CENTRE OF EXPERTISE FOR WATERS

A state of knowledge overview of identified pathways of diffuse pollutants to the water environment

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Cover photographs: (Tramlines, soil erosion and sward lifter) courtesy of: Joanna Cloy and Nikki Baggaley

Glossary of terms

The following definitions apply in this review:

Compacted soils	Soils with compressed pores, poor infiltration properties and more closely packed soil particles.
Controlled Traffic Farming (CTF)	A whole farm approach to the separation of crops and wheelings; it is a system that avoids extensive soil damage and costs. Soil in the intervening areas is managed to provide the most favourable conditions for crop performance uncompromised by traffic and associated compaction.
Drain-flow	The flow of water (and, potentially, soluble pollutants and small particles) into an artificial subsurface drainage network (e.g., pipes) connected to surface water.
Field capacity	Water held in the soil after excess water has drained away.
Hotspots	Areas of land with specific land management features (e.g., feeding troughs, gateways) that result in the application and concentration of pollutants that can be rapidly released in association with runoff or drainage.
Leaching	The flow or infiltration of water and soluble and insoluble pollutants down the soil profile into groundwater and loss through drains.
Soil structure	The aggregation of soil particles (sand, silt, clay and organic matter) into granules, crumbs or blocks.
Tramlines	Undrilled unvegetated wheeled rows in cereal fields that over time can progressively become compacted.
Wheelings	Gaps or tracks in the crop or field repeatedly used for mechanical traffic.

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Research questions

The overall aim of the project is to provide a state of knowledge overview on pathways of diffuse pollution from agriculture to the water environment and to produce Knowledge Exchange (KE) products that will help address these issues. This report addresses the former, answering questions posed around scale and extent, solutions, costs, impacts and gaps in knowledge and these will help inform the KE products.

Background

The River Basin Management Plans for the Scotland and the Solway Tweed river basin districts set out Scotland's ambition to improve from 62% of waterbodies in Scotland at good status to 88% by 2027, and 93% in the longer term. Tackling rural diffuse pollution is key to achieving these aims. The primary focus of Scotland's strategy to tackling diffuse pollution is centred on achieving compliance with the diffuse pollution General Binding Rules, Nitrate Vulnerable Zones, promoting good practice and encouraging uptake of additional measures through funding schemes such as the Scotland Rural Development Programme. While this effort has significantly improved compliance and good practice, it will not be sufficient to achieve good status in all catchments. We therefore need to better understand where the gaps are, particularly regarding important pathways i.e., how pollutants are transferred from land to water and what practical measures are required to help fill these gaps to help Scotland achieve water quality objectives.

Research undertaken

Focussing on the pollutants phosphorus (P) and nitrogen (N), a systematic review of existing information and evidence was undertaken of the current scientific understanding of runoff and erosion diffuse pollution pathways. The following pathways of diffuse pollution were investigated: i) **surface runoff and soil erosion, exacerbated by soil compaction and structural degradation** ii) **tramlines**, iii) **leaching,** iv) **drain-flow** and v) **hotspots**. Gathering evidence for each of these pathways, the following areas were investigated: a) **scale and extent of the problem**, b) **practical preventative measures** and **solutions to prevent or minimise losses of potential pollutants**, c) **costs associated with identified preventative measures and solutions**, d) **impacts on water quality if solutions were put in place** and e) **knowledge gaps and recommendations for future research**. Also included is a review of evidence of the use of Visual Evaluation of Soil Structure (VESS) scores for assessing drivers of diffuse pollution under different scenarios. This report summarises the overall findings from relevant applied scientific literature, practical guidance publications that are available to farmers and other appropriate supporting evidence.

Key findings

- Agricultural diffuse pollution into water bodies is a significant environmental issue.
- Good soil nutrient management such as the use of a fertiliser plan linked to soil sampling for nutrient status and soil pH is important.
- Standard agricultural practices are the main source of N and P pollution rather than poor nutrient management practices in Scotland.
- Surface runoff and erosion are the principal source of P loss in cultivated, drier soils while P loss through drains is the dominant pathway in improved grasslands on wetter soils.

