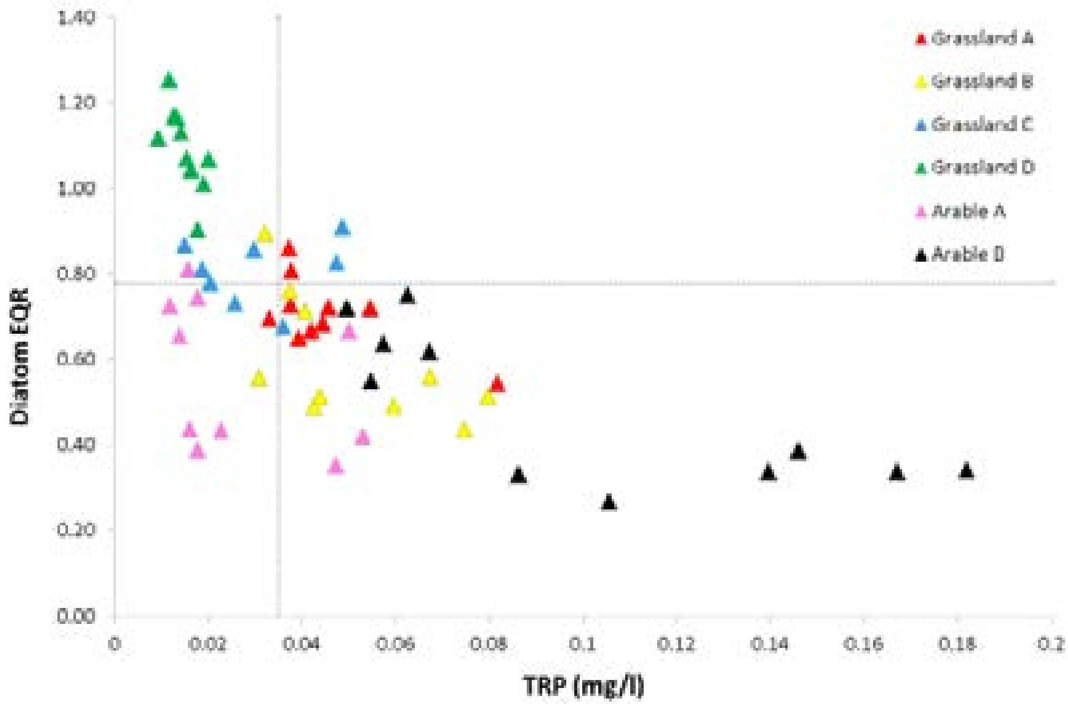


Figure 3: Relationship between diatom EQR and TRP concentrations (median of the three the preceding months) over five years (2009 -2014). Solid lines show 'Good' diatom status and TRP concentration thresholds

Case study host associations of faecal matter

Sampling during periods of low to high discharge in Arable B showed that P concentrations and (to a less extent) E. coli numbers were high at both low and high river discharge conditions (Fig. 4a and 4b). This shows, at low flows, an association with P and bacteria due to loss of dilution likely from persistent point sources and an association at high flows due to storm flow path connection with soil surfaces. E. coli can be present in both faecal matter and also from the natural soil flora. However, when Bacteroidales markers were analysied in the same range of samples, they appeared to be persistently high at low flows for both human and ruminant sources but not at as persistent at high flows (Fig. 5 a and 5b). This indicates that these long duration low flows were likely polluted with rural point sources such as domestic waste water discharges and farmyards. While P concentrations were also high during episodic high discharges (from diffuse, hydrologically connected sources), the human and ruminant associated faecal markers were diluted to less than detection.

Ongoing work will determine whether the seasonal ecological data are reflective of multiple stressors having seasonal impacts – or are reflective of ecological life-cycle stages.

However, reducing summer point source discharges may be an important way to improve ecological quality in these and similar catchment streams. This would at least enable this type of ecological monitoring to be reflective of changed diffuse source pressures and their cumulative downstream impacts and trajectories.

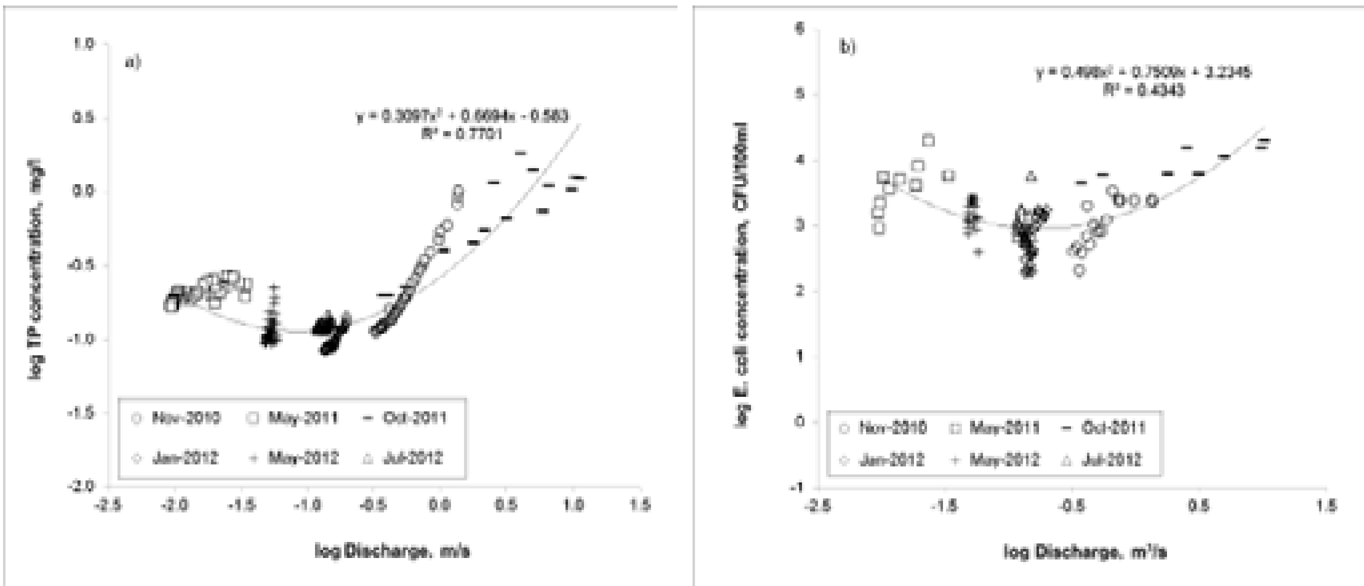


Figure 4: a) Phosphorus concentrations and b) E. coli numbers in a series of low to high flow periods in the Arable B catchment river.

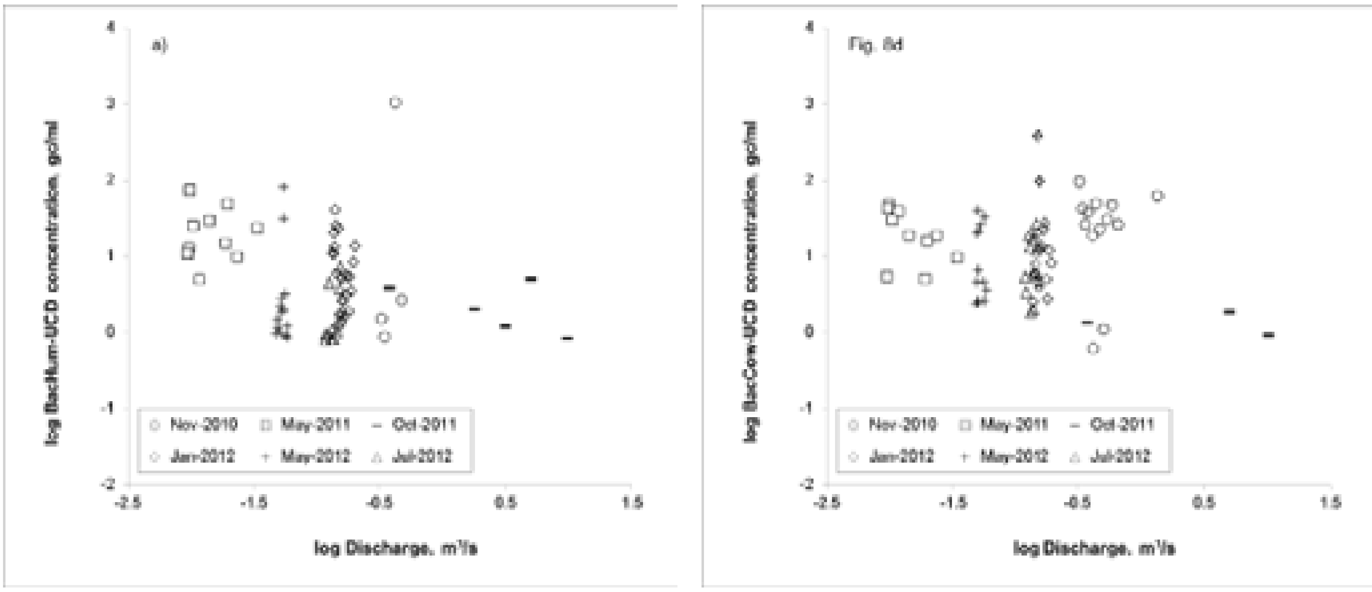


Figure 5: a) Human associated markers using Bacteroidales and ruminant associated markers from low to high flow periods in the Arable B catchment river.

Paper 7:

Groundwater denitrification in two agricultural river catchments: coupling of NO_3- consumption and N_2O/N_2 production

McAleer et al. (2017)

KEY MESSAGES

- Denitrification represents a significant nitrate (NO_3^-) removal mechanism in groundwater, but is spatially heterogeneous across hillslope zones and aquifer depths.
- Complete denitrification accounted for in excess of 90% removal of agriculturally derived NO_3^- where appropriate environmental criteria were met.
- In some places incomplete denitrification resulted in high nitrous oxide (N_2O) emissions.
- The five year spatiotemporal mean (2010-2015) NO_3^- concentrations were below the Irish drinking water standards (8.5 mg N/L) for two groundwater fed catchments
- For WFD (and drinking water) objectives, targeted mitigation measures must both consider and protect denitrifying zones to reduce nitrate leaching to groundwater or losses to surface waters.

SYNOPSIS

Increased agricultural productivity is coupled with an increase in the availability of nitrate (NO_3^-) to surface and groundwater. The identification of subsurface environments with a natural capacity to attenuate NO_3^- is essential to the development of sustainable management strategies. Denitrification is a microbially mediated process whereby NO_3^- is reduced to dinitrogen (N_2) gas. In base flow dominated catchments, groundwater denitrification has the capacity to mitigate stream water nitrogen (N) enrichment by returning N to the long residence time atmospheric pool.

Denitrification can represent an environmentally positive process; however, such a characterisation is subject to an important caveat. The reaction is sequential and as such there are several intermediary products including nitrite (NO_2^-), nitric oxide (NO) and nitrous oxide (N_2O). The differentiation between which reaction product is dominant is of key environmental concern: N_2 gas is environmentally benign whereas N_2O production represents a potent greenhouse gas source. The efficiency of NO_3^- removal versus the ratio of reaction products in groundwater is highly variable and depends upon aquifer hydrology, mineralogy, dissolved oxygen, energy sources and redox chemistry.

The objectives of the study were 1) to quantify the capacity of groundwater pathways to naturally attenuate agriculturally derived NO_3^- and 2) to elucidate the environmental parameters governing denitrification progress and N_2/N_2O emission ratios.

Spatial and temporal monitoring (shallow to deep groundwater pathways) was undertaken along four hillslopes in two ca. 10km^2 catchments. Both catchments are characterised by well drained soils, but exhibit contrasting subsurface lithologies (Devonian sandstone vs. Ordovician slate). The capacity for groundwater denitrification was assessed by measuring the concentration and distribution patterns of N species and aquifer hydro-geochemistry, in monthly samples from a network of piezometers (n=37) from 2010-2015. From 2013 – 2015, the gaseous products of denitrification (excess N_2 and N_2O) were measured seasonally.

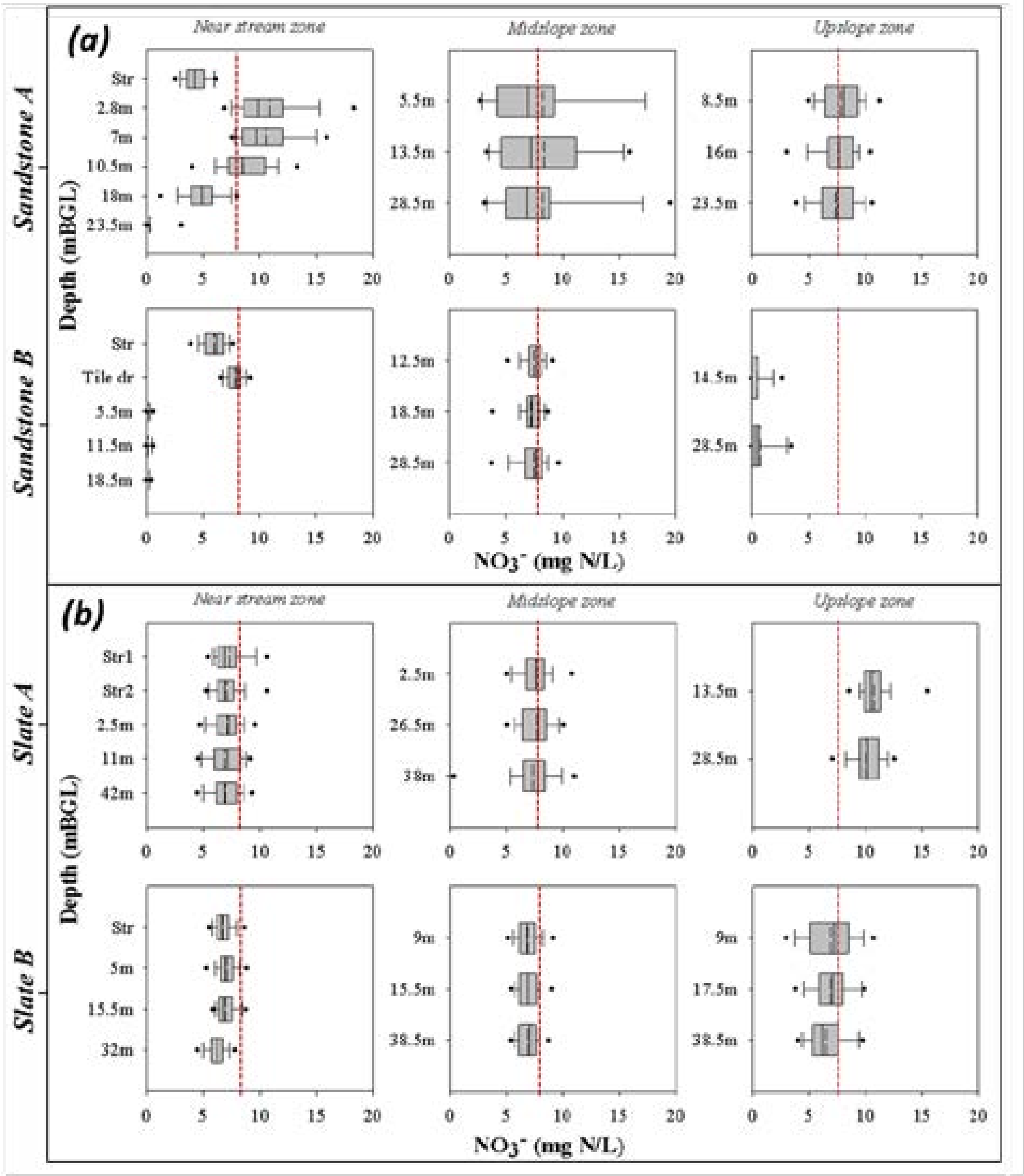


Figure 1: Boxplots of groundwater NO_3^- concentrations from four hillslopes in two catchments with contrasting geology and aquifer flow paths. The two hillslopes in each catchment are labelled Hillslope A and Hillslope B respectively.

Groundwater in the sandstone catchment had a lower spatiotemporal mean NO_3^- concentration (5.6 mg N/L) than the slate catchment but exhibited substantially greater variability (SE: 0.12, CV: 81%), with hillslope zone and groundwater depth being statistically significant ($p < 0.001$) (Fig.1a). N_2/N_2O accumulation was high with NO_3^- and N_2 strongly correlated to dissolved oxygen concentration (NO_3^- positively & N_2 negatively) (Figs. 2a, b, c).

In the slate catchment groundwater was characterised by homogeneity (Fig. 1b). The five year spatio-temporal mean NO_3^- concentration of 6.8 mg N/L exhibited limited variation throughout the sampling period (SE: 0.06, CV: 25%). Elevated dissolved oxygen and positive redox potential across hillslope zones i.e. upslope vs. midslope vs. near stream and sample depths indicated a setting with little denitrification potential This was reflected in high groundwater/stream NO_3^- concentrations (Figure 1b), a limited accumulation of excess N_2/N_2O (Figures 2a, b, c) and denitrification rates consistently below 20% (Figs. 2d, e, f).

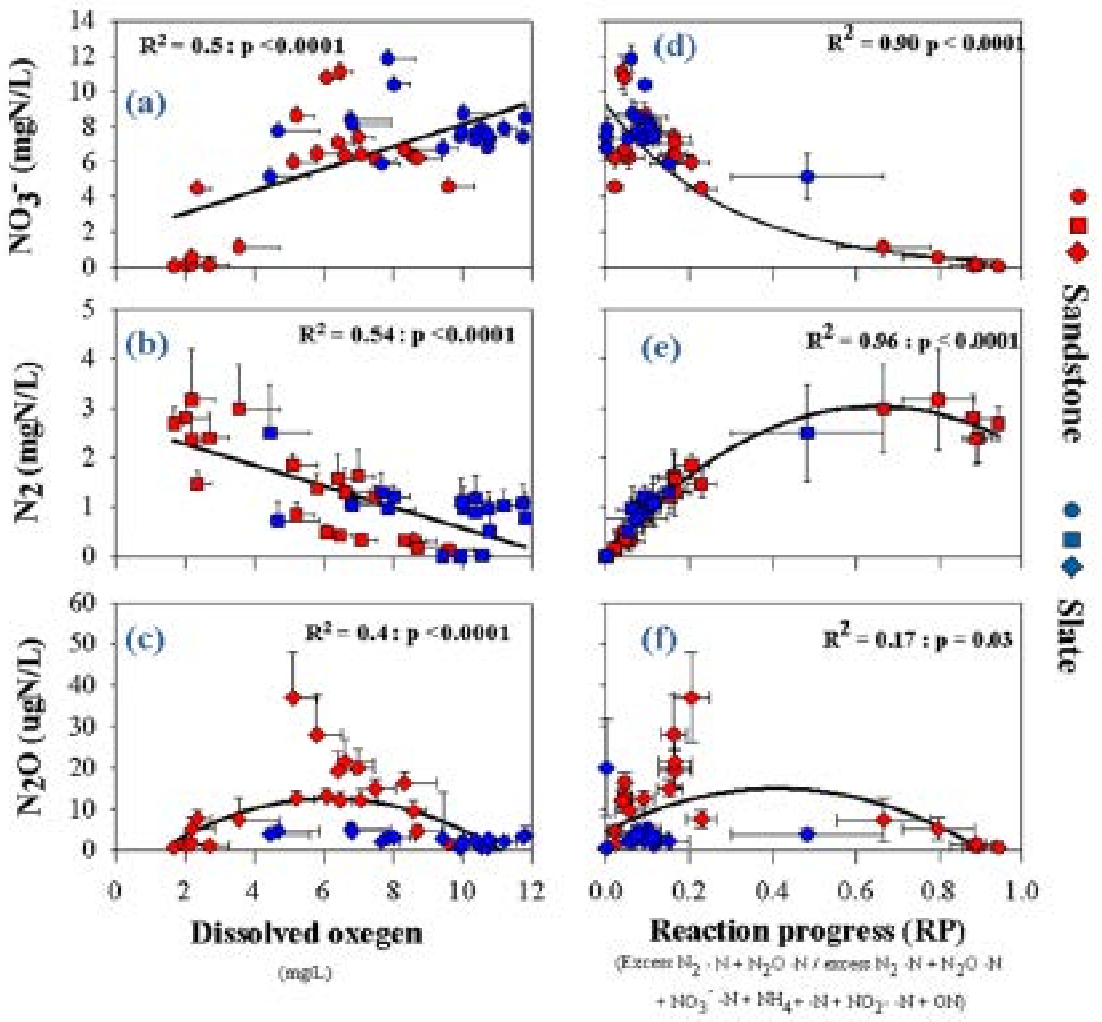


Figure 2a–2c: Correlation between groundwater NO_3^-, excess N_2 and N_2O versus groundwater dissolved oxygen concentration. Figure 2d-2f. Correlation between groundwater NO_3^-, excess N_2 and N_2O versus reaction progress.

The average N2O emission factor (EF5g) of 0.00034 was an order of magnitude lower than the Intergovernmental Panel on Climate Change (IPCC) default value (0.0025), which was not exceeded at any time or at any sample location throughout the monitoring period (Fig. 3).

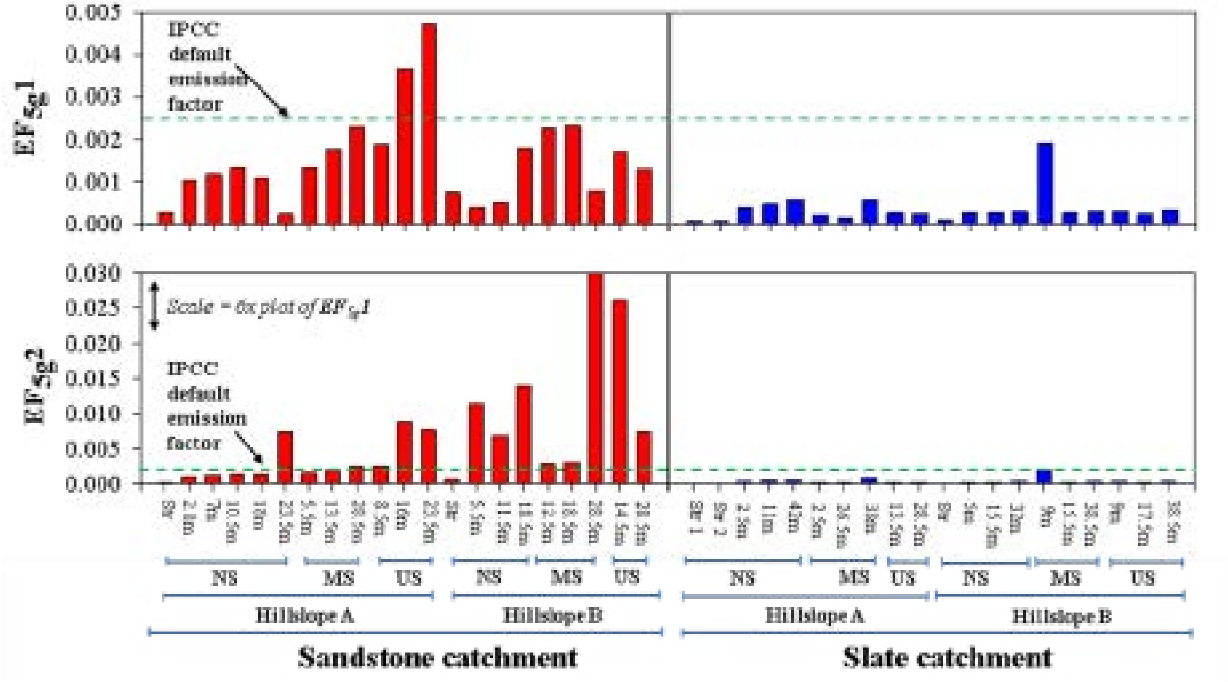


Figure 3: Groundwater N_2O emission factors (average values from 2013-2015) across hillslopes and sample depths for both catchments. NS, near stream hillslope zone: MS, Midslope hillslope zone: US, Upslope hillslope zone.

Results indicated that complete denitrification of NO_3^- to N_2 occurred in anaerobic conditions, with denitrification rates between 80 and 90% within specific zones and depths. NO_3^- removal was greatest in the deeper groundwater pathways, while a coupling of low permeability and a shallow unsaturated zone supported the development of anaerobic conditions. Despite greater inputs of both organic and inorganic N in the sandstone catchment and large exceedances of the water framework directive threshold NO_3^- concentration in both shallow groundwater and upslope zones, stream concentrations remained very low throughout the sampling period (Fig. 1a), indicative of the positive environmental effect of natural NO_3^- removal in groundwater. These removal pathways are particularly important in near stream zones, but were shown to be bypassed by enhanced drainage mechanisms within both catchments. At intermediate dissolved oxygen concentrations/denitrification rates, N_2O was the dominant reaction product, with a mean EF5g (0.0035) in excess of the IPCC default. The positive effect of NO_3^- consumption in the sandstone catchment was therefore offset by N2O production, highlighting the need for future research into the area of pollutant swapping of NO_3^- for N_2O.

Reference: McAleer, E., Coxon, C., Richards, K.G., Jahangir, M.M.R., Grant, J., Mellander, P.-E. 2017. Groundwater nitrate reduction versus dissolved gas production: A tale of two catchments. Science of the Total Environment, 10.1016/j.scitotenv.2016.11.083.

CHAPTER 3

UNDERSTANDING THE CHALLANGES


5
km
2.5
COURTMACSHERRY
TIMOLEAGUE
3
km
2.5
7
km
8
BROAD STRAND
COURTMACSHERRY
BARRYROE G.A.A.

Paper 1: Weather amplifications as overriding drivers of nutrient pollution patterns in agricultural catchments

Subject to peer-review

KEY MESSAGES

- The effects of catchment pressures (including agriculture) on nitrogen (N) and phosphorus (P) concentrations and loads, can be influenced by larger climate processes (such as the North Atlantic Oscillation – NAO) and regional weather amplifications.
- Weather variations are important and may be site-specific depending on the characteristics of the local landscape together with factors that determine flow in water courses (including build-up of water during high rainfall and loss of dilution during dry periods).
- Depending on site-specific conditions in some ACP catchments nitrate-N and reactive P concentrations were positively correlated to the oceanic NAO and in other catchments there were negative correlations, poor or no correlation.
- Data suggest that a positive NAO phase over the last approximately 10 years has resulted in potential amplifications of summer point sources and also winter diffuse sources in vulnerable catchments.
- These processes should be considered by policy makers when reviewing policy on diffuse and point source pollution management and also in deeper analyses of wider water quality data.

SYNOPSIS

In Europe weather patterns and trends can be influenced by large-scale climate systems over the North Atlantic. One of the most prominent is the North Atlantic Oscillation (NAO) caused by differentials in pressure systems and can be expressed with an index (NAOi). In northwestern Europe a positive phase in the NAOi over the winter period is often associated with elevated air temperatures in summer and more frequent large rain events in winter than normal. This will affect both soil P and N and subsequent surface runoff and leaching processes. This may be regionally amplified and also impact summer low flows in rivers.

Regional weather amplification was investigated by comparing long-term average daily rainfall and air temperature (1961-1990) with recent data (2009-2015). Six hydrological years (2009-2015) of monthly average nitrate-N and reactive P concentrations in stream water (aggregated from high frequency monitoring) were correlated to the NAOi for the ACP catchments. The NAOi were in some cases filtered with antecedent moving averages (2-5 years). The degree of correlation was analysed in terms of mobilisation, connectivity, pathway, storage and weather amplification. More recent analysis was undertaken to investigate extreme drought and flood conditions on monthly collations of high resolution data.

During the monitored period there was an increase in wintertime NAOi, reaching more positive values in recent years, resulting in more days with high average air temperatures (>15oC) and more frequent large rain events (>10mm) in winter. This was amplified in some areas.

Consequently, mean annual N and P concentrations were correlated to NAOi to some degree in the ACP catchments. In some catchments annual average nitrate-N and reactive P concentrations were positively correlated to the NAOi (R2 up to 0.97) and in other catchments there were negative correlations, poor or no correlation. In some catchments NAOi needed to be expressed as a moving average and a time shift was needed to achieve a stronger correlation (Fig. 1).

Catchments with well-drained soils and permeable bedrock appeared sensitive to weather shifts for mostly N loss but also for P loss. In catchments with well-drained soils but low permeability bedrock, the transfer pathways were likely attenuated resulting in a poor correlation of N and P concentrations to NAOi. In catchments with poorly drained soils, P was likely lost via surface runoff and P concentrations were positively correlated to NAOi. In those catchments N concentrations were instead diluted and poorly or negatively correlated to NAOi. In catchments where N and P concentrations were negatively correlated to NAOi it was likely that nutrients were either not mobilized or not hydrologically connected to the streams. Where NAOi was required to be expressed by a moving average to achieve a strong correlation it was likely that there was a longer memory within the catchment due to time lag processes.

The more recent collations (2012-2015) of monthly rain and water quality data showed the extent of these amplifications on both winter high flow and summer low flow nutrient patterns in rivers (Fig. 2) during the period of upward NAOi trend since c. 2006.

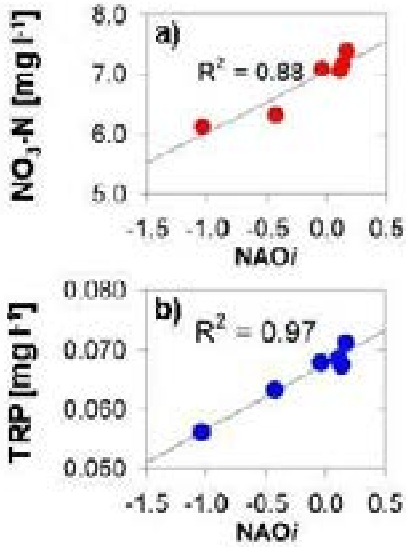


Figure 1: a) Annual average nitrate-N concentrations correlated to NAOi in an ACP catchment with well-drained soils and permeable bedrock and b) annual average TRP concentrations correlated to NAOi in an ACP catchment with poorly drained soils.

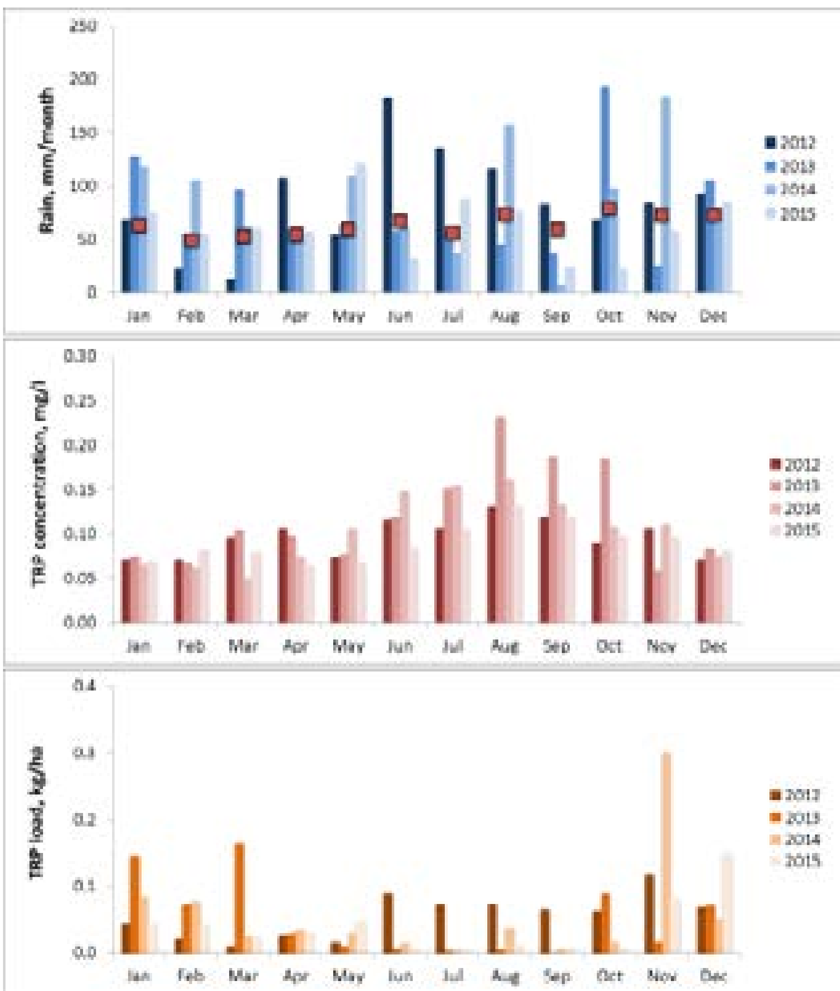


Figure 2: Monthly collations of high resolution data from 2012 to 2015 (example from Dunleer – Arable B) of rainfall (also showing long term mean data 1982-2010 red squares), TRP concentration and TRP load.

The highest P concentrations were associated with drought summers when stream water discharge was particularly low - especially August and September 2013 in the Figure 2 example. These concentrations are likely to have had an immediate impact on stream water quality during this time and are associated with poor dilution of chronic point sources, and/or the presence of groundwater P pathways. In the example shown in Figure 2 there was no evidence of excessive groundwater P but prior evidence of point sources (see Synopsis on stream ecology and faecal source tracking) and so the actions should be to target rural point source mitigation.

Highest P loads tend to occur during autumn and winter due to above average rainfall and high stream discharges - especially January 2013 and November 2014 in the example shown. These are likely to contribute to a carry-over impact to standing water bodies during the following spring/summer season and are likely associated with autumn incidental losses of organic slurry/manure P from end of open season and residual soil P losses later in the winter. Actions would need to be cognisant of late open period nutrient spreading management and also to manage high soil P fields for source control, or more effectively manage the transport component as outlined elsewhere in these Synopses. Summers experiencing above average rainfall such as the exceptionally wet summer of 2012, especially June, July, August and September will create additional challenges. There were increased P loads during this time and this will increase the ecological burden on streams and add to that for standing water bodies for that year and possibly the following year.

These relationships have implications for data showing decreases in nutrient source pressures or actions to increase catchment resilience to nutrient transfers. Amplified weather patterns may override these potentially positive benefits in some years or indicate greater benefits in other years – and this will be catchment specific. A consideration of these processes should, therefore, be included in policy reviews of diffuse and point source pollution management and also be included as considerations in deeper analyses of wider water quality data.

Paper 2:

Quantification of phosphorus transport from a karstic agricultural watershed to emerging spring water

Mellander et al. (2013)

KEY MESSAGES

- Farming in the studied karst area could pose less intrinsic risk to groundwater than was anticipated.
- A revised groundwater vulnerability assessment was used to produce a specific P vulnerability map that used the soil and hydro-geological P buffering potential of the catchment as key assumptions in moderating P export to the emergent spring.
- The proposed vulnerability map classified 14% of the site as highly vulnerable for P loss to groundwater.
- A fine scale 'Critical Source Area' map identified only 2% of the area as at high risk and this complimented the observations of low P exports from the spring.
- Developing these Critical Source Area concepts into at least national knowledge transfer schemes (or at most regulations) will require consideration and investment.

SYNOPSIS

In karst landscapes there is a particular concern that nutrients may move quickly and easily from the overlying agricultural land to the groundwater and below-ground network of channels. This may happen via swallow holes (vertical shafts) and dolines (bowl-shaped depressions) due to low potential for soil buffering (retention and/or release of phosphorus (P) in a controlled manner). This study applied concepts of specific P vulnerability to develop original intrinsic groundwater vulnerability risk assessments in a 32 km2 karst watershed (spring zone of contribution) in a relatively intensive agricultural landscape.

To explain the contradiction of extreme risk for pollution and good water quality, the potential for P retention along the nutrient transfer pathways was investigated based on soil P buffering, depth to bedrock and P retention within the aquifer.

Although the soils were mostly shallow in this area; this study showed that much of the P deposited from agriculture is buffered by the soil due to a combination of clay rich top soils and calcium rich sub-soils. Even in the dolines, bedrock fissures and larger conduits, P was, to some degree, likely to be buffered. The most common surface karst feature in the area are the dolines of which 1,327 were mapped and re-classified based on the potential to buffer P by the soil at the base (Figure 1). Only about 3% of the dolines in the area had no soil at their base and were classified to be of high risk for P loss to groundwater; 4-5% were mapped as moderately risky; and over 90% had enough soil at base to buffer against P leaching loss.

Analysis techniques using the high frequency monitoring of P loss in the emergent spring made it possible to quantify the proportion of P entering the groundwater via different pathways (Figure 2). This technique further allowed an estimate of how much P may be retained within the aquifer. The analysis revealed that most P moves through small to medium sized fissures which delivered 52-90% of P loads during storms. The loss of P via the spring was 93kg total P in the first monitored year and 138kg in the second (52 and 91kg of total reactive P). During one large winter flow event close to half of the event total P was estimated to be retained in the limestone aquifer (18kg of total P and 12kg of total reactive P).

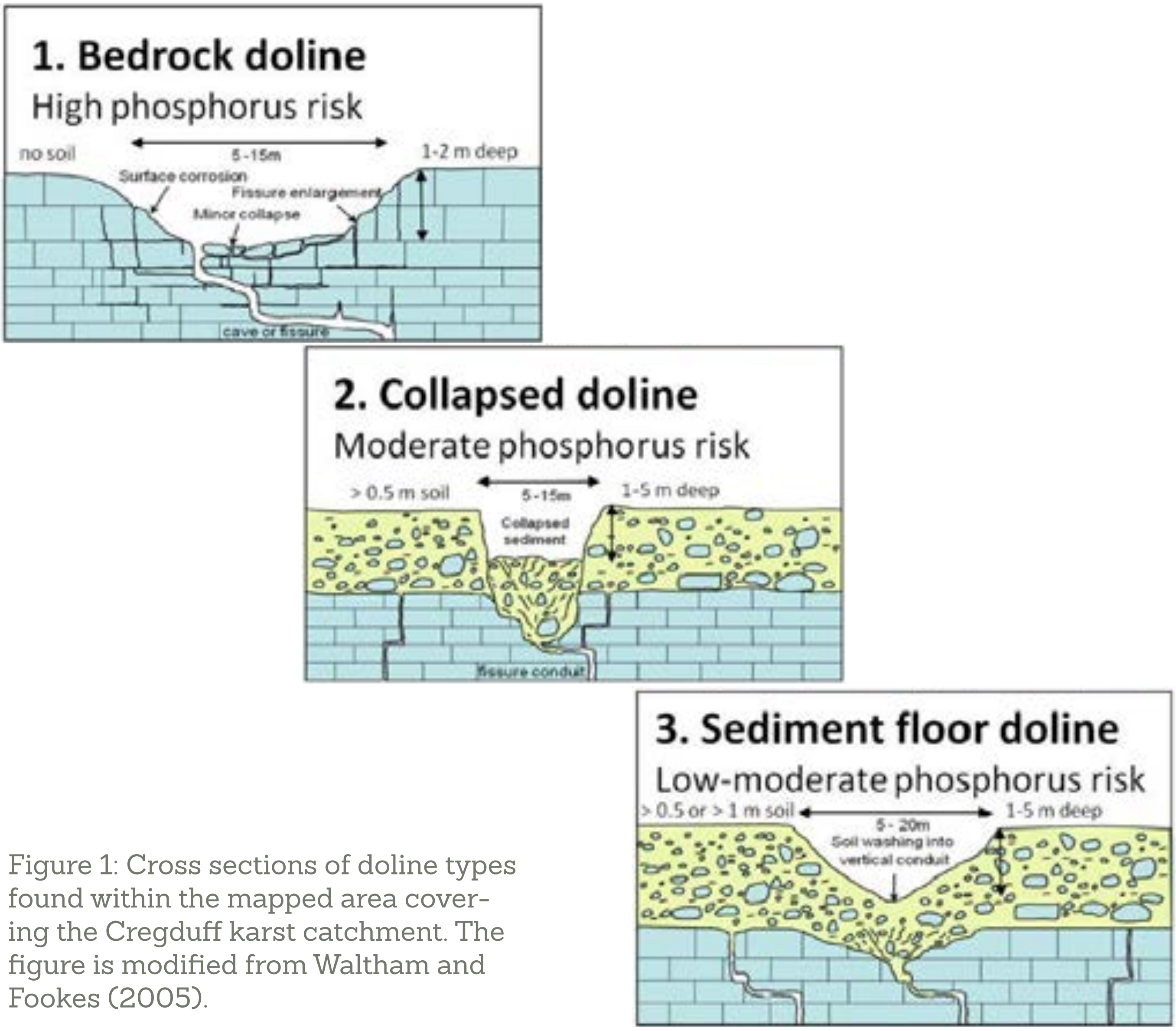


Figure 1: Cross sections of doline types found within the mapped area covering the Cregduff karst catchment. The figure is modified from Waltham and Fookes (2005).

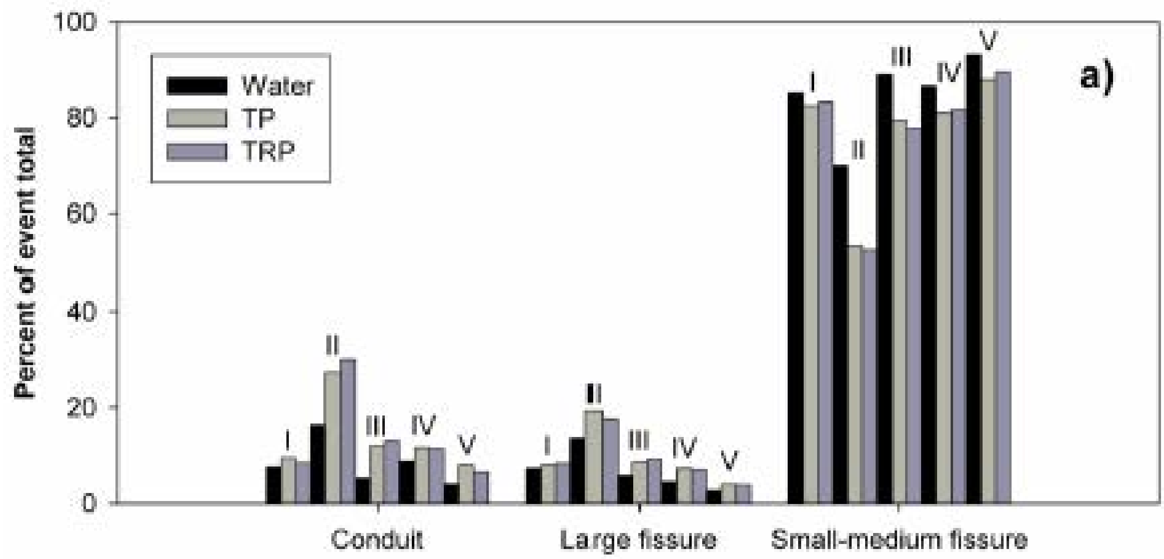


Figure 2: Proportion of water and phosphorus transfer pathways estimated for five flow events using hydrograph separation and Loadograph Recession Analysis.