Pathways of diffuse pollution:

- Soil type, climate, landscape characteristics and land management contribute to diffuse N and P water pollution.
- Arable soils in England showed that tramlines represented the dominant pathway for surface runoff and transport of sediment, N and P from cereal crops. This is also likely to be the case for Scotland.
- Drains provide a pathway for the delivery of sediment and N and P to surface waters but the dominant pathway of diffuse pollution is through erosion and sediment transport. This erosion and sediment transport is increased and exacerbated by damage to soil structure.
- One of the key causes of poor soil structure is compaction caused by trafficking along tramlines, therefore structural degradation and tramlines contribute to losses of N and P from Scottish agricultural soils.
- Reducing traffic when the soil is close to field capacity (i.e., water held in the soil after excess water has drained away) would reduce the potential for compaction, this can be achieved by considering the timing of operations.
- Use of controlled traffic farming (CTF) has been shown to improve 'untrafficked' soil structure and water movement and storage in Scotland but tramlines (which are necessary for CTF) are a dominant pathway of diffuse pollution.

- Alleviation of topsoil and subsoil compaction is recommended, with ploughing for arable crops as well as amendment of the soil through increased organic matter, tied ridging with potatoes and surface spiking and sward lifting in grasslands.
- Alleviation of subsoil compaction is more costly and difficult.
- Reduction of tramlines and aligning them across the slope, reduced or no tillage, spreading machinery loads as evenly as possible over a larger tyre diameter, use of correctly inflated very flexible tyres, delaying of tramline establishment and use of buffer strips (including novel 3D buffers) all can reduce the effect of tramlines on pollutant and sediment transport.
- The use of either very flexible tyres, or tramline disruption using a spiked harrow, has been shown to significantly decrease losses of sediment, N and P from Scottish soils under winter sown combinable crops.
- Up and down tramlines were shown to increase surface runoff from Scottish soils by around 50% compared to untrafficked or ploughed areas.
- Improvements in water quality were shown for a range of vulnerable English soils after the use of the following mitigation options: tramline disruption, minimum tillage, crop residue incorporation, contour cultivation and beetle banks.
- Conservation tillage systems are beneficial to soil and water quality but choice of tillage system should be flexible depending on specific conditions such as soil surface and structural conditions before crop establishment, preceding crop and amount and decomposition status of plant residues.
- The use of rotations, cover crops and CTF offer opportunities to realize the full benefits of no-till.
- Reducing the source of nutrient loss by employing nutrient management plans, growing suitable crops for the soil type, retention of stubble, contour farming and controlling the out-flow of field drains before they reach a water course need to be considered.
- Use of Nitrate Vulnerable Zones, control of cultivation and animal movements close to water courses help control N leaching but further research is needed to address P leaching.

Relative contribution and spatial distribution:

- An index of land use intensity (LUI) was developed to identify the spatial distribution of management and cultivation practices to assess management impacts on diffuse pollution risk.
- P loss due to runoff and soil erosion across Scotland has been estimated for combined soil erosion and LUI classes.
- P leaching to drains was greater than P loss due to runoff and soil erosion for 55% of agricultural land likely to have been drained.
- P leaching to drains was the most important pathway of P diffuse pollution in permanent grasslands (74% of total grassland area), but runoff and soil erosion contributed more to P diffuse pollution in 84% of the area covered by root vegetables.
- For P loss from arable land with cereals, relative pathway importance was slightly greater for runoff and soil erosion than for leaching to drains.
- Use of Visual Evaluation of Soil Structure (VESS) - topsoil VESS and subsoil subVESS tools can be used to assess the structural damage of soils and their susceptibility to erosion and nutrient loss.
- Agreement between VESS assessments and compaction risk mapping in Scotland.
- VESS and subVESS scores of 3 need to be monitored to ensure no further deterioration of soil structure.
- VESS and subVESS scores of 4 and 5 require direct intervention to restore soil structure and prevent potential erosion or nutrient losses.
- Greater topsoil physical degradation after harvest of potatoes and carrots.

Recommendations and knowledge gaps

- This review highlighted that effective land drainage and nutrient management is a fundamental part of modern agriculture but currently evidence of the relationships between specific Scottish agricultural drainage systems that contribute to diffuse pollution as well as the location, condition, functioning and flow volumes of these artificial drain systems is limited.
- More research is needed across all pathways. There are also many other knowledge gaps, particularly being able to identify diffuse pollution 'hot spots' in fields within Scottish catchments and our understanding of the impacts of recommended mitigation measures on water quality (as well as gathering more evidence linking VESS scores with water quality degradation).
- There is still uncertainty in erosion rates for soil and land use combinations, in particular, the erosion rate for grasslands is likely to be overestimated.
- It is recommended that future research efforts focus on gathering further evidence for the effectiveness

of practical diffuse pollution mitigation measures. All measures that have been investigated provide reduced diffuse pollution benefits with cost of implementation being the only potential drawback. More novel measures such as improved drainage design, alternative tramline and wheelings management options and 3D buffer strips should be tested further.

- Further research should be directed towards understanding and comparing the proportion of diffuse pollutants attributed to leaching, soil and particle erosion and surface runoff, particularly connectivity between source and waterbody.
- This review has found that all mitigation measures researched offer reductions in diffuse pollution. Overall, encouraging more farmers and land managers to use recommended practical mitigation measures identified here (focussing on pathways identified as being most important) is essential and indeed this is one of the next tasks within this CREW-funded diffuse pollution project.
- Based on this review, there is insufficient research or scientific understanding of mitigation measures such as compaction remediation, tramline and wheelings management, drainage management and treatment methods to definitively identify the methods that would have a cost effective or environmentally positive impact in **all situations and all Scottish soil types and climate**. However, useful UK-relevant research that has been conducted, such as detailed field investigations in England, appears to show that the measures outlined in this report can make a difference.
- Many of the most cost effective and high-level reduction practical measures identified are already included in environmental legislation (i.e., 2 m safe working distance from waterways, fertiliser application timings) but additional measures such as compaction remediation, tramline and wheelings management, drainage design/management and treatment methods need to be promoted more widely in the future to help meet water quality targets.

Introduction

Background and scope

The River Basin Management Plans for the Scotland and the Solway Tweed river basin districts set out Scotland's ambition to improve from 62% of waterbodies in Scotland at good status to 88% by 2027, and 93% in the longer term. Tackling rural diffuse pollution (the single greatest pollution pressure) is key to achieving these aims. The primary focus of Scotland's strategy to tackling diffuse pollution is centred on achieving compliance with the diffuse pollution General Binding Rules, Nitrate Vulnerable Zones, promoting good practice and encouraging uptake of additional measures through funding schemes such as the Scotland Rural Development Programme. While this effort has significantly improved compliance and good practice it is unlikely to be sufficient to achieve good status in all catchments. Therefore, there is a need to better understand where the knowledge gaps are, particularly regarding important pathways i.e., how pollutants are transferred from land to water, which areas are likely to be most affected and what practical measures are required to help fill these gaps to help Scotland achieve its water quality objectives.

Project objectives

The project set out to provide a state of knowledge overview for each identified pathway of diffuse pollutants to the water environment; runoff and erosion caused by compaction/soil structural degradation, tramlines, drain-flow, leaching and other pathways including hotspots such as field gates) to include:

- **Scale**: What do we know about the scale and extent of the problem? What is the relative contribution from each pathway and how does that vary spatially? Are there any areas or soil/climate/land use scenarios that are likely to be a particular problem?
- **Solutions**: What measures are required to address (prevent where possible and minimise) pollutant movement via each of the pathways? What is known about the efficacy of different measures? Are there any new practical measures with evidence that we can put in place?
- **Costs**: What are the best estimated costs associated with the solutions/options (including costs to the farm business of not implementing them)?
- **Impact**: Where possible, assess the likely impact on water quality if solutions were put in place?
- **Gaps**: What are the gaps in knowledge that are preventing implementation of measures to better manage diffuse pollution pathways?

Outline of the report

The report focuses on the potential pollutants, phosphorus (P) and nitrogen (N) with a systematic review of existing information and evidence of the current scientific understanding of the role of runoff and erosion as diffuse pollution pathways. The report summarises the overall findings from relevant applied scientific literature, practical guidance publications that are available to farmers and other relevant, supporting evidence and uses current understanding to assess the areas most likely to contribute to diffuse pollution in Scottish surface waters and to model the relative contributions of surface runoff and drain-flow to diffuse pollution.

The report is structured in terms of the pathways of diffuse pollution that were investigated: i) **soil erosion exacerbated by soil compaction and structural degradation using land use intensity as a proxy indicator**, ii) the role of **tramlines**, iii) **leaching,** iv) **drain-flow** and v) **hotspots**. Within each of these pathways, there are subsections on: a) scale of the problem (extent and magnitude), b) practical preventative measures and solutions to prevent or minimise pollutants, c) costs associated with identified preventative measures and solutions, d) impacts on water quality if solutions were put in place and e) knowledge gaps and recommendations for future research.