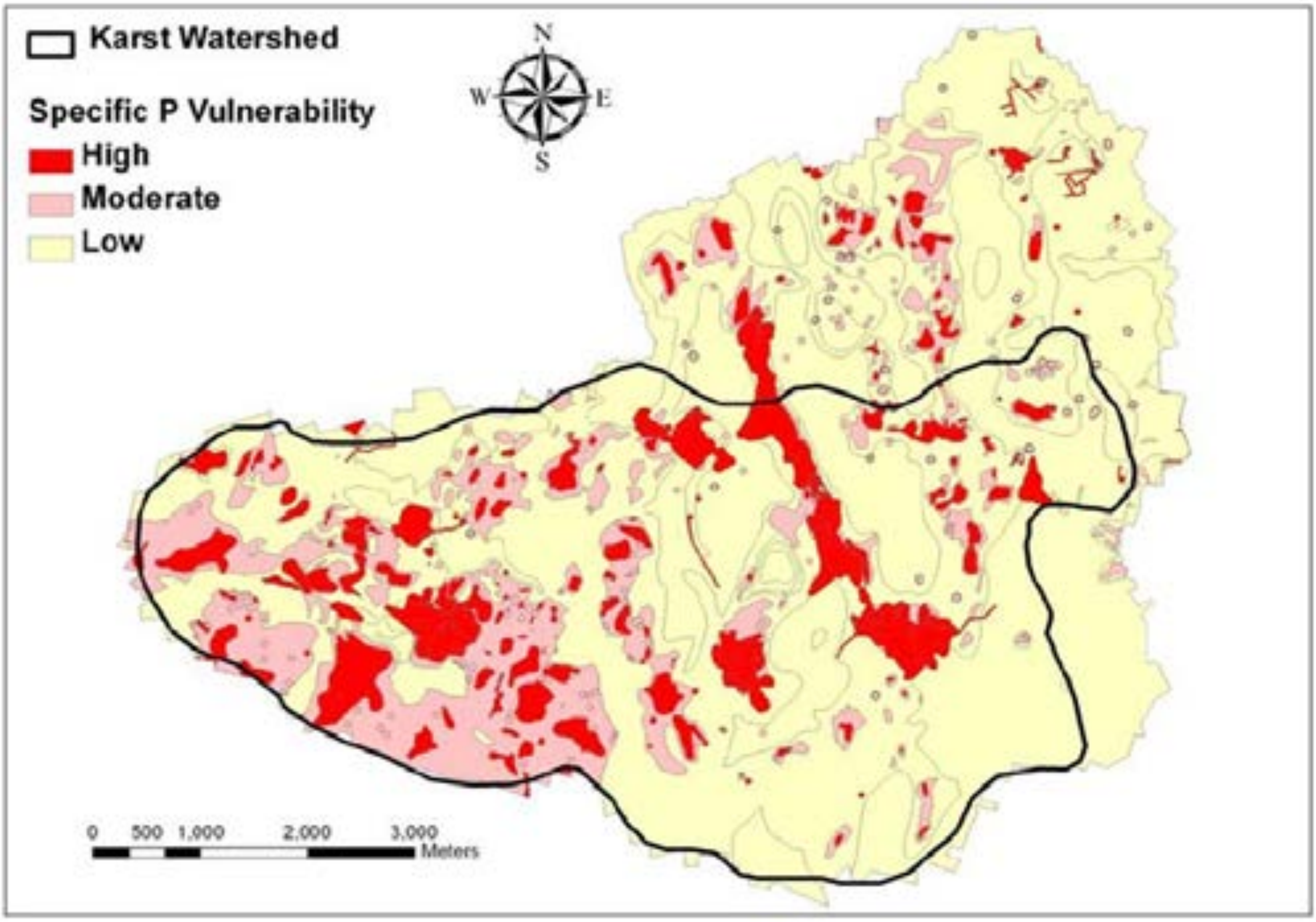


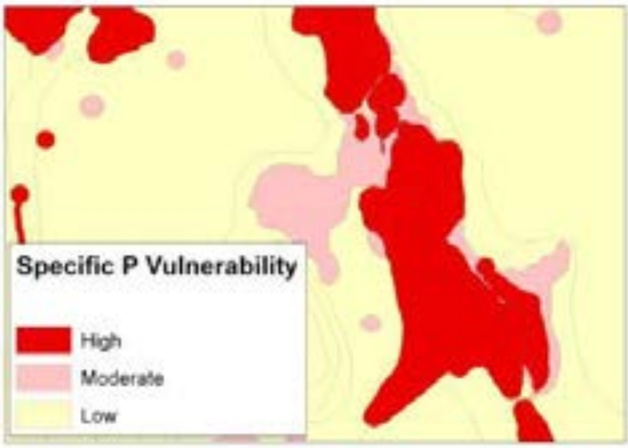
Figure 3: Specific groundwater phosphorus vulnerability of the mapped area covering the Cregduff karst watershed.

Based on these new conceptual models of nutrient loss and buffering processes, in this particular karst landscape, new categories of risk assessment were set. Those categories were used together with data on source pressures to develop the previous 'intrinsic vulnerability map' into a 'specific vulnerability map' (Figure 3). This proposed vulnerability map classified 14% of the site as highly vulnerable for P loss to groundwater with two thirds of low vulnerability and the remainder moderate. This was, therefore, a better comparison with the landscapes' P buffering and attenuation processes and observed water quality in the emerging spring. By overlaying areas of high source pressure (P index 4 soils) on high vulnerability areas, a 'Critical Source Area' map identified only 2% of the area as at high risk (Figure 4). Reducing legacies of high soil P to the optimum for grass and crop production and following existing regulations with regard to fertilizer and slurry applications offers a simple way to reduce that risk further. The assessment can be used to modify expectations of risk and focus management efforts in karst landscapes sensitive to nutrient loss and eutrophication. The change required for this field-scale focus either at the national advisory (knowledge transfer schemes) or regulatory scale will require careful consideration and investment. The study is described in detail in Mellander et al. (2013).

A

Figure 4: An example of how (a) soil phosphorus status and (b) specific groundwater phosphorus vulnerability can be used to produce a (c) critical source area map for phosphorus transfer to groundwater over a section of the karst catchment.

B



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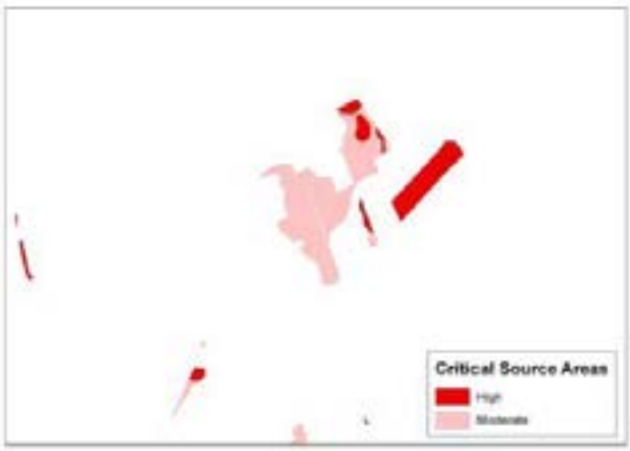

Reference: Mellander P-E, Jordan P, Melland AR, Murphy PNC, Wall DP, Mechan S, Meehan R, Kelly C, Shine O, Shortle G (2013). Quantification of phosphorus transport from a karstic agricultural watershed to emerging spring water. Environmmental Science and Technology, 47, 6111-6119.

http://pubs.acs.org/doi/abs/10.1021/es304909y


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Paper 3:

Coupling of surface water and groundwater nitrate-dynamics in two permeable agricultural catchments

Mellander et al. (2014)

KEY MESSAGES

- Catchments with little landscape attenuation of Nitrogen (N), and/or a dense under-field drainage system, may deliver more nitrate-N to surrounding waters as agriculture intensifies.
- An intensively managed grassland catchment with high risk for N leaching to groundwater had relatively low nitrate-N loss likely due to buffering zone near the stream.
- Impacts of land management on groundwater nitrate-N concentration were occasionally significant but localised to zones and geological strata within the hillslope scale.
- Spatiotemporal mean nitrate-N concentration in groundwater was below current regulatory standards and was similar to the temporal average in the stream outlet.
- An increase in annual spatial nitrate-N concentration (+ 0.11 mg l^{-1}) in the groundwater of an Arable catchment increased the nitrate-N load in the stream outlet by 15%, but the total loads were more influenced by the coincidental amount of runoff.
- To monitor the environmental burden of increased food production in vulnerable catchments it will be important to account for nitrate-N concentrations in groundwaters, receiving stream waters and as loads to estuarine waters with the same kind of land and river monitoring demonstrated here.

SYNOPSIS

This study investigated the coupling of groundwater and surface water N dynamics over three years, and considered intensive agricultural land-management influences over this period where the risk of nitrogen loss to water was considered high. Groundwater nitrate-N was monitored monthly in different geological strata in four hillslopes in two groundwater driven catchments (Arable A and Grassland A, both ca 10 km2) and stream water nitrate-N flux was monitored sub-hourly in the catchment outlets.

Field N sources were connected to surface water via groundwater, and the nitrate-N in the groundwater was influenced spatiotemporally by management, soil and bedrock permeability and by weather. Land management impacts on groundwater were sometimes significant but were also localised to zones and geological strata within the hillslope (Figure 1). The potential for localised land management impacts to affect downstream groundwater and stream water quality depended on the chemical and hydrological buffering capacity of the catchment and particularly so in the near stream zone. The variability in nitrate-N concentration highlight a need for insight into these differences when interpreting groundwater quality data from a limited number of sampling points and occasions, such as in national monitoring campaigns.

Despite local and temporary peaks, the spatiotemporal mean nitrate-N concentration in groundwater of both catchments was below current regulatory standards and was similar to the temporal average in the stream water. Peaks were mostly in the top of slopes when the water table was high and when there was a temporal influence from land management. Additionally, nitrate-N loads were deemed high but not relative to any standard target. Furthermore, a relatively small increase in annual spatial nitrate-N concentration (+ 0.11 mg l^{-1}) in the groundwater of the Arable catchment was reflected in an increase in the relative nitrate-N load in the stream outlet by 15%, but the total loads were more influenced by the coincidental amount of runoff (Figure 2).

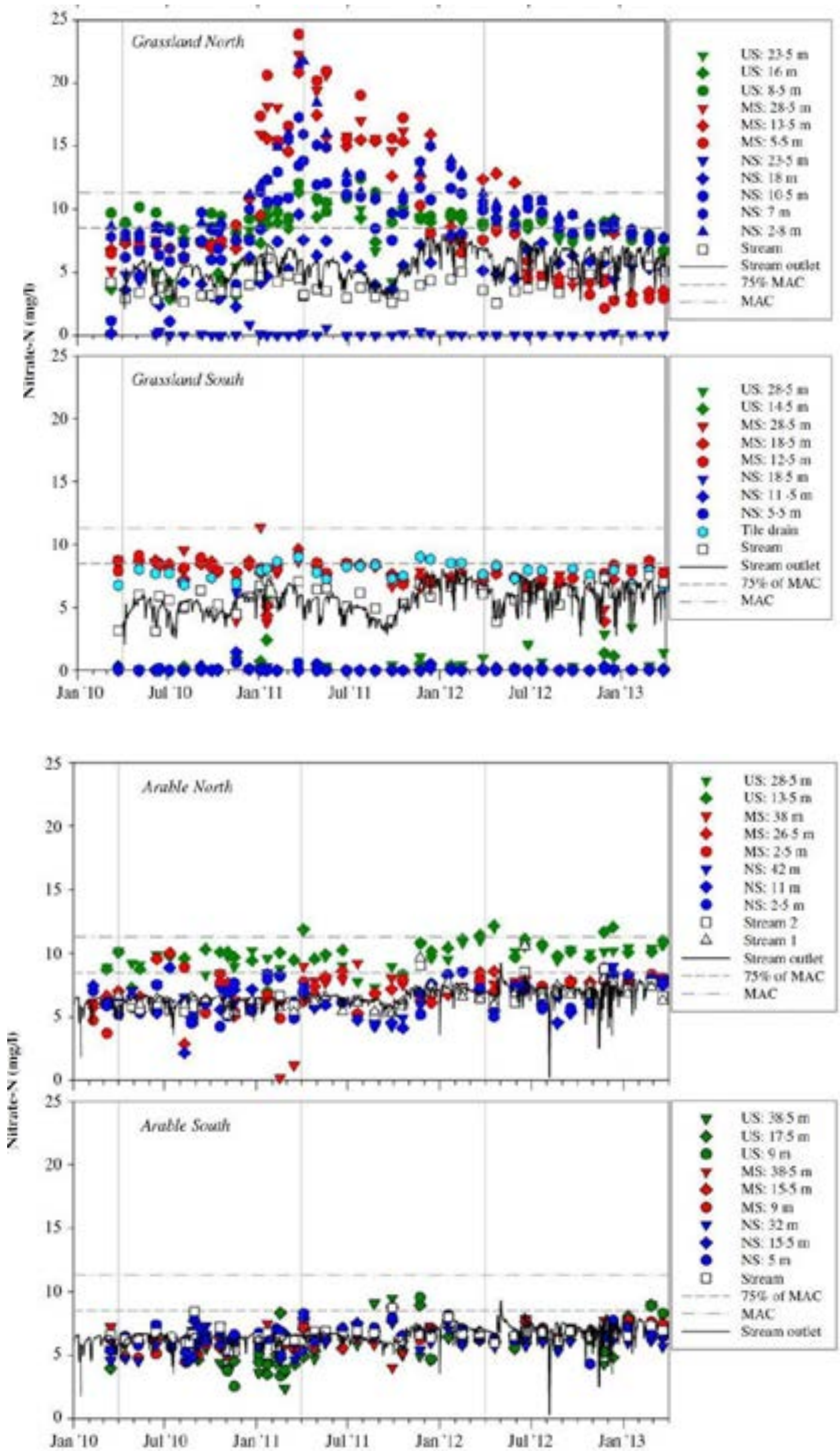


Figure 1: Time series of monthly sampled nitrate-N concentration in groundwater and stream water in the two hillslopes and daily averaged nitrate-N concentration monitored in the stream outlet in the Arable catchment on slate bedrock and in the Grassland catchment on sandstone bedrock.

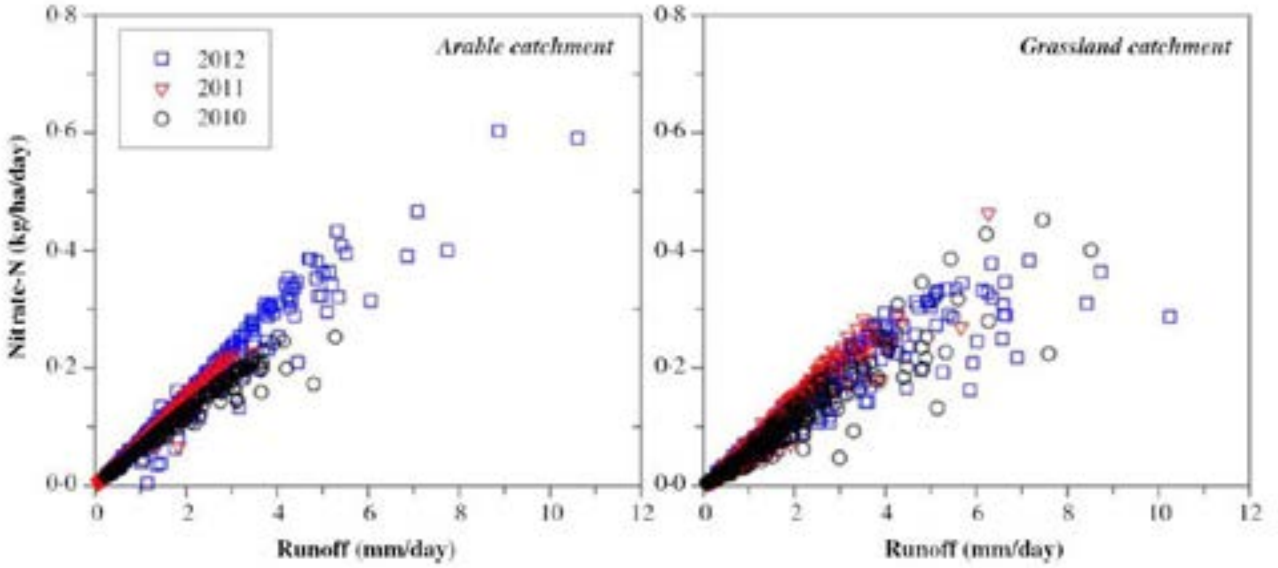


Figure 2: Daily Nitrate-N load as a function of daily catchment runoff for three hydrological years (1 Apr 2010 – 31 Mar 2013) in the Arable catchment and Grassland catchment.

The grassland dominated catchment on sandstone was hydrologically and chemically more buffered than the catchment dominated by arable land on slate bedrock but in both catchments there was less hydrological buffering and more chemical buffering closer to the stream. As intensified agriculture may locally elevate nitrate-N concentrations in groundwater, catchments with little chemical attenuation within the landscape and/or a dense under-field drainage system may possibly deliver more nitrate-N to surrounding waters.

As Ireland seeks to increase food production in the next several years it will be important to consider these factors in terms of nitrate-N concentrations in groundwaters, receiving stream waters and as loads to estuarine waters – a strategy that may only be realised with the same kind of land and river monitoring demonstrated here.

The study is described in detail in Mellander et al. (2014).

Reference: Mellander, P.-E., Melland, A.R., Murphy, P.N.C., Shortle, G., Jordan, P. (2014). Coupling of surface water and groundwater nitrate-N dynamics in two permeable agricultural catchments. Journal of Agricultural Science (Special Issue), 152, 107-124.

https://www.cambridge.org/core/journals/journal-of-agricultural-science/article/coupling-of-surface-water-and-groundwater-nitraten-dynamics-in-two-permeable-agricultural-catchments/6DD15B5D2042D0053E9138F3646A3DD8

Paper 4:

Flow paths and phosphorus transfer pathways in two agricultural streams with contrasting flow controls

Mellander et al. (2015)

KEY MESSAGES

- Schemes designed to attenuate diffuse P after mobilisation from soil surfaces can be targeted (and resourced) more effectively.
- To reduce diffuse pollution it may be necessary to account for the contrast in hydrological function before, or in addition to, any of the other factors known to influence P losses from catchments (such as soil P and land use).
- A grassland catchment with a flashy hydrology had three times higher annual P loss than an arable, mostly groundwater fed catchment despite the latter having higher soil P sources prone to losses.
- The poorly drained grassland catchment was P transfer risky rather than P source risky and the magnitude of the P losses from the two catchments were defined by basic rainfall to runoff partitioning influences that determine proportions of quickflow and slowflow.
- There were larger differences in annual P loss between the years than between the catchments.
- There is a need to manage the quickflow components of runoff in order to moderate P transfers. Defining which catchments are susceptible will be important – defining this susceptibility at farm and field scale will be more important.

SYNOPSIS

In this study four years of data from simultaneous high-frequency monitoring of streamflow and phosphorus (P) concentration was analysed in order to investigate the role of hydrolological pathways and P transfer pathways from diffuse sources in two intensively farmed small river catchments (ca. 10 km2) with contrasting flow characteristics and land use (Arable A and Grassland B). In Ireland, such contrasting settings exist even within small areas.
The results of this integrated catchment scale study of flow paths and diffuse nutrient transfer pathways confirms the need to manage the quickflow components of runoff to moderate P transfers. Quickflows, as identified via a validated Loadograph Recession Analysis of high frequency discharge and P concentration data, appeared as the dominant transfer pathway in both a grassland

and an arable land use setting. However, the difference in magnitude of the P loss from the two catchments were not defined by land use, source pressure or discharge volume (the Arable catchment had more annual runoff and a higher source of P [R = 0.55, Q = 529 mm yr-1 and 18% fields with excessive Morgan's P] than the Grassland catchment [R = 0.47, Q = 475 mm yr-1 and 6% fields with excessive Morgan P]) but rather by more basic rainfall to runoff partitioning influences that determine proportions of quickflow and slowflow. In the Arable catchment, with mostly well drained soils, there was a large proportion of P slowflow transfer via groundwater. Over the four-year monitoring period, the Grassland catchment yielded three times more total P (TP) loss than the Arable catchment (Figure 1) (double amount of TP flux for the same discharge volume without any indications of supply limitations) and was more likely to remobilise P along pathways in subsequent storm events (Figure 2). This was attributed to the poorly drained soils in the Grassland catchment giving rise to a flashier and more rain responsive flow regime with higher flow-weighted mean TP concentrations. Even so, the average 1.035 kg ha-1 yr-1 loss of TP and 0.434 kg ha-1 yr-1 loss of total reactive P (TRP) from the Grassland catchment is noteworthy as being low compared to other loss rates reported in the literature. Despite the large difference in TP and TRP flux attributed to contrasting catchment flow characteristics, such as proportion of quickflow to baseflow rather than annual discharge and runoff coefficient, there was a larger difference between the years than between the catchments and the Arable catchment responded more to wet years thus highlighting an overriding role of shifts in weather.

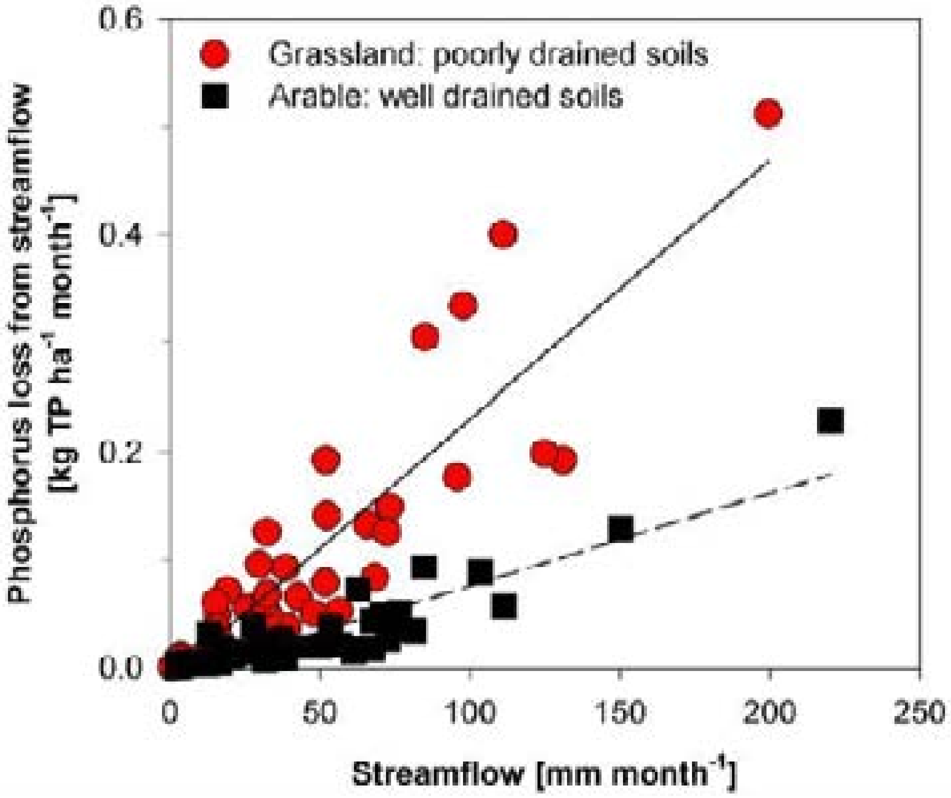
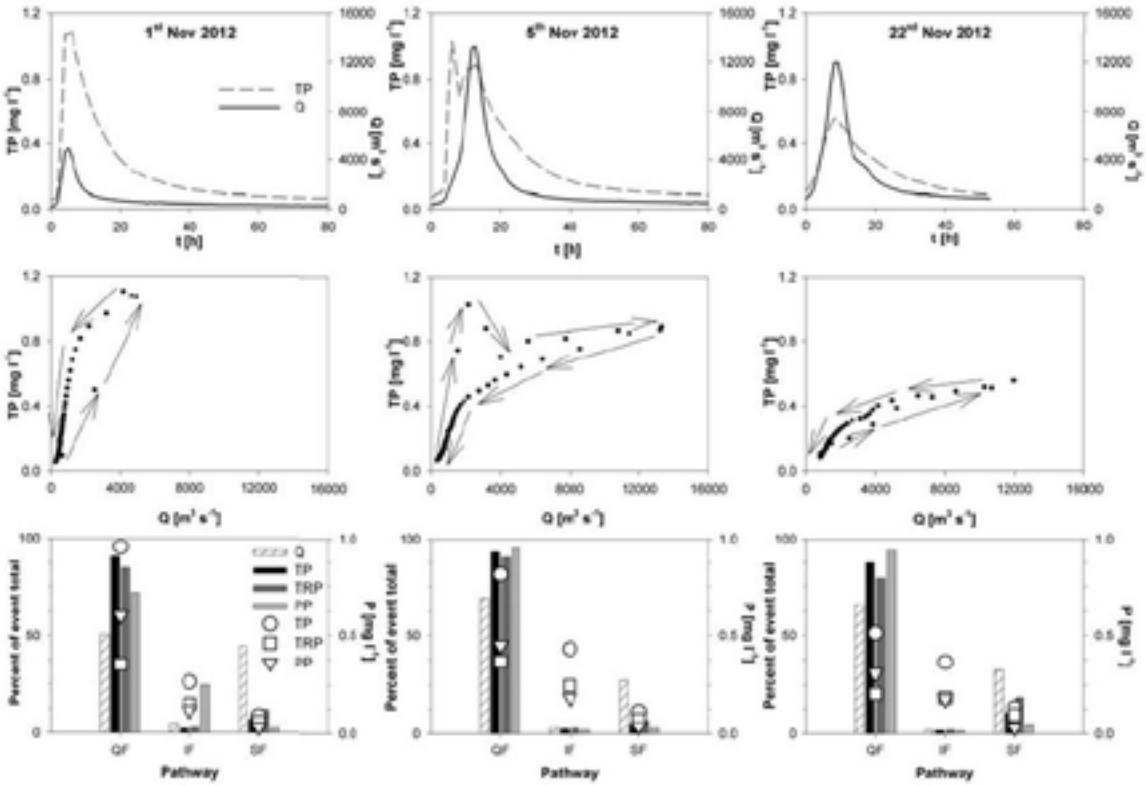


Figure 1: Four years of monthly Total Phosphorus (TP) loss related to stream discharge in two catchments with different flow controls (Grassland with poorly drained soils and Arable land with well drained soils).

a) Grassland catchment



b) Arable catchment

FLOW PATHS AND PHOSPHORUS TRANSFER PATHWAYS

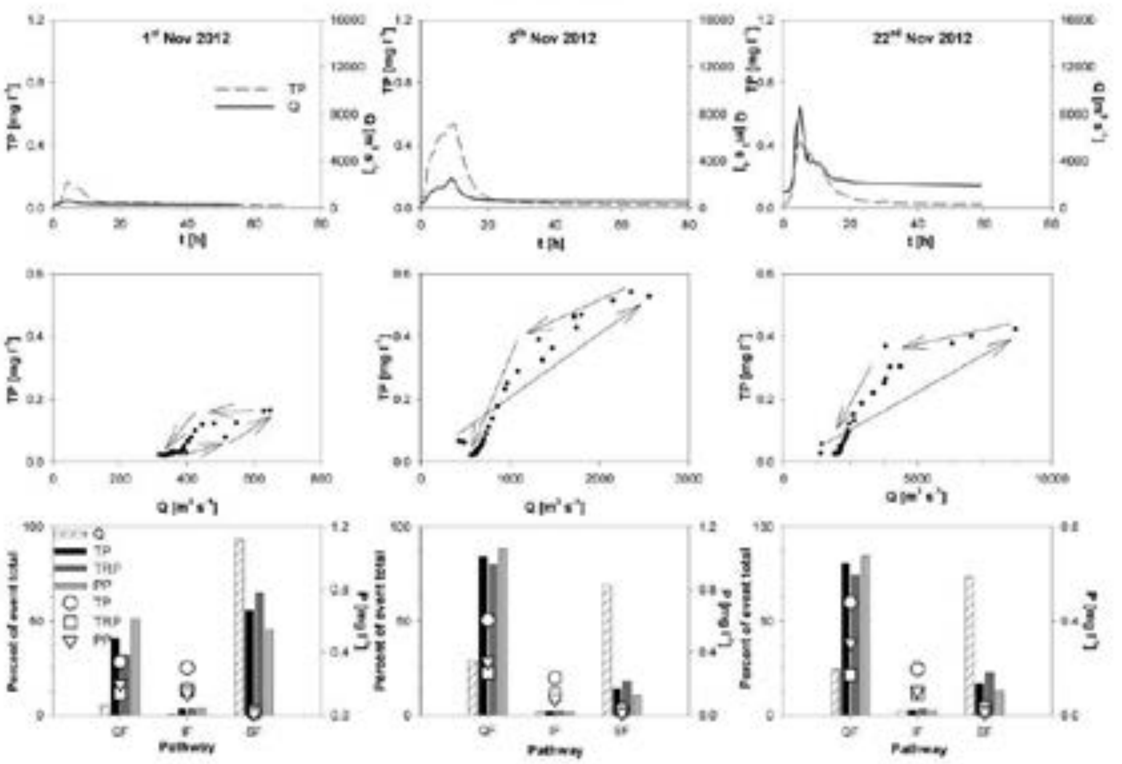


Figure 2: Above: hourly Total Phosphorus (TP) concentration and stream discharge (Q), middle: hysteresis loop and trajectories in the Q and TP concentration relation, and below: proportion of event total pathways (bars) and modelled P concentrations in pathways (symbols) for three sequential flow events in November 2012.

As river basin plans seek to review policies to further manage P transfers, it will be important to recognise associated processes and concentrate efforts on reviewing the influences of quickflows in catchments – here most likely due to soil drainage type and temporally influenced by climate and not landuse. Where such influences are found to be predominant, mitigation measures that target the modes of P mobilisation as well as conveyance after mobilisation will be important. The converse of this might be a consideration in areas where quickflow is not as widespread. Agri-environmental schemes designed to target such processes can then be planned and resourced more effectively.

In the Grassland catchment, with its low P sources but relatively high annual TP loss, it would be more efficient to address the active transfer pathways rather than source management. Losses of particulate P (PP) and TRP via surface transfer pathways may be minimised by creating runoff attenuation features. Such features could be targeted to areas prone to runoff as identified by topographic wetness indices (see Synopses below on hydrologically sensitive and critical source areas). Losses of PP and TRP via surface transfer pathways may also be minimised by managing existing P attenuation features such as agricultural drainage ditches. Simple changes in ditch design (widening and deepening) and management (regular dredging) could enhance sediment associated P retention in ditches (see Synopsis below on ditch classifications). Stabilising channel banks and avoiding compaction in near-stream zones may also be useful for minimising PP and TRP mobilisation in in-stream and near-stream zones.

The Arable catchment, with its high source pressure but low annual P loss, had flow characteristics that were dominated by belowground slowflow pathways with a constant transfer of TRP during large parts of the year. During wet soil conditions, mostly in winter, the flow characteristics became flashy with active quickflow pathways that transferred PP. In those settings source management should take these temporal aspects of PP transfer potential into account. While the PP transfer by quickflow could be managed by the approaches and features described above for the Grassland catchment, as well as by approaches specific to PP transfer such as conservation tillage and attenuation features, there is a need to explore methods for preventing soil P mobilisation and transfer to groundwater as well as targeting zones of source management. Clearly, in terms of catchment specific measures, schemes targeted towards reducing P loss in quickflow pathways, by attenuating surface runoff and associated P transfer, would be more suited to catchments with characteristics such as the Grassland one in this study, rather than the Arable catchment. This study is described in detail in Mellander et al. (2015).

Reference: Mellander, P.-E., Jordan, P., Shore, M., Melland, A.R., Shortle, G. Flow paths and phosphorus transfer pathways: comparing two agricultural streams with contrasting flow characteristics. Hydrological Processes (Special Issue), 2015, 29, 3504-3518.

http://onlinelibrary.wiley.com/doi/10.1002/hyp.10415/abstract

Paper 5

Identifying contrasting influences and surface water signals for specific groundwater phosphorus vulnerability

Mellander et al. (2017)

KEY MESSAGES

- Susceptibility of P via groundwater should in some settings be considered for mitigation.
- P transfer via groundwater to rivers was investigated in two groundwater fed agricultural catchments.
- Fe-rich soils favour P mobilisation into soluble form and transfer to groundwater.
- P concentrations in near-stream groundwater influence stream P concentrations.
- Groundwater contribution to stream TRP flux was 50% and 59% in winter.
- A first step to minimise P loss via groundwater will be to identify P leaching potential based on finer scale soil property surveys.

SYNOPSIS

Two groundwater dominated catchments with contrasting land use (Grassland A and Arable A) and soil chemistry were investigated for influences on P transfer below the rooting zone, via the aquifer and into the rivers. The objective was to improve the understanding of hydrochemical process for best management practise and determine the importance of P transfer via groundwater pathways.

Phosphorus was more likely mobilised into a soluble form and transferred to shallow groundwater in a well-drained iron-rich soil (Grassland catchment in this study), compared to well-drained aluminium-rich soils (Arable catchment this study) (Figure 1).

This was further reflected by elevated DRP concentrations in the shallow near-stream groundwater in the Grassland catchment, which likely influenced stream P concentrations (Figure 2). While the average annual P flux from the rivers was relatively low, the Grassland catchment had three time higher TRP flux and flow-weighted mean TRP concentration than the Arable catchment (0.385 kg ha^{-1} and 0.128 kg ha^{-1}, and 0.067 mg l^{-1} and 0.023 mg l^{-1}

respectively). High frequency monitoring of river discharge and P concentrations in the outlets enabled a method to quantify P loads and concentrations in conceptualised transfer pathways (Figure 3). During three-month closed periods for fertilizer applications, on average 50 and 59% of the TRP was lost via slow-flow pathways in groundwater in the Grassland and Arable catchment respectively (Figure 4).

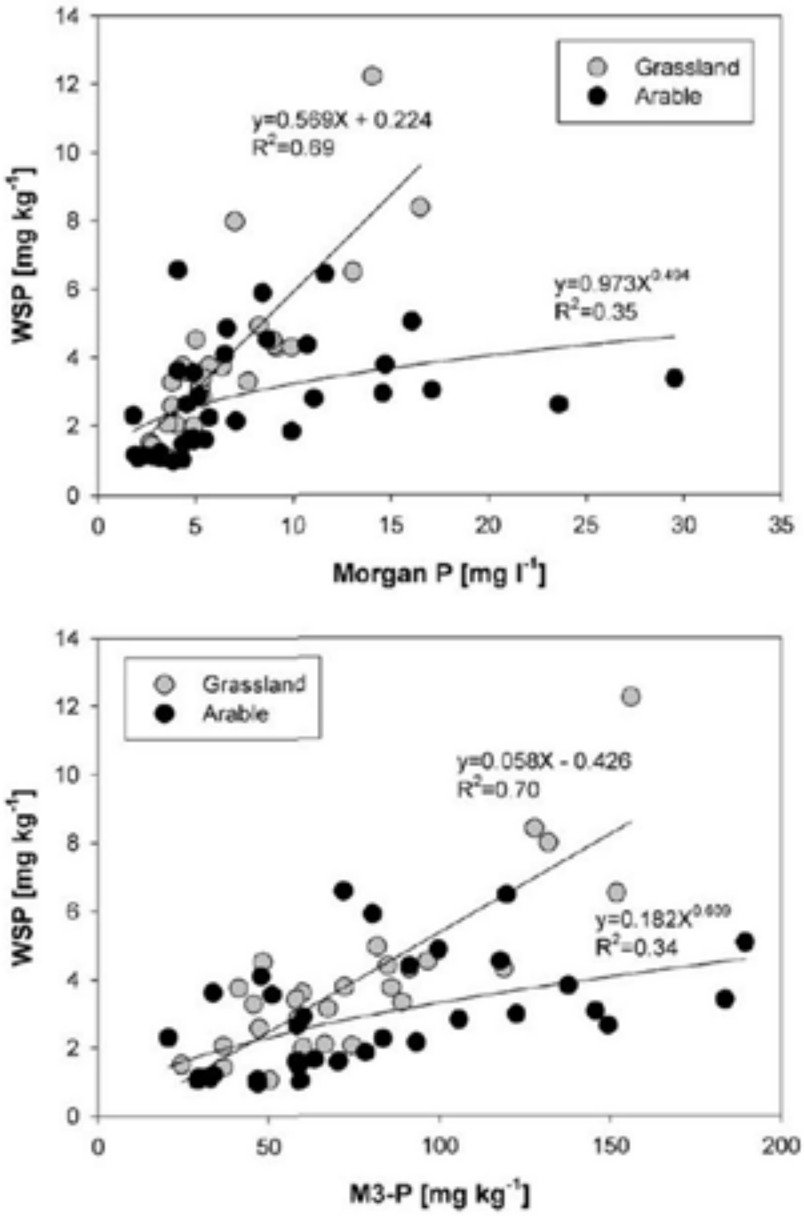
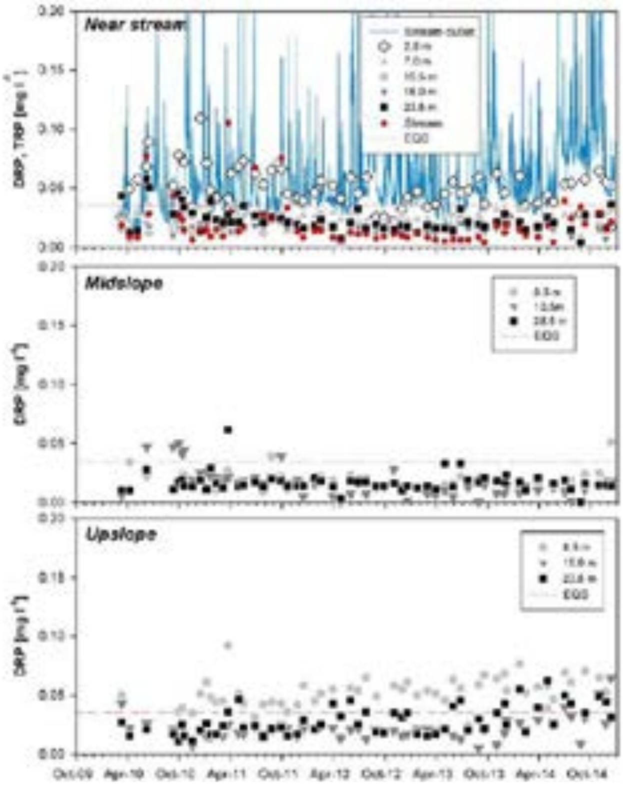


Figure 1: Divergent relationships between water soluble P and plant-available P. (a) Morgan extractable P and (b) Mehlich 3 extractable-P (M3-P) for both catchments, illustrating higher soil-P solubility in the Grassland compared to Arable catchment soils.

Grassland catchment (northern hillslope)



Arable catchment (southern hillslope)

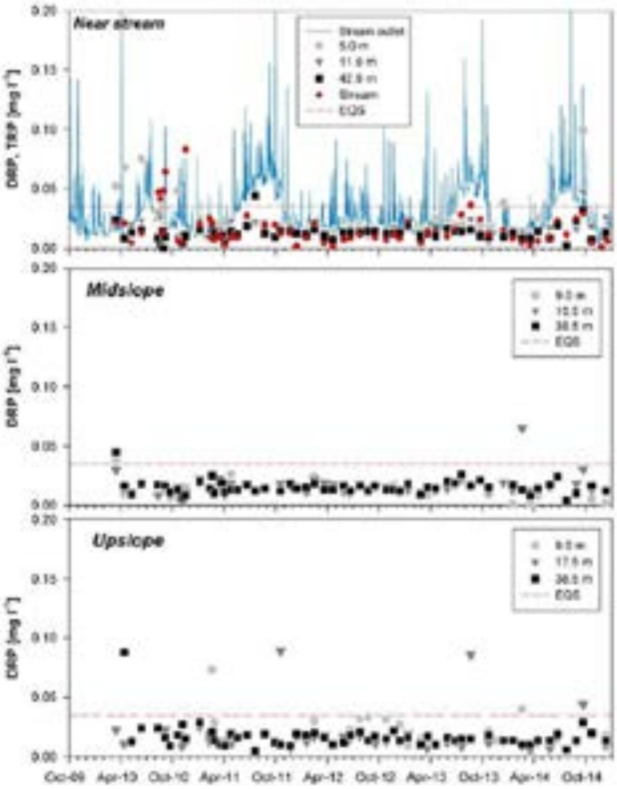


Figure 2: Five years of P concentration in groundwater and stream water. These graphs show monthly samples of DRP concentrations in the groundwater at given depths (metre below ground) in one out of two hillslopes per catchment, TRP concentration in the stream water adjacent to the hillslopes and daily TRP concentrations monitored in the stream outlets. The environmental quality standard (EQS) of 0.035 mg unfiltered TRP l-1 is marked as a red line.

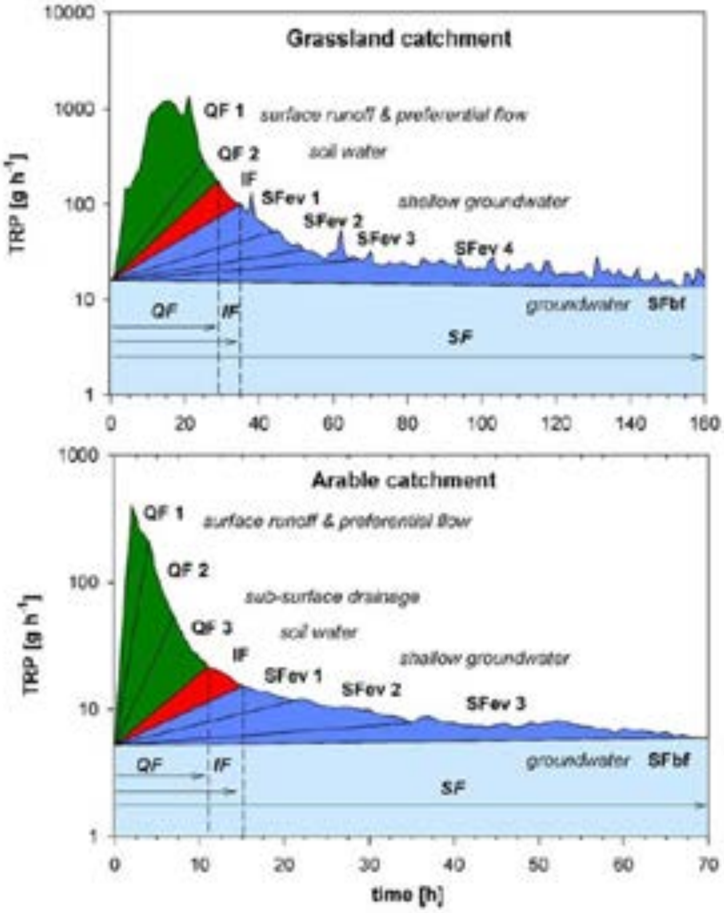


Figure 3: Event phosphorus transfer pathways. Example of a Loadograph Recession Analysis and conceptual pathway model for a flow event during 7-13 June 2012 in the Grassland catchment and 8 – 11 June 2010 in the Arable catchment (QF = quick-flow, IF = interflow, SFev = elevated slow-flow during event and SFbf = slow-flow during baseflow).

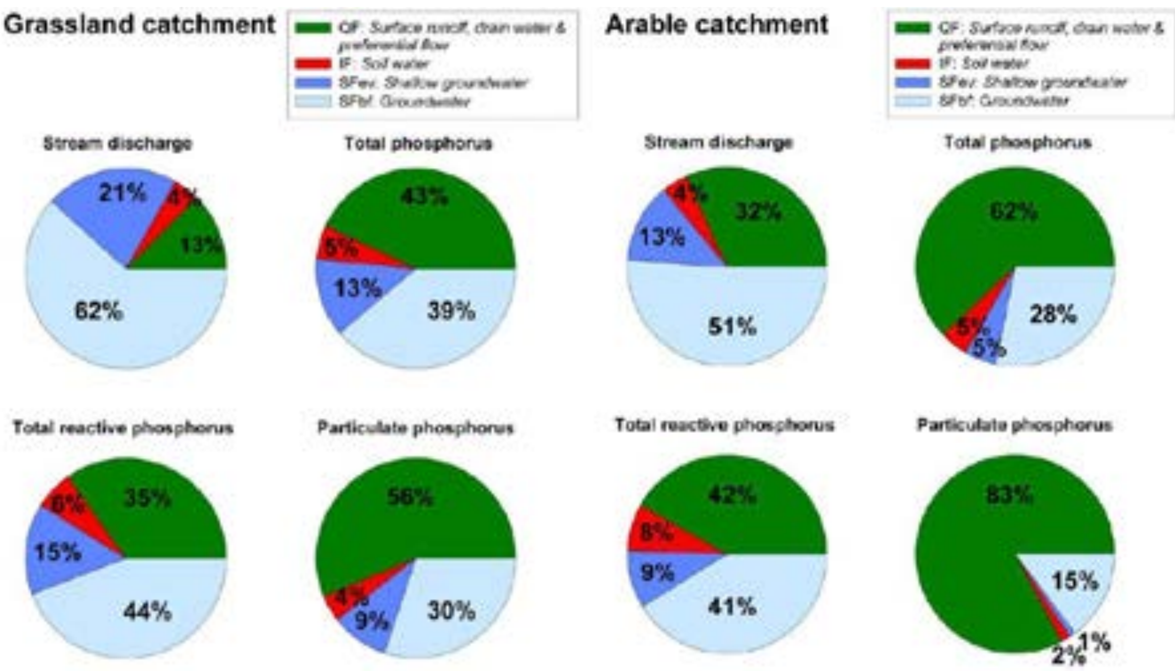


Figure 4: Proportions of stream discharge (Q), Total phosphorus (TP), Total Reactive Phosphorus (TRP), Particulate Phosphorus (PP) pathways during the closed periods, 15th October – 12th January (when no fertilizers are allowed to be applied on fields).

These findings suggest that P flux via slow-flow pathways and associated time-lags between fertilizer application, mobilisation of P reserves and delivering to the river in groundwater should be considered when reviewing mitigating strategies and efficacy of mitigating measures in groundwater fed catchments. Despite overall quite modest annual P fluxes, in these well-drained catchments, they were sufficiently spread in annual runoff to cause a protracted elevated baseflow concentration in the Grassland catchment that was only partially reflected in certain groundwater zones and strata and at certain times. The absence of such zones in the Arable catchment, and the presence of a point source signal, indicated that care is required when defining groundwater P risk. This indicates a need to consider the identification of susceptible groundwater 'hotspots' and 'hot moments' beyond the more usual coarse space-time groundwater monitoring routines.

A first step to minimise P loss via groundwater transfer could, therefore, be to identify groundwater CSAs based on the specific P leaching potential to shallow groundwater on targeted areas by finer scale soil property surveys. Here, this is likely to be defined by elevated soil P concentrations associated with Fe or Al-rich soils, thereby influencing the solubility and hence mobilisation of P in such soils. While the Grassland catchment indicated a soil-P chemistry susceptibility, the Arable catchment indicated a transient point source control; both resulted in sustained or transient periods of elevated low river-flow P concentrations, respectively.

This study is described in detail in Mellander et al. (2016).

Reference: Mellander, P.-E., Jordan, P., Shore, M., McDonald, N.T., Wall, D.P., Shortle, G., Daly, K. (2016). Identifying contrasting influences and surface water signals for specific groundwater phosphorus vulnerability. Science of the Total Environment, 541, 292-302.

http://www.sciencedirect.com/science/article/pii/S0048969715307427

Paper 6: A methodological toolkit to assess unsaturated soil time lags in agricultural catchments

Vero et al. (2014)

KEY MESSAGES

- This research presents a methodological toolkit by which the unsaturated soil componant of time lag in water quality response to agricultural programmes of measures (POM) (e.g. Nitrates Directive) can be assessed.
- This can be used to assess trends in response to past and present agricultural policies (such as the Water Framework Directive (WFD)), to develop effective POM in future.
- The toolkit comprises of free-licence hydrological software (Hydrus 1D), and readily available meteorological (Met Eireann) and soil (Irish Soil Information System) input data, coupled with bedrock or groundwater information.
- The toolkit was demonstrated in two groundwater fed catchments. Ranges of intrinsic time lag (tu) were determined, which reflect the diversity of soil series and bedrock depths present within each catchment.
- Results indicated that tu would preclude full effects of Nitrates Directive POM within the first WFD reporting period, although trends in water quality response should begin to be observed.

SYNOPSIS

Time lag is the intrinsic delay in water quality response to POM, reflecting the movement of water and nutrients from a source to a receptor. This intrinsic time lag is typically divided into unsaturated/soil (tu) and saturated/groundwater (ts) components (Fig. 1). Analysis of the preliminary stages of tu (indicated by initial solute breakthrough at the base of the soil profile) can identify trends in water quality response, and so provide an early indication of the efficacy of POM. As a catchment exhibits multiple soil series and depths, a single value cannot reflect the full range of tu influencing ground- and surface-water quality. This knowledge gap impairs the ability to assess the efficacy of current POM, and is required in order to inform policy makers and monitoring agencies of water quality trends, in advance of nutrient detection at groundwater. This study developed a toolkit for assessing tu ranges, which was demonstrated in the Grassland A and Arable A catchments.

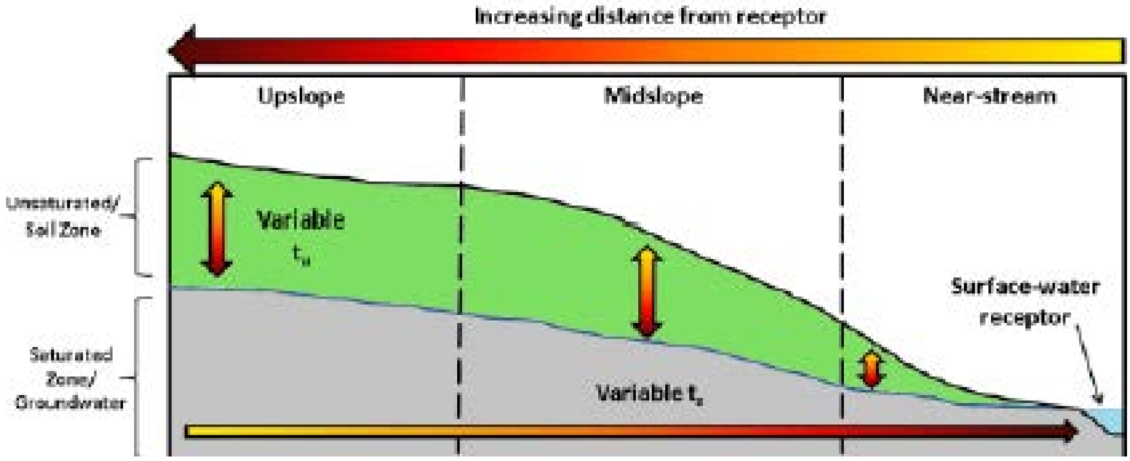


Figure 1: Conceptual diagram indicating total time lag from a source to a surface-water receptor, subdivided into unsaturated/soil zone (tu) and saturated/groundwater zone (ts) componants.

The toolkit consists of a low-complexity model framework. A conservative tracer was simulated, and so the results preclude any attenuation or chemical transformation of the applied nutrients.

Meteorological data was obtained from on-site recording stations. Data from 1st January 2012, to 10th December 2014 was applied, in order to comment on the likely water quality response subsequent to full implementation of POM by the 2012 deadline. In addition, a long-term dataset of moderate meteorological conditions (rainfall – 865 mm, evapotranspiration – 443 mm (hence; effective rainfall – 422 mm) and exhibiting stereotypical distributions) was prepared in order to estimate the full extent of tu.

Both catchments were delineated using GIS software, which was used to derive the dominant soil series from the SIS online map. Each soil series is affiliated with model profiles representing the characteristics typical of that series. The model profiles indicate horizon-specific soil textural and bulk density data, from which soil hydraulic parameters were inferred using pedotransfer functions. In addition, soil auguring was conducted in areas of the catchment in order to validate the soil series assumptions.

Lower boundaries (i.e. the depth of the interface of the soil profile and either bedrock or groundwater) were ascertained from ground penetrating radar (GPR) surveys conducted as part of the catchment characterisation. As such, the depth of the soil profile can indicate the position of the profile along a slope, and hence, proximity to a surface-water receptor. Free drainage conditions were assumed, except for the shallowest profiles (corresponding to near-stream or low-slope positions), in which a fixed watertable was applied. Taking Grassland A as an example (Fig. 2); results indicated one dominant soil association and three affiliated soil series (Ballylanders, Rosscarbery and Driminidy). The minimum and maximum profile depths derived from GPR were 0.5 m and 10 m, respectively, and interim profile depths (3 and 5 m) were selected to reflect mid-slope positions, and subsoil thickness vulnerability rating depths.

Results for the grassland and arable catchment are indicated in Tables 1 and 2, respectively. Depending on the soil series and profile depth, trends start to be observed at the base of the soil between 0.05 yrs and 2.34 yrs. This indicates that response to POM should start to be observed in groundwater within the first reporting period. However, the full effect of POM (as indicated by 'Exit' of solute from the profile) cannot be observed within this timeframe. Long-term simulations indicated that under moderate conditions (precluding periods of extreme rainfall or drought), tu may exceed 11 yrs subsequent to implementation. This is in agreement with other Irish research which suggested that mitigation timeframes between 2019 and 2033 are realistic. In-situ bromide tracer tests in both catchments have established that the toolkit approach is capable of trend estimation.

Association	**Series**	**Area**	**Depth**	**Breakthrough Stage (yrs)**		
				Post-2012 t_u		**Long-term t_u (moderate rainfall scenarios)**
		%	**m**	**Trend**	**Exit**	
Rosscarbery	Ballylanders	50	0.5	0.05	1.05	1.23
			3	0.43	X	4.13
			5	0.74	X	6.06
			10	1.54	X	9.96
	Rosscarbery	34	0.5	0.03	0.98	1.09
			3	0.32	2.93	3.94
			5	0.68	X	5.66
			10	1.45	X	9.55
	Driminidy/ Newport	16	0.5	0.01	0.92	1.00
			3	0.54	X	4.28
			5	1.09	X	6.66
			10	2.34	X	11.57

This methodological toolkit may be applied in catchments which are either failing present water quality requirements, or are identified as vulnerable by the EPA Catchment Management Tool. At present, the input data requirements are largely fulfilled using exisiting resources (Met Eireann, Irish SIS). Some additional field surveying is required in order to ascertain the area within a specific catchment represented by each series within a soil association. However, even omiting this parameter, the ranges established are still informative of overall catchment behaviour. Regarding the boundary information, the practitioner has several options, from generic depths such as those corresponding to subsoil thickness vulnerability rating depths, or highly site-specific (e.g. results of GPR surveys). This allows flexibility in response to the site-specificity of the tu estimate required (which will be higher for monitoring agencies than for informing policymakers), and in respect of resource availability. This study is described in detail in Vero et al. (2014).

Association	Series	Area	Depth	Breakthrough Stage (yrs)		
				Post-2012 t_u		Long-term t_u (moderate rainfall scenarios)
		%	m	Trend	Exit	
Rosscarbery	Ballylanders	50	0.5	0.05	1.05	1.23
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	Rosscarbery	34	0.5	0.03	0.98	1.09
			3	0.32	2.93	3.94
			5	0.68	X	5.66
			10	1.45	X	9.55
	Driminidy/ Newport	16	0.5	0.01	0.92	1.00
			3	0.54	X	4.28
			5	1.09	X	6.66
			10	2.34	X	11.57

Table 1: Trend and full response (indicated by Exit) to POM applied in 2012, and long-term tu in the Grassland A catchment. X indicates a failure to observe full effect of POM within three years subsequent to implementation.

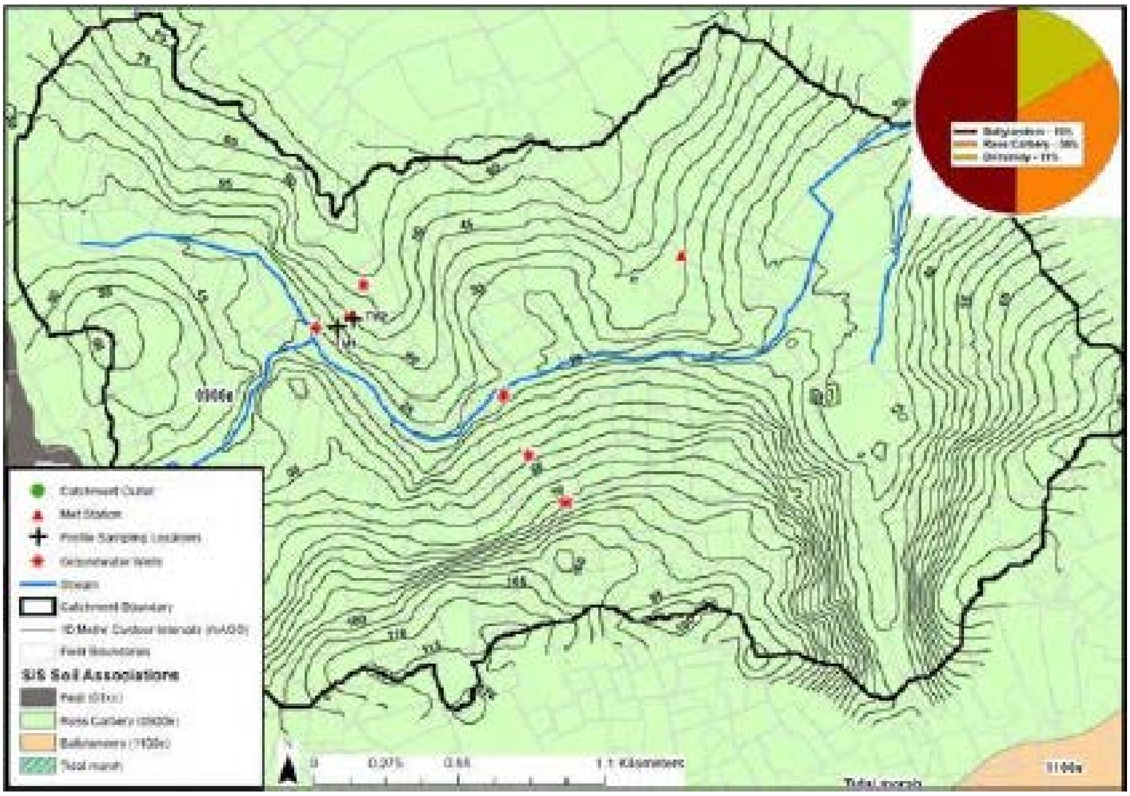


Figure 2: Soil association map of the Grassland A catchment. The pie chart indicates the area represented by each affiliated soil series.

Reference: Vero, S.E., Ibrahim, T.G., Creamer, R.E., Grant, J., Healy, M.G., Henry, T., Kramers, G., Richards, K.G., Fenton, O., 2014. Consequences of varied soil hydraulic and meteorological complexity on unsaturated zone time lag estimates. Journal of Contaminant Hydrology, 170: 53-67

http://www.sciencedirect.com/science/article/pii/S0169772214001806

Paper 7: Investigating suspended sediment dynamics using ex situ turbidity-based suspended sediment monitoring

Sheffiff et al. (2015)

KEY MESSAGES

- Suspended sediment concentrations (SSC) in rivers can carry pollutants and also be a pollutant; accurate measurement is therefore essential.
- Using an ex situ (i.e. not in the river) turbidity continuous monitoring approach, in five ACP catchments, mean annual SSCs were less than the FFD threshold of 25 mg L-1 in all catchments.
- Strong suspended sediment yield (SSY) inter-annual variability was attributed to the timing and character of rainfall events in relation to land management.
- Average annual SSYs in five ACP catchments were low compared to similar catchments elsewhere in Europe.
- Within the study catchments, SSY was higher in catchments dominated by poorly drained soils than those with well drained soils.
- Catchments draining poorly-drained soils and a higher proportion of arable land use reported the highest annual average SSY.
- Well drained soils dominated by arable crops showed the potential to supply significant quantities of sediment despite lower annual average metrics.
- Promoting a varied arrangement of landscape features (hedge-rows, drainage ditches and irregular field sizes) may provide better options to manage hillslope soil erosion and/or sediment transport - even in intensive catchments.

SYNOPSIS

Excessive soil erosion and sediment delivery to watercourses may negatively impact aquatic ecosystems and impede Water Framework Directive (WFD) aims to achieve "good" ecological status. Agricultural practices can modify erosion and transport of sediment such that the robust measurement of sediment and the impact of land use type on sediment export in agricultural catchments is necessary but challenging.

This study assessed the efficacy of novel ex situ SS monitoring techniques in two of the ACP catchments (Arable B and Grassland B), where the high-resolution instrumentation was installed on the bank-side, compared to traditional in situ (i.e. in the river) turbidity-based sediment monitoring techniques – referenced to a 'gold standard' but coarser sampling method. Annual average sediment exports (suspended sediment concentration – SSC, and suspended sediment yield – SSY) were further investigated in five ACP catchments (Table 1) and related to soil drainage class and land use type using the ex situ approach.

Instantaneous suspended sediment metrics estimated using high resolution ex situ methodologies were not significantly different to the 'gold standard' sediment measurement techniques. The ex situ instrumentation, as installed in the ACP catchments, was less sensitive to spurious data peaks compared to in situ instrumentation (possibly caused by larger entrained debris). However, the ex situ instruments were at risk of short-term blockages in the pump lines during extreme sediment and debris transfer following severe rainfall events which accounted for 5% of the total sediment load during the monitoring period in Arable B catchment but did not occur at Grassland B.

Table 1: Summary of catchment physical, climatic and landscape conditions

Catchment	Size (km^2)	30-year average rainfall (mm yr^{-1})	Dominant soil drainage class/ *flow pathway*	Land-use	Landscape complexity features			
					Mean field size (ha)	Mean maximum down-slope length (m)	Hedgerow density (km^{-2}/km^2)	Ditch density (km/km^2)
Grassland A	7.9	1228	Well-drained *Sub-surface*	89% grassland predominantly for dairy cattle; 5% arable	2.00	170	0.061	1.7
Grassland B	11.5	906	Poorly-drained *Surface*	77% grassland for dairy cattle, beef cattle and sheep; 12% spring crops 2% winter crops	3.04	189	0.011	5.7
Grassland C	3.3	960	Moderately- to poorly-drained *Surface*	94% grassland for beef cattle, dairy cattle and sheep	1.12	114	0.044	2.6
Arable A	11.2	906	Well-drained *Sub-surface*	54% arable predominantly spring crops; 39% grassland mainly for beef cattle and sheep	3.32	194	0.011	1.3[b]
Arable B	9.4	758	Poorly-drained *Surface*	42% arable crops; 29% grazing for beef cattle and sheep; 19% dairy cattle grazing	2.70	200	0.011	2.3

Annual average SSCs were less than the repealed Freshwater Fish Directive guideline of 25 mg L^{-1} in all catchments (Figure 1). Concentrations were greater in Grassland B and Arable B with a 3-year average suspended sediment concentration (from 2010-2013) of 8 mg L-1 and 13 mg L^{-1}, respectively compared to Grassland A, Grassland C and Arable A which reported values less than 5 mg L^{-1}. Concentrations of suspended sediment instantaneously exceeded 25 mg L^{-1} less than 12% of the time.

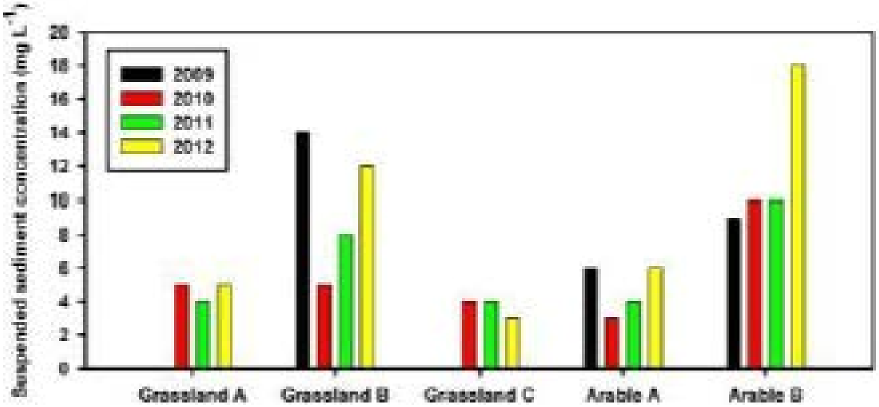


Figure 1: Annual average suspended sediment concentration in five catchments.

Annual average SSYs were low in comparison to UK and other European catchments with similar landscape settings and climatic characteristics (Figure 2). This is attributed to the complexity of landscape features which characterise the Irish landscape such as small field sizes, high densities of field boundaries and drainage ditches, and low downslope lengths which act to reduce connectivity of hillslopes and increase attenuation of sediment in transport. Strong inter-annual variability was attributed to the timing, and character of rainfall events in relation to land management.

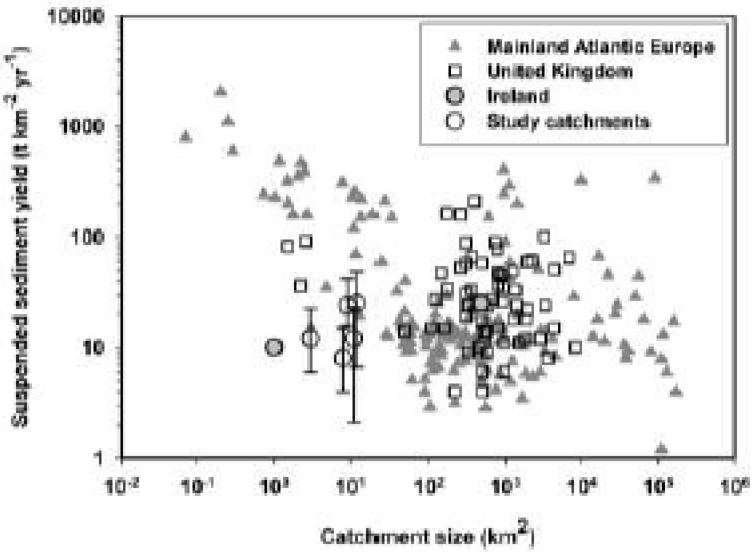


Figure 2: Catchment size and suspended sediment yield of European river catchments; ACP catchments are displayed with inter-annual range

Higher annual average SSYs of ~25 t km^{-2} yr^{-1} occurred from catchments Grassland B and Arable B which drain predominantly poorly-drained soils (Figure 3) due to reduced infiltration capacity and increased connectivity of hillslope soils. Where arable land use is proportionally greater on poorly-drained soils, SSYs exceeded the grass-based catchment likely due to increased availability during periods of low groundcover in arable fields. Catchments draining predominantly well-drained soils exported less than 12 t km^{-2} yr^{-1}

(Figure 3). Lower connectivity due to the dominance of sub-surface hydrological pathways reduces the likelihood of surface soil erosion therefore reducing sediment export. In the Arable A catchment with the greatest proportion of arable land use, the resilience to soil erosion from well-drained soils could be surpassed, likely where surface connectivity is established.

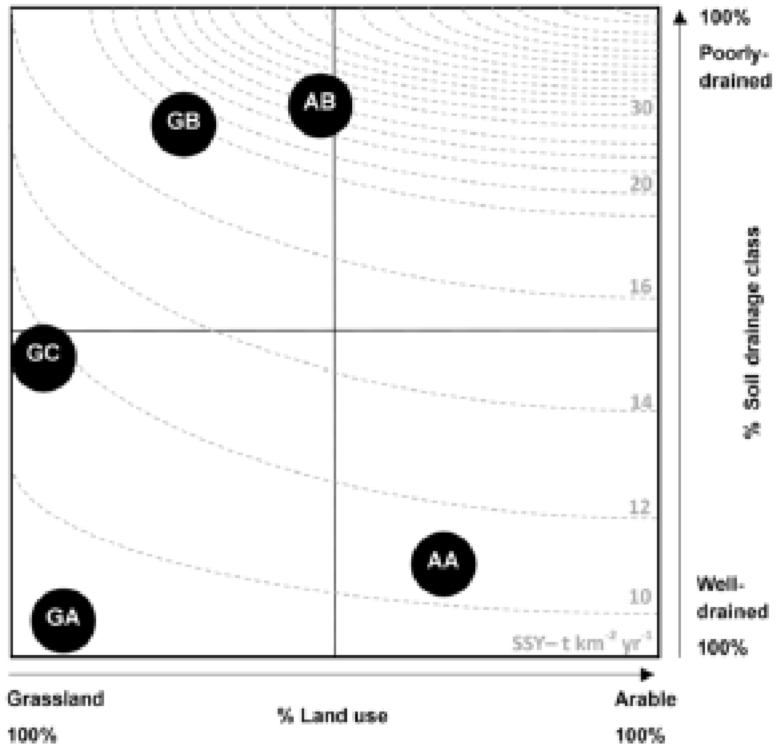


Figure 3: Conceptual diagram of suspended sediment yield as represented by iso-lines according to land use and dominant soil drainage class. Catchment abbreviations: GA – Grassland A, GB – Grassland B, GC – Grassland C, AA – Arable A, AB – Arable B.

These findings validate a new, secure method for suspended sediment monitoring and illustrate that interactions between climate, landscape and land use regulate the supply of sediments from Irish agricultural catchments. The complexity of landscape features reduces sediment loss risk and is, therefore, an important consideration for future management under increasing intensity of agricultural production and changing rainfall patterns due to climate change. This study is described in more detail in Sherriff et al. (2015).

Reference: Sherriff, S. C., Rowan, J. S., Melland, A. R., Jordan, P., Fenton, O., and O hUallacháin, D. 2015. Investigating suspended sediment dynamics in contrasting agricultural catchments using ex situ turbidity-based suspended sediment monitoring, Hydrology and Earth System Sciences, 19, 3349-3363

http://www.hydrol-earth-syst-sci.net/19/3349/2015/hess-19-3349-2015.html

Paper 8: Storm event suspended sediment-discharge hysteresis and controls in agricultural watersheds: implications for watershed scale sediment management

Sherriff et al. (2016)

KEY MESSAGES

- Seasonality of suspended sediment-discharge hysteresis was attributed to seasonal rainfall variability, i.e. degree of hydrological connectivity, and location of sediment sources.
- Flow-weighted suspended sediment export was greater during periods of low groundcover in Arable A and Arable B catchments.
- In the poorly-drained grassland catchment, channels were the most frequent source and yielded the highest sediment quantity.
- Sediments were lost from near-channel and surface (from the hillslope) sources in the moderately-drained arable catchment but events with surface sources exported more sediment.
- In the well-drained arable catchment, channel and near-channel sources were most common but greater sediment quantities were exported from rarely connected surface sources.
- Targeted management alternatives are proposed to reduce sediment loss from catchments – either hillslope/connectivity options or channel/riparian options depending on the dominant hysteresis patterns measured.

SYNOPSIS

Accelerated delivery of suspended sediments and sediment-associated nutrients such as phosphorus from agricultural catchments following rainfall-runoff, or storm events, can degrade the ecological and chemical quality of aquatic ecosystems. Management of sediment loss risk requires knowledge of the controls on sediment sources and pathways which are variable in time and space.

The relationship between discharge and suspended sediment delivery, termed hysteresis, can infer catchment dynamics during storm events using high-resolution monitoring at a catchment outlet. The hysteretic effect can be estimated in two ways; qualitatively, using categories, or quantitatively using a hysteresis index. Main qualitative categories include clockwise, anti-clockwise and no-hysteresis, which are consistent with positive, negative and near-zero hysteresis index values (Table 1).

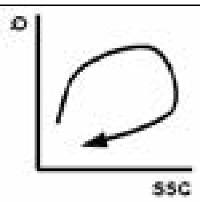
Furthermore, the quantity of sediment exported can be statistically compared to other catchment characteristics that may drive sediment erosion and/or transport e.g., rainfall amount, duration and intensity, stream hydrology metrics and antecedent soil moisture and rainfall (termed 'controls').

In this study, numeric hysteresis analysis was used to explore discrete and seasonal catchment suspended sediment dynamics over two years in three catchments. The event database at each catchment was further separated by hysteresis category, firstly, to determine the relationship between hysteresis type and sediment export, and secondly, to statistically evaluate event controls.

Table 1: Summary of hysteresis metrics and interpretation of catchment sediment processes

Hysteresis category	**Hysteresis index**	**Description**
Clockwise[a]	Positive	*Proximal sediment supply* – sediment peak precedes discharge peak Source located in or near to the channel network and/or transported by a rapidly established delivery pathway
Anti-clockwise[b]	Negative	*Distal sediment supply* – sediment peak follows discharge peak Sediments have a longer transit time from source (e.g., hillslopes) and/or transported by a delayed transport pathways
No hysteresis[c]	Near zero	*Constant supply* – sediment and discharge peaks are synchronous Sediment is present from all hydrologically active sources
Figure-8[d]	Any	*Proximal and distal supply* – two sediment peaks occur during one discharge peak Both proximal and distal sediment sources occur
Complex[e]	Any	*Complex characteristics* – hysteresis relationship not consistent with any other category Difficult to attribute a specific cause, likely a response to multiple sources and transport pathways

Examples



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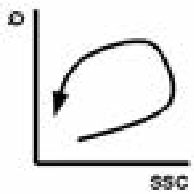

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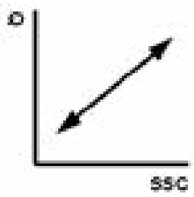

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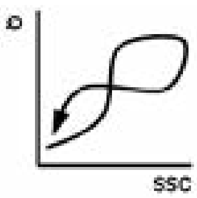

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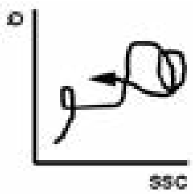


The hysteresis index showed the predominant character of sediment export events contrasted between the three catchments and the frequency of a particular hysteresis type did not necessarily determine the significance towards total yield (Figure 1). Storm-event sediment transfers in Grassland B predominantly originated from locations near to the river network as indicated by clockwise hysteresis and were attributed primarily to hydrological controls. Clockwise hysteresis events also yielded greater sediment quantities in Grassland B.

Arable A displayed predominantly clockwise hysteresis, but also a large proportion of events were attributed to anti-clockwise hysteresis. No hysteresis events were infrequent yet yielded the greatest sediment quantities. The most frequent clockwise events were controlled by stream hydrology drivers which suggested sediment originated from the channel network. No hysteresis events were strongly related to rainfall and precipitation drivers which suggests sediments originated from surfaces on the hillslope.

In Arable B, anti-clockwise events were most frequent but did not yield the greatest sediment quantity. Figure-8 hysteresis was less frequent but, similarly to anti-clockwise hysteresis, displayed a delayed sediment peak. Figure-8 events were driven by rainfall and stream hydrology characteristics suggesting sediment originated from field surfaces.

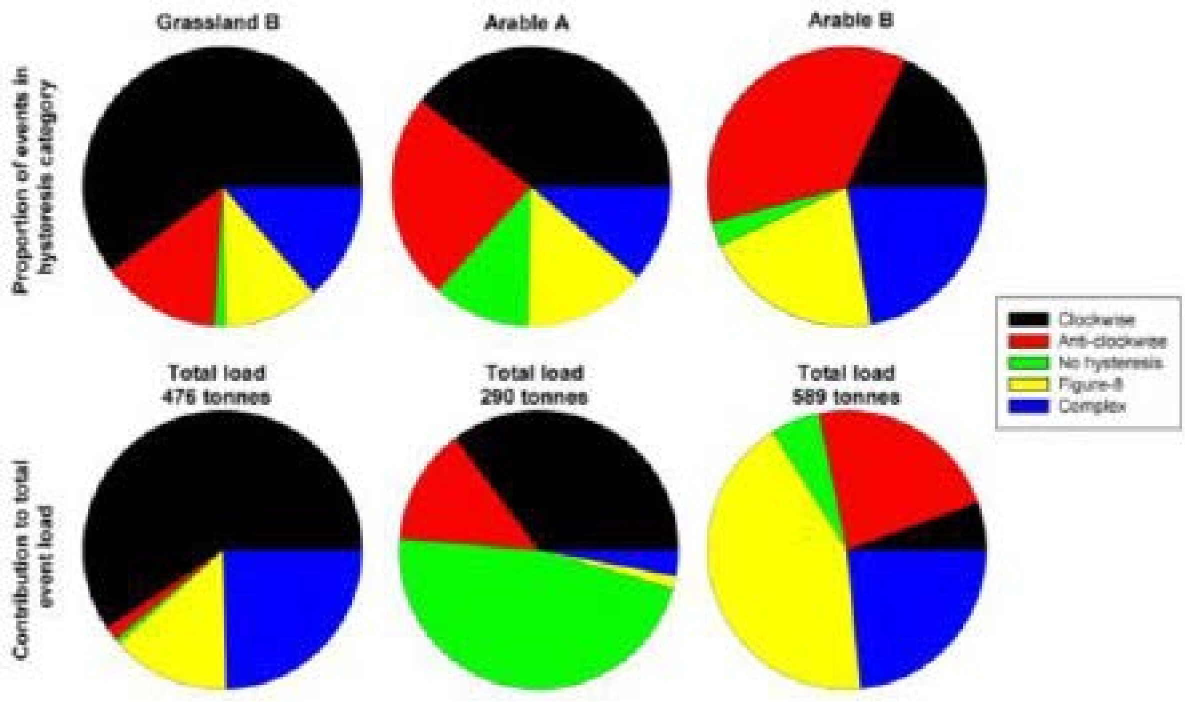


Figure 1: Proportion of events categorised by hysteresis type (top row), and the contribution of events from each category to total event load over monitoring period (bottom row) in Grassland B, Arable A and Arable B.

The evolution of sediment hysteresis of catchment sediment dynamics over time, therefore, showed underlying seasonal fluctuations in all catchments. This trend coincided with rainfall but the hysteresis outcomes contrasted between catchments due to the location of available sources and hydrological connectivity (Figure 2).

In Grassland B, increased rainfall was likely to increase surface hydrological connectivity on surface hillslopes due to predominantly low permeability soils. The magnitude of positive (clockwise) hysteresis events, indicative of channel sediments, however, increased with wetter weather demonstrating that permanent pasture of hillslopes reduced sediment delivery from hillslopes despite good connectivity. Channel bank erosion was likely to be more efficient following sustained wetter weather due to the expansive artificial drainage network across the catchment and, in particular, the inconsistency of vegetation along the riparian corridor. Increased pressure from perched groundwater was also likely to encourage erosion due to lateral pressure on channel banks. Channel erosion is the greatest sediment loss risk in Grassland B.

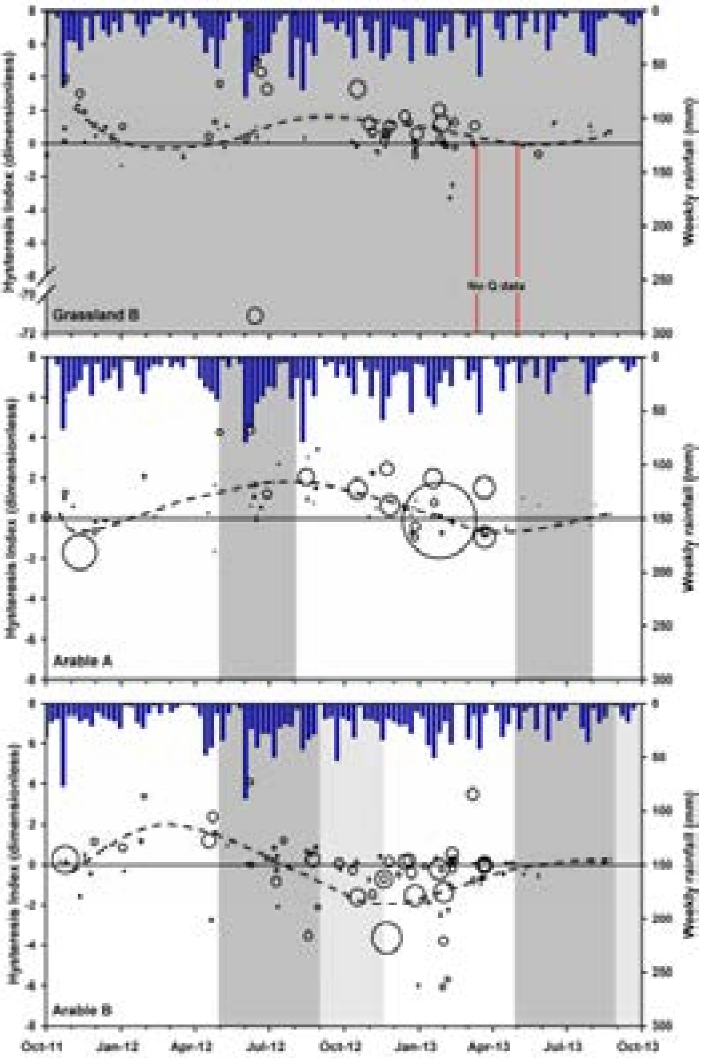


Figure 2: Hysteresis index, weekly rainfall and magnitude of flow-weighted suspended sediment concentration response (indicated by size of circle) over monitoring period in Grassland B (top), Arable A (middle) and Arable B (bottom). Grey panel: high groundcover (>70%), grey-white panel: a reduced proportion of catchment fields had low groundcover. Dashed line indicates seasonal trend.

In Arable A, the high permeability catchment with well-drained soils and underlying fractured bedrock reduced the likelihood of surface hydrological connectivity and negative hysteresis index values despite low groundcover (and high sediment availability) on hillslopes. Sustained wetter weather, coinciding with greater sediment source availability on hillslopes, gradually reduced the proximity of sediment sources such that more sediment was also exported (larger circles). The largest export event followed a period of greater storm activity which increased the groundwater storage and coincided with extreme rainfall characteristics; long duration, high amount and intensity and low groundcover. Under these conditions, surface hydrological connectivity can be established and extreme sediment quantities exported. Hillslopes with low groundcover are the greatest sediment loss risk in Arable A when surface hydrological connectivity can be established. The catchment with predominantly moderately-drained soils supporting arable land use, Arable B, demonstrated increased surface hydrological connectivity during sustained wetter weather. When increased connectivity coincided with low ground cover in the majority or only a proportion of arable fields (white and grey-white panel respectively), the greatest storm event sediment export occurred (larger circles).