Background, policy and previous studies

Agricultural diffuse pollution into water bodies is a significant environmental issue in many countries across the world (FAO, 2017). Eutrophication due to nutrients such as phosphorus (P) and nitrogen (N), the pollutants of interest in this review, reduces drinking water quality, affects the use of water for industry and recreational purposes (Withers & Haygarth, 2007) and impacts negatively on the aquatic environment. In Scotland, the primary strategy for tackling diffuse pollution from agriculturally derived nutrients is centred on achieving compliance with the diffuse pollution General Binding Rules, Nitrate Vulnerable Zones and promoting good practice. The 'Prevention of Environmental Pollution from Agricultural Activity' (PEPFAA) code is an example of advice that is given to farmers to help with compliance with legal and statutory requirements. However, more recent advice is available from Farming and Water Scotland (www.farmingandwaterscotland.org) that concentrates not only not diffuse pollution but also the benefits from reduction.

The contribution of nutrients to water bodies from arable inputs is widely known. Zhang et al. (2014) suggested that agriculture was responsible for 72% of sediment, 31% of phosphorus (P) and 81% of nitrogen (N) incidences of non-compliance with drinking water standards in the UK. Recent research demonstrates significant potential inputs from lowland grasslands in southern England that are intensively managed for livestock production (Peukert et al., 2014). In Scotland, there are many studies showing agriculture as a major contributor to pollutants (Dawson et al., 2012; Ball et al., 2005; Crooks et al., 2012). It is widely recognised that soil and land management in agriculture can be important factors contributing to the pathways of diffuse pollution to the water environment. Appendix 1 describes some of these drivers of diffuse pollution in more detail.

Key pollutants

The crop nutrient requirement and the application, rate, timing, type and incorporation of nutrients to agricultural soils are important considerations to make in a farm nutrient management plan. Nutrients are mainly applied as commercial inorganic fertiliser, liming materials, organic manures and slurries or other waste derived organic materials such anaerobic digestates or composts. Nutrients are the main focus of this review but agricultural pollutants from all fertiliser sources are not limited to nutrients and other contaminants which should be noted include: suspended sediments (particulate and colloidal soil material); organic wastes (manure, slurry and non-farm materials); ionic salts; pathogens (E. coli and coliforms); potentially toxic elements (e.g., lead); low levels of pesticides, as well as emerging environmental contaminants such as drug residues, hormones and feed additives (FAO, 2017). There are regulations relating to the use of sewage sludge as a fertiliser in agriculture (Sewage Sludge (Use in Agriculture) Regulations (1989)) which include limitations on the concentration of heavy metals and contaminants applied to agricultural land.

Some other organic materials can be applied to land provided this is carried out in accordance with the Waste Management Licensing Regulations 2011. Detailed guidance on this is provided on SEPA's website (https://www.sepa.org.uk/regulations/waste/activities-exempt-from-waste-management-licensing/). It is important for farmers to ensure that the application rate, timing and method of spreading nutrients are appropriate to the weather conditions along with the requirements of the crop being grown and the land conditions at the time of application, in order to comply with legal requirements, particularly relating to nutrient (N and P) management.

Nutrient pollution

Catt et al. (1998) suggested that surface runoff and erosion represent the principal mechanism for P loss, accounting for 90% of the P transported from arable land in the UK. Nitrogen and P pollutants may be dissolved within runoff water or be adsorbed onto particulates washed from the land (D'Arcy and Frost, 2001).

Agricultural soils are highly susceptible to diffuse P loss when soil P levels have accumulated in excess of crop needs. The widespread use of fertilisers, particularly since the 1950s, has increased the soil-P status of Scottish agricultural land from very low levels to generally medium and high levels (SRUC TN668, 2015). A certain critical optimal soil P level is necessary for economically viable crop production, but above this level, there is little increase in yield and the risks of environmental loss rise. Further increase in soil-P status is not economically or environmentally sustainable and therefore sustainable agriculture requires fertilisation strategies that give profitable production but minimise adverse environmental effects (Dils et al., 2001). In addition, nutrients should not be applied in excess of crop requirements in order to remain compliant with the Scottish regulations.