These findings are the first to identify seasonal fluctuations in catchment sediment dynamics and, therefore, validate the importance of source availability and hydrological connectivity (controlled by antecedent wetness and discrete rainfall characteristics) on sediment erosion and transport.

Distinguishing between the frequency and significant of sediment event characteristics is essential to guide cost-effective sediment management strategies. Determining hysteresis behaviour using this type of storm monitoring provides managers with targeted alternatives for reducing sediment loss risk. At the most extreme, this management would be: i) hillslope cover and connectivity management where anti-clockwise patterns emerge, and ii) channel/riparian management where clockwise patterns dominate. This study (and the management options and land use implications for all hysteresis patterns) is described in more detail in Sherriff et al., (2016).

Reference: Sherriff, S.C., Rowan, J.S., Fenton, O., Jordan, P., Melland, A.R., Mellander, P.-E. and Ó hUallacháin, D. 2016. Storm Event Suspended Sediment-Discharge Hysteresis and Controls in Agricultural Watersheds: Implications for Watershed Scale Sediment Management. Environmental Science and Technology, 50, 1769-1778.

http://pubs.acs.org/doi/abs/10.1021/acs.est.5b04573

Paper 9:

Phosphorus load apportionment modelling in rivers and the effect of sampling frequency and timing

Subject to peer-review

KEY MESSAGES

- It was hypothesised that coarse scale river sampling frequencies would compromise water quality model predictions.
- High-resolution total reactive phosphorus (TRP) data were restructured into nine different sampling strategies, ranging from daily to monthly sampling frequencies.
- Two example load apportionment models (LAMs), were used to test sample frequencies and predictions.
- Both models apportioned the TRP load between point and diffuse sources, but widely differing apportionment to point sources (51.4 and 4.2%).
- Both models suffered from increased model component variability to an unacceptable degree as model input resolution was reduced to monthly samples.
- Daily sampling was identified as a parsimonious solution for model precision, and a trade-off between sample temporal resolution and model requirement at the (9.48 km2) scale of study.
- For model use, for definition of pollution sources and subsequent assessment of mitigation, at least daily river chemistry sampling is recommended; uncertainty would be further decreased with sub-daily in some catchments.

SYNOPSIS

Determining the relative importance of the contributions of point and diffuse sources to river phosphorus (P) load can be an important, early step towards targets within water quality regulations. Load apportionment models (LAMs) offer a low data requirement solution to source apportionment but may be constrained by the range of river flow and P concentration data available.

To investigate this constraint in a nutrient impacted river, this study investigated the effect of sampling frequency and timing on apportionment estimates of two example LAMs using synchronous and high temporal resolution flow and P concentration data. (Table1)

Table 1: Description and summary statistics of resampled datasets for each sampling combination

C	Meta Data	No. of Datasets	No. of Datapoints per Dataset Mean	SD	Median	Min	Max
C1a	Daily – Random in 24 hours, 7 days per week	2000	1069	0.00	1069	1069	1069
C1b	Daily (same hour each day)	24	1036	4.45	1036	1029	1044
C1c	Daily (Night) - Random 18.00 - 05.00	2000	1068	0.00	1068	1068	1068
C1d	Daily (Day) – Random Mon - Fri, 08.00-18.00	2000	769	0.00	769	769	769
C2a	Three days per week - random (Mon-Fri 08.00-18.00)	2000	461	1.44	462	459	463
C2b	Three days per week - Mon Tue Thu 08.00-18.00	2000	462	0.00	462	462	462
C2c	Three days per week - Mon Wed Fri 08.00-18.00	2000	460	0.00	460	460	460
C3	Weekly – Random, Mon-Fri 08.00-18.00	2000	157	0.00	157	157	157
C4	Monthly – Random, Mon-Fri 08.00-18.00	999	36	0.00	36	36	36

Model outputs included estimation of total annual cumulative TRP load, apportionment of the load to point and diffuse sources, percentage of flows dominated by point sources and an estimation of the river flow at which the dominant contributory source of P changes from point to diffuse.

Outputs from both models, in particular estimation of total TRP loads, varied widely across the range of sampling combinations. Daily data appeared to provide a parsimonious solution for model precision, and a trade-off between sample temporal resolution and model requirement at the (9.48 km2) scale of study. However, source apportionment outputs from the two LAMs were significantly different ($p<0.01$) from each other for all sampling combinations (Figure 1), one predicting a diffuse P dominance (magnitude-centric) and the other a point source dominance (duration-centric).

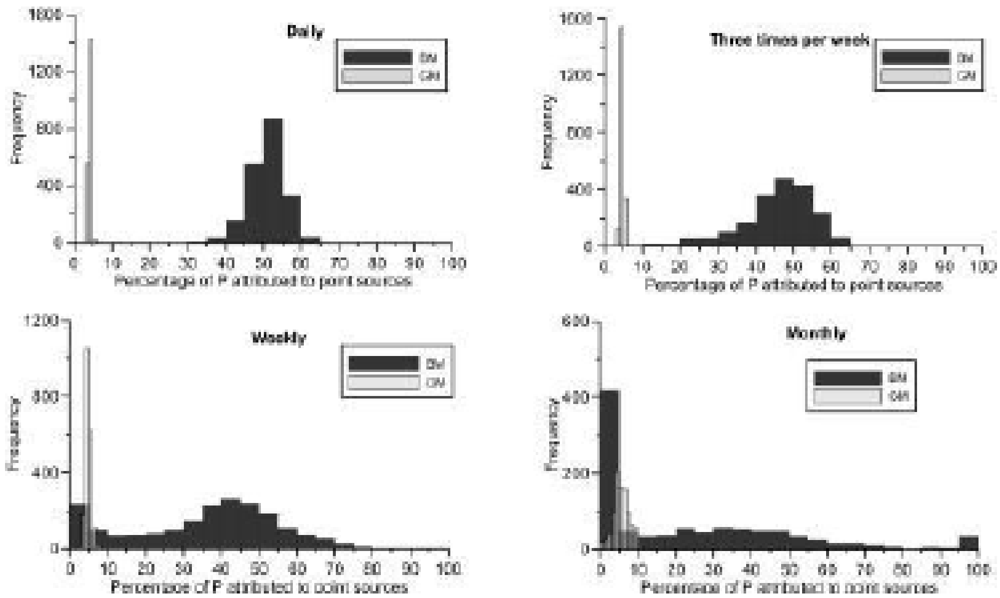


Figure 1: Apportionment of phosphorus load to point sources for four example sampling combinations using the two LAMS (here described as BM and GM). Bin size was 100 for both models.

The coefficients obtained for each model varied widely. The variance in those coefficients that describe diffuse sources increased substantially as sampling frequency decreased, which is indicative of the difficulty in accurately defining contributions from diffuse sources with a reduced sample number.

Although a higher sampling frequency will potentially provide more precise outcomes when modelling environmental data, balancing resources and uncertainty must be considered when designing a sampling regime. In this study, as the sampling frequency increased, the residual error was reduced and the range of load estimation and other model outcomes narrowed. However, when sampling frequency was reduced to once per month, nearly all of the resampled datasets overestimated the total cumulative TRP load and, in some cases, by several orders of magnitude.

LAMs simplify nutrient transfer dynamics by the use of a single modelled line and the clustering of points at low flows may (due to the probabilistic omission of high flow datapoints with coarse resolution sampling), therefore, lead to an incorrect identification of the primary contributor of P in some catchments. As a consequence of the complex relationship between P and Q, which may be masked by coarser data, more complex LAM assumptions are required to improve the use of these types of models.

Water Framework Directive implementation has generally resulted in a hierarchical design for sampling frequency, with EU member states putting more resources into failing catchments to identify the driving factors of eutrophication. Consequently, in most other catchments where sampling frequency remains low, usually monthly due to sampling budget constraints, the results from this study indicate that the output from models may be highly variable, reducing their effectiveness as a management tool, unless fitted with (at least) daily data.

Paper 10:

Storm-triggered, increased supply of sediment-derived phosphorus to the epilimnion in a small freshwater lake

Crockford et al. (2015)

KEY MESSAGES

- Internal loading of sediment-derived phosphorus (P) is hypothesised as a significant contributor to an overall lake P budget, particularly if summer thermal stratification is present.
- High frequency water quality data were collected from three data-sondes deployed on a small meso-eutrophic lake in north central Ireland over 2.5 years. These were compared to high frequency catchment loading data collected in an adjacent proxy catchment.
- Internal loading was found to be higher than catchment loading by 300% in year 1 and to contribute to the high chlorophyll a concentration observed. This loading was a result of breakdown of the thermocline during stratification due to meteorological changes.
- Incomplete breakdown of stratification in year 2 contributed to an already high catchment P loading which served to exacerbate the eutrophication problem.
- Lakes subject to high internal sediment-derived P loading, particularly over the summer, may display a lag time before measures to improve water quality prove successful. Internal P loading should be accounted for when designing remediation.

SYNOPSIS

Freshwater eutrophication effects may persist long after implementation of measures in lake catchments aimed at improving water quality. One potential and often overlooked cause is continued and possibly increased internal loading of bioavailable phosphorus (P) released by lake sediments. Such sediment-derived loading can be considered a delayed effect of decades of deposition of P transported to the lake from sources in the catchment.

This study investigated internal loading of sediment-derived phosphorus (P) in a small, meso-eutrophic lake (surface area 0.2 km2, catchment area 2.7 km2, mean depth 6 m, maximum depth 14 m) during the growing season, and its impact on algal growth and resulting water quality over the period April 2011 – March 2013. Lough Namachree, located in the Grassland C catchment in north eastern Ireland (Figure 1a-c), was instrumented with three data sondes (Hydrolab 5SX) containing sensors for hourly monitoring of chlorophyll a, turbidity, conductivity, temperature, dissolved oxygen, pH and redox potential, suspended from two buoys. A thermistor chain measuring temperature at 1m intervals was installed in Jan 2012. One data sonde was positioned at 1m depth in the eastern shallow end of the lake, and the other two at the central deep basin at 1m and 9m depths.

A neighbouring stream catchment was used as a proxy measurement for catchment P loading using high frequency data from a bankside analyser (HACH-Lange Phosphax). A meteorological station, located next to the lake, measured rainfall, wind speed/direction, and air temperature for the duration.

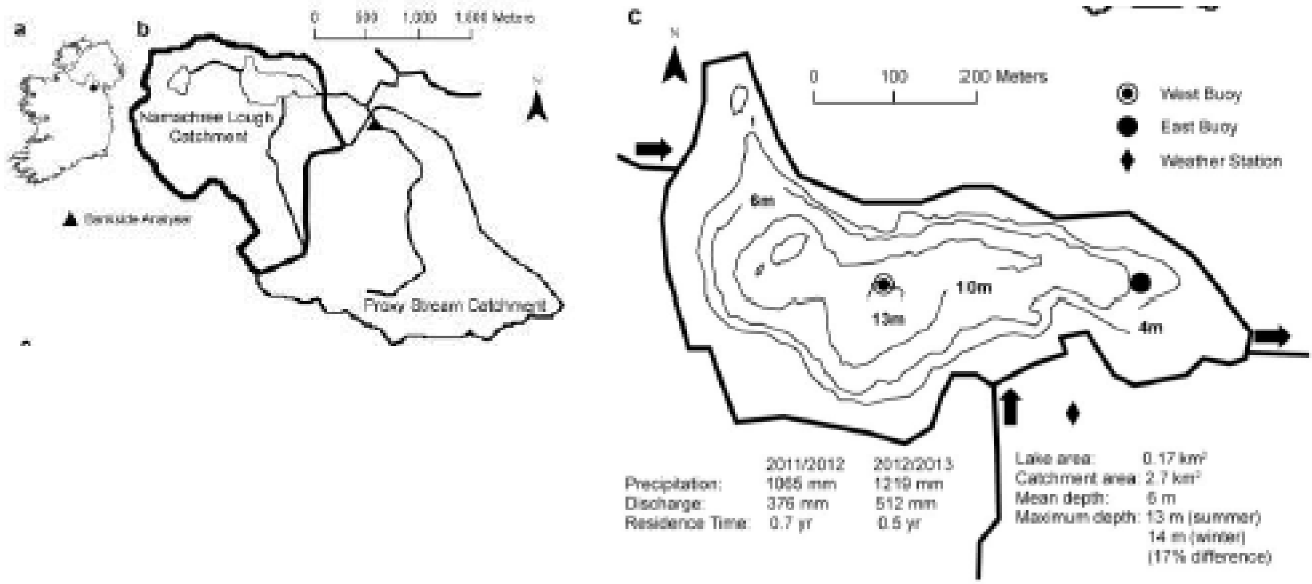


Figure 1: (a) Catchment location, (b) lake and stream catchments and (c) lake instrumentation and inflow and outflow

The lake experienced stratification during spring 2011 and both summers 2011 and 2012 as identified by decreased oxygen saturation in the hypolimnion (Figure 2). Late spring early summer mixing in 2011 saw the reintroduction of a substantial amount of sediment-derived SRP (4.8kg) in comparison with catchment SRP loading of 1.68kg. This instantaneous addition of sediment-derived P provided a boost for algal growth, as seen in Figure 3.

Annual catchment RP loading totalled 42.24kg for 2011-2012 and 54.48 kg for 2012-2013 far exceeding sediment-derived SRP of 12.24kg and 5.62kg respectively. However the bulk of catchment loading occurred during autumn and winter periods (88% 2011-2012 and 68% 2012-2013) when conditions were not conducive for algal growth.

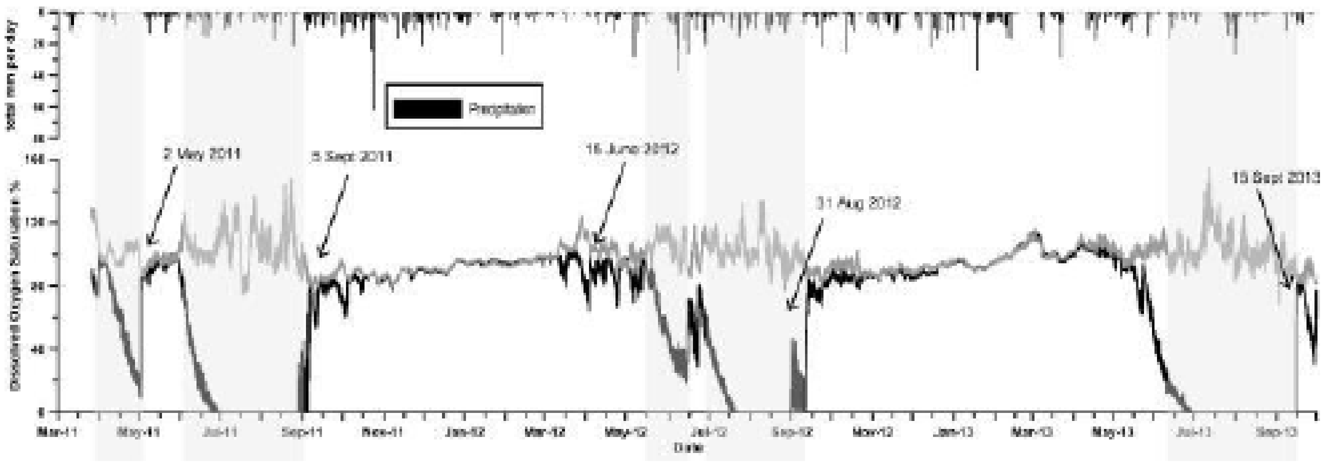


Figure 2: Total daily rainfall (top) and dissolved oxygen saturation in the epi- and hypo-limnia. Dates identify incidences of lake turnover (grey line – epilimnion, black line – hypolimnion)

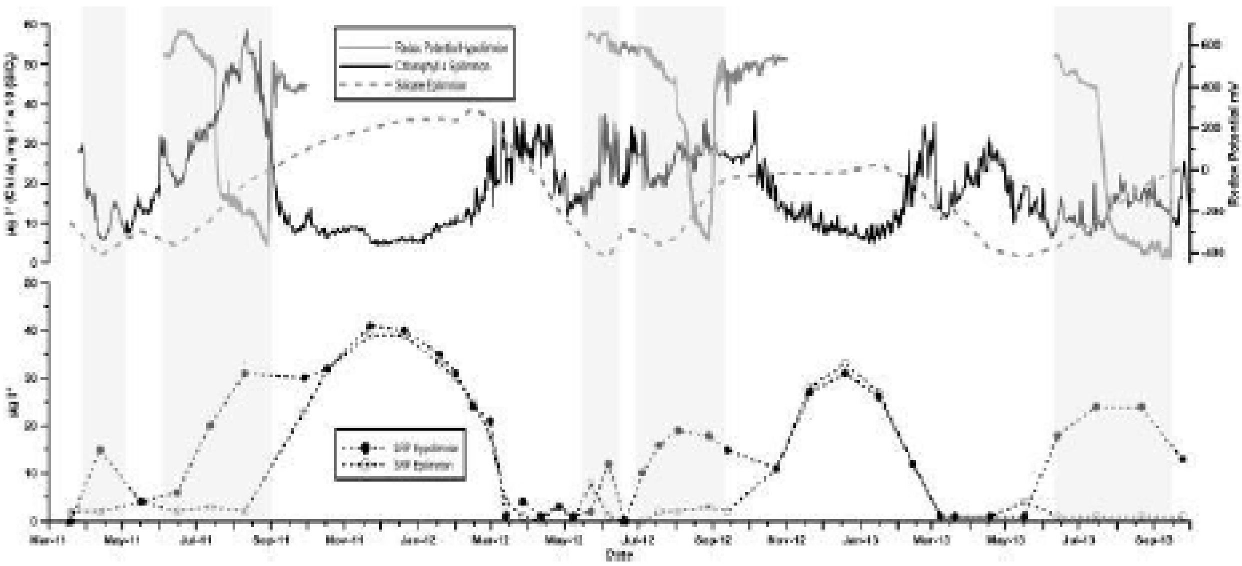


Figure 3: Hypolimnetic redox potential, and eplimnetic silicate and chlorophyll a (top); SRP concentration in the deep (hypolimnion) and shallow (epilimnion) waters

High resolution data collected over 2.5 years (1 Mar 2011 to 30 Sep 2013) revealed inconsistent patterns in (1) the timing and magnitude of lake turnover; and (2) the relative importance of the transfer of hypolimnetic sediment-derived P to the epilimnion when compared with external catchment loading. Efforts to mitigate eutrophication are often based on estimates of the most likely contributors to an overall TP budget and their relative weightings. However, the use of annual budgets of TP may:

- miss the timing of variations in P loads, which can be critical if changes occur during nutrient sensitive times, such as late spring–early summer;
- fail to account for the proportion of P allocated to the biologically available SRP fraction; and
- potentially lead to an inaccurate identification of the primary cause of intra-annual eutrophication.

An increased risk of lake turnover due to a changing climate, and with it increased loading of sediment-derived P, will require the consideration of these processes if eutrophication effects are to be mitigated. These considerations may include the prevention of thermal stratification or the prevention of P release from sediments where appropriate and/or possible. More realistically, in cases with a significant accumulation of P in sediments over many decades, there is likely to be a considerable lag or slower response before the real effectiveness of measures aimed at mitigating eutrophication impacts through reducing external loading is evident. This study is described in detail in Crockford et al. (2015).

To link to Phase 1 studies, longer term palaeolimnological results indicated a ten year cycle of subtle recovery based on the analysis of sediments (diatom sub-fossils) in Sreenty lake. During Phase 2, the high resolution lake monitoring described above indicated that, sub-annually, this recovery trajectory was interrupted by shorter term weather events related to short periods of warm followed by colder/windier weather – causing periods of eutrophication impact from internal lake sources (sediments). This interrupted trajectory of change can be conceptualised as a 'saw-tooth' pattern – i.e. not a smooth transition due to the complexity of climate-chemical interactions, in this case.

Reference: Crockford L., Jordan P., Melland A.R., and Taylor D. 2015. Storm-triggered, increased supply of sediment-derived phosphorus to the epilimnion in a small freshwater lake, Inland Waters, 5, 15-26

https://www.fba.org.uk/journals/index.php/IW/article/viewFile/738/439

Paper 11:

Determining optimum DEM resolutions for critical source areas at sub-field scale

Thomas et al. (2015)

KEY MESSAGES

- Optimal resolutions of elevation data (Digital Elevation Models; DEMs) used to model runoff-generating-areas and critical source areas of diffuse pollution need to be identified.
- Runoff-generating-areas were modelled using high resolution (0.25, 1 and 2 m) LiDAR DEMs and a conventional 5 m DEM and validated using surface runoff field observations.
- Accuracies were much higher using 0.25-2 m LiDAR DEMs compared to the 5 m DEM because they captured hedgerows, roads and tracks which controlled surface runoff pathways.
- Optimal DEM resolutions of 1-2 m were identified, as they were able to model the influence of such features as well as the natural hillslope scale movement of flow.
- They could also more accurately identify breakthrough points and delivery points along runoff pathways where nutrients and pollutants are transported between fields or delivered to the stream, respectively.
- For future field scale mapping of surface runoff generating areas and critical source areas (and correctly defining where pollution hotspots can be managed), 1-2m DEMs is the maximum scale that should be used.

SYNOPSIS

Diffuse losses of pollutants (such as phosphorus (P)) from agricultural land to surface waters can be a major cause of water quality degradation. Catchment areas of highest risk are termed critical source areas (CSAs), where sources of pollutants such as P coincide with areas of high mobilisation potential and surface runoff pathways that are hydrologically connected to streams. If degradation of water quality is to be minimised, surface runoff pathways and CSAs need to be modelled more accurately in order to spatially target mitigation measures and best management practices.

As topography is a dominant factor controlling surface runoff generation, pathways can be modelled using the Topographic Wetness Index (TWI). The TWI uses topographic attributes derived from Digital Elevation Models (DEMs), and is defined as ln(/tanß), where is the cumulative upslope drainage area per unit contour length and tanß is the surface slope gradient. Larger upslope drainage areas and shallower slopes will produce larger TWI values, indicating higher propensity for runoff and pollutant transport. Such topographic indices could be used to improve the identification of CSAs of, for example, P delivery to receiving waters.

However, the TWI is sensitive to DEM grid resolution because it affects both terrain representation and the topographic attributes used within the index. Coarser DEM resolutions tend to predict larger mean TWI values (attributed to the smoothing of topography and loss of topographic detail). The optimal DEM resolution for deriving the TWI depends on the scale of the topographic features controlling runoff propensity. Microtopographic features such as hedgerows, roads and tracks can intercept and divert surface runoff pathways that transport and deliver nutrients and pollutants such as P to watercourses. These can now be captured in high resolution DEMs derived from LiDAR technology, which could ultimately improve surface runoff modelling.

This study aimed to identify an optimal DEM resolution for modelling the TWI and pathways of surface runoff and pollutant transfer within agricultural catchments where microtopography is prevalent, for onward use within CSA modelling. A major working hypothesis was that sub-metre resolution DEMs were optimal based on the assumption that greater topographic detail provides better model performance. The study also aimed to identify a reduced point density appropriate for the optimal DEM resolution that minimised vertical error and oversampling.

The study was undertaken in the Arable A and Grassland B catchments. For each catchment, bare-earth 0.25 m resolution LiDAR DEMs and proprietary 5 m resolution DEMs (Intermap NEXTMap Type II+ v1.5) were obtained. LiDAR DEMs were then resampled to 1 m and 2 m resolutions, and the TWI computed at the four grid resolutions. Runoff-prone areas were modelled using 5%, 10% and 15% of the catchment area with the highest TWI values, and validated using field observations of surface runoff pathways during storm events within target sites. The effects of LiDAR point density reductions on DEM elevations were also analysed at the catchment scale and at microtopographic features (specifically hedgerow banks) within Arable A target sites.

Results show that microtopographic features were captured within all LiDAR DEM resolutions but not in 5 m DEMs (Fig. 1). The variation in topographic information contained within each DEM had significant effects on the spatial distributions of TWI and component values (Fig. 2) and larger ranges of values. Very high topographic variability and very low flow accumulations were shown in 0.25 m resolutions.

Although modelled surface runoff pathways tended to follow hillslope scale topography at all DEM resolutions, hedgerow banks, roads, tracks and tramlines in LiDAR DEMs acted as topographic barriers or channels that accumulated flow and diverted it away from its natural flow path until a gap in the feature was encountered (Fig. 3). Coarser LiDAR resolutions captured microtopographic features in poorer detail which tended to produce a greater number of gaps and hence smaller flow diversions. As in-field microtopography was prevalent at 0.25 m resolution, hillslope topography showed less influence on flow pathways and TWI values. Grids were also much less visually interpretable at this resolution, and high runoff propensity was predicted throughout every field. Spatial similarities in lower hillslope positions were found at 1-5 m resolutions, where runoff often converged to the same location.

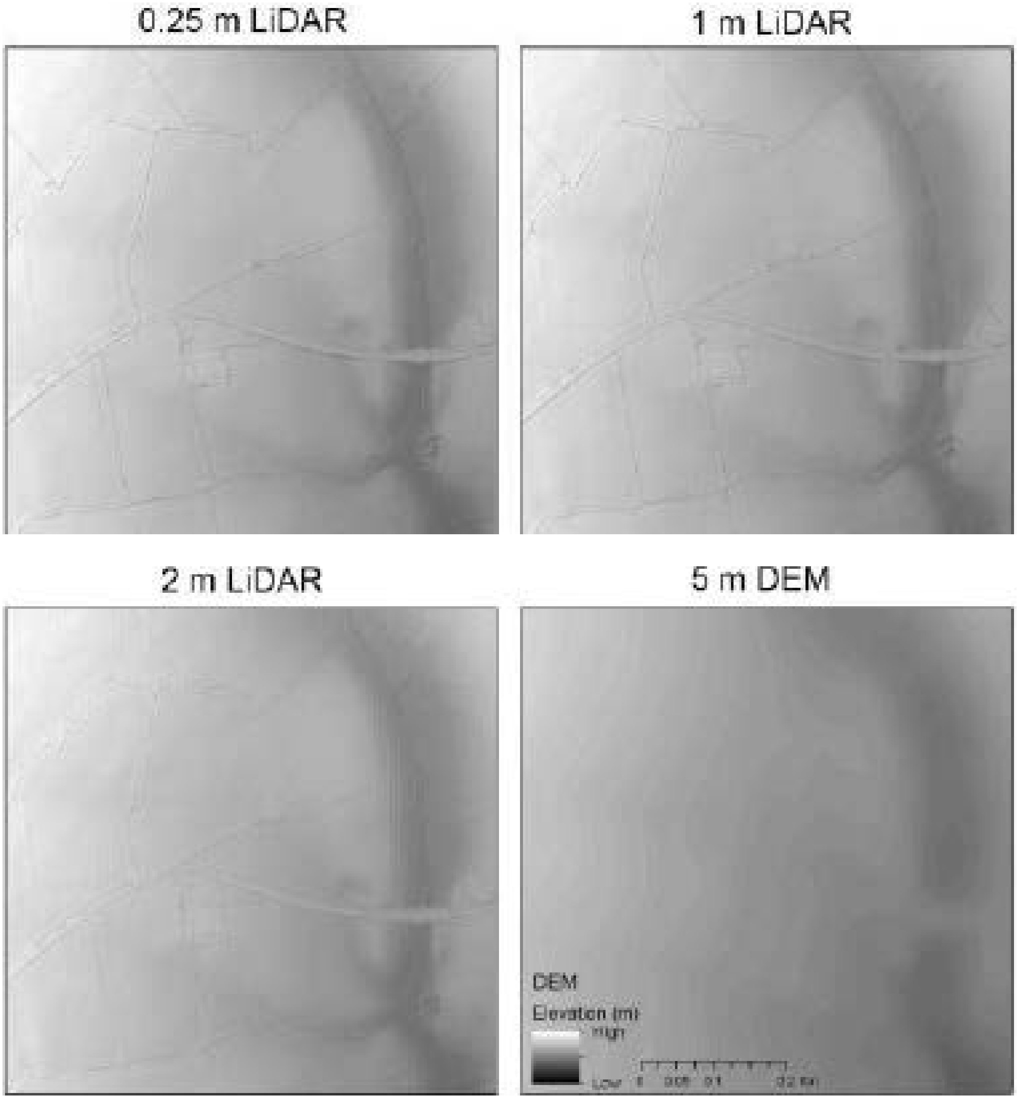


Figure 1: LiDAR DEMs at 0.25, 1 and 2 m resolution, and a conventional 5 m NextMAP DEM. Examples of microtopographic features captured in LiDAR DEMs include tramlines, hedgerow banks, gateways, roads, farmyards, ditches, small stream channels, open agricultural drains, bridges and hollows – which are lost (smoothed) in the 5m DEM.

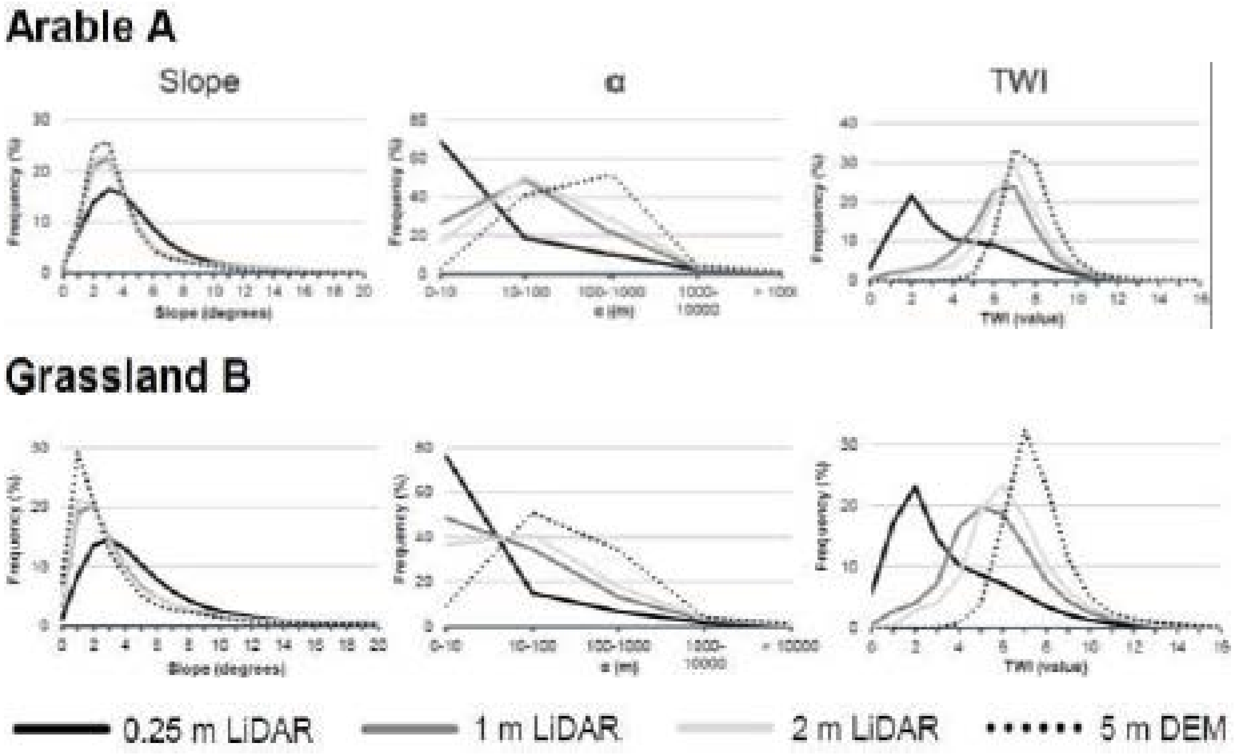


Figure 2: Frequency distributions of values of the TWI and its components derived from each DEM resolution for each catchment (is flow accumulation).

For each target site, LiDAR DEMs modelled runoff-prone areas at much higher spatial accuracies compared to 5 m maps (Fig. 3). Using 5%, 10% and 15% of the catchment area with the highest TWI values, LiDAR resolutions correctly predicted 70-100%, 75-100% and 85-100% of sub-field areas where surface runoff or overland flow was observed, respectively, compared to 10-58%, 40-74% and 60-84% using 5 m TWI maps. Breakthrough points, delivery points and field boundary flow sinks were predicted with 75-100% accuracy at the varying LiDAR resolutions and thresholds, compared to 0-100% accuracy at the 5 m resolution. For all DEM resolutions, modelled runoff pathways tended to extend further into upper hillslope positions than field observations, suggesting that soil hydrological properties (e.g. soil drainage and depth) also needs to be considered. As 0.25 m resolutions over-predicted runoff risk by modelling high runoff propensity throughout every field, the optimal DEM resolutions for modelling pathways of surface runoff and pollutant transfer were identified as between 1-2 m. They were able to capture both surface and subsurface flow pathways, and provided a balance between topographic detail and surface generalisations, allowing modelled surface runoff to be diverted but not permanently re-routed.

Results suggest great potential for using optimal resolution LiDAR DEMs to improve the modelling of runoff pathways and P transport risk within CSA Index tools and the accuracy of CSA delineations. The ability of LiDAR DEMs to accurately identify breakthrough and delivery points allow CSA mitigation measures and agri-environment schemes to be targeted at these critical locations of pollutant transfer, which could also significantly improve cost-effectiveness.

Compared to the initial LiDAR DEM (40 points m-2), reduced densities of between 5 and 2 points m-2 produced 1 and 2 m DEMs with elevations largely unchanged, suggesting that these are optimal in terms of cost-benefit. When analysis focused on hedgerow banks within target sites of Arable A, mean absolute differences remained very small at these densities (3-9 cm), but markedly increased at densities of ≤ 1 point m-2 which were too coarse. This study is described in detail in Thomas et al. (2017).

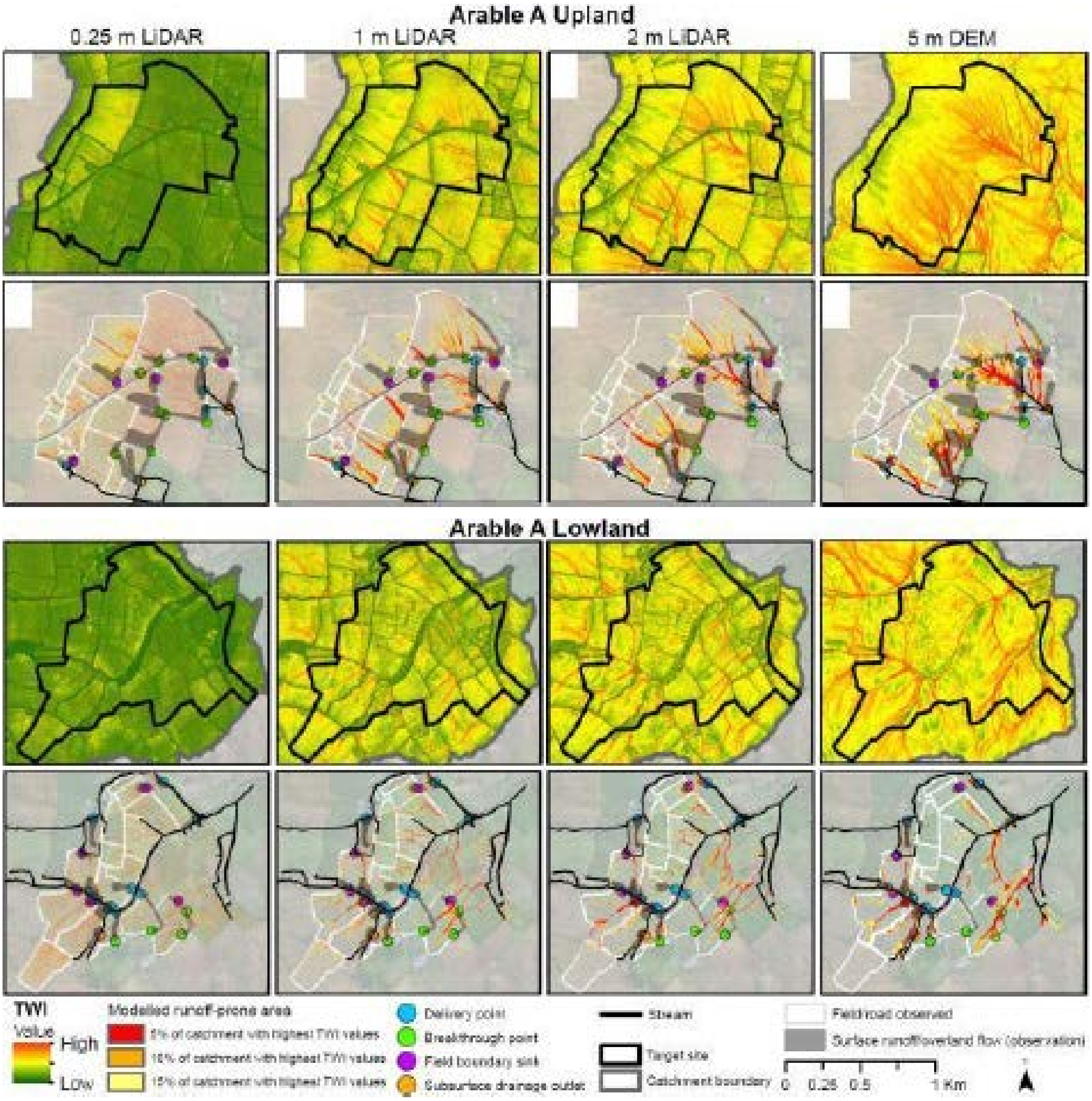


Fig. 3. TWI and runoff-prone area maps at each grid resolution for Arable A target sites, overlaid with field observations of surface runoff and overland flow, breakthrough points, delivery points and field boundary flow sinks.

Reference: Thomas, I.A., Jordan, P., Shine, O., Fenton, O., Mellander, P.-E, Dunlop, P., . and Murphy, P.N.C. 2017. Defining optimal DEM resolutions and point densities for modelling hydrologically sensitive areas in agricultural catchments dominated by microtopography. International Journal of Applied Earth Observation and Geoinformation. 54, 38-52.

http://www.sciencedirect.com/science/article/pii/S0303243416301519

CHAPTER 4

POTENTIAL FUTURE SOLUTIONS

Paper 1:

The role of differing farming motivations on the adoption of nutrient management practices

Buckley et al. (2017)

KEY MESSAGES

- Farmers more motivated by classifications of ‘farm stewardship’, ‘ecocentric’ and ‘productivist’ considerations were more likely to adopt a greater number of the nutrient management best practices under review.
- ‘Anthropocentric’ considerations were important to some farmers and this had a negative effect on adoption rates.
- Demographic and structural variables such as age, off-farm employment, farm-yard manure systems (all negative) and contact with extension services (positive) were found to significantly influence adoption of nutrient management practices examined.
- This work helps to identify the motivations that matter when it comes to policy makers and advisory services influencing the uptake of best management practices by farmers and should be considered as these services are reviewed.

SYNOPSIS

This study examined nutrient management practice adoption across a cohort of farmers in the Republic of Ireland with particular emphasis on the role played by different farming motivations as well as socio-demographic and farm structural factors. The data for this analysis were derived from a survey of farmers across 12 river catchments located throughout the Republic of Ireland, 6 of which were contained within the Agricultural Catchments Programme. A questionnaire instrument was designed to collect data across a range of topics including attitudes to farming and the environment, farm structures and profile, socio-demographics, contact with extension services and adoption of a range of nutrient management best practices. The questionnaire was administered by a team of professional recorders to a total of 402 farmers across the 12 catchments in 2010. For the purposes of this analysis the sample size is restricted to systems which generate and store organic manures so the effective sample size for this analysis is 271 farmers.

A total of 10 nutrient management practices were selected for investigation. These encompassed the nutrient management planning, application and recording best practice continuum. As the number of practices adopted was recorded in non-negative integers, a count data model was used to predict the number of times an event occurs where the dependant variable is measured by the number of nutrient management practices undertaken by a farmer in the survey year.

Through presenting farmers with various attitude based statements (and asking to rank) different sets of farming motivations were identified. Following a principal component analysis 4 motivational factors emerged and these were labelled "farm stewardship", "ecocentric", "productivist" and "anthropocentric". A number of socio-demographic and farm structural factors were also hypothesized to influence the uptake of nutrient management practices including contact with advisory services and discussion group membership, age, off-farm employment, farm size, stocking rate and the type of organic manure storage system in place. All the aforementioned variables were included in a count data model to explore rates of nutrient management practice adoption.

Results indicated that recording of chemical fertiliser applications (74%) and majority springtime application of organic manures (70%) were the most popular practices adopted across the sample, while use of a nutrient management plan (27%) and use of newer organic manure application methods (5%) were the least popular as seen in Table 1.

Table 1: Type of nutrient management practices undertaken by farmers

Nutrient Management Practice	Numbers adopting	Percent Adopting
Chemical fertiliser recording	201	74%
Springtime organic manure application	191	70%
Soil testing	180	66%
Chemical fertiliser field calibration	170	63%
Organic manure recording	156	58%
Liming	140	52%
Organic manure field calibration	130	48%
Estimation of nutrient content of organic manures	128	47%
Nutrient management plan	72	27%
Organic manure application – Trailing shoe, band or injection.	14	5%

A total of 1% of the sample (3 farmers) didn't undertake any of the practices while the same proportion undertook all 10 practices. The mean number of practices undertaken across the sample was 5.26 as outlined in Table 2.

Table 2: Number of nutrient management practices undertaken by farmers

Number of practice	Number of farmers undertaking practice(s)	Percent of farmers undertaking practices
0	3	1%
1	14	5%
2	21	8%
3	29	11%
4	41	15%
5	43	16%
6	30	11%
7	23	8%
8	47	17%
9	18	7%
10	3	1%
Mean	5.26	
Standard deviation	2.38	

Results of the count data model indicated that a number of distinct farming motivations were positively related to farmers' behaviour in the adoption of nutrient management best practices. Specifically farmers more motivated by classifications of 'farm stewardship', 'ecocentric' and 'productivist' considerations were more likely to adopt a greater number of the nutrient management best practices under review. Conversely, the results also indicated that 'anthropocentric' considerations were important to some farmers and this had a negative effect on adoption. Demographic and structural variables such as age, off-farm employment status, farm-yard manure storage systems were associated with lower adoption rates while contact with extension services (agricultural advisors and discussion group membership) was found to positively influence adoption rates (see Table 3).

This analysis highlights important considerations for targeting farmer cohorts for forward land-use planning with regard to tailoring policy measures and incentives in onward reviews of environmental directives and schemes. These are also important considerations when striving to maximise the role of, and the return on investment in, advisory services and advisory service reviews. This study is described in detail in Buckley et al. (2015).

	Parametric estimates	Marginal effects
Farm stewardship	0.08**	0.38
	(0.03)	
Ecocentric	0.08***	0.42
	(0.03)	
Productivist	0.07**	0.37
	(0.03)	
Antropocentric	-0.04*	-0.21
	(0.02)	
Advisor contact	0.20***	1.01
	(0.06)	
Advisor contact & discussion group	0.20***	1.09
	(0.07)	
Age	-0.116**	-0.59
	(0.05)	
Partial FYM system	-0.13*	-0.63
	(0.07)	
Full FYM system	-0.26**	-1.17
	(0.12)	
Off-farm employment	-0.17**	-0.85
	(0.07)	
Total Organic N Ha-1	0.001	0.003
	(0.00)	
Farm size	0.001	0.003
	(0.00)	
Constant	1.72***	
	(0.14)	

Table 3: Results of Poisson regression for nutrient management practice adoption
***1% level, **5% level, *10% level, †Discrete changes (from 0 to 1) for these variables.

Reference: Buckley, C., Howley, P., Jordan, P., 2015. The role of differing farming motivations on the adoption of nutrient management practices. International Journal of Agricultural Management, 4(4), 152-162.

http://www.ingentaconnect.com/content/iagrm/ijam/2015/00000004/00000004/art00003

Paper 2:

Understanding Soil Testing on Dairy Farms

Kelly et al. (2017)

KEY MESSAGES

- Findings comparing testers and non-testers show all farmers testing their soil on a regular basis are younger, have larger farms and herds, have larger gross output, have greater expenditure on nitrogen, and are more profitable, compared to farmers who do not.
- The analysis also shows nationally there is no significant difference in fertilizer and concentrate expenditure per hectare between soil test users and non-users.
- The logit regression analysis suggests policy and extension programmes have a significant effect on adoption. However, given national falling soil fertility trends farmers may not be using the results to achieve optimal outcomes.
- These findings are important in the context of the somewhat contradictory environmentally-focused and productivity-focused policy instruments that drive regular soil testing behaviour and the anomaly of high rates of soil testing with declining national soil fertility levels.

SYNOPSIS

This research reports findings from the first phase of a more extensive social science-based mixed methods research project examining Irish dairy farmers' use of soil test information. The study addressed three main questions. First, what are the farm and farmer characteristics of Irish dairy farmers who soil test? Second, are there differences in terms of cost savings between those farmers who soil test and those who do not? Third, what are the characteristics of farms and farmers who soil test voluntarily? The objective was to identify the cohorts of farmers who are more or less likely to soil test on a regular basis nationally and to compare with the characteristics of sample of voluntary soil testers.

Data were collected using the Teagasc National Farm Survey (NFS). The NFS is collected annually as part of the Farm Accountancy Data Network (FADN) requirements of the European Union. Collectively these data sources contain information relating to farm activities, financial returns to agriculture and demographic characteristics. The NFS records information from a representative weighted sample of farms throughout the Republic of Ireland. The study uses data across specialist dairy farmers included in the 2009 NFS survey.

Specialist dairy farms are defined as systems where at least two-thirds of farm standard output is from grazing livestock and dairy cows are responsible for at least three-quarters of the grazing livestock output. The total sample size in this analysis is 231 specialist dairy farmers. This is representative of approximately 14,000 specialist dairy farms in Ireland when population weighted. The average age of farmers is 50 years old and they have an average farm size of 57.6 hectares with an average dairy herd of 64.1 cows.

Results suggest that there are two broad categories of farmers who test their soil; (i) those who test voluntarily and (ii) those who are required to test due to a policy-driven incentive or requirement such as the rural environment protection scheme (REPS) or to secure Derogation under the Nitrates Directive. As shown in Table 1, farmers who test their soil regularly are younger, have larger farm and herd sizes and have higher farm gross margin and gross output compared to those farmers who don't regularly test their soil.

Variable	**Regular Soil Testers n=165**	**Non regular Soil Testers n=66**
Age	Younger**	-
Farm Size	Larger**	-
Size of Dairy Herd (Avg)	Larger**	-
Farm Gross Margin (GM) (€)/UAA	Higher**	-
Farm Gross Output (GO) (€)/UAA	Higher**	-
Nitrogen (kg)/UAA	Higher**	-
Direct Cost(€)/UAA	No Difference	
Fertiliser(€)/UAA	No Difference	

*p<0.1, **p<0.05, ***p<0.001

Table 1: Comparison between all soil testing and non-soil testing dairy farmers

Table 1 also addresses the second research question. The data confirm that there is higher gross output and gross margin per hectare associated with the regular soil testers yet there was no significant difference between the two groups in relation to direct costs and fertiliser costs per hectare. Farmers who regularly soil test also use greater quantities of nitrogen, which is anecdotally linked to more intensive grass production systems. A notable aspect of the research was the almost equivalent average fertiliser expenditure per hectare by farmers who do not test (€155) as those who do (€168) suggesting inefficiency in the system with associated environmental risk as non-regular soil testers were also achieving lower outputs.

In relation to the third research question on the characteristics of farmers who voluntarily test their soil (compared to non-testers), results of a logistic regression shown in Table 2 confirm that farmers with formal agricultural education are almost four (3.69) times more likely to soil test. Farm size (measured by dairy platform) also has a positive impact on the likelihood of soil testing. For each additional (hectare) increase in the size of the dairy grazing platform there is a 5.5% increase in the odds of testing. Although the cohort of farmers used in the voluntary model is much smaller (n=86), the strong positive relationship indicates the potential benefits of education for voluntary users.

Explanatory Variable	**Estimated Coefficient Standard Error**	**Odds Ratio**	**95% CI**
Dairy Platform	0.0535** (.02)	1.055	[.0152667 .0918649]
Formal Ag. Training	1.3074** (.64)	3.696	[.0486439 2.566285]
Log pseudo likelihood -2343.51			

*p<0.1, **p<0.05, ***p<0.001

Table 2: Key characteristics of voluntary soil testers

Given the anomalies identified during this research in terms of fertiliser expenditure, different characteristics of who do and do not soil test as well as the mandatory requirement underpinning much soil testing, we suspect, though not investigate here that Irish dairy farmers are not making full use of their soil test results as a decision making input to nutrient management practices. They may not be doing so for various reasons. Additional research is on-going to explore these issues.

This work is described in more detail in Kelly et al. (2017).

Reference: Kelly, E., Heanue, K., Buckley, C. and O'Gorman, C., (2017). High rates of regular soil testing by Irish dairy farmers but nationally soil fertility is declining: Factors influencing national and voluntary adoption. International Journal of Agricultural Management

http://www.ingentaconnect.com/contentone/iagrm/ijam/2016/00000005/00000004/art00003

Paper 3:

Willingness to pay for achieving good status across water bodies in the Republic of Ireland.

Buckley et al. (2014)

KEY MESSAGES

- Findings from this study indicated that the general population places a high rating on water quality related environmental issues.
- Of the nine environmental issues explored, tackling poor drinking water quality and pollution of rivers and lakes were the top ranked priority issues across the sample.
- Damage from flooding was jointly ranked third and water pollution at beaches was ranked seventh.
- Results indicated that over 50% of the sample indicated a €0 willingness to pay (WTP) for achieving 100% good status across Irish rivers from the existing position of 68.9%.
- Mean WTP for achieving full good status across rivers in the Republic of Ireland was estimated at €19 per respondent per annum. Aggregating this up across the general population indicates a total WTP for achieving good status across rivers in the Republic of Ireland of €65.35 million.

SYNOPSIS

The Water Framework Directive (WFD) requires member states to achieve good status across all surface waters by review deadlines following the first in 2015. Derogations from this target have to be proven based on infeasibility or disproportionate cost. Hence, quantification of benefits is an important element in the assessment of the proportionality of costs in the implementation of the WFD.

Assessing whether the achievement of good status is disproportionately expensive requires a comparison of the costs of putting measures in place to achieve good status versus the benefits that might come about as a result of the water body achieving good status. Very few studies have looked at the benefit side of this equation in the Republic of Ireland and this research aimed to address this research gap by undertaking a survey of the general population using a non-market valuation contingent valuation methodology to explore willingness to pay (WTP) of the general population to achieve good status across all rivers in the Republic of Ireland.

The main issues addressed in this research included: (i) to examine the public attitudes towards water quality. This included an examination of the priority the general public places on water quality related objectives compared to other environmental objectives, (ii) to estimate the general publics' willingness to pay for achieving good status across all rivers in the Republic of Ireland and (iii) to examine the impact of socio-demographic characteristics and environmental values towards achieving good status across rivers in the Republic of Ireland.

A questionnaire instrument was designed to examine the general public preferences regarding water quality objectives and willingness to pay for measures aimed at achieving good status across all rivers in the Republic of Ireland. Following a pilot phase a total of 615 face to face interviews were conducted. The target group for the surveys was the general public, i.e. adults aged 18 years or over. Stratified quota sampling was used to ensure a nationally representative sample of the population. In the questionnaire respondents were presented with the scenario that described how under the EU Water Framework Directive all rivers in the EU are mandated to achieve good status by 2015 or targets thereafter. Failure to comply with this standard where possible will lead to reoccurring fines from EU enforcement institutions. A show card was developed to take account of the various attributes (including water clarity and composition, fish, plant and insects life as well as bankside condition) associated with good status. Once respondents had examined the show card they were asked how much in increased annual taxation they would be WTP to get all rivers in Ireland to a point where they would be classified as being of good status. Additionally, a series of questions were also included in the questionnaire to capture relevant socio-demographic characteristics of the respondents such as age, education, income and recreational use of rivers. Finally, a series of statements were constructed to establish respondents' environmental values.

Findings from this study indicated that the general population places a high rating on water quality related environmental issues. Of the nine environmental issues explored, tackling poor drinking water quality and pollution of rivers and lakes were the top ranked priority issues across the sample. Damage from flooding was jointly ranked third and water pollution at beaches was ranked seventh. Results indicated that 41% of the total sample indicated using a river for recreational purposes in the previous year. Walking was by far the most popular activity with 36% of the total sample undertaking this activity along rivers. Between 3-4% of total sample engaged in either nature or bird watching, swimming, fishing or water sports relating to boats.

Excluding protest responses, results indicated that over 50% of the sample indicated a €0 willingness to pay for achieving 100% good status across Irish rivers from the existing position of 68.9%. Results from the WTP regression analysis indicated that socio-demographic factors including actual income and subjective perceptions relating to household financial status as well as education were found to have a positive impact on the general public's WTP for achieving good status across Irish rivers. Recreational use values were also found to have an effect in that average number of trips taken to the river for recreational purposes and average distance travelled for access were both positively and significantly associated with WTP for achieving good status across Irish rivers. Environmental values were also found to be significantly associated with overall WTP for achieving good status across Irish rivers.

Willingness to pay values were found to be higher among respondents living in river basin districts where rivers were generally of lower surface water quality status. Mean WTP for achieving full good status across rivers in the Republic of Ireland was estimated at €19 per respondent per annum. Aggregating this up across the general population indicates a total WTP for achieving good status across rivers in the Republic of Ireland of €65.35 million.

Reference: Buckley, C., Howley, P., O'Donoghue, C., Kilgarriff, P., Lennon, J., McIntyre, B. and Campbell, D. (2014). Are we willing to pay for good river water quality? Willingness to pay for achieving good status across rivers in the Republic of Ireland. EPA Strive Report No. 129

http://www.epa.ie/pubs/reports/research/water/researchreport129.html

http://www.esr.ie/article/view/610

Paper 4:

Evaluation of soil tests for predicting nitrogen mineralisation in temperate grassland soils

McDonald et al. (2014)

KEY MESSAGES

- Current N recommendations for Irish grassland systems do not account for N supplied from native soil organic matter (SOM) through the processes of mineralisation, but are based on grass growth demand (grazing or cutting), adjusted to account for stocking rate (LU ha^{-1}) and limited by the European Union Nitrates Directive.
- A rapid and reliable soil testing procedure that predicts mineralisable N (MN) is needed for temperate soils as it would help to improve N fertilizer use efficiency (NfUE), which is important for both agronomic and environmental sustainability.
- The Illinois soil N test (ISNT) was the most effective test for predicting MN across a range of 35 productive mineral grassland soil types, as it explained 69% of MN measured using a standard reference of a 7 day anaerobic incubation (AI-7).
- The ISNT is a simple, reliable and robust test suitable as a routine test to predict MN. However, additional studies are required to evaluate the effectiveness of ISNT to predict N supply for grass growth with the aim of improving efficiencies and this is on-going work.

SYNOPSIS

Existing measures of N availability test for mineral N levels; however, these are unreliable due to the temporal nature of mineral N pools under humid and high rainfall climates. Development of practical applications to measure soil N supply through the mineralisation of labile SOM-N has taken place over a number of decades. Biological N tests that include long and short term soil incubations create a soil environment that promotes biological activity and the result is N mineralisation of liable organic pools over a defined period of time. The 7 day anaerobic incubation (AI-7) is recognised as being a suitable reference indicator of a soil's MN potential. Although these biological incubations are reliable, they are rarely used, as they are too time-consuming and impractical for high throughput analysis by soil laboratories. The alternative by many studies has been to develop chemical methods and evaluate their effectiveness to extract the mineralisable N fraction through correlation with standard biological measures. Given the lack of knowledge regarding the effectiveness of many chemical tests to predict soil N availability in temperate grassland soils, seven rapid chemical N tests were evaluated and the relationships between soil N pools measured by these tests and soil properties such as total N, carbon (C) and SOM were explored against MN (i.e. AI-7) for 35 productive mineral grassland soils collected at 10cm depth across the Island of Ireland (Table 1).

A large range in MN (as measured by AI-7) of 92 to 403 mg NH4-N kg^{-1} was found among the different grassland soil types typical to Ireland. This indicates the need to account for different levels of N supplied through N mineralisation within these soils. Therefore, highlighting the potential benefits that could be accrued by adjusting the current "one size fits all" N fertilizer recommendations for these grassland soils.

Table 1. Linear regression equations † of mineralisable N (MN) versus soil N indices across 35 temperate grassland soils.

	Intercept		**Slope**				
N index‡	**Estimate**	**Standard error**	**Estimate**	**Standard error**	**P >F§**	**RMSE¶**	**r^2**
TN	22.63	28.06	48.39	5.90	<0.0001	45.18	0.67
TC	66.79	24.09	3.66	0.47	<0.0001	46.73	0.65
SOM	29.72	30.99	1.94	0.27	<0.0001	49.2	0.61
Cold_KCL$_{NH4}$	248.01	20.03	-1.04	4.05	0.7982	78.68	0.00
Cold_KCl$_{NO3}$	215.50	21.48	1.40	0.84	0.1064	75.67	0.08
Hot_KCl$_{NH4}$	142.20	33.93	2.00	0.62	0.003	68.81	0.24
Hyd_N	155.78	30.88	1.86	0.60	0.004	69.35	0.22
Acid_Oxd_N	182.59	84.45	0.45	0.61	0.4658	78.12	0.02
UV_260	83.72	36.82	369.34	81.28	<0.0001	61.77	0.39
UV_210	161.46	24.17	469.58	122.02	0.0005	65.44	0.31
Fl_CO2	-169.60	77.03	6.94	1.28	<0.0001	57.32	0.47
ISNT-N	3.38	29.32	0.68	0.08	<0.0001	44.14	0.69

†Equations are of the form Y=intercept +slope(x), where x is the measured N index, and the intercept and slope were estimated by regression

‡TN, total soil nitrogen; TC; total soil carbon; SOM; soil organic matter; Cold_KCl$_{NH4}$, KCl extractable NH_4-N; Cold_KCl$_{NO3}$, KCl extractable NO_3+NO_2-N; Hot_KCl$_{NH4}$, heated KCl extractable NH_4-N; Hyd_N, Hydrolyzable N determined as the difference between hot and cold extractable NH_4-N; $KMnO_4$_oxd_N, potassium permanganate oxidation measured as NH_4-N; UV_260, ultraviolet absorption of KCl extract at 260 nm wavelength; UV_210, ultraviolet absorption of KCl extract at 210 nm wavelength; Fl_CO_2, flush of carbon dioxide in 24 h; ISNT-N, Illinois Soil Nitrogen Test N

Although shown to be highly related with MN ($r2 = 0.61$ to 0.67, shown in Table 1), the stable nature of the soil properties total N, C and SOM makes these indices less sensitive to soil management practices such as organic and inorganic fertilizer inputs as well as short-term structural changes caused by soil drying and wetting cycles, typically experienced under temperate climates. These indices may not reflect the potentially labile N supply available for plant uptake in a growing season, but do indicate changes over a longer period of time (i.e. years). In contrast soil mineral N pools measured using KCl extraction did not correlate with MN ($r2<0.08$, as shown in Table 1), as this measure of N has been shown to be too transient for estimating plant available N, even under shorter periods (i.e. days) under high rainfall environments, particular to Ireland.

The Illinois N test (Photo 1) determines amino sugars and NH_4-N with direct alkaline hydrolysis in a diffusion method and is based on the theory that the amino sugar fraction of soil organic N is a labile source of N released by mineralisation. In previous studies, mostly in North American Arable fields, ISNT was shown to be a good predictor of crop response to N fertilizer. Across the 35 temperate mineral grassland soils in this study, the ISNT was found to be the most effective predictor of MN ($r2 = 0.69$, as shown in Table 1).

Photo 1: Laboratory images of the Illinois soil N nitrogen test (ISNT) being carried out at the Johnstown castle Environmental Research Centre , images are courtesy of ACP soil scientist Dr Noeleen McDonald.

Grouping of soils based on similar textural properties did not give any significant improvement in predicting MN (as shown in Fig 1).

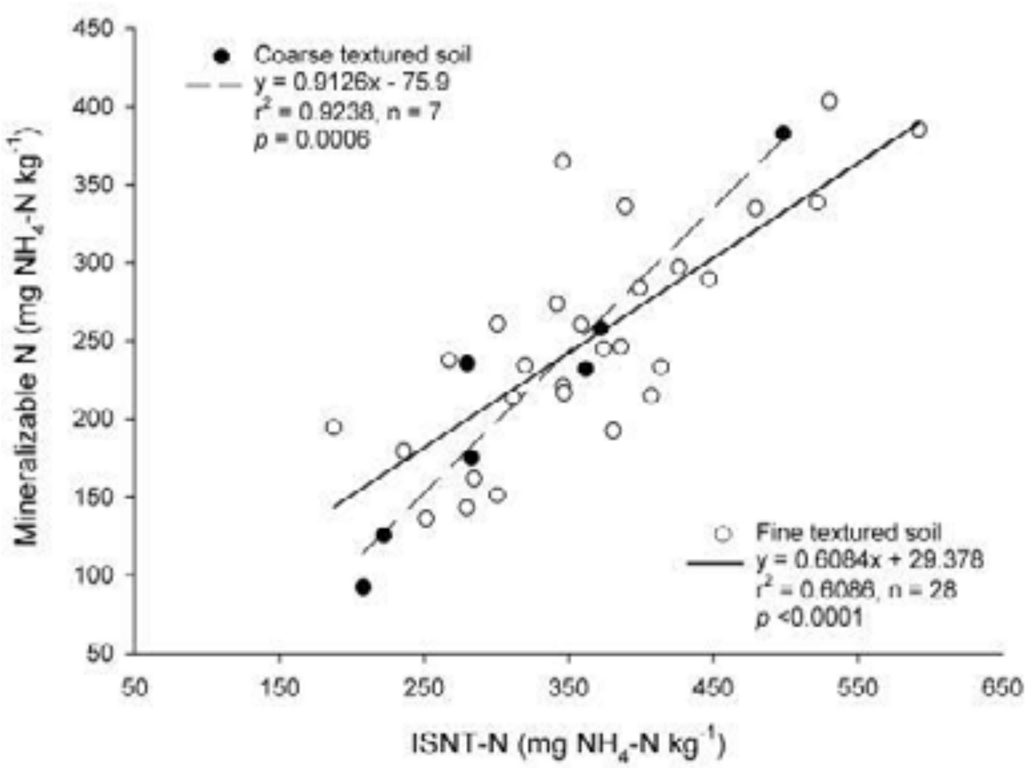


Figure 1: The relationship between mineralisable N measured using a 7 day anaerobic incubation (AI-7) versus the Illinois soil N test (ISNT) across coarse and fine textured soils.

Given the simplicity, reliability, and robustness of the ISNT, it shows the most promise towards routinely predicting MN across various Irish soil types. Further development of the ISNT for this purpose could enable the development of precise N fertilizer recommendations and improve NfUE on farms and reduce losses and associated environmental impacts. Continued research is needed to validate the effectiveness of ISNT to predict N supply for grass growth across varying temporal, climatic and management conditions.

Reference: McDonald, N.T., Watson, C.J., Lalor, S.T.J., Laughlin, R.J. and Wall, D.P. 2014a. Evaluation of soil tests for predicting nitrogen mineralization in temperate grassland soils. Soil Science Society of America Journal, 78; 1051-1064.

https://dl.sciencesocieties.org/publications/sssaj/pdfs/78/3/1051

Paper 5:

Identifying nitrogen and carbon metabolites associated with N mineralisation in grassland soils using ^{1}H NMR.

McDonald et al. (2016)

KEY MESSAGES

- Better knowledge of the important soil metabolites that drive the rate of N mineralisation is essential for managing N inputs to soils in order to increase N fertilizer use efficiency (NfUE) and reduce environmental losses of N.
- Metabolites present in mineral soils can be effectively detected, identified and quantified using high resolution ^{1}H NMR and in this study of 35 grassland soils, seven metabolites were identified that were associated with the N mineralisation process.
- Glucose was present in the highest concentrations and explained 72% of the variability in mineralisable N. This suggests that labile carbon (C) is one of the main substrates regulating microbial N mineralisation and soil N availability in temperate grassland soils.
- Additional investigations of the variability of metabolites identified in this study (i.e. Glucose, glutamic acid, 4-aminohippuric acid, aspartic acid, serine and trimethylamine), under different soil management regimes would also help to increase our knowledge of the interactions between these metabolites, the soil microbial communities and their influence on soil N mineralisation and immobilisation processes.

SYNOPSIS

Soil metabolites are compounds of amino acids, amino sugars, carbohydrates, nucleic acids and lipids, which are the result of decomposed soil organic matter (SOM). These metabolites can be further processed by soil microbes to release ammonium (NH_{4}-N), known as mineralisation, which in turn is available N for plant uptake. Understanding which of these metabolites are pivotal in driving the rate of N mineralisation is essential for managing N inputs to soils in order to increase N fertilizer use efficiency (N_fUE) and reduce environmental losses of N. Considerable effort and resources have been invested in developing suitable biological (e.g. aerobic and anaerobic incubations) and chemical tests to identify and quantify the N supply capacity of soils.

Previous work (see previous Synopsis and reference) reported that the ISNT-N (Illinois soil nitrogen test) explained 69% of mineralisable N [(MN) measured using a seven day anaerobic incubation procedure] across a range of 35 temperate grassland soils. While these results are important in terms of quantifying the potential of these soils to mineralise N, increased knowledge and understanding of the SOM-N components (metabolites) intrinsic to the mineralisation process are required. To fully decrypt the amine N compounds, proton nuclear magnetic resonance (^{1}H NMR) spectroscopy is an emerging technology for profiling various groups of metabolites in soils. However, few studies until now have employed ^{1}H NMR to characterise the nitrogenous and carboniferous metabolites in temperate grassland soils or to link identified metabolites with N mineralisation processes. Using a methanol/water extant procedure and following analysis on a Bruker AVANCE III 400 MHz spectrometer (Bruker-Biospin, UK), 1 dimensional ^{1}H NMR spectra of 35 Irish grassland soils samples were recorded.

Following multivariate statistical (cluster and discriminant function) analysis of ^{1}H NMR spectra integral data and soil properties two spectral integral regions namely: 3.82 - 3.82 ppm and 2.88 - 2.90 ppm (subsequently identified as glucose (Glc) and trimethylamine (TMA), best explained the differences between two cluster groupings (Clustered as soils A and B) of the 35 soils in this study. Separately, a mixed stepwise regression statistical analysis using all the NMR spectra peak integral data, resulted in the selection of 7 spectra integrals, with subsequent identification of 6 metabolites, namely; 3.74 - 3.77 ppm (Glc), 2.05 - 2.05 ppm (glutamic acid; Glu), 2.50 - 2.51 ppm (citric acid; Cit), 3.49 - 3.49 ppm (unidentified), 3.97 - 3.97 ppm (4-aminohippuric acid; 4-AHA), 2.74 - 2.75 ppm (aspartic acid; Asp) and 3.93 -3.94 ppm (serine; Ser), combined these peak integral areas significantly ($P < 0.001$) accounted for 97% of the variance in MN. With the exception of the spectral integral region of 3.47 -3.49 ppm subsequently also identified as Glc, the principal component statistical analysis was found to be less useful to clearly isolating metabolites that separated soil groups or identifying relationships with MN. Figure 1 represents a typical ^{1}H NMR spectra where these metabolites were present in a soil sample, excluding the unidentified metabolite 3.49 - 3.49 ppm and the other multiple integral peak areas of 3.47-3.49 and 3.82-3.82 , in which Glc was also identified.

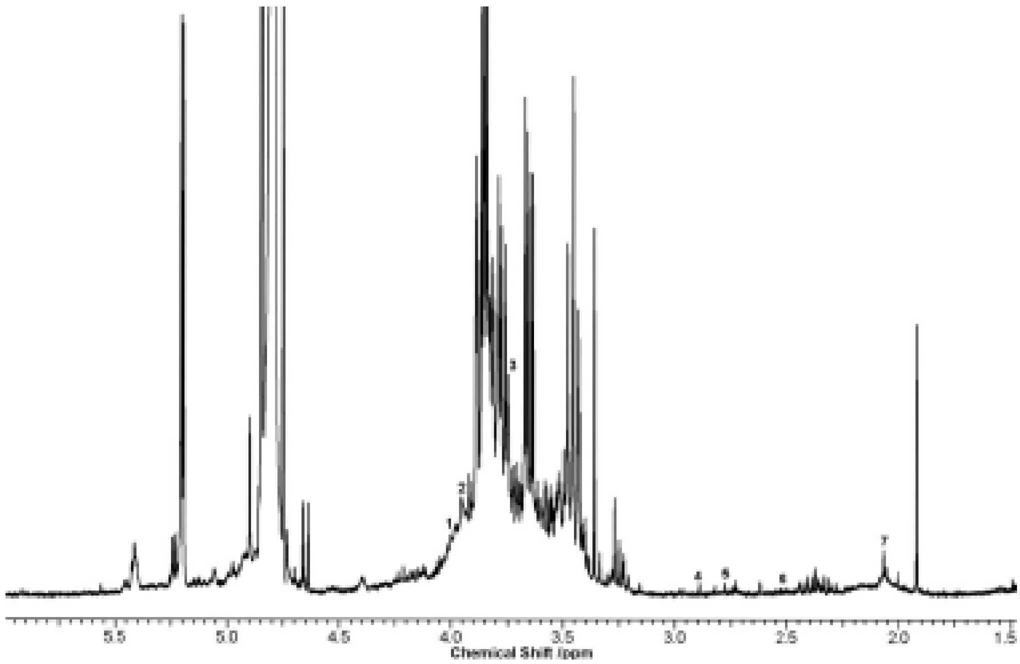


Figure 1: Typical 1H NMR spectra of metabolites present in a soil sample (number 3). Peak assignments of identified metabolites related to mineralisable N (MN) and selected soil properties; 1, 4-aminohippuric acid (4-AHA); 2, serine (Ser); 3, glucose (Glc); 4, trimethylamine (TMA); 5, aspartic acid (Asp); 6, citric acid (cit); and 7, glutamic acid (Glu).

Once identified these metabolites were then quantified based on a calculation that uses the known concentration of the reference standard known as sodium trimethylsiyl-2, 2, 3, 3-tetradeuteropropionate (TSP), where Glc (chemical formula; $C_6H_{12}O_6$) was found to be the metabolite in greatest concentration across the 35 soils (mean 57.55 µmol g^{-1}), ranging from 154.32 µmol g^{-1} in a gleyed loam soil to 16.98 µmol g^{-1} in a loamy sand soil (Table 1). On average the concentrations of the remaining six metabolites were 62 times smaller than Glc, but these concentrations also varied greatly between the 35 soils (Table 1). Quantified Glc also explained the largest percentage of variability in MN (R^2 = 0.72; Figure 2). This significant association with N cycling is not unexpected, as Glc is a main source of labile C provided by root exudates, which stimulates microbial mobilisation of SOM-N across various soil pools.

Table 1: Mean, maximum and minimum values of the identified and quantified metabolites for 35 mineral grassland soils. Numbers in parentheses represent one standard deviation. NS= non signifcant P >0.05

Metabolite	Soils	Max	Min	Mean	S.D
Glc / µ mol g^{-1}	All samples	154.32	16.98	57.55	(27.91)
	Group A	84.03	16.98	48.40	(18.86)
	Group B	154.32	49.81	83.97	(33.79)
Glu / µ mol g^{-1}	All samples	1.08	0.17	0.41	(0.21)
	Group A	0.61	0.17	0.34	(0.13)
	Group B	1.08	0.36	0.63	(0.24)
TMA / µ mol g^{-1}	All samples	0.74	0.13	0.35	(0.12)
	Group A	0.55	0.13	0.34	(0.11)
	Group B	0.74	0.16	0.36	(0.16)
Ser / µ mol g^{-1}	All samples	6.61	0.50	1.88	(1.45)
	Group A	5.81	0.50	1.73	(1.34)
	Group B	6.61	0.90	2.30	(1.74)
4-AHA / µ mol g^{-1}	All samples	1.86	0.11	0.36	(0.33)
	Group A	0.81	0.11	0.28	(0.17)
	Group B	1.86	0.19	0.61	(0.54)
Asp / µ mol g^{-1}	All samples	4.00	0.46	0.98	(0.64)
	Group A	4.00	0.46	0.96	(0.70)
	Group B	1.81	0.65	1.05	(0.45)
Cit / µ mol g^{-1}	All samples	1.14	0.21	0.35	(0.16)
	Group A	1.14	0.21	0.34	(0.17)
	Group B	0.62	0.22	0.37	(0.13)

Unlike previous chemical extraction methods, high resolution ^{1}H NMR was effectively capable of simultaneously detecting, identifying and quantifying a range of C and N metabolites present across the 35 different grassland soil types. However, given the infancy of this approach, comparative studies with other cutting edge soil analytical methods are recommended.

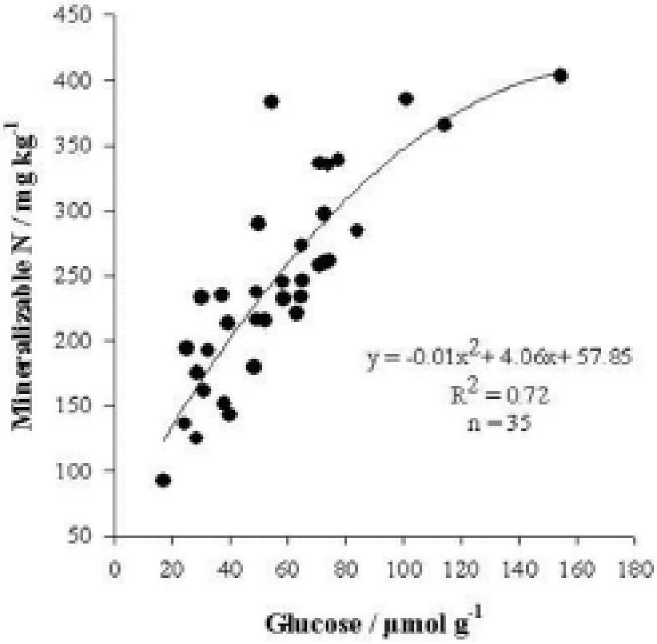


Figure 2: As identified by 1H NMR the relationship between glucose and mineralisable N (MN).

Seven of these metabolites identified were associated with the N mineralisation process. Glucose explained 72% of the variability in MN, while the remaining metabolites of TMA, 4-AHA, Asp, Glu and Asp had comparable weaker or negligible relationships with MN. Overall the findings suggest that labile C is one of the main substrates regulating microbial N mineralisation and soil N availability in temperate grassland soils. Future i investigations of the variability of metabolites identified regarding their influence on soil N mineralisation and immobilisation processes in Irish soils and under different management systems are required. Further detail can be found in McDonald et al. (2016).

Reference: McDonald, N.T., Graham, S.F., Watson, C.J., Gordon, A., Lalor, S.T.J., Laughlin, R.J., Elliott, C.T., Wall, D.P. 2016. Use of 1H NMR to identify nitrogen and carbon metabolites associated with mineralizable N in grassland soil. European Journal of Soil Science. 67, 835-846.

https://dl.sciencesocieties.org/publications/sssaj/pdfs/78/3/1051


4.2
4.3
Soil type
dwater Gley
Grange
Co. Meath
Soil type
Luvisol
Johnstown Castle
Soil type
Brown Earth
Moorepark
Soil type
Brown Podzolic
Screen
Co. Wexford

Paper 6:

Soil Tests for Predicting Nitrogen Supply for Grassland Under Controlled Environmental Conditions

McDonald et al. (2014)

KEY MESSAGES

- Measuring mineralisable nitrogen (N) (MN) using the Illinois Soil Nitrogen Test (ISNT) and/or a 7 day anaerobic incubation test (AI-7), Irish soils were found to have a large variability in soil N supply across mineral grassland soil types.
- Evaluating the effectiveness of ISNT and other chemical soil N indices to predict plant N availability in these temperate soil types under controlled environmental conditions is necessary, in order to understand which measureable pools of N is provided to the plant within a growth period.
- A model with the ISNT-N, the soil carbon (C) to N ratio (C:N) and total oxidized N (TON, as log transformed TON) best explained 55% and 79% of the variability in grass dry matter (DM) production and herbage N uptake, respectively, across 30 different Irish grassland soil types.
- Prior to fertilizer recommendations, routine analysis of field samples to gauge a field N supply is possible using these rapid soil parameters. However, further evaluation of these tests are needed from field studies across multiple and diverse growing conditions.
- This could eventually help to adjust fertilizer recommendations accordingly and therefore allow for improved fertilizer N use efficiency (NfUE) and losses of reactive N to the environment.

SYNOPSIS

Estimating the quantities of N released can be difficult and many soil, climatic and land management factors affect N supply through a mineralisation processes. In temperate climates the temporal nature of N makes it difficult to predict long term supplies of soil N for uptake into the grass plant. The levels of N uptake in grass can vary considerably within and across different soil types. Findings of a recent laboratory study (see previous Synopses and references), the mineralisable N (MN) of 35 temperate grassland soils ranged from 92 to 403 mg NH_4-N kg^{-1} using a 7 day anaerobic incubation test (AI-7). However, the work also found that the more rapid ISNT had a strong relationship with the AI-7 measure of MN (R^2=0.69), and therefore highlighted ISNT as a rapid chemical test capable

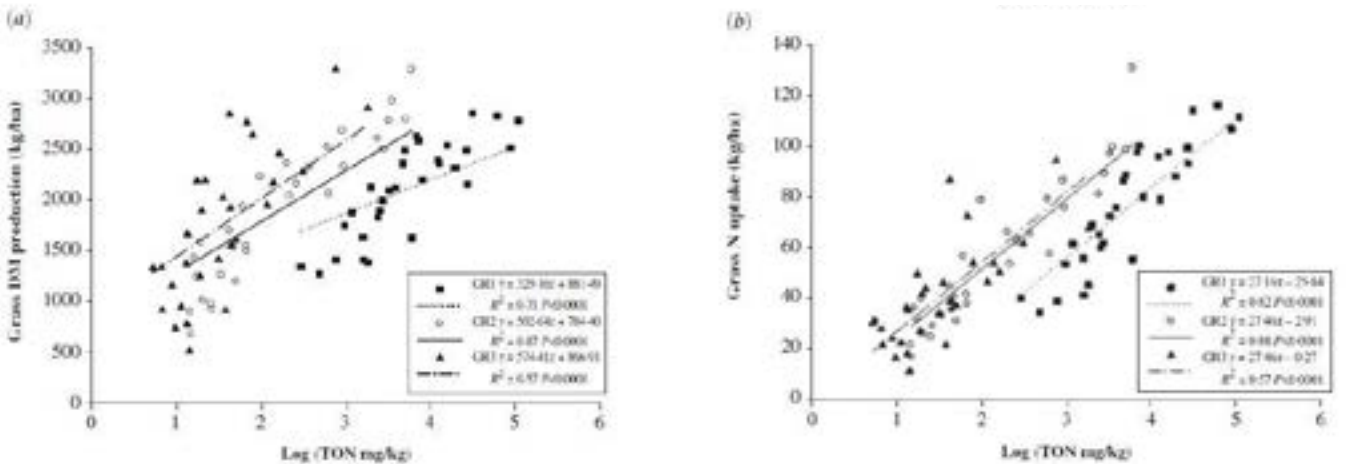


Figure 1: Relationship between log transformed total oxidized N (TON) and ***(a)*** grass dry matter (DM) production ***(b)*** grass N uptake for each growth period (GR1, GR2 and GR3). Fitted models account for the significant interaction of log TON X growth period.

of predicting MN. Nevertheless, there was no validation from this previous study of ISNT predicting N recovery in grass herbage and its accuracy for making N recommendations across various soil types. Within this present study the effectiveness of chemical N tests was evaluated across three successive 5-week growth periods: TON, ammonium (NH4-N) TC, TC C:N and, in particular ISNT-N, to predict soil N supply for plant uptake through MN, in grass N uptake and dry matter (DM) yield, for a range of 30 Irish soil types under controlled environmental conditions (65% field capacity, 15oC, 16 hour daylight and 80% humidity) (Photo 1).

Mineral N in the form of TON (that was log transformed) had the strongest relationship with grass DM production (R2=0.72, 0.87 and 0.57; P<0.0001; Figure 1a) and N uptake (R2=0.82, 0.88 and 0.57 P<0.0001; Figure. 1b) in each of the growth periods (GR1, GR2 and GR3). The high proportion of variability explained by TON for both grass DM production and N uptake particularly in the first two growth periods (GR1 and GR2) can be credited to the varied but high initial levels of TON at the start of GR1 (10.8 to 153 mg kg-1) in these 30 soils. These high concentrations can be attributed to increase in N mineralisation following soil preparation handling and grass seeding similar to the effect generally observed after ploughing of grass swards.

Photo 1: Grass pots in the environmentally controlled growth facility.

Compared to TON, ISNT-N which cannot measure TON, had a poorer relationship with grass DM production ($R2=0.25$, 0.32 and 0.34; $P<0.05$; Figure 2a) and N uptake ($R2=0.27$, 0.33 and 0.35 $P<0.05$; Figure. 2b) at each of the growth periods (GR1, GR2 and GR3), respectively. Under the optimum growth conditions the plant would have consumed the readily available TON in the earlier growth periods (GR1 and GR2), but as the concentrations of TON declined over the growth periods, the grass plant seemed to assimilate a larger proportion of the N from the mineralised N pool.

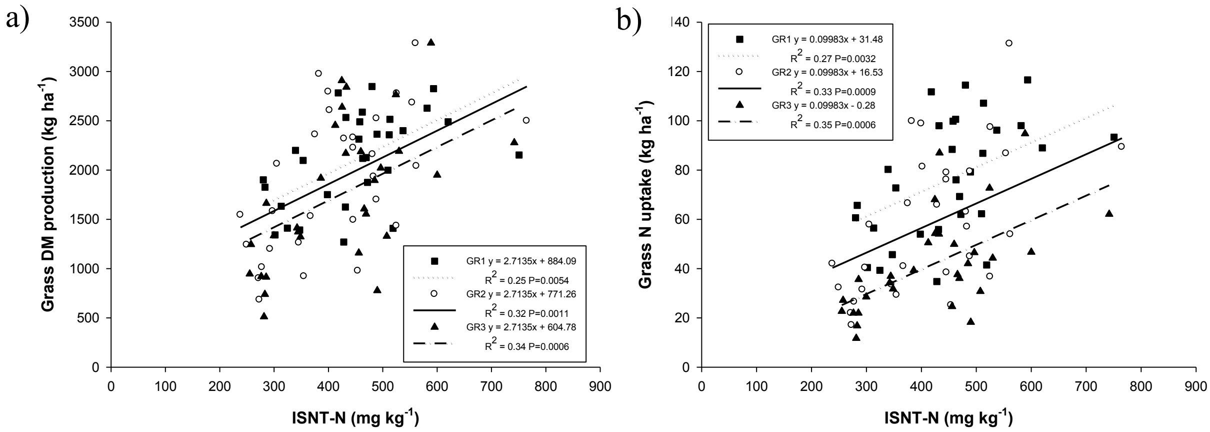


Figure 2: Relationship between Illinois soil N test (ISNT-N) values and (a) grass dry matter (DM) production and (b*)* N uptake for each growth period (GR1, GR2 and GR3). Fitted models account for significant main effect of growth period.

Following a multiple stepwise regression analysis, the combination of log TON, ISNT-N and C:N gave the best fit prediction models for both grass DM production and N uptake in each of the three growth periods. With the inclusion of the interaction of ISNT-N X C:N the best model explained 55% of grass DM production and 79% of herbage N uptake, where all growth periods combined (n=90) (Table 1 and 2). The interaction between C:N ratio and MN as measured by ISNT-N, found that, as the C:N ratio increased, the MN as measured by ISNT-N starts to become immobilised by microbes, therefore less N becomes available to the plant and vice versa.

The combination of three rapid soil N indices (TON, ISNT-N and C:N) into a model, where each represent the different soil N pools of available and potentially available N, gave the best prediction of grass DM yield and N uptake for each growth period and for all growth periods combined.

While this study was conducted under controlled environmental conditions, it does provide a method to assess the potential of a grassland soil to supply MN, and regardless of the future N losses that would be noticeable at field scale, it is still important to know the base N supply prior to making N management decisions which promote efficient and sustainable N use. This emphasises the additional need for these findings to be further validated across these soils under a varying seasonal environments of field trials, before a soil N testing system or recommendation system can be used on grassland farms. This study is further described in McDonald at el. (2014b).

Reference: McDonald, N.T., Watson, C.J., Laughlin, R.J., Lalor, S.T.J., Grant, J., Wall, D.P., 2014b. Soil tests for predicting nitrogen supply for grassland under controlled environmental conditions. The Journal of Agricultural Science, 152, 82-95.

https://www.cambridge.org/core/services/aop-cambridge-core/content/view/BB5170B236B53BD4112796D710A2A4C4/S0021859614000264a.pdf/div-class-title-soil-tests-for-predicting-nitrogen-supply-for-grassland-under-controlled-environmental-conditions-div.pdf

Table 1: Regression model of soil N indices for predicting grass DM production (kg ha^{-1}).

Growth period	Variable (X)	Parameter estimate	S E	P>t	95% Confidence limits		RMSE[a]	Model R^2
GR1	intercept	1076.10	391.23	0.0043	270.35	1881.84	188.98	0.86
	log TON	498.34	62.88	<0.0001	368.83	627.85		
	ISNT-N	1.61	0.43	0.0029	0.71	2.50		
	C:N	–152.30	36.91	0.0004	–228.32	–76.28		
	ISNT-N × C:N	–0.41	0.23	0.0864	–0.88	–0.06		
GR2	intercept	873.39	441.88	0.0592	–36.68	1783.46	225.32	0.91
	log TON	647.27	59.97	<0.0001	523.77	770.78		
	ISNT	1.45	0.48	0.0058	0.46	2.44		
	C:N	–94.93	41.98	0.0327	–181.39	–8.47		
	ISNT-N × C:N	–0.47	0.25	0.0772	–0.99	0.05		
GR3	intercept	404.62	883.37	0.6509	–1414.71	2223.95	441.80	0.68
	log TON	661.48	162.92	0.0004	325.93	997.02		
	ISNT-N	2.36	0.91	0.0156	0.49	4.22		
	C:N	–60.30	85.40	0.4764	–232.07	111.47		
	ISNT-N × C:N	–0.92	0.53	0.0940	–2.00	0.17		
Combined growth periods (GR1-GR3)	intercept	–1156.51	1215.4	0.35	–3462.1	1329.31	308.37	0.55
	log TON	560.87	59.81	<0.0001	440.95	680.79		
	ISNT-N	7.56	2.58	0.005	2.38	12.75		
	C:N	121.64	114.58	0.29	–108.09	351.36		
	ISNT-N × C:N	–0.54	0.25	0.025	–1.02	–0.07		

Table 2: Regression model of soil N indices for predicting grass N uptake (kg ha^{-1}).

Growth period	Variable (X)	Parameter estimate	S.E	P>t	95% Confidence limits		RMSE[a]	Model R^2
GR1	intercept	–0.401	16.89	0.98	–35.19	34.39	8.16	0.90
	log TON	29.07	2.72	<0.0001	23.48	34.66		
	ISNT-N	0.07	0.02	0.0017	0.03	0.10		
	C:N	–6.02	1.59	0.0009	–9.31	–2.74		
	ISNT-N × C:N	–0.12	0.01	0.25	–0.03	0.01		
GR2	intercept	6.92	18.11	0.71	–30.36	44.22	9.24	0.91
	log TON	26.83	2.46	<0.0001	21.76	31.89		
	ISNT-N	0.05	0.02	0.0109	0.01	0.09		
	C:N	–2.89	1.72	0.1049	–6.44	0.65		
	ISNT-N × C:N	–0.02	0.01	0.1305	–0.04	0.01		
GR3	intercept	–1.93	25.96	0.94	–55.39	51.53	12.98	0.64
	log TON	17.95	4.79	0.0009	8.09	27.81		
	ISNT-N	0.06	0.03	0.0240	0.01	0.12		
	C:N	–0.96	2.46	0.70	–6.01	4.08		
	ISNT-N × C:N	–0.02	0.02	0.18	–0.05	0.01		
Combined growth periods (GR1-GR3)	intercept	–59.39	41.02	0.16	–143.29	24.5	10.24	0.79
	log TON	17.17	3.32	<0.0001	10.51	23.84		
	ISNT-N	0.25	0.09	0.0049	0.08	0.43		
	C:N	4.77	3.84	0.22	–2.93	12.47		
	ISNT-N X C:N	–0.02	0.01	0.023	–0.04	0.00		

Equation formula for each growth period is constructed as follows: $Y=aX_1+bX_2+cX_3+d$, where X is the measured N indices (variable), a,b,c, are parameter estimates and d is the intercept

Equation formula for the combined growth periods is constructed as follows: $Y=aX_1+bX_2+cX_3+dX_4+e$, where X is the measured N indices (variable) or their interaction, a,b,c,d are parameter estimates and e is the intercept (intercept is for final harvest) [a]RMSE, Root mean square error.

Paper 7:

Evaluation of a surface hydrological connectivity index in agricultural catchments

Shore et al. (2013)

KEY MESSAGES

- Accurate characterisation of hydrological connectivity (the propensity for connection of surface flows to the river channel,) is important for identifying critical source areas of phosphorus loss (i.e. where high-P sources have a high propensity for connection to receiving water-bodies via effective transport pathways).
- However, there is a lack of suitable metrics for characterising hydrological connectivity at scales where P losses can be managed.
- This study shows the potential of the 'Network Index' model to characterise hydrological connectivity at land-management scales in two contrasting agricultural catchments (ca. 12 km^2) using a 5 m digital elevation model.
- At the subcatchment scale (ca. 130 ha), modelled connectivity matched observations well (R^2 = 0.52) despite soil type variability. Ditch information was not required to model subcatchment connectivity; however it was required to model subcatchment boundaries and thus the extent of critical source areas.
- For further development at the field scale, the NI has potential for broadly discerning the most connected from the least connected fields which is valuable for identifying where critical source areas-based management should be targeted.

SYNOPSIS

The Network Index (NI) approach is based on the concept that the driest point along a flowpath to the stream is likely to have the greatest potential for infiltration of surface water and therefore limits the degree of connectivity to the stream. Connectivity is represented by the probability that lower NI values are likely to be connected less frequently and for shorter periods of time than higher NI values. In this paper three hypotheses were evaluated.

Hypothesis 1

The accuracy of the NI would be poor in landscapes with variable soil types.
As the NI is typically applied using digital elevation models (DEMs), the potential for the NI Index to accurately predict surface connectivity depends on the degree to which topography controls connectivity. Soil drainage capacity is a non-topographic control, thus is not accounted for in the model.

Hypothesis 1 rejected. At the subcatchment scale, modelled surface connectivity matched observations reasonably well (R2 = 0.52) despite soil type variability (Fig. 1). However this was because poorly drained soils generally coincided with areas high connectivity (i.e. low slopes in the low-lands and with short flow paths to the stream) and well drained soils generally coincided with areas of low connectivity (high slopes in the uplands with longer flow paths to the stream). At the field scale, the NI was reliable for distinguishing the most connected from the least connected fields. Of the most connected fields 83% were poorly drained and of the least connected fields 92% were well drained, demonstrating a strong association between connectivity and soil type also at this scale.

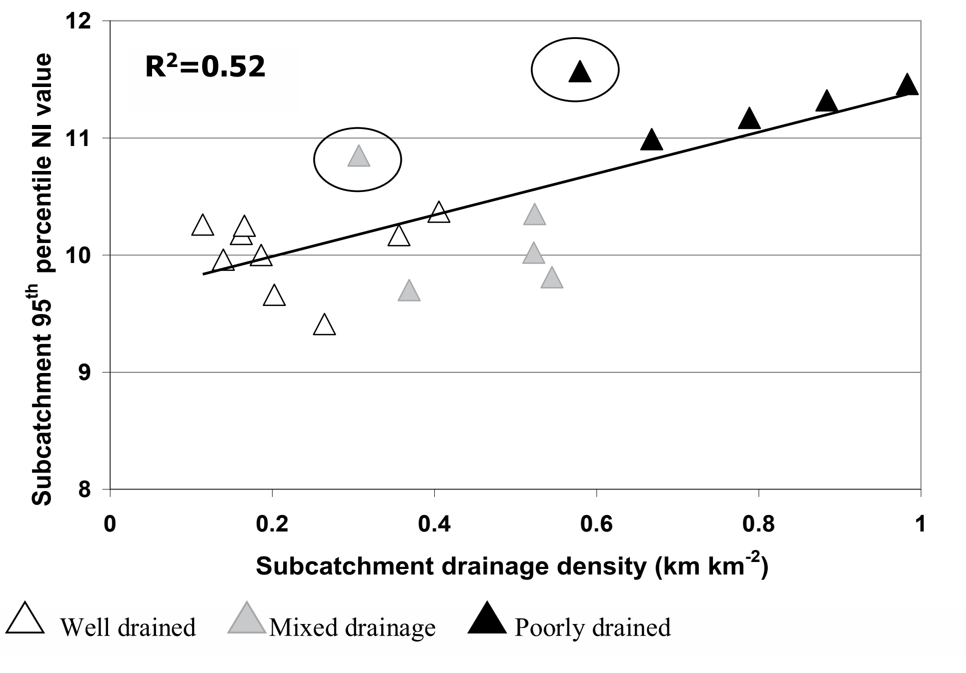


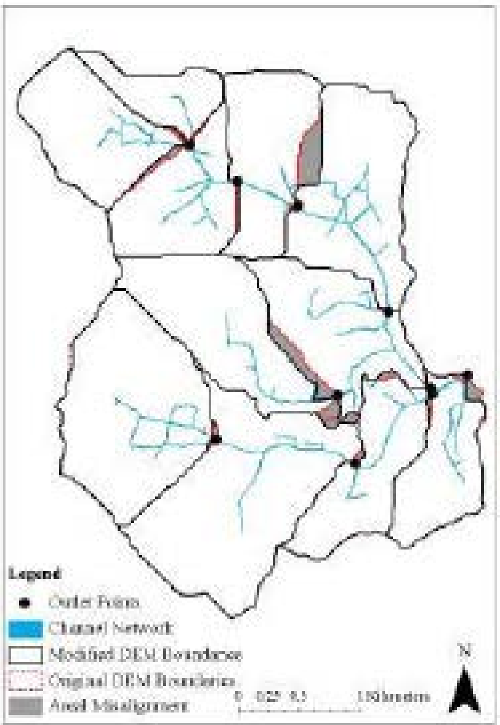
Figure 1: Predicted connectivity (95th percentile NI values) vs. observed connectivity (channel density) for subcatchments across both catchments. Subcatchments where NI values were particularly over-estimated are circled

Hypothesis 2

Application of the NI to a DEM which does not capture ditch features will be constrained by inaccurate prediction of flow location.

Micro-topographic features such as surface ditches influence the location of surface connectivity by capturing and re-routing surface flow along the channel (ditch and stream) network and away from its natural flowpath. As the resolution of the DEM in this study (5m) was coarser than the resolution of surface ditch features, it likely did not capture surface ditch features.

Hypothesis 2 accepted. The locations of modelled channel networks were within 39 m of observed channel networks for Arable A and within 60 m for Grassland B (at the 95% confidence level). The total area assigned to incorrect subcatchments was 31 ha in Arable A (2.8% of the total catchment area) and 133 ha in Grassland B (11% of the total catchment area) (Fig. 2). 133 ha is equivalent to the total area encompassed by the sum of four average-sized farms in Ireland. Thus, if the NI was used to identify subcatchments at high risk of P loss, four farmers in this catchment area could be advised to introduce mitigation measures needlessly, and/or four higher risk farms may remain un-detected.



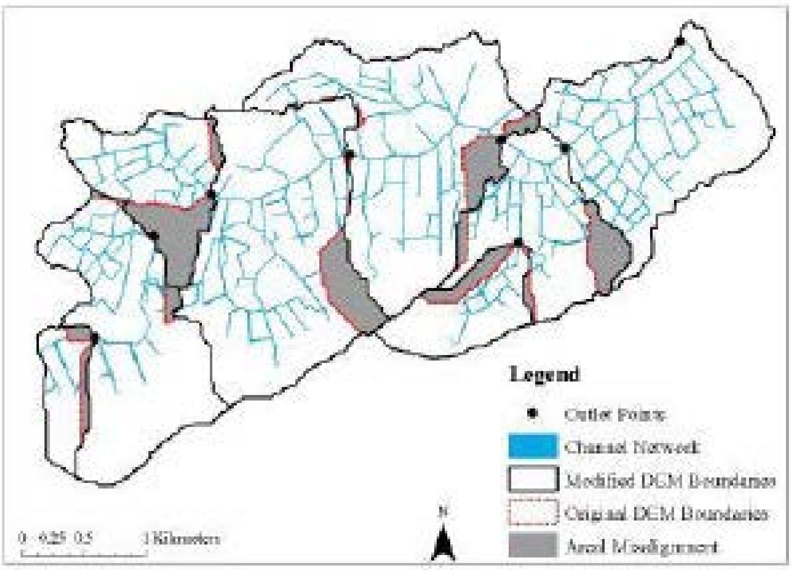


Figure 2: Alignment of subcatchment boundaries derived from the original DEM (red) and a modified DEM (hydrologically corrected) (black) with the channel network, for a) Arable A and b) Grassland B.

Hypothesis 3

Application of the NI to a DEM which does not capture ditch features will over-estimate the magnitude of surface connectivity in landscapes where surface flows are prevalent. In surface-flow driven landscapes, ditches may re-route a large proportion of total flows along the channel network instead of downslope. This may result in a reduction in surface saturation and connectivity in downslope fields.

Hypothesis 3 rejected. Large over-estimations of surface connectivity were only observed in two out of ten subcatchments (circled in Fig. 1). Rejection of hypothesis 3 indicates that ditches had a low over-all influence on the magnitude of observed surface connectivity in these subcatchments, even where surface flows were prevalent. This suggests that less topographic detail may be better for predicting surface saturation (and thus connectivity) at the subcatchment scale*. This work is described in detail in Shore et al. (2013).

Reference: Shore, M., Murphy, P.N.C., Jordan, P., Mellander, P-E., Kelly-Quinn, M., Cushen, M., Mechan, S., Shine, O., Melland, A.R., 2013. Evaluation of a surface hydrological connectivity index in agricultural catchments. Environmental Modelling and Software. 47, 7-15.

http://www.sciencedirect.com/science/article/pii/S1364815213001023

*This work was subsequently developed by Thomas et al. (2017), above, which shows the limitations of the 5m DEM when actually compared with finer scale DEMs at the field scale.

Paper 8: Evaluating the critical source area concept of phosphorus loss from soils to water bodies in agricultural catchments

Shore et al. (2014)

KEY MESSAGES

- This study investigated whether transport metrics alone provide better estimates of phosphorus (P) concentrations and loads from agricultural basins than critical source area metrics which combine source factors as well.
- Relative P losses between basins did not reflect trends in predicted critical source area risk.
- Relative P losses between hydrologically contrasting basins were primarily hydrologically controlled.
- Relative P losses between hydrologically contrasting basins could be predicted using static transport metrics.
- Relative P losses between hydrologically similar basins were highly variable.
- Understanding the relative importance of hydrological controls on P loss at catchment scales will be important for achieving Water Framework Directive objectives.

SYNOPSIS

Studies of source and transport controls on P loss in runoff or stream flow can be separated into three types: 1) Those linking P losses primarily to source factors (e.g. soil P, organic P loadings) 2) Those linking P losses primarily to critical source areas (CSAs), i.e. where high-P sources coincide with high P transport risk and 3) Those linking P losses primarily to transport factors (e.g. surface runoff).

Type 1 studies supported the rationale for focusing NAP measures on soil P availability, but have been mainly conducted at lab/field scales where hydrological variability was very small. Type 2 studies provided the rationale for the P index used in the U.S.A. and elsewhere. Many studies are now suggesting that a CSA approach might be an appropriate policy tool to manage diffuse P pollution in Europe. Type 3 studies are still emerging and highlight the complexity of hydrological processes across landscapes, scales and storms. Recent studies have demonstrated that hydrological factors were more important than source factors in determining P loss at particular sites. However, more information is needed on whether transport metrics alone provide better estimates of P loss than CSA metrics which combine source factors as well, thus was the objective of this study. Understanding the importance of hydrological controls on P loss at catchment scales is important for achieving Water Framework Directive objectives by targeting of mitigation.

Six basins located across two hydrologically contrasting agricultural catchments were selected for this study. A predominantly well-drained arable catchment and a predominantly poorly-drained grassland catchment.

Concentrations and loads of P in surface runoff (or more precisely quickflow) were measured at basin outlets during four storm events and were compared with dynamic (quickflow magnitude – Fig. 1) and static (extent of highly-connected, poorly-drained soils) transport metrics and a CSA metric (extent of highly-connected, poorly-drained soils with excess plant-available P –Fig. 2).

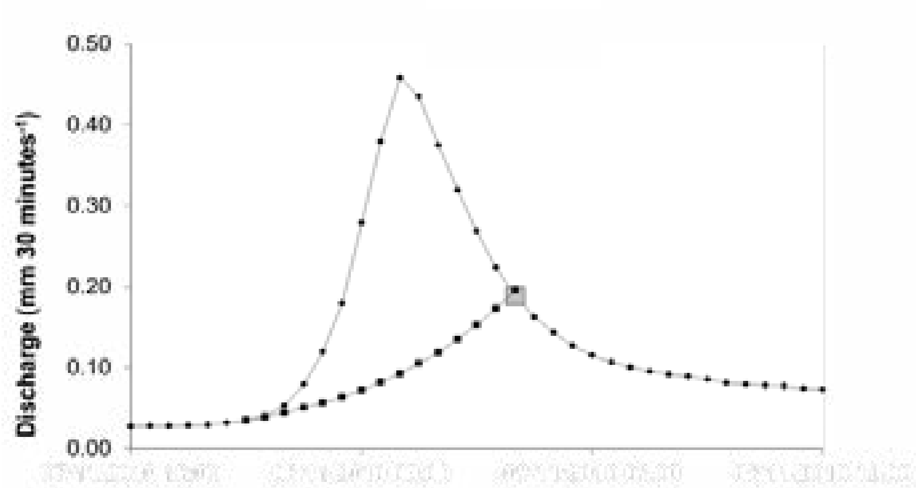


Figure 1: The hydrograph separation technique used to quantify quick flow (QF) magnitude at each monitoring site, demonstrated here a sampled event. Inflection points used to identify the QF component are indicated by the enlarged grey marker.

Figure 2: The process of defining the CSAs using an example from the arable catchment. The white circle illustrates a CSA, where highly-connected, poorly-drained soils coincide with P-index 3 or 4 soils. The blue circle is not a CSA because it is not highly-connected. The yellow circle is not a CSA because it is not on poorly-drained soils. The pink circle is not a CSA because it is not on P-index 3 or 4 soils.

The study found that:

- Where differences in P transport risk were large, reactive P concentrations and loads were well differentiated by transport metrics alone (static and non-static), regardless of differences in soil P.
- Where P transport risks were similar, non-static transport metrics (e.g. quickflow) and P source information additional to soil P, may be required to predict trends in reactive P concentrations and loads between these basins.
- Regardless of differences in P transport risk, information on land use and management, such as time of ploughing, may be required to predict trends in particulate P concentrations between these basins.

The policy implications from the study are:

- A CSA approach will undoubtedly be better for reducing P losses than the more traditional source-focused approach that is still currently used in many countries (including Ireland). Additionally, limiting P sources in areas with a high P transport potential will also likely reduce the magnitude of P losses.
- However, it is likely that approaches focused primarily at managing the transport potential of P will be the most effective strategy for reducing P losses in the study catchments and other similar catchments.
- Phosphorus loss mitigation efforts could be greatly enhanced by managing the sur face runoff in basins where hydrological transfers of P are greatest.
- Such highly-connected basins, and their field scale components, could be identified using appropriate surface runoff identification tools*.

Reference: Shore, M., Jordan, P., Mellander, P-E., Kelly-Quinn, M., Wall, D.P., Murphy, P.N.C., Melland, A.R. 2014. Evaluating the critical source area concept of phosphorus loss from soils to water-bodies in agricultural catchments. Science of the Total Environment. 490, 405-415.

http://www.sciencedirect.com/science/article/pii/S0048969714006470

*This work was developed by Thomas et al. (2016a, 2016b, 2017) to show how these field scale components could only be defined in surface runoff tools by using finer scale (1-2m DEMs) and hydraulic soil properties. See Synopses herein.

Paper 9: An agricultural drainage channel classification system for phosphorus management

Shore et al. (2014)

KEY MESSAGES

- Surface channels were classified into fine sediment retention/ transfer classes.
- Ditches with low slopes are likely to primarily retain sediment.
- Ditches with high slopes are likely to mobilise sediment during storms.
- Tailoring management (i.e. widening, deepening and/or enlarging vegetation cover) according to channel classes may reduce P transfers downstream.
- Certain ditches were over-engineered with potentially positive effects on P transfer which could be an important policy consideration for Water Framework Planning targets.

SYNOPSIS

A better understanding of the potential for ditches and streams to retain or transfer fine sediment is important for identifying their potential to attenuate particulate and soluble P losses from contributing fields and for developing appropriate channel management strategies. This information is important for reviews of nutrient mitigation methods in agricultural catchments which need to meet Water Framework Directive planning targets.

Herein, a first-attempt at a minimum information, GIS-based channel classification was developed which draws on observations of fine sediment accumulation in channels with the aim of classifying channels according to their potential to retain or transfer fine sediment.

Using a detailed field survey of surface channel networks in a well-drained arable and a poorly-drained grassland catchment, this study (i) characterised the surface channels in both catchments, (ii) classified the channels into four classes of fine sediment retention and/or transfer likelihood based on a comparison of physical characteristics (slope and drainage area) with observations of fine sediment accumulation and (iii) considered P management strategies that are suited to each class.

The study found that:

- In general, ditches with low slopes had the greatest potential to retain fine sediment and, assuming sediments primarily adsorb, rather than release soluble P, are likely to reduce particulate and soluble P loading downstream. The capacity of these channels to retain fine sediment should be maintained, for example by periodically removing the fine sediment, i.e. ditch dredging. Ditch dredging operations should be restricted to the summer period when P delivery to drainage channels is minimised and when the spawning and incubation stages of certain fish species' development have ended.
- Ditches with moderate-high slopes had the greatest potential to mobilise fine sediment and associated P during event flows. The potential for these ditches to mobilise bed and bank sediments should be minimised, for example by encouraging more vegetation growth on channel beds and banks to promote sedimentation.
- Streams had the greatest potential to convey fine sediment and associated P during event flows. Management practices should be focussed on reducing P transfers to these channels rather than on controlling P transfers within these channels. Strategies to reduce P transfers to channels could include reducing soil P levels where they are in excess of the agronomic optimum and for poorly drained catchments, moderating surface runoff.
- Ditch dimensions were broadly similar to those of streams but contrary to streams, ditch dimensions were not closely related to their expected flow volumes and were over-engineered (potentially reducing downstream P transfer).

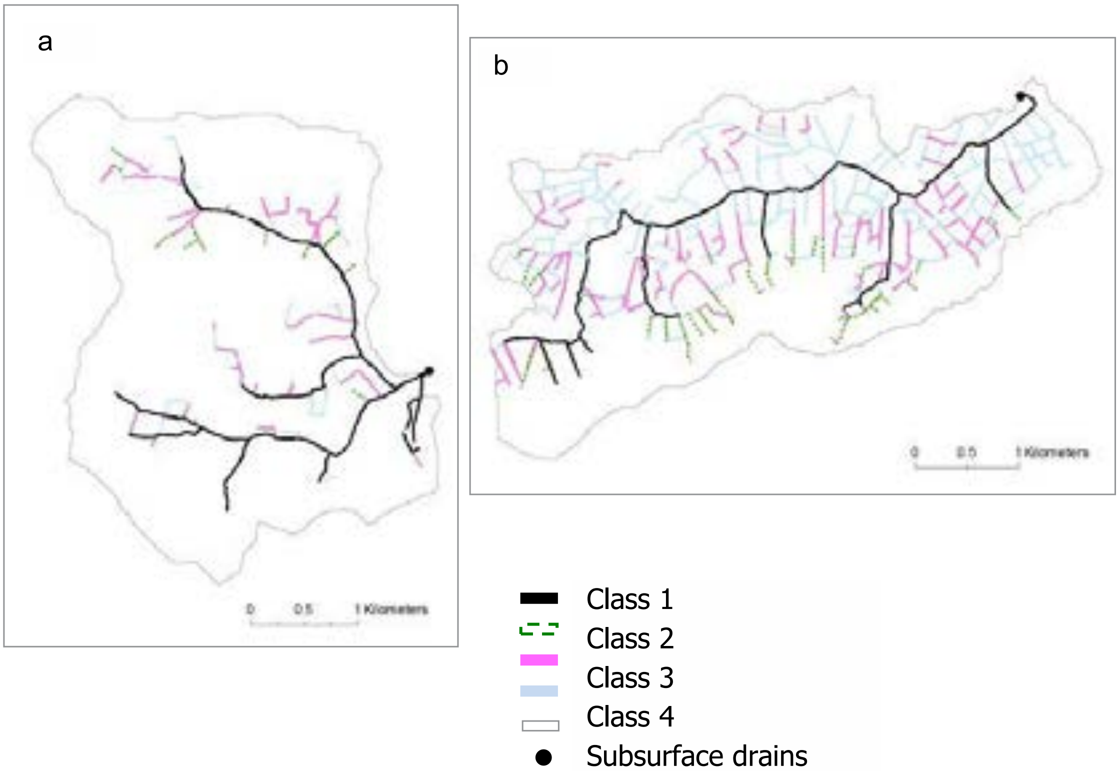


Figure 1: Classification of the drainage network into four classes describing their relative fine sediment retention or transfer potential for a) the arable catchment b) the grassland catchment. Class 1 networks have the greatest potential to convey fine sediment, Classes 2 and 3 have the greatest potential to mobilise fine sediment and Class 4 networks have the greatest potential to retain fine sediment.

Current design of agri-drainage solutions in Ireland is based on two soil profile types; those with or without a shallow water table:

- Enlarging (widening and deepening) ditches in soils with a shallow water table may lower the water table if groundwaters are intercepted, thus reducing the potential for P mobilisation in surface runoff. However, enhanced drainage of groundwater flows may increase flow volumes and velocities in the ditches thus reducing their PP retention capacity.
- Enlarging ditches in soils without a shallow groundwater table may reduce flow velocities, thus enhancing PP retention. In addition, it would increase their capacity to accommodate high flows, thus achieving both soil drainage and environmental objectives. These scenarios would, however, need to be validated.

Reference: Shore, M., Jordan, P., Mellander, P.-E., Kelly-Quinn, M., Melland, A.R., 2015. An agricultural drainage channel classification system for phosphorus management. Agriculture, Ecosystems and Environment. 199, 207-215.

http://www.sciencedirect.com/science/article/pii/S016788091400440X

Paper 10: Characterisation of agricultural drainage ditch sediments along the phosphorus transfer continuum in two contrasting headwater catchments

Shore et al. (2016)

KEY MESSAGES

- The P contents of ditch sediments were similar to those of field soils and higher than those of bank soils, but were generally below thresholds considered to pose a risk to water-quality.
- Al/P and Ca/P contents of ditch sediments in Castledockerell (non-calcareous) and Ballycanew (calcareous) respectively, indicated potential for soluble P retention.
- However, sediments were less aggregated than field soils and may mobilise more particulate P (PP) during rain events.
- Nevertheless, the majority of surveyed ditches dried out from March-September 2011, thus their potential to mobilise PP may be less important than their capacity to attenuate soluble and PP during this eutrophication-sensitive time.
- These findings can help inform farmers and policy makers of how to optimise channel management to maximise P retention in risky catchments.

SYNOPSIS

Heavy, clay-rich soils are prone to high P losses because of their high propensity to generate overland flow. These soils also tend to have a dense network of open drains, here termed ditches, to enhance their drainage capacity. The sediment in the bottom of these ditches can be rich in P. If the a) P content of the ditch bed sediments, b) potential for this P to become mobilised from the sediment into the water, or conversely retained in the sediment and c) potential for ditches to transfer P in the water-column, are all known, then it is possible to develop appropriate P loss mitigation strategies for these features. With this in mind, this study investigated the phosphorus (P) source, mobilisation and transport potential of ditch bed sediments as well as surrounding field and bank soils in two agricultural headwater catchments; 'Subcatchment A' (89ha) with well-drained soils and 'Subcatchment B' (60ha) ca. 30 km away, with poorly-drained soils.

As illustrated in Figure 1, ditch sediments had similar mean Mehlich3-P contents to the surrounding field soils and higher mean Mehlich3-P contents than bank soils. The mean Mehlich3-P contents of ditch sediments was below the threshold of 89 mg kg $^{-1}$, above which soils have demonstrated more rapid increases in plant-available P.

P sources

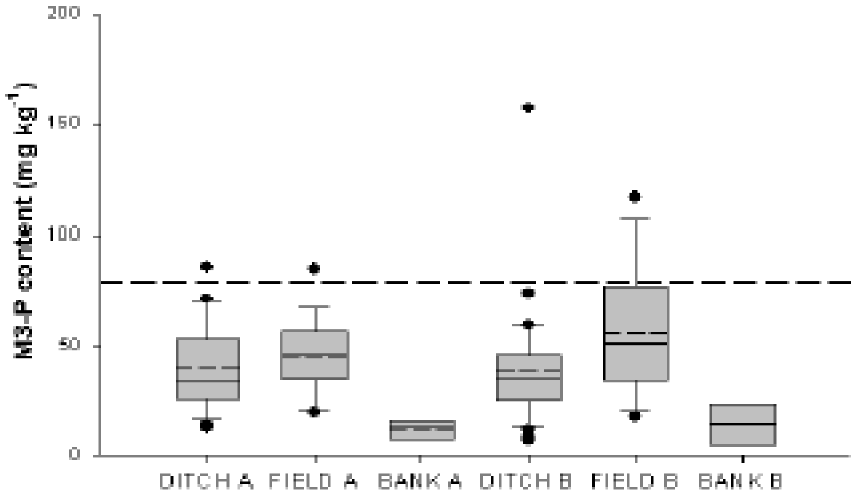


Figure 1: Boxplot of Mehlich3-P content for soils and sediments in Subcatchments A (denoted by A) and B (denoted by B). Mean and medians of the distributions are illustrated by dashed and solid lines, respectively. The dashed line at 89 mg kg-1 represents the change-point above which Irish soils have demonstrated rapid increases in plant-available P.

Soluble P mobilisation potential

The chemical nature of the ditch sediments in Subcatchment B were defined by elevated Ca concentrations, characteristic of the deeper calcareous sub-soils in the adjacent fields. This suggests that, in addition to eroded top-soils a substantial proportion of ditch sediments consisted of in situ sub-soils. Mean M3-Ca/P ratios in these sediments were above the threshold values associated with reduced P solubility reported in the literature, which is characteristic of processes of Ca-P precipitation. It is likely that elevated Ca concentrations in ditch sediments in Subcatchment B produced Ca-P precipitates causing a reduction in soluble P concentrations in the overlying waters. This hypothesis is supported by the coincidence of high sediment M3-Ca/P ratios >74 with low P concentrations in the overlying water (< 0.035) and low M3-Ca/P ratios with very high P concentrations in the overlying water (Fig. 2).

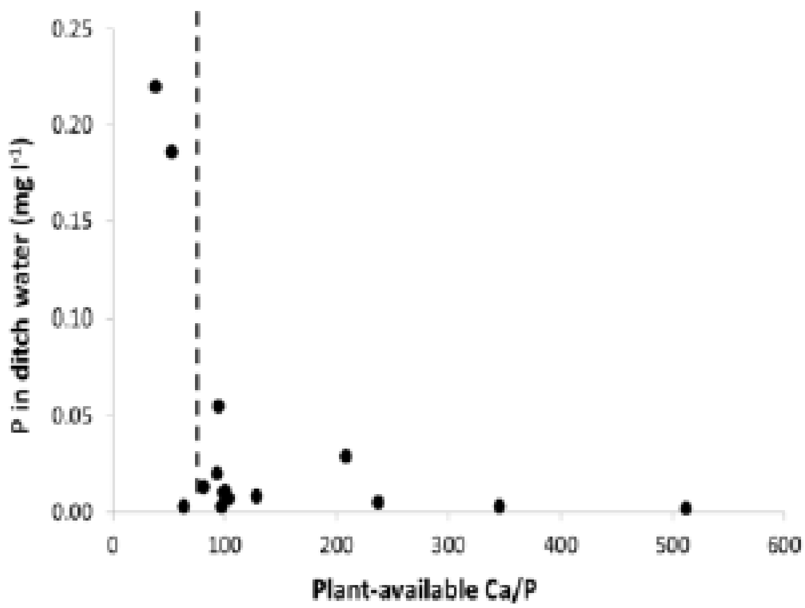


Figure 2: Relationship between M3-Ca/P and ditch water SRP concentrations for sediments in Subcatchment A

Ditch sediments in Subcatchment B were non-calcareous and were slightly acidic, thus aluminium was expected to control soluble P dynamics. Mean M3-Al/P ratios in these sediments were above the threshold values associated with reduced P solubility indicating they were unlikely to provide biologically-significant concentrations of soluble P to channel or runoff waters and had capacity for further P retention via adsorption of water column P. This notion is further supported by the low SRP concentrations measured in overlying waters (Fig. 3) and points to the strong affinity that Al has for P in soils and sediments as described in similar studies

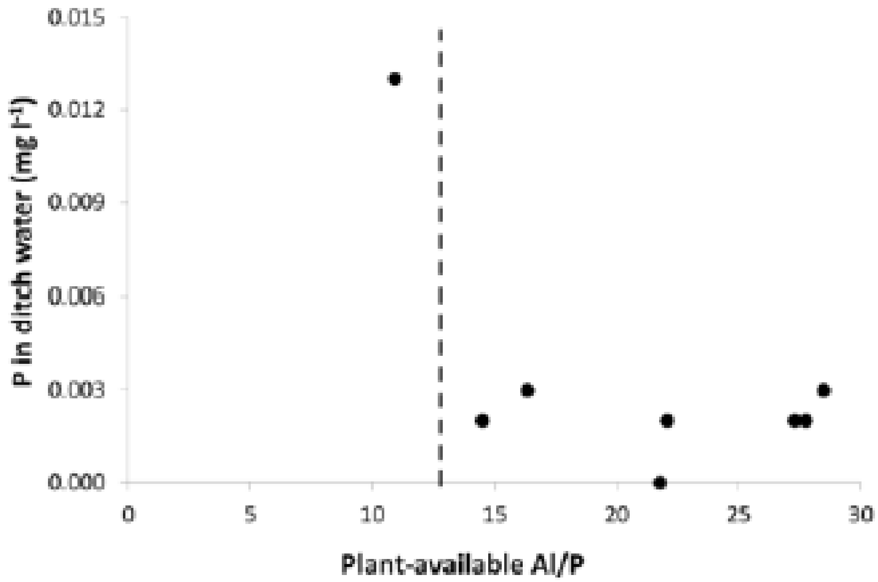


Figure 3: Relationship between M3-Al/P and ditch water DRP concentrations for sediments in Subcatchment B

Particulate P mobilisation potential

There was a substantial proportion of fine textured particles (silt and clay) in the ditch sediments in Subcatchment A (58% in March to 36% in September) and Subcatchment B (69% in March and 64% in September), which could be mobilised during rainfall events as PP and desorbed as soluble P. When mobilised, using the DESPRAL test, field soil particles from both subcatchments were more enriched with P than the bed sediments and bank soils. However, sediments were more dispersive. As a result, ditch sediments may supply relatively more PP to the water column and downstream environments than field soils during event flows.

P transport potential

During this survey period (March –September 2011), the majority of surveyed ditches dried out by July, thereby preventing the downstream transport of any mobilised P. Whilst they may temporally re-wet and transport sediment and P during summer storms, wider catchment outlet data showed that such storms likely only occurred ca. 4% of the time during the survey period. For the remaining 96% of the time, the potential for sediments to attenuate P (soluble and particulate) may during this time, on balance, outweigh their potential to mobilise PP.

These findings can help inform farmers and policy makers of how to optimise channel management to maximise P retention in risky catchments. For example, where sub-soil horizons have contrasting chemistry (as in Subcatchment B), ditch depths could be designed/altered to intercept the most desirable sub-soil layer from a P retention perspective. Management strategies should be targeted to maximise the potential for bed sediments to act as a sink for soluble P whilst minimising PP mobilisation. For example, regular cleaning out of fine sediments may help to prevent sediments reaching their critical saturation capacities, so they can continue to be refreshed and bind P. Encouraging vegetative growth in ditches may increase the contact time between water and sediment to enhance the potential for P retention to sediments and uptake by plants, whilst reducing the amount of bare soil available for erosion and maintaining high OM contents which can improve aggregation.

Reference: Shore, M., Jordan, P., Mellander, P-E., Kelly-Quinn, M., Daly, K., Sims, J.T., Wall. D.P., Melland, A.R. 2016. Characterisation of agricultural drainage ditch sediments along the phosphorus transfer continuum in two contrasting headwater catchments. Journal of Soils and Sediments, 16, 1643-1654.

http://rd.springer.com/article/10.1007/s11368-015-1330-0

Paper 11:

Fingerprinting the sources of suspended sediment in agricultural catchments

Subject to peer review

KEY MESSAGES

- Sediment fingerprinting is an effective management tool to determine suspended sediment sources.
- Non-field sources were dominant in two of three study catchments due to low source availability or sub-surface transport, respectively.
- Where source availability and surface transport pathways occur, fields are at an increased risk of soil loss.
- Where high soil permeability can be exceeded by prolonged wetness and surface pathways established, sediment delivery from field soils is increased.
- These findings demonstrate the importance of managing sediment sources and flow pathways to reduce sediment delivery to aquatic ecosystems and maintain agricultural production in catchments with contrasting landscape characteristics and land use enterprises.
- Mitigation considerations are proposed for different catchment land uses and soil types and which could be integrated into policy reviews.
- The sediment fingerprinting approach is validated as an essential tool to facilitate cost effective sediment management strategies.

SYNOPSIS

Cost-effective management of catchment scale soil losses requires knowledge of dominant sediment sources. Intensive agricultural catchments contain numerous potential sediment sources, e.g., field topsoils with low groundcover, channel banks, un-metalled tracks and road verges. The contribution of sediment from each source may be spatially and temporally variable due to the interactions between hydrological connectivity, transport pathways, land management and landscape characteristics. Disentangling this variability is challenging but is made possible by techniques such as sediment fingerprinting.

Sediment fingerprinting distinguishes potential sediment sources using physico-chemical characteristics including geochemistry, radionuclides and mineral magnetics. A river sediment sample is considered a mixture of these sources; therefore, assessing the same characteristics and 'un-mixing' the signal using a statistical model can determine the contribution from each sediment source.

Sources of suspended sediment were investigated in three catchments; Grassland B, Arable A and Arable B. In all catchments, grassland and arable field topsoils, eroding channel and ditch (open drain) banks, damaged road verges and un-metalled tracks were sampled as potential sources. River sediments were collected over a six to twelve week period using time-integrated suspended sediment samplers situated at each catchment outlet (Figure 1).

Over the two year study period (May 2012 – May 2014) multiple time-integrated samples were analysed to show seasonal fluctuations in sediment sources. Sediment quantity, estimated using the turbidity-based apparatus in the ex situ kiosk (described in a previous Synopsis) was combined with fingerprinting data from each collection period.

Physico-chemical characteristics of potential sources could define three groups; field topsoils (grassland and arable fields), channels (eroding stream and ditch banks) and roads (damaged road verges and tracks – Figure 2).

Figure 1: A time-integrated suspended sediment sampler deployed in Arable B.

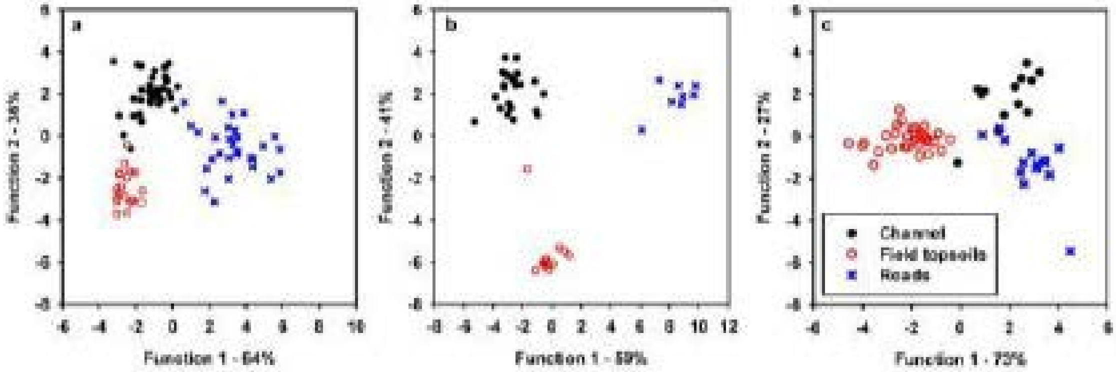


Figure 2: Groupings of samples collected from channel, field topsoil and road sources based on their physico-chemical characteristics in a) Grassland B, b) Arable A, c) Arable B.

In Grassland B, channel sources were the dominant source of sediment in every collected sample (Figure 3) and overall accounted for 70% of the total load. Field topsoils contributed 25% of sediment to the catchment outlet and sediment derived from road sources was negligible. This confirms in this predominantly low permeability catchment, that permanent grassland land cover reduces the risk of hillslope sediment loss despite the dominance of surface hydrological pathways.

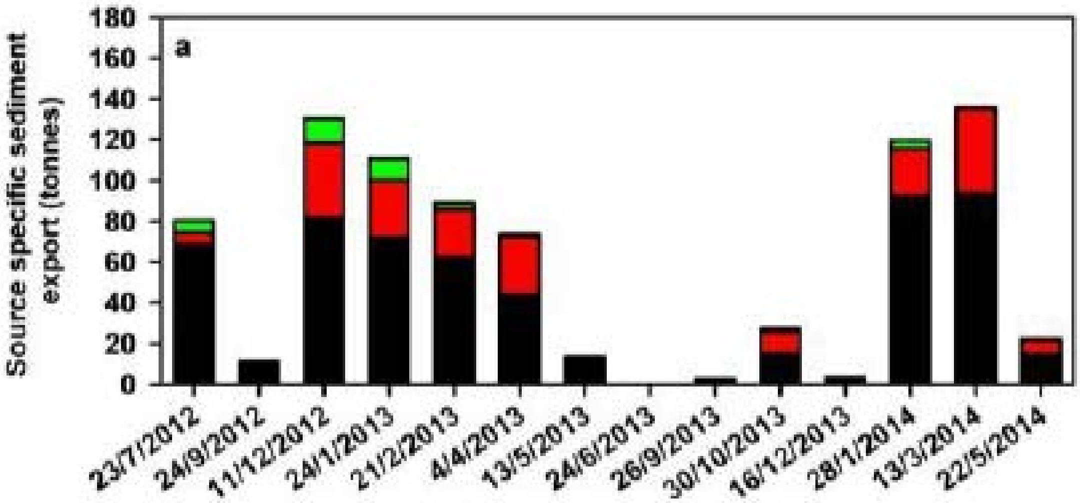


Figure 3: Load specific un-mixing of median source predictions in Grassland B.

The high permeability arable catchment (Arable A), generally exported less sediment except for the February 2013 collection (representing the period from 09/01/2013 – 12/02/2013) which was greater than any other collection from the three catchments. Sediments primarily originated from channel/sub-surface areas which accounted for 59% of the total sediment export during the monitoring period. An established riparian corridor along lower reaches of channel network protects channel banks; therefore, unprotected banks or sub-surface sources are likely important. Again, road and field sources contributed smaller proportions but were greater where sediment exports were increased. This reflects increased surface hydrological connectivity of the hillslope during wetter conditions.

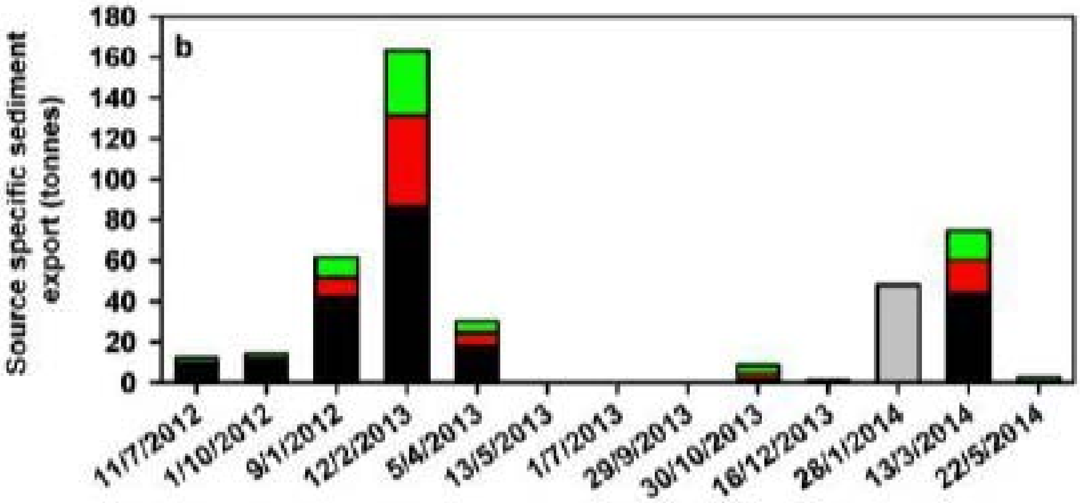


Figure 4: Load specific un-mixing of median source predictions in Arable A. Grey bar denoted sediment export during period when time-integrated sampler was blocked.

In Arable B, field topsoils were the dominant source of sediment collected at the catchment outlet – 74%. The moderately-drained soils were likely to establish surface hydrological connectivity and surface pathways relatively quickly following rainfall. Greater source availability due to low groundcover causes vulnerability to erosion on bare arable soils. The quantity of sediment exported was greater here compared to Arable A. Contributions from channel and road sources were broadly consistent through time and accounted for 17% and 9%, respectively.

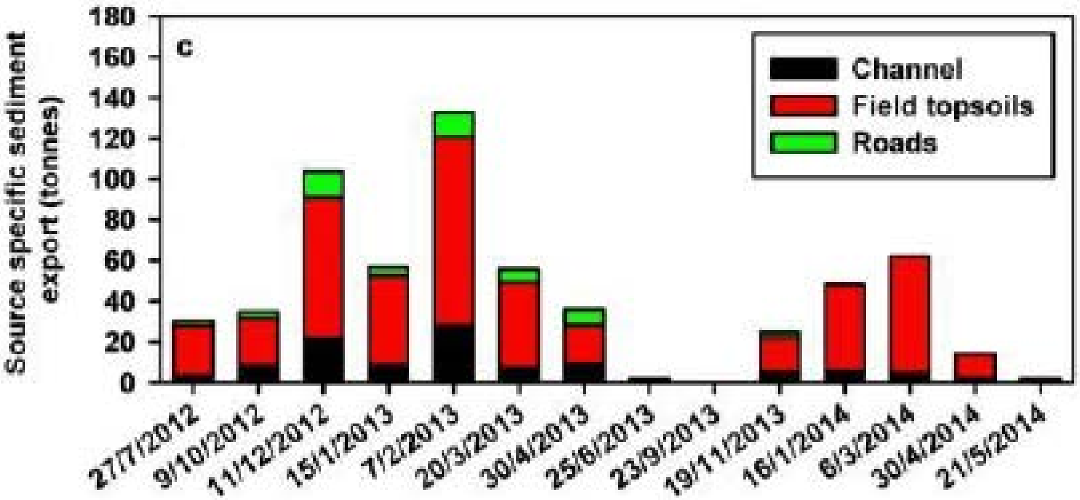


Figure 5: Load specific un-mixing of median source predictions in Arable B.

Management strategies must consider catchment specific source availability and hydrological connectivity. In catchments such as Grassland B, extensive artificial drainage networks increase the proportion and speed of water diverted from the hillslope to the channel network. This encourages bank erosion due to high channel velocities and increased capacity of water to entrain and transport sediment particles. Over-deepened channels, particularly in the lower reaches disconnects the ability of vegetation (through root networks) to stabilise channel banks. Management must consider dissipation of flow energy and increase the efficacy of bank protection by vegetation to reduce erosion.

The increased risk of soil erosion associated with large proportions of low groundcover soils in Arable A was reduced by predominantly well-drained soils and resultant sub-surface flow pathways. However, where surface hydrological connectivity and resultant surface flow pathways can be established, the soil loss can be considerable. Temporary structures to intercept and dissipate surface flow pathways and encourage deposition of transported particles may be effective at preventing sediment loss at the field-scale.
In Arable B, the soil loss risk from field topsoils due to surface flow pathways was shown to be fairly consistent over time. Conversion of arable enterprises to grassland, however, cannot be adopted without risk of relocating soil loss risk to channel banks (as in Grassland B). Reduction of hillslope sediment connectivity should be prioritised through Rural Sustainable Drainage Systems (RSuDS) to reduce surface flow velocity, encourage deposition and require minimal land to be set-aside.

These findings demonstrate the importance of managing sediment sources and flow pathways to reduce sediment delivery to aquatic ecosystems and maintain agricultural production in catchments with contrasting landscape characteristics and land use enterprises. The sediment fingerprinting approach is validated as an essential tool to facilitate cost-effective sediment management strategies.

Paper 12:

Delineating hydrologically sensitive areas as key drivers of sub-field critical source areas

Thomas et al. (2016)

KEY MESSAGES

- A Hydrologically Sensitive Area (HSA) Index is presented which more accurately identifies runoff-generating-areas and locations for targeting diffuse pollution mitigation measures in agricultural catchments.
- It uses high resolution elevation data (Digital Elevation Models; DEMs) to identify depressions or hedgerows that are impeding runoff and reducing diffuse pollution.
- These features caused 8.5-23% of runoff-generating-areas and 16.8-33.5% of catchment areas to become hydrologically disconnected from the watercourse in four ACP catchments.
- The size of runoff-generating-areas estimated using rainfall-runoff measurements ranged from 1.6-3.4% of the catchment during median storm events and 2.9-8.5%during upper quartile events depending on whether well or poorly drained soils dominated, respectively. These results validated the HSA Index.
- Using maps of runoff-generating-areas to target riparian buffer strips at points where runoff is delivered to the watercourse could reduce costs of implementation in the GLAS agri-environment scheme on average by 66% and 91% over 1 and 5 years, respectively.
- Runoff-generating-areas at field scale are the dominant CSA factor in these catchments, overriding source pressures. Targeting measures at runoff-generating-areas can also mitigate a range of pollutants transported within runoff. It is therefore potentially a longer-term, more sustainable, cost-effective and policy-applicable strategy for mitigating diffuse pollution.

SYNOPSIS

Critical source areas (CSAs) of pollutant transfers are where diffuse source pressures coincide with areas of high mobilisation potential and hydrologically sensitive areas (HSAs). HSAs are the hydrologically active areas (HAAs) generating overland flow which is hydrologically connected to the drainage channel network, and thus are runoff-generating-areas at highest propensity for pollutant transport and delivery. If mitigation measures and best management practices aimed at reducing diffuse pollution are to be cost-effective then targeted HSAs, runoff pathways and CSAs must be accurately identified. This targeting is best done at the farming scale of management which is the individual field.

Indices such as the Soil Topographic Index (STI) identifies HSAs by accounting for the slope and upslope drainage area at each point in the landscape (derived from Digital Elevation Models; DEMs) and soil hydrological properties such as soil depth and saturated hydraulic conductivity. However, such indices do not consider the impacts of flow sinks (e.g. depressions or hedgerow banks) on the hydrological connectivity of overland flow to the drainage channel network. Such features impede overland flow, causing reinfiltration and deposition and immobilisation of dissolved or entrained pollutants such as P. They often dominate agricultural catchments and represent existing mitigating features in the landscape, and as such must be considered when identifying HSAs and CSAs and targeting mitigation measures. High resolution LiDAR DEMs can now accurately capture these microtopographic flow sinks (Fig. 1). Furthermore, they can model HSAs, runoff pathways and CSAs at optimal resolutions, and allow the identification of breakthrough and delivery points. LiDAR DEMs could therefore significantly improve the identification of HSAs and targeting of mitigation measures such as riparian buffer strips (RBS) within agricultural policies.

This study aimed to (a) develop a GIS-based HSA Index which could accurately identify HSAs by accounting for impacts of flow sinks on hydrological connectivity; (b) identify cost-effective locations at identified HSAs where sub-field scale diffuse pollution mitigation measures such as RBS could be targeted; (c) validate the HSA Index using rainfall-quickflow measurements. Four of the ACP catchments were studied.

Rainfall-quickflow measurements collected from gauging stations from 2009-2014 and a soil moisture deficit model were used to empirically estimate HSA and HAA sizes during saturated storm events in each catchment. An HSA Index was then developed by modifying the STI so that values were reduced in upslope drainage areas of flow sinks which were likely to topographically impede overland flow. STI values were reduced based on the potential of flow sinks to 'fill and spill', calculated using the flow sink volume capacity (m3), upslope HAA size (m2) and the upper quartile rainfall depth (m). HSA maps were then created by selecting the catchment area with the highest HSA Index values up to the lower quartile, median and upper quartile HSA sizes empirically estimated. The costs of blanket implementation of RBS measures and a targeted approach at HSA delivery points were calculated for each catchment using the GLAS agri-environment scheme in Ireland as a case study.

Results show that flow sinks were prolific in all catchments (Fig. 1). Total flow sink volume capacities ranged from 8298-59584 m3 and caused 8.5-23% of overland-flow-generating-areas and 16.8-33.5% of the catchment to become hydrologically disconnected from the stream (Table 1). HSA sizes estimated using rainfall-quickflow measurements ranged from 1.6-3.4% during median storm events and 2.9-8.5% during upper quartile events depending on whether well or poorly drained soils dominated, respectively. Magnitudes of rainfall-quickflow responses (Fig. 2) showed good agreement with the distributions of the highest HSA Index values. Grassland B had the largest, most hydrologically sensitive response to rainfall, followed by Arable B. Grassland A was predicted as the least sensitive, which was also shown by the rainfall-quickflow data. However, Arable A was predicted to have slightly higher runoff propensity than was observed. Results also showed that using HSA maps (Fig. 3) to target riparian buffer strips (RBS) at delivery points could reduce costs of implementation in GLAS on average by 66% and 91% over 1 and 5 years, which includes the cost of LiDAR acquisition.

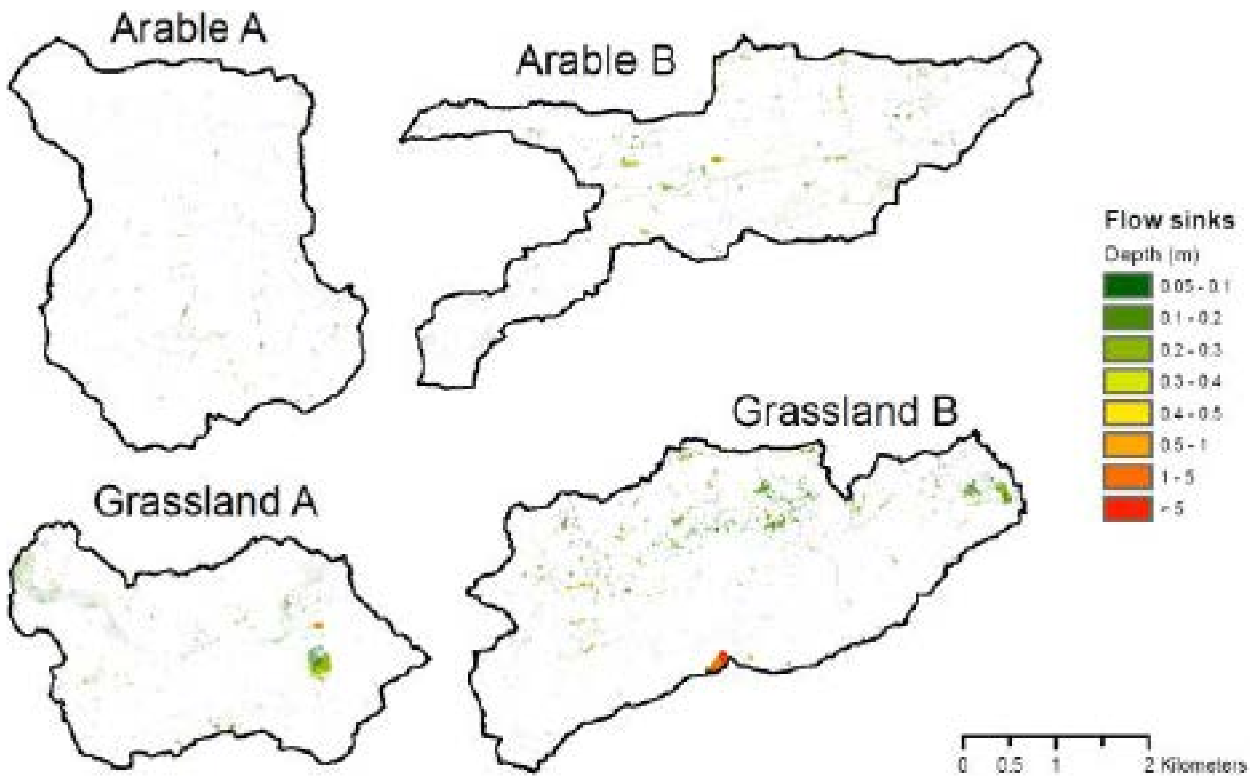


Figure 1: Flow sinks map for each catchment extracted from LiDAR DEMs.

Table 1: Flow sink volume capacities and their impacts on the hydrological connectivity of HAAs during upper quartile rainfall-quickflow events under saturated conditions.

	Arable A	Arable B	Grassland A	Grassland B
Total number of flow sinks with volume capacities ≥ $1m^3$	800	2487	1715	3101
Total flow sink volume capacity (m^3)	8298.1	24388.5	29444.9	59584.1
Total HAA area (m^2)	369692	632952	284476	1307268
HAA area (m^2) that is hydrologically disconnected	31376	123560	64904	300888
% of HAAs which are hydrologically disconnected	8.5	19.5	22.8	23.0
Proportion of HAAs that are HSAs (%)	91.5	80.5	77.2	77.0
Catchment area (m^2)	11031016	9373932	7560056	11811172
Flow sink upslope drainage area (m^2) that is hydrologically disconnected	1851780	2584228	2531508	2938368
% of catchment area which is hydrologically disconnected	16.8	27.6	33.5	24.9

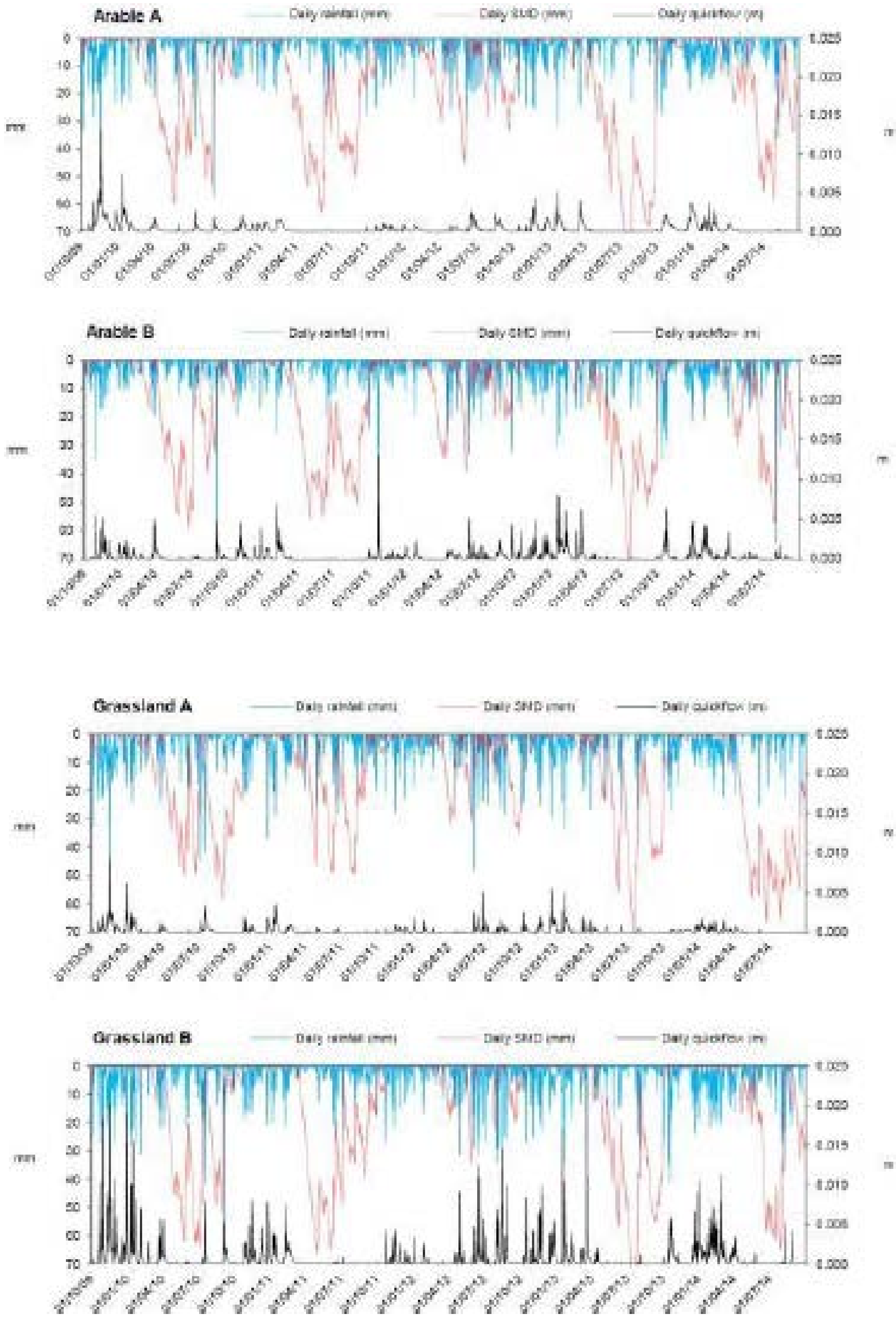


Figure 2: Daily rainfall, soil moisture deficit (SMD) and quickflow (runoff) from 2009-2014.

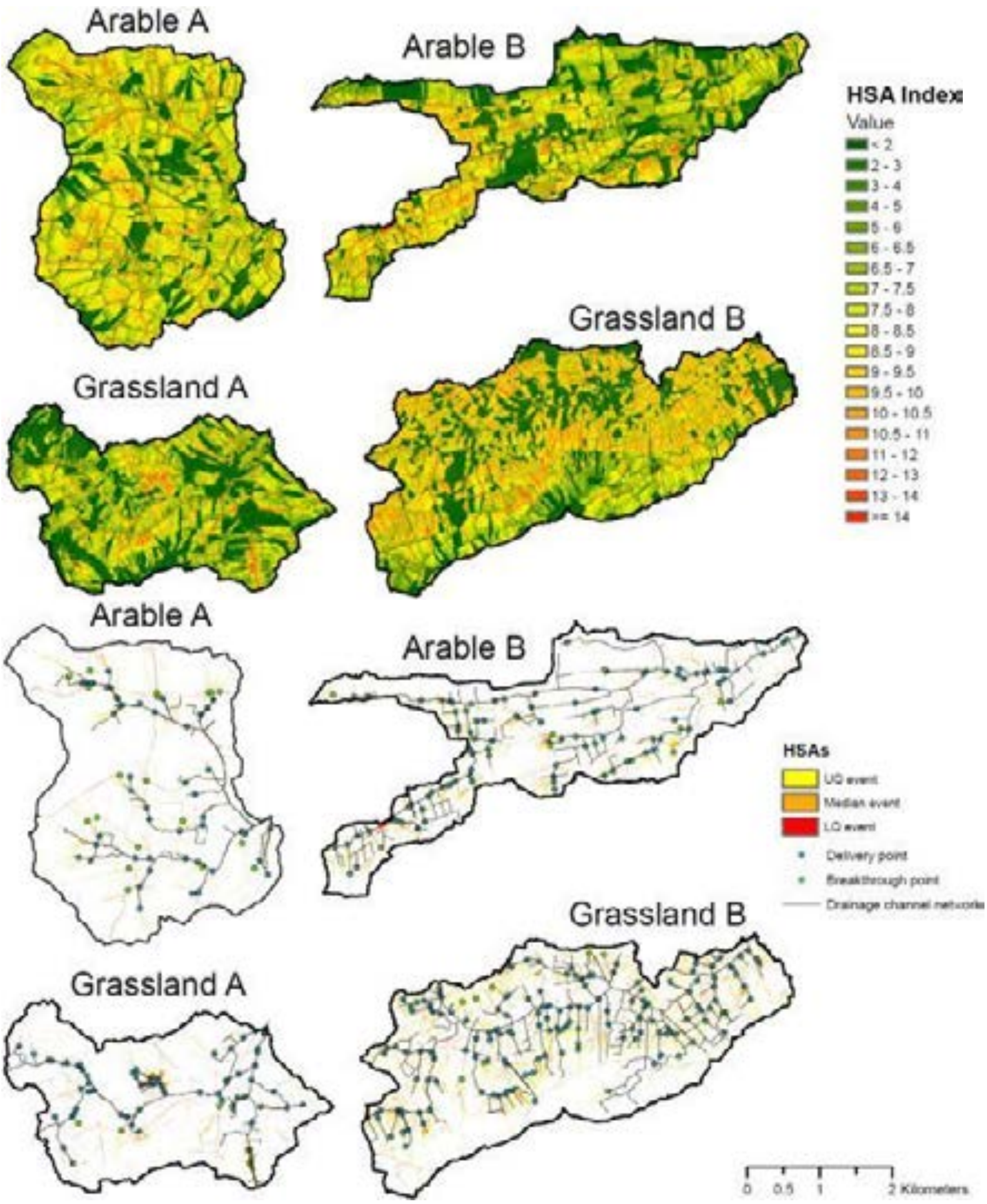


Figure 3: Maps of HSA Index (upper), HSAs and breakthrough and delivery points (lower). Targeting breakthrough and delivery points using a riparian buffer strip strategy takes account of hydrological pathway process and would also offer more cost-benefit compared with blanket or ad hoc placement.

Reference: Thomas, I.A., Jordan, P., Mellander, P.-E., Fenton, O., Shine, O., D. Ó hUallacháin, Creamer, R., McDonald, R., Dunlop, P., Murphy, P.N.C. 2016a. Improving the identification of hydrologically sensitive areas using LiDAR DEMs for the delineation and mitigation of critical source areas of diffuse pollution. Science of the Total Environment. 556, 276-290.

http://www.sciencedirect.com/science/article/pii/S0048969716303941

Paper 13:

A sub-field scale Critical Source Area index for phosphorus management

Thomas et al. (2016)

KEY MESSAGES

- Areas at highest risk of phosphorus (P) losses from agricultural land to watercourses are called Critical Source Areas (CSAs). These need to be accurately identified in order to cost-effectively target mitigation measures and best management practices designed to reduce nutrient losses, conserve soil fertility and protect water quality.
- A new sub-field scale P CSA Index is presented which aims to improve the identification and mitigation of P CSAs at the scale that is reflective of the hotspot origins of surface runoff diffuse pollution.
- The CSA Index integrates source, mobilisation and transport factors of P losses within mapping software to create CSA maps which can be used by farmers and farm advisors to target mitigation measures and best management practices.
- Source and mobilisation datasets include soil P concentrations (Morgan's P), degree of P saturation and water soluble P.
- Transport risk is determined using the Hydrologically Sensitive Area (HSA) Index developed in a previous study, which identifies runoff-generating-areas and hydrological connectivity of runoff pathways.
- Preliminary results show that the new CSA Index identifies CSAs at the sub-field scale and captures the influence of microtopography.
- The approach provides more scientifically robust estimates of P loss risk compared to conventional spreadsheet-based CSA Indices, by accounting for P mobilisation potential and microtopographic controls on HSAs, erosion and hydrological connectivity. The methodology can also be applied to identify CSAs of other diffuse pollutants.

SYNOPSIS

Diffuse phosphorus (P) losses from agricultural land to watercourses must be controlled to conserve soil fertility and reduce eutrophication and water quality degradation. Areas at highest risk of P transfers are called Critical Source Areas (CSAs). These are where diffuse source pressures coincide with areas of high mobilisation potential and runoff-generating-areas called hydrologically sensitive areas (HSAs) which are at highest risk of P transport and delivery. CSAs need to be accurately identified to cost-effectively target mitigation measures and best management practices designed to reduce P losses, conserve soil fertility and protect water quality.

Existing P CSA Indices (termed P Indices in the US) used to identify CSAs have limitations:

- they are spreadsheet-based
- watercourse proximity is used as a proxy of runoff propensity and P transport risk, which does not account for realistic topographic or microtopographic controls
- mobilisation potential and hydrological connectivity are poorly defined

These limitations could be addressed using improved conceptual models (Fig. 1), high resolution LiDAR Digital Elevation Models (DEMs) and Geographical Information Systems (GIS) A new GIS-based CSA Index was developed, which integrates source, mobilisation and transport factors of dissolved P losses (Table 1). Source and mobilisation factors include soil P concentrations (Morgan's P) and soil water soluble P. Transport risk is determined using the Hydrologically Sensitive Area (HSA) Index developed in a previous study, which identifies runoff-generating-areas and hydrological connectivity of runoff pathways. The CSA Index was applied to Arable A and B and Grassland A and B catchments which represent contrasting agri-environmental conditions found in Ireland. CSA factor datasets were collected (Table 1 and Figs. 2-3) and rasterised in ArcGIS, and values were categorised and assigned relative risk scores ranking P loss potential. A CSA Index was then created by totalling risk scores for dissolved P losses using a component formulation. Grid cells within the highest risk scores were identified as CSAs.

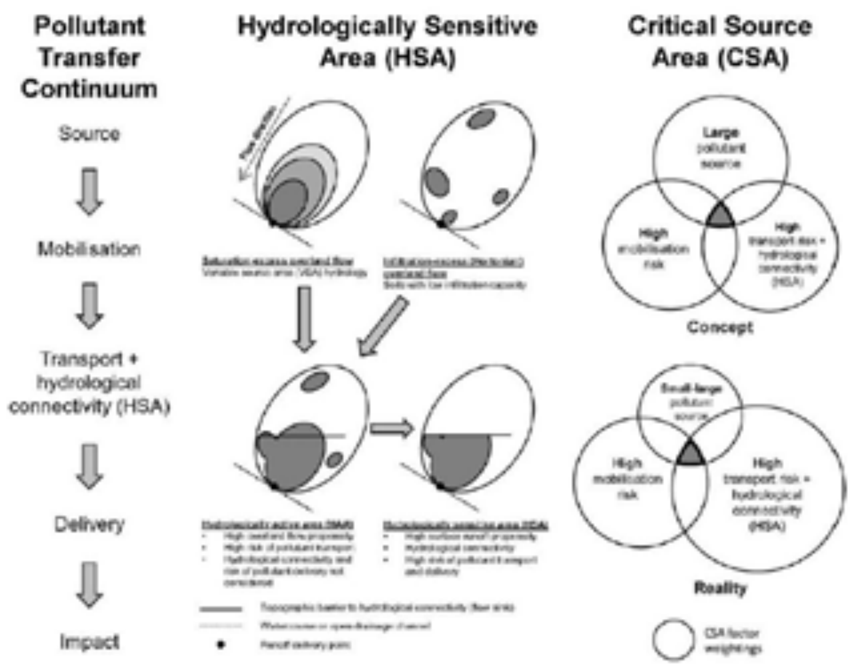


Figure 1: Using the P transfer continuum and HSA/CSA concepts to identify CSAs

Preliminary results show that the new CSA Index identifies CSAs at the sub-field scale and captures the influence of microtopography such as roads and hedgerows. Breakthrough points and delivery points along CSA pathways, where P is transported between fields or delivered to the drainage network, are easily identifiable, allowing the targeting of sub-field scale mitigation measures to reduce P losses at these most cost-effective locations (Fig. 4). The approach provides more scientifically robust estimates of P loss risk compared to conventional spreadsheet-based CSA Indices, by accounting for differences in P mobilisation potential between catchments (based on soil chemistry) and microtopographic controls on HSAs and erosion at and within field scale. Calibration of CSA Index factor weightings and validation of the CSA maps was undertaken using measured P loss data at catchment and subcatchment scales.

Table 1: CSA Index factors used in this study and advantages over existing CSA Indices

Factor type	Factor	Factor details	Datasets used	Advantages over existing CSA Indices
Source	Soil P concentration	Morgans P (mg/l)	Soil samples (25 per field)	None
Mobilisation	Water soluble P	Morgan P pedo-transfer	Soil samples (~30 per catchment)	Accounts for differences in P mobilisation potential across soil types
Transport + hydrological connectivity	HSA Index	Uses a Soil Topographic Index and reduces runoff risk where flow sinks reduce hydrological connectivity	0.25m and 2 m LiDAR DEMs, SMD model, rainfall, quickflow, soil samples and Irish Soil Information System	Accounts for topographic and microtopographic controls on runoff propensity, pathways and hydrological connectivity
Mobilisation + transport	Erosion risk	Unit Stream Power Erosion Deposition (USPED) model	2 m LiDAR DEM, land use, soil properties, rainfall	Integrates DEM-derived slope and flow accumulation with Revised Universal Soil Loss Equation (RUSLE)

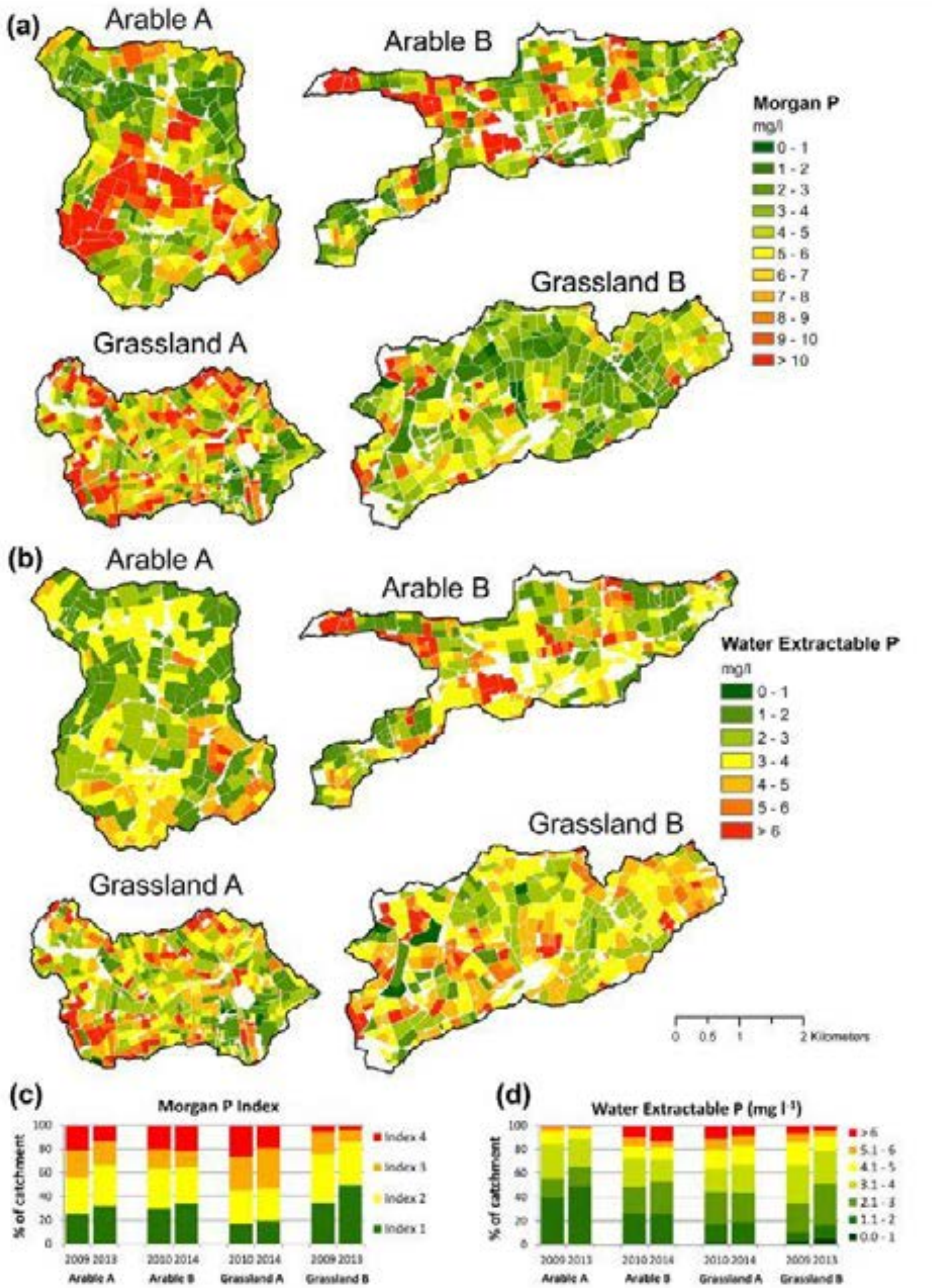


Figure 2: Morgan P concentrations (a) and water extractable P concentrations (b) (and summary statistics – c and d). The WEP data were used as a P mobilisation factor in the CSA formulation.

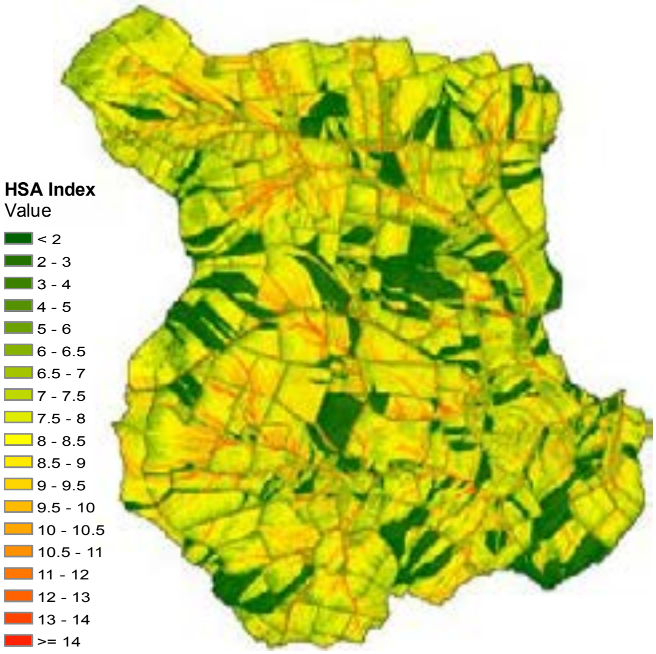


Figure 3: Hydrologically Sensitive Areas (HSAs) at sub-field scale and which considers microtopographic influences of surface runoff diversions, barriers and impedances. Higher values in red and lower values in green indicate higher and lower runoff propensity, respectively.

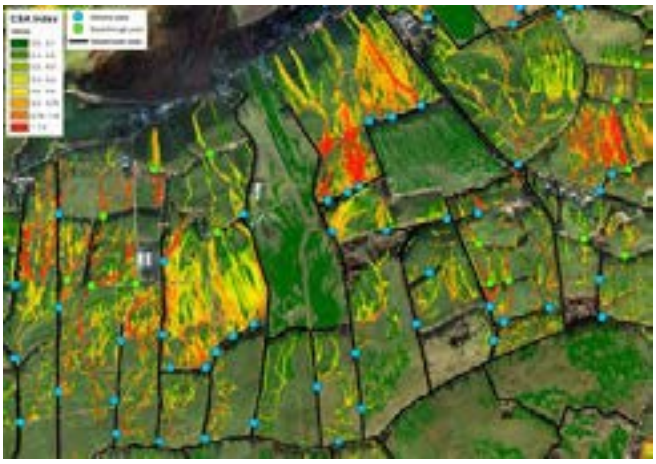


Figure 4: Sample close-up of CSA Index integrating all CSA factors. Areas with the highest CSA Index values (red) are identified as CSAs. Also shown are breakthrough (green circles) and delivery points (blue circles) where sub-field scale mitigation actions/schemes could be targeted.

Reference: Thomas, I.A., Mellander, P.-E., Murphy, P.N.C., Fenton, O., Shine, O., Djodjic, F., Dunlop, P. and Jordan, P. (2016b). A sub-field scale critical source area index for legacy phosphorus management using high resolution data. Agriculture, Ecosystems and Environment. 233, 238-252.

http://www.sciencedirect.com/science/article/pii/S0167880916304637

CHAPTER 5

KNOWLEDGE TRANSFER & FARMER PARTICIPATION

Knowledge Transfer in the Agricultural Catchments Programme

The support given by the catchments' farmers to the ACP is the cornerstone of its success. The ACP agricultural advisers have played the key role building the relationships with farmers and providing the main channel for two-way communication of ideas, concerns and information. The programme technicians, whose main role is in sampling data collection and equipment maintenance, are an important support to the advisers in building and maintaining relationships with the farmers.

ADVISERS ROLE

The job of the ACP adviser is in many ways more challenging than that of a mainstream Teagasc adviser as it entails the delivery of an intensive advisory service to meet the requirements of all the catchments' farmers across a wide range of farm types and enterpriser. The farmers were not selected but rather were included in the programme because they farmed some land in the catchment. Some farmers have the bulk of their land in the catchment while others may have only a portion, perhaps only a part of a field, of their land in the catchment. This diversity among the farmers adds variety and vibrancy to the programme but also makes the delivery of an advisory service substantially more difficult.

In addition to provision of advisory support to the farmers the adviser is responsible for the collection of environmental, economic and production data from the farms and for the dissemination of information generated by the programme to the farmers and to other stakeholders. Thus the variety of the work is a welcome aspect of the role but it does require the advisers to be very flexible in how they get the work done.

Mark Treacy, former ACP adviser, Dr Tim Mackle, Chief Executive, DairyNZ and Kevin Collins at the catchment outlet on his farm in Timoleague.

The main knowledge transfer methods used by the advisers are discussed below:

One-to-one contact

The advisers devote most of their time to dealing with farmers on a one-to-one basis. These contacts can be during on-farms visits, in office consultation, by phone or through written communications in emails, texts or advisory notes. During Phase 2 of the programme there were 2,972 individual visits and consultations with catchment farmers. Apart from delivering an advisory service they have a very important role in facilitating the research and dissemination elements of the programme through liaising with farmers regarding the collection of samples, siting of instrumentation, location of trial plots and organisation of catchment and farm visits.

The advisors other main role is in the collection of nutrient management and financial records. The Teagasc National Farm Survey and eProfit Monitor methods are both used to gather information on the farm enterprises and the data is used in the analysis of the farm business as well as for research purposes.

Farmer meetings and Farm Walks

Eighty events aimed at delivering information to farmers and receiving their feedback were held during Phase 2 of the programme. The events vary in size, content and style of delivery in order to match the farmers' needs. Typically the topics dealt with might include outcomes from the research programme and what they are they tell us about the impact of farming in the catchments or how farm practices could be adapted based on the new information. However some meetings focussed more on the farm management and agronomy priorities of the farmers, for example very successful farm walks were held in conjunction with the Department of Agriculture, Food and the Marine on the Greening Measures for tillage farmers. Group meetings were held across all the main enterprises: dairy, beef, sheep and tillage and while this method of knowledge exchange does not appeal to all farmers, those who participate find the meetings useful and of benefit to their farm business. These meeting are also beneficial to the ACP as they provide an effective channel for feedback from the farmers and an additional opportunity for them to share their ideas and voice any concerns they may have about any aspects of the programme.

Noel Meehan ACP adviser at a Farm Walk in the Cregduff catchment jointly organised with Teagasc Mayo staff.

Farmer Participation

The six catchments on which the ACP is based were selected through a thorough and rigorous process using, what is known as a Multi Criteria Decision Analysis (MCDA). This process used a wide range of information layers stored in a Geographical Information System (GIS) and ultimately produced a ranked list of 1,300 catchments from which six of the highest-scoring catchments were selected (see Chapter 2 of the ACP Phase 1 Report). Thus, the catchment selection was selected based purely on the physical and agricultural characteristics extracted from the GIS layers. The farmers who farmed the land in the catchments did not know that this land fell within the boundaries of the selected catchments and were not in any way selected from the rest of the farming population. Once the catchments were selected the next task for the ACP team was to visit each of the 320 farmers and explain what the programme was trying to achieve and to ask for their support. Following this extensive consultation the farmers agreed to participate and their support and engagement has become the cornerstone of the programme.

The six people featured in the following pages have all been great friends and supporters of the ACP and represent their community of farmers without whom the programme would have been impossible to deliver.

Kevin Murphy and his ACP adviser, Eddie Burgess addressing a group on a field trip from the Teagasc Knowledge Transfer Programme in 2013.

Kevin Murphy – Ballycanew Catchment, Co. Wexford.

Kevin is a dairy farmer with a 200 cow herd on 80 hectares of grassland on a heavy, high clay content soil. This are of poorly to moderately drained soils is typical of a coastal strip in south Wicklow and north Wexford area. Three quarters of the Ballycanew catchment area has this soil type.

Kevin's dairy herd is all spring-calving and is of high genetic merit with an average Economic Breeding Index (EBI) of €175 which is in the top 10% of Irish herds. Over the years Kevin has focused his farming enterprise on a grass-based milk production system. He measures his grass across the farm and completes a grass budget weekly. He has expanded his herd size significantly by (a) replacing another farm enterprise with dairy cows, (b) increasing his stocking rate and (c) increasing the area farmed. In 1998 Kevin completed an advanced Dairy Farm Management course in Teagasc's Kildalton Agricultural College. On completion, the participants of that course formed a dairy discussion group which continues to meet regularly. Much of the focus and enthusiasm that Kevin has for farming is both supported and driven by this group of colleagues.

Farm stocking rate exceeds the 170 kg N/hectare Nitrates limit. This necessitates an annual application to the Department of Agriculture, Food and the Marine (DAFM) for a derogation which permits Kevin to farm at a whole farm stocking rate of up to 250 kg N/hectare. Due to Kevin's participation in the ACP, there has been an increased focus on nutrient management planning on the farm in comparison to other most farms. The number of soil samples taken and the frequency of repeat sampling on Kevin's farm are well in excess of statutory requirements. Interestingly, there has been no significant increase or trend in the soil concentrations of available phosphorous or potassium since the start of the Catchments Programme despite the applications of fertiliser to build up soil fertility levels from index 2 (low) to index 3 (medium).

All slurry produced on the farm is spread using a low emissions / trailing shoe application system which was grant-aided by the DAFM Agri-Environmental Options Scheme under the Rural Development Programme. In addition to improved nitrogen use efficiency, this allows slurry to be spread on fields that have a reasonable cover of grass. Slurry can therefore be spread throughout the grass growing season on fields and at times that would be very restricted using a conventional splash plate slurry tanker.

Kevin is pleased to have the ACP working on his farm and has a keen interest in the findings of the programme. He took part in the EPA funded programme, "AG-Impact Knowledge Transfer Workshop", representing farmers from the Catchments programme and has facilitated group visits to the Ballycanew Catchment area, such as a field trip associated with Teagasc's international "Knowledge Transfer Conference".

"It is great to be part of a programme that shows scientifically, using real farm data, that it is possible to increase farm production and intensity without a negative impact on water quality. A good advisory service is key to achieving this objective. No one wants to spend money on fertiliser and see it being lost to watercourses".

Carmel O'Hea – Timoleague Catchment, Co. Cork

Carmel is a dairy farmer in the heart of the Timoleague catchment, she began farming full time in 2009 and currently farms 46.45 hectares of land, 40 hectares of which is in grassland with the rest growing maize for winter feed. Carmel succeeded her father, PJ O'Hea, on the family farm and now has a dairy herd of 90 cows with approximately 60 other stock, mainly replacement heifers. She has also bred some successful High EBI AI bulls such Ahafore Franko.

Carmel's entire farm falls within the boundary of the Timoleague catchment and like many farmers in the catchments she has facilitates the programme by providing a site for some monitoring equipment on her land. In Carmel's case this is a rain gauge which is part of the network of instruments providing weather data vital to programme.

Carmel has a well-run dairy enterprise and her soil management is excellent with 63% of her land falling into phosphorus index 3 or 4 with the remaining land at index 2. As a dairy farmer she engages with Teagasc for Basic Payment scheme and derogation applications every year and makes full use of the soil analysis and nutrient planning advice made available to her through the ACP. The efficient use of slurry and soiled water by Carmel is evident as there is minimal phosphorus brought onto the farm in the form of chemical fertiliser. Soiled water is spread on paddocks after grazing and slurry is generally kept for silage and maize ground where it is required most.

Carmel at a Timoleague catchment farmers meeting with her some of her neighbours

David Mitchell – Sreenty/Corduff Catchment, Co. Monaghan

David Mitchell farms in Shantonagh, Co Monaghan and has played a key role in the Agricultural Catchments Programme. He is also actively involved in the local group water scheme which supplies 560 households with drinking water. This is sourced from Lough Namachree in the catchment and which has been the subject of an ACP study.

He operates a cattle suckler herd of approximately 40 cows and a sheep flock of 75 ewes. David's farm is typical of others in the area, being located on drumlin ground with varying soils. The farm consists of 48 ha of grassland and is fragmented into a number of separate blocks. Drainage has been carried out to maintain land in good condition.

Cows are mainly Limousin and Simmental cross animals with a small number of purebred Hereford cows for the sale of young bulls. A Charolais stock bull is run with the commercial cows and AI is used to breed replacements. All progeny are taken through to finish for both the suckler herd and sheep flock. Cattle are finished as steers and heifers. Heifers are slaughtered at 21 to 22 months and steers at 25 months. Target slaughter weight for steers is 400 kg and for heifers is 320 kg approximately. The finishing diet is based on good-quality silage and supplemented with high quality concentrate.

Farmer, David Mitchell with his ACP Agricultural adviser, Tom O'Connell.

David works closely with his Teagasc advisers both through the Agricultural Catchments Programme and BETTER farm programme. One of the main benefits of this advisory input according to David is that is helps him make better use of grass.

"Ireland with its plentiful rain and mild weather is one of the best places to grow grass in the world. Working with Teagasc and seeing the results from its research has made me realise the importance of this. With a little better management such as increased use of paddocks, I can make better use of this grass. My whole farm has been soil sampled and I now target chemical and slurry where most benefit is to be got. These two together have allowed me to produce more beef and lamb from my land since the start of the project"

Joe Doyle – Castledockerell Catchment, Co. Wexford

Joe farms 100 hectares of free draining tillage ground in the Castledockerell catchment, located in north County Wexford. 75 hectares is tilled each year and is mostly sown with malting spring barley. Joe also grows barley for seed production. Traditionally there has been an early lambing flock of 300 ewes kept on the farm, but this enterprise was replaced with a spring calving dairy herd which is now in its third year of producing milk. There are currently 60 high EBI cows being milked using a robotic milking machine. They are grazing high clover swards that were reseeded from tillage ground following the harvest three years ago. During the dry period the cows are housed in a straw bedded loose house. In 2015 Joe's average fat and protein yield per cow was 476 kg, with a Fat % of 4.27 and Protein of 3.71%

Joe has worked very closely with the catchments programme since its initiation and has facilitated many of its activities. For example, a series of three multi-level ground water monitoring wells were bored and installed on his farm. He has also hosted, on numerous years, multi-replicated plots for research trials on yield and quality response of spring barley to fertiliser rates, application methods and application timings. The results of these trials were of particular interest to farmers in the locality and always drew a big attendance to field demonstrations and open days held on the site. In addition to these farmer groups visiting Joe's farm, he has hosted numerous other national and international groups including students, advisers, researchers and policy makers. Joe also presented at the EPA's annual Water Conference in Galway to 300+ delegates on a farmer's involvement in the ACP.

The most significant change Joe has made to his day-to-day farm management practice as a consequence of the ACP is the implementation of a targeted nutrient management plan. Previously, the same chemical fertilisers would have been blanket spread across all the tillage ground, using 18.6.12 at sowing and Sulpha CAN for top dressing the crop with Nitrogen. Now, as a result of soil analysis and advice, pig slurry is imported and ploughed into seed beds prior to sowing in the spring maximising the efficiency of nutrient recovery while reducing chemical fertiliser use. Also a range of compound chemical fertiliser types and rates are used to balance the P and K requirements. Decisions on this are made based on the crop sown, yield and soil fertility status. The results of this change in practice are evident in not only the increase in average yield across the farm, but also by the fact that both quality (protein % for malting) and yield have become uniform across all the different fields on the farm. Previously there was significant variation in both yield and quality of grain from field to field indicating inaccurate targeting of nutrients to meet crop requirements thus reducing nutrient use efficiency.

Joe Doyle with Dr Rachel Creamer, Minister Damien English, Prof Gerry Boyle and his ACP Adviser Eddie Burgess at the launch of the LANDMARK Project on his farm.

Shane O' Reilly – Cregduff Catchment, Co. Mayo

Shane runs a weanling to beef enterprise on shallow free draining soil over karst limestone bedrock. He also keeps a pedigree Limousin herd, breeding high quality bulls for the suckler farmer market and heifers with strong maternal traits. He owns 16 ha and leases a further 20 ha. He also owns 15 Ha of SAC.

His system is designed to avail of the plentiful supply of good quality continental bull weanlings available in Mayo. These he purchases during September and October. He targets animals that have the potential to grade well focusing on Charolais and Limousin cross animals. These animals are carefully managed upon arrival to ensure they are healthy going into the shed and target weight gain is 0.6-0.7 kg per day. These are fed high quality silage and 1.5 kg meal/head per day for 10-12 weeks with the meal gradually reduced before turnout to grass. The aim is to get grass back into the diet as early as possible. Early grazing is difficult to achieve due to high levels of rainfall so he has recently purchased a 'zero grazer' which he uses to provide grass at the shoulders of the grazing season thus reducing the amount of silage required over the winter. These animals are either sold as forward stores or killed directly off the farm at 18 – 24 months of age.

Since the ACP started in 2009, Shane has been an enthusiastic participant and has assisted the programme in achieving its objectives. He has facilitated the programme by hosting numerous visitors to the catchment and providing sites for project instruments.

Shane has engaged with the advisory service from the outset, providing records and information and willingness to adopt new ideas and technologies, the most noteworthy being his use of the ACP Fertiliser Plan giving a paddock by paddock fertiliser recommendation for his farm. This has allowed Shane to utilise his lime, slurry and chemical fertiliser inputs in a more targeted and effective way by applying lime and fertilisers to the paddocks that need them most.

Shane highly values the help he gets on nutrient management, as he says, 'Before I got soil samples taken and a fertiliser plan I was only shooting in the dark. I didn't know what fields needed lime, P or K. Now I know exactly what fields need what and how much to fertiliser to put out. I can refer back to the map for the recommendation and apply accordingly; to be honest I couldn't work without it now'.

After participating in the first 2 phases of the ACP Shane is clear of the benefits to the farmer and the environment in the Cregduff area and he is looking forward to further improvements in Phase 3.

Farmer, Shane O'Reilly with his ACP adviser, Noel Meehan.

Farmer, Pat Callan with his ACP
Agricultural adviser, Tom O'Connell.

Pat Callan – Dunleer Catchment, Co. Louth

Pat Callan, together with his son Aaron, farms in Phillipstown and has played an important role in the ACP. Aaron has recently completed a Level 8 degree in Agricultural Science and is currently working part-time with a local farm supply business. Eventually he would like to return full-time to the home farm.

Farming 160 ha, they operate a dairy herd of approximately 200 cows – a large farm by Irish standards. In common with many of his farming colleagues, the farm is fragmented into several separate blocks and a significant portion is rented.

The dairy herd is unusual in Ireland in that the main breed is the Montbeliarde. This is a dual purpose French breed. Pat and Aaron's Montbeliarde herd is one of the largest in Ireland. In addition to dairying, there is some tillage on the farm. They grow their own cereals, mainly wheat, oats and barley for home feeding and straw for bedding. Following the abolition of milk quotas the Callans are planning to further increase cow numbers. Running any successful dairy herd requires keeping a close eye on costs especially feed and fertiliser. As part of the programme they are keeping detailed financial records which they find of increasing benefit in tracking and optimising farm performance.

"Milk price has dropped considerably over the last year and prospects are not looking great for the foreseeable future. As our cows spend most of their time outside on grass, growing more grass and making better use of it is vital. The catchments programme has highlighted the benefits of soil sampling. The gains to be got from sitting down with your adviser and going through soil results field -by- field are great. Compared to a few years ago, we now feel that slurries are being better used. They are too valuable not to be used properly and chemical fertilisers need to be used where the most benefit is to be got"

CHAPTER 6

DISSEMINATION

Dissemination

A key objective of the ACP is to disseminate its outputs to all stakeholders with an interest in agriculture and water quality. To this end the programme engaged in a broad range of dissemination activities beginning with the farmers in the catchments and extending to the worldwide research community and policy makers.

Dissemination to the farmers is mainly carried out by the advisers and is dealt with in the previous chapter – this chapter deals with the other dissemination activities carried out by the ACP.

Publications

The papers so far published from Phase 2 data are featured in chapters 2, 3 and 4 of this report. It should be noted that the long time series data going back to Phase 1 and Phase 2 becomes more valuable with each additional year's data and will yield further publications either on its own or in combination with Phase 3 data. These peer-reviewed papers are the primary means of ensuring the high quality of ACP research outputs as well as communicating these outputs to the research community and policy makers. They provide the evidence which is essential to support the evaluation of the effectiveness of the NAP measures and the Derogation. They also make a significant contribution to the reporting that is mandatory under the Nitrates Directive and Water Framework Directive.

In addition to the peer-reviewed papers popular and technical articles were produced for the Teagasc publications, TResearch and Today's Farm as well as other publications.

See appendix 1 for the full list of publications produced during Phase 2.

Conferences

The ACP team continued to be very active in contributing to national and international conferences and meetings. This important dissemination activity helped the programme reach a wide range of stakeholders especially in the research community and also enhanced the network of national and international contacts. This led to the realisation of several collaboration opportunities.

Catchment Science 2015

The ACP repeated the success of the Catchment Science 2011 conference with the Catchment Science 2015 conference held in September 2015 in Wexford. The conference explored the latest developments in catchment science and their application to the environmental and economic challenges facing farmers, policy makers and regulators. Speakers from leading catchment science research institutes in Ireland, the EU, USA, Australia and New Zealand delivered papers on the themes of:

- Detecting change and lag times - patience and policy implementation.
- Integrated management, stakeholder engagement and catchment economics.
- Soil analysis and nutrient management – achieving environmental and agronomic goals.
- Adaptive management approaches to reducing nutrient loss risk.
- Disentangling the impact of multiple stressors on aquatic ecology.

The three-day conference included two separate field trips to the two Wexford catchments. One 'Monitoring the catchment continuum from soils to stoneflies' focussing on the biophysical science and technology of the ACP and its outcomes and the second 'Farming Under the Nitrates Directive' concentrating on the socio-economic monitoring and outcomes as well as the practical farming challenges encountered in the catchments and the farm practice solutions implemented by the farmers in conjunction with the ACP advisers.

Full details including conference proceedings are available at:
www.teagasc.ie/agcatchments

Discussion at the Castledockerell catchment outlet during the 'Monitoring the catchment continuum from soils to stoneflies' fieldtrip.

Catchment Science into Policy Briefing

This briefing on the main findings of the Agricultural Catchments Programme and the policy implications in the context of meeting Ireland's water quality and food production goals was held in March 2015 in Portlaoise. The invited audience was made up of policy makers, researchers, knowledge transfer professionals and stakeholder representatives. The themed sessions covered key outcomes of the programme and through discussion their relevance to current and future agri-environmental policy were explored and debated.

The presentations and posters from the briefing are available at:
www.teagasc.ie/agcatchments

ACP team members Ger Shortle, John Kennedy, Tom O'Connell and Phil Jordan at the ACP Science into Policy Briefing with Mairead McGuinness MEP who opened the event.

A discussion during the International Association of Hydrologists Fieldtrip to Cregduff Catchment.

Other Dissemination Events

During Phase 2 ACP staff and students continued to contribute oral papers and posters to national and international conferences. Over the four years 93 papers and posters were presented. During Phase 2 catchment visits and briefings for groups of students, agricultural advisers, researchers and other stake holder groups have been organised and facilitated by the ACP team. These events are an important part of the programme's dissemination efforts and they include practical sessions for students, briefing sessions with a wide variety of visiting groups including scientists, farmers, advisers, local authority staff etc. This work is time consuming but very important as it facilitates not just dissemination but also the exchange of knowledge and ideas among a wide range of stakeholders. During Phase 2 82 such events were hosted by the ACP across all the catchments.

Website, Television, Radio, Press

The ACP maintains a website at https://www.teagasc.ie/environment/water-quality/agricultural-catchments/ to facilitate the understanding of the programme and how it operates. The website content includes a series of short videos produced by the ACP team to explain aspects of the programme and to describe each of the catchments. These aim to illustrate the programme's approach and the range of activities undertaken in its operation.

The website contains general information about the ACP, its objectives, design and development and outputs from the programme are posted on the website regularly. The website also carries regularly updated forecasts and weather data from each of the catchments as well as summaries of weather records since the project began collecting them.

The ACP has featured in a number of local radio and national TV programmes during Phase 2 including the RTE series 'Four Seasons in One Day' as well as articles in local and national newspapers.

John Creedon of RTE interviewing Colin Bateman, a farmer in the Timoleague catchment for the series 'Four Seasons in One Day'

APPENDIX 1

2012

1. Buckley, C. (2012). Implementation of the EU Nitrates Directive in the Republic of Ireland - A view from the farm. Ecological Economics 78: 29-36

2. Buckley, C. and Fealy, R. (2012). Intra-national importation of pig and poultry manure: acceptability under EU Nitrates Directive constraints. International Journal of Agricultural Management Vol 1 Issue 4: 41-47

3. Buckley, C., Hynes, S. and Mechan, S. (2012). Supply of an ecosystem service - Farmers' willingness to adopt riparian buffer zones in agricultural catchments. Environmental Science & Policy 24: 101-109

4. Jordan, P., Melland, A., Mellander, P., Shortle, G and Wall, D. (2012). The seasonality of phosphorus transfers from land to water: implications for trophic impacts and policy evaluation. Science of the Total Environment 434: 101-109

5. Melland, A., Mellander, P., Murphy, Paul, Wall, D., Mechan, S., Shine, O., Shortle, G and Jordan, P. (2012). Stream water quality in intensive cereal cropping catchments with regulated nutrient management. Environmental Science & Policy 24, 58-70

6. Mellander, P., Melland, A., Jordan, P., Wall, D., Murphy, Paul and Shortle, G (2012). Quantifying nutrient transfer pathways in agricultural catchments using high temporal resolution data. Environmental Science & Policy 24: 44-57

7. Mellander, P., Wall, D., Jordan, P., Melland, A., Mechan, S., Kelly, C. and Shortle, G (2012). Delivery and impact bypass in a karst aquifer with high phosphorus source and pathway potential. Water Research 46: 2225-2236

8. Murphy, Paul and Sims, T. (2012). Effects of lime and phosphorus application on phosphorus run-off risk. Water Air Soil Pollution 223 (8) 5459-5471

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8. Melland, A., Jordan, P., Murphy, Paul, Mellander, P. and Shortle, G (2013). A review of monitoring approaches and outcomes of surface water quality mitigation measures in meso-scale agricultural catchments. In: European Geosciences Union General Assembly 2013, Austria. (Abstract) Conference Book of Abstracts p. 10446

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APPENDIX 2

Agricultural Catchments Programme (ACP) Staff

Ger Shortle

Role: Programme Manager

Ger has been with Teagasc since 1993 and has worked in a variety of roles in research, advisory and training. Prior to his appointment as ACP manager he ran the Organic Research Unit at Johnstown Castle Research Centre and liaised closely with the Teagasc advisory service in delivering the organic advisory and training programme.

Before moving to Johnstown Castle Research Centre in 2005 he was Principal of Mellows Agricultural College in Athenry, Co. Galway and prior to that he worked as an agricultural adviser in Teagasc and in the private sector. Ger has been manager of the ACP since its inception and is responsible for the all aspects of the development, implementation and delivery of the project as agreed with the funder, the Department of Agriculture, Food and the Marine.

Ger sits on the National Implementation Group for Water Framework Directive, the Management Strategies for Agriculture Working Group, the Water Framework Directive Programmes of Measures Steering Group and he chairs the Teagasc Water Framework Directive Working Group.

Phil Jordan

Role: Principal Scientist

Phil is Professor of Catchment Science at Ulster University and has a range of research interests in hydrology, hydrochemistry and limnology concerned with the transfer and fate of nutrients and pollutants in the aquatic environment. He was previously Head of the School of Environmental Sciences, Ulster University and has had a number of research collaborations with Teagasc and other Irish research and University departments.

In Phase 1 of the ACP his role as Principal Scientist was to direct the scientific team and the bio-physical evaluation of the Good Agricultural Practice regulations as determined in the Nitrates Directive NAP. Specifically, this part of the Programme provides a link between compliance and resulting parameters of water quality in catchment rivers.

Maria Merriman

Role: Programme Administrator

Maria Merriman has worked in an administrative role in the private and public sectors. Prior to working in the ACP she was Staff Officer for Teagasc in Westmeath having previously worked in the Franciscan College of Agriculture in Multyfarnham.

Maria's role as Administrator is to produce, compile and monitor management budgets and reports and provide administrative support to the ACP team liaising with and supporting a participative project internal and external stakeholder network. She oversees the implementation of agreed protocols, assisting in the development and monitoring of the programme business plan. Maria provides administrative support at programme local, national and international meetings and promotes dissemination of the project outputs and other information through organizing and supporting meetings and open days with participating farmers and other stakeholders in the catchments..

STAFF

Simon Leach

Role: Data Technologist (GIS and Data Management)

Simon has been an ACP data technologist since September 2013. The data technologist role involves the technical support of ACP researchers and other team members in the management, analysis and manipulation of ACP data. Simon's role has particular focus on Nutrient Management Recording, Soils Survey Data, and other non-time series data sources. Simon also provides a technical support function for GIS users in the ACP team.

Simon has a background in ecological science and postgraduate qualification and experience in remote sensing and geographic information systems. Simon has previously worked as a Remote Sensing and GIS specialist with a number of environmentally focused government agencies and public bodies in the UK. Previous roles have included the provision of analytical support, cartographic services and technical training in the fields of remote sensing and the wider spatial sciences.

Per-Erik Mellander

Role: Catchment Scientist

Per-Erik's role in the team is to investigate temporal, spatial and quantitative linkages between nutrient losses from source through pathways to receptors within the agricultural catchments.
He has a Ph.D. in Environmental Assessment from the Swedish University of Agricultural Sciences, Upssala, Sweden. Since 2008 he is a Research Officer within the project. His research interests are to understand the influences of climate and human impact on ecosystem processes.

Noeleen McDonald

Role: Soil Scientist

Noeleen has been a soil researcher with the ACP since the start of 2014. Her role is to provide the enhanced knowledge of the processes involved in understanding the pivotal linkages between nutrient sources and their availability for transport and loss to water. Noeleen is responsible for overseeing the collection, monitoring and quantifying of nitrogen and phosphorus dynamics on farms within the six catchments. Noeleen's research interests are in nutrient management and soil and nutrient methodologies/techniques, which can offer enhanced understanding of nutrient cycling processes that will provide improved agronomic gains and mitigate against adverse impacts on the environment, especially in the context of water quality and greenhouse gases.

Previous to this role Noeleen completed her PhD as a Teagasc Walsh Fellow with the ACP based in Johnstown castle. This work focused on evaluating soil tests to predict the nitrogen supply in Irish grassland soils. The significance of this research was recognised in 2012, when Noeleen presented this work at the annual Teagasc Walsh Fellowship seminar and subsequently awarded an RDS gold medal. Before her research career, Noeleen worked in the Teagasc advisory service in the Wexford region for two years as a rural environmental protection scheme (REPS) and nitrates derogation planner.

David Ryan

Role: Technologist (Instrumentation)

David commenced work with Teagasc at Johnstown Castle Environment Research Centre in 2006 as a Research Technician working on Ammonia Emissions and Nutrient Efficiency. Prior to this, since graduating from University College Cork, he had worked extensively in the Food Industry throughout Ireland.

As Instrumentation Technologist with the ACP, David is responsible for the management of the water quality data stream and ensuring the efficient running of analytical field equipment across all the sites, monitoring of Laboratory Information Management System (LIMS) and facilitating data quality control.

Dermot Leahy

Role: Technologist (Advisory/Technical)

Dermot started work with the ACP in September 2014 as a Technologist in the Timoleague Catchment in Co. Cork. This role combines the duties of Technician and Advisor where he encourages farmer participation in the programme and delivers an advisory service that helps farmers to fulfil their obligations under the NAP. He is also responsible for data collection, sample collection, equipment monitoring and stakeholder interaction.

Dermot is based in the Agricultural College in Clonakilty. He has previously worked in Tipperary as a REPS planner/Environmental Advisor and with piggeries in the areas of waste management.

Sara Vero

Role: Researcher - Hydrochemistry

Sara joined the ACP in 2017. Prior to this, she completed her degree in Agricultural Science in University College Dublin. Her MSc research developed threshold soil moisture limits for minimising soil compaction during slurry spreading. As a Walsh Fellow with NUI Galway and Teagasc, Sara investigated the time lag of nitrate transport to groundwater and the implications for Water Framework Directive deadlines. Sara graduated with her PhD in 2016 and worked as a post-doctoral researcher in Kansas State University, developing soil/water research on the prairie of central Kansas and teaching graduate and undergraduate hydrology. Sara's role within the ACP is to evaluate the impact of nutrient delivery on waterbodies.

Mick Fleming

Role: Technician

Mick was brought up on a farm in Co. Wicklow and graduated from Limerick Institute of Technology in 2012 with a BSc in Environmental and Natural Resource Management. Prior to joining the ACP, Mick worked with an Environmental consultancy as an Environmental Scientist carrying out contract work for the EPA. He also undertook a range of work including noise, air, dust, vibration and water monitoring for various companies as part of the requirements of their IPPC licence.

Mick joined the ACP in 2015 and is based in Johnstown Castle Co. Wexford. Mick works closely with the research and advisory staff within the ACP team and is responsible for data collection, sample collection, equipment monitoring and maintenance and stakeholder interaction. Mick has a keen interest in Agriculture and water quality and this is what drives him to work in this area.

Una Cullen

Role: Technologist (Data)

Una commenced work with Teagasc at Johnstown Castle Environment Research Centre in 2016 as a Data Technologist. Prior to this, Una worked for a number of years in both I.T. and the environmental sector. Her previous experience ranges from computer programming and analysis to data management. As a Data Analyst in the Environmental sector, she worked on the EDEN (Environmental Data Exchange Network) website used by a number of government departments for the exchange of environmental data.

As a Data Technologist with the ACP, Una's role is to support data management making sure the data collected in the field is available to researchers for manipulation and extraction in a timely manner.

Edward Burgess

Role: Agricultural Adviser

Prior to joining the ACP, Edward worked as an agricultural advisor with Teagasc in Co. Wicklow for 13 years. His initial role was general advisor for cattle, sheep and tillage farmers, based in Tinahely. Following the restructuring of the advisory programme in 2007 he was the Business and Technology advisor for dry-stock (cattle and sheep) farmers in Counties Carlow and Wicklow. In this post he established and facilitated two sheep discussion groups in Co. Wicklow, a Suckler Discussion group in Co. Carlow and a "BETTER" farm on the border of the two counties. (The BETTER programme is a joint research / advisory programme using ten beef farms throughout the country).

Edward's current role is as an Adviser to the farmers in the Castledockrell and Ballycanew catchments. He provides an advisory service to help farmer's compliance with NAP measures and maximize farm profits through improved business management and technical performance and facilitate the research team with data collection. He is also a member of Teagasc's Water Framework Directive Working Group and the EPA's Investigative Assessment Development Group.

Tom O'Connell

Role: Agricultural Adviser

Tom has wide experience in both the private and public sector working in the mushroom, food and pharmaceutical sectors. After joining Teagasc in 2000 he was based at the National Crops Research Centre, Oak Park, Carlow. A graduate in agricultural science from University College, Dublin, he has since gained various qualifications in management and leadership from the Irish Management Institute.

Tom joined the ACP team in 2009 and is based in the Drogheda office covering the Dunleer and Sreenty/Corduff catchments. He provides an advisory service to help farmers' compliance with NAP measures, optimize farm profits and enhance long-term viability through improved business management and technical performance. His role also involves facilitating the research team with data collection and fostering continued farmer involvement in the programme.

Additionally, he is involved in dissemination of information generated by the programme. Communication of ACP findings to catchment farmers is primarily through one-to-one and group events. Outside the catchments, this dissemination is incorporated into Teagasc's advisory and educational programmes via the Knowledge Transfer directorate and linkages with other organisations.

Patricia Lynch

Role: Agricultural Adviser

Prior to working in the ACP, Patricia had worked as an Agricultural Consultant in West Galway for over two years. Previous to that she spent four years working with the National Cattle Breeding Centre, where she helped establish the country's first Dairy Breeding programme. In this position Patricia played a fundamental role in achieving the aim of improving the future genetics of the Dairy Herd.

As an advisor to the farmers in the Cregduff catchment, Patricia works to encourage farmer participation in the programme, offering an advisory service that will help farmers to satisfy their obligations under the NAP as well as boosting profitability on their farm enterprise through improving technical efficiency. She is also responsible for the analysis and data collection from the catchment to facilitate and aid the work of the research team.

John Kennedy

Role: Technician

John was brought up on a farm in county Offaly and graduated from Kildalton College of Horticulture with a Senior Certificate in Commercial Horticulture in 1978. He has worked as a Technician in An Grianan College of Horticulture in Termonfeckin Co. Louth and in Warrenstown College Co. Meath since leaving college. He developed and managed a commercial fruit section at An Grianan and designed, constructed and managed organic fruit, vegetable and herb gardens at Warrenstown. As well as teaching a wide range of skills and modules he was Safety Officer and the Manual Handling Instructor for Warrenstown College.

John is based at Drogheda covering the Dunleer and Sreenty/Corduff catchments. He is responsible for data collection, sample collection, equipment monitoring and stakeholder interaction.

Evgenia (Nenia) Micha

Role: Environmental – Economic Modeller

Evgenia is an agricultural economist with a PhD degree for the University of Reading, UK. Before joining the Catchments Programme she worked for the Teagasc Rural Economy and Development Programme, as a Post-doctoral researcher, focusing on farm sustainability and adoption of innovation. Prior to that, she worked as an assistant lecturer for the Thessaloniki Institute of Technology and as a consultant agronomist in various Mediterranean countries. Her previous research work involved the impact of socio-economic environments on farm systems' management, with particular focus on farmers' decision making processes. Her role in the programme involves modelling and estimating the cost-effectiveness of agri-environmental practices at farm and catchment level, to assess their utility for river pollution mitigation, under the scope of the Water Framework Directive.

Former ACP Staff who worked on Phase 2

Brian O'Connor

Role: Technician

Brian joined the ACP in January 2011. He was based in Johnstown Castle working in the Ballycanew and Castledockerell Catchments. Prior to joining the ACP Brian worked as an Agricultural Consultant; areas of work included Nutrient Management Planning, Field Registration and Research Trial Management and general farm consultancy.

As a Research Technician, Brian was responsible for data collection, sample collection, equipment monitoring and stakeholder interaction. He now works as an Assistant Agricultural Inspector with DAFM.

Oliver Shine

Role: Data Technologist

Oliver originally studied Environmental Science for his undergraduate training and has a post-graduate in both IT and GIS systems. He has several years experience in both IT and environmental data management. His previous experience in IT ranges from website and internet technologies, to database and server management. Within the environmental data sector, he has worked as a biological records database manager and has been the technical lead and consultant on many web based GIS systems. He was previously the technical lead on the Irish Spatial Data Exchange Programme, an intergovernmental spatial data portal, which subsequently won an eGovernment award for excellence in 2009.

Oliver's role within the catchments programme was to support data management and spatial analysis. He now works in an Applications Analyst Role in the Teagasc ICT Department.

Mark Treacy

Role: Technologist (Advisory/Technical)

Mark started work with the ACP in November 2010 as a Technologist in Timoleague, Co. Cork. This role combined the duties of Technician and Advisor and he facilitated the Programme's research in the Timoleague catchment as well as delivering an advisory service to the farmers there. Mark was based in the Agricultural College in Clonakilty. He had worked with Teagasc before as an Agricultural Adviser based in Cork East. His Masters work involved an on-farm study of nutrient management practices on 21 intensive dairy farms in the south of Ireland as part of the Green Dairy Project.

Mark now works as a dairy adviser in the Cork West Regional Management Unit of Teagasc.

Noel Meehan

Role: Agricultural Adviser

Noel comes from a farming background and has worked with Teagasc since May 2007. His initial posting was as a REPS Advisor in Galway.

He commenced work on the ACP in May 2009 as an agricultural advisor for the programme and was based in the Cregduff catchment near Ballinrobe, Co Mayo. In this role he encouraged farmer participation in the programme delivering an advisory service to help farmers to fulfil their obligations under the NAP and improve profitability of their farm enterprise through improved business management and technical performance. He also facilitated and aided the research team with data collection and analysis and disseminated research information to farmers, advisers, students and the general public.

He now works as an Agricultural Adviser in the Galway Regional Management Unit of Teagasc.

Paul Murphy

Role: Soil Scientist

Dr. Paul Murphy is a soil scientist with research interests in soil nutrient and solutions to environmental problems in agricultural and forestry resource management, particularly relating to soil and nutrient management practices, water quality and greenhouse gas emissions.

Paul's role in the ACP was to monitor and quantify nitrogen and phosphorus dynamics on farms in the six agricultural catchments so as to improve our understanding of the linkages between nutrient sources and their availability for transport and loss to water. This deeper understanding of these processes plays a key role in the assessment of the efficacy of the NAP measures. He now works as a lecturer in the UCD School of Agriculture & Food Science.

Cathal Buckley

Role: Economist

Cathal now works as a lecturer in the Institute of Technology Tralee. His research on the ACP focused on nutrient management efficiency among farmers, adoption of nutrient management best practices and provision of environmental public goods related to agriculture. He was associated with the publication of 20 peer reviewed article during his time in the ACP, nine as first author.

Mairead Shore

Role: Former Hydrochemist

Mairead worked with the ACP for nearly 7 years, initially as a PhD student and from 2013-2016 as the team's Hydrochemist. During her time on the ACP, her research primarily focused on understanding the source and transport controls on phosphorus loss from farms to waterbodies, subsequent impacts on stream biota and potential mitigation features (e.g. drainage ditches). Since July 2016, she has been working as an Agricultural Scientist with Wexford County Council where she hopes to improve the water quality in County Wexford by working with farmers to reduce pollution from agricultural sources.

Sarah Mechan

Role: Data Manager

Sarah studied in Dundee where her background was in bioinformatics and data analysis in plant science and conservation. She spent several years working in both the public and private sectors ensuring data integrity and consistency for numerous databases and products including GIS systems.

Her core role in the ACP was to develop and maintain an information management system to ensure the most efficient data capture and integration from multiple sources including data collection via telemetry, surveys, GIS data and imagery. She now works at the Environmental Protection Agency (EPA) as a Strategic Business Analyst identifying opportunities to assist the Agency in getting the most out of critically evaluating their business processes and ensuing IT solutions.

Alice Melland

Role: Hydrogeochemist

Alice Melland hails from Victoria, in south-east Australia, where she completed an Agricultural Science degree and a PhD study of phosphorus in runoff and drainage from grassland. Since then Alice has worked in the research division of the Department of Primary Industries in Victoria where she developed a decision support tool for assessing nutrient loss risk from farms, has applied farm and catchment scale hydrology and nutrient transport models to investigate the influence of farm management on surface water quality and was a hydrogeochemist in the ACP team from 2008-2013. Alice has a strong interest in developing ways to keep nutrients on farms, by identifying fields and times of the year when nutrients are most at risk of leaking and developing solutions to minimise the leakage.

Alice is now a Research Fellow in Soils and Environmental Chemistry at the University of Southern Queensland in Australia where she works in soil nutrient management and water quality research across a range of industries including cotton, dairy, sugar, horticulture (in Cambodia and Lao PDR) and mine rehabilitation. Alice co-supervised three successfully completed ACP PhD students and continues to publish research with these and other ACP colleagues.

Frank Lennon

Role: Technician

Frank comes from a farming background and has 12 years experience in Nutrient Management Planning for farmers throughout a wide area of Ireland and within a wide range of enterprises. He has worked on contract for Industry, REPS planners, and directly for farmers. He joined the programme with enthusiasm that the programme will continue to play an important role in gathering valuable information and providing an invaluable guide to farming with a view to achieving excellent water quality. Frank provided Technical support and gathered information for the programme in the Cregduff Catchment in Ballinrobe.

APPENDIX 3

ACP Agricultural Catchments Programme
AGU American Geophysical Union
ASA American Society of Agronomy
BETTER Business, Environment and Technology through Training Extension and Research
BF Baseflow
BR Bedrock
BSSS British Soil Science Society
cCREW Cold Climate Research in Boreal Watersheds
CELUP Crops, Environment and Land Use Programme
CIG Consultation and Implementation Group
CSSA Crop Science Society of America
DAFM Department of Agriculture, Food and the Marine
DEA Data Envelopment Analysis
DipCon Conference on Diffuse Pollution and Eutrophication
DI-TP Diatom-inferred Total Phosphorus
DMT Data Management Team
DM Data Manager
DRP Dissolved Reactive Phosphorus
EA Environment Agency
EC European Community
EGU European Geosciences Union
EPA Environmental Protection Agency
EQS Environmental Quality Standard
ESG Expert Steering Group
EU European Union
FH2020 FoodHarvest 2020
GAP Good Agricultural Practice
GIS Geographical Information System
GMP Grassland Management Practices
GWD Groundwater Directive
IFS Irish Forest Soils
IFS Interflow
IPW6 6th International Workshop on Phosphorus
IT Information Technology
IUSS International Union of Soil Sciences
IWA International Water Association
KT Knowledge Transfer

ACRONYMS

LiDAR	Light Detection and Ranging
LPIS	Land Parcel Information System
MAC	Maximum Acceptable Concentration
MRP	Molybdate Reactive Phosphorus
MS	Member States
N	Nitrogen
NAP	National Action Programme
ND	Nitrates Directive
NFS	National Farm Survey
NUI	National University of Ireland
P	Phosphorus
PM	Programme Manager
PS	Principal Scientist
QC	Quality Control
QF	Quick Flow
RBDMS	River Basin District Management Systems
REPS	Rural Environment Protection Scheme
RHAT	River Hydromorphological Assessment Technique
RTE	Radio Telefís Eireann
SEMRU	Socio-Economic Marine Research Unit
SI	Statutory Instrument
SS	Subsoil
SSRS	Small Stream Risk Score
SSSA	Soil Science Society of America
SSSI	Soil Science Society of Ireland
STP	Soil Test Phosphorus
TL	Task Leader
TON	Total Oxidised Nitrogen
TP	Total Phosphorus
TRP	Total Reactive Phosphorus
UK	United Kingdom
WFD	Water Framework Directive
WTI	Willing To Import