Small scale experiments found that the concentration of P in overland flow from soluble P fertiliser (single superphosphate) treatments was significantly greater than that of slow-release P fertiliser (direct application rock phosphate) for approximately 60 d following fertilizer application (Hart et al., 2004). Similarly, Brannan et al. (2000) suggest that manure management plans can reduce particulate P and dissolved P concentration losses to watercourses by 78% and 39%, respectively.

Fertiliser plans

The use of a fertiliser plan in conjunction to soil testing on farm should ensure a suitable use of fertilisers, applied at the time of year most beneficial to the growing crop. Decision support tools, such as, PLANET (Planning Land Applications of Nutrients for Efficiency and the environmenT) are available for field level nutrient planning and especially for assessing and demonstrating compliance with the Nitrate Vulnerable Zone (NVZ) rules. This should include the application of lime to the soil, as pH can have a major influence on the movement of soil nutrients. Studies in Republic of Ireland (Buckley and Carney, 2013) have shown an average over application of N of between 22.8 to 32.8 kg N ha^{-1} and of P, 2.9 to 3.5 kg P ha^{-1}, this would have equated to £32.5 ha^{-1} to £40.5 ha^{-1} savings (based on 2012 prices). Whole farm assessments of cost of a variety of mitigation methods including alternative fertiliser use have been investigated using models for the different components of P loss (Cuttle et al., 2016) and were used in the FARMSCOPER decision tool (Gooday et al., 2014; ADAS, 2015, see Appendix 4 for further information).

Without the implementation of a fertiliser plan, especially one that is linked to soil sampling for nutrient status, the temptation is to continue with the levels of fertiliser use that has always been employed. This ignores any evidence of overuse by not knowing the status of the soils and the amount the current crop is taking off. Adding P fertiliser to soils that already have a status of greater than M+ (moderately high P status) is wasteful and can result in surface runoff (SRUC TN668, 2015). Reducing fertiliser costs would provide economic benefit for the farmer without using the wider environment as a sink.

A study commissioned by SEPA assessed the soil test P (STP) status, derived using the Modified Morgan's extraction, in agricultural soils across two priority catchments in Scotland (Crooks, 2018). The study found that the STP in the majority of fields in both catchments was either at or below recommended levels. The report concluded that if soil mediated sources of P arising from agriculture are identified as pollution sources, standard agricultural management practices rather than poor nutrient management are the most likely causes of this pollution. Based on the results from Crooks (2018), Edwards et al. (2016) conducted a review of STP soil analyses results gathered by the Analytical Services Department of Scotland's Rural College from 1993 to 2010 which consisted of more than 180,000 samples split across four regions of Scotland. The purpose was to evaluate regional and spatial trends in STP and soil pH results and compare these to annual British Fertiliser Survey results. They argue that STP had changed little between 1993 and 2010 despite a national trend of decline in rates of fertiliser P usage and suggest this may be due to a lag effect caused by soil P storage after P application, and that P is released back in a soluble form slowly over time. They also showed important regional and temporal variations in soil pH status (which is important for efficient P usage), and variations in STP in relation to crop type and rotation (Crooks, 2018; Edwards et al., 2016). Low soil pH can lead to the accumulation of fertiliser P and associated contaminants (As, Cd and U) in the topsoil at lower pH values (< pH 5.5) and enhance the re-distribution of total, extractable and labile forms of P from the topsoil to subsoil (where it will accumulate) between pH 6.0 and 7.0 (Dolan, 2019).

A second study commissioned by SEPA established a link between soil P dynamics and soil characteristics that can be mapped (Sinclair et al., 2013). This was used as an advisory tool to identify those soils in Scotland that required specialised management to ensure that P is used efficiently and does not pose an enhanced risk to water quality. This was used to adjust Scotland's fertiliser management advice based on soil types and the P sorption capacity (PSC) of the soil series (SRUC TN668, 2015).

Introduction summary

- **Agricultural diffuse pollution into water bodies is a significant environmental issue.**
- **The main pollutants considered in this review are sediment, Nitrogen (N) and Phosphorus (P).**
- **Good soil nutrient management such as the use of a fertiliser plan linked to soil sampling for nutrient status and soil pH is important.**
- **Standard agricultural practices are the main source of the pollution rather than poor nutrient management practices in Scotland.**

Pathways of diffuse pollution

It is widely recognised that soil type, landscape characteristics and land management can be important factors contributing to diffuse water pollution. While soil erosion is part of a natural cycle where soil particles are redistributed in the landscape by wind or water, it can be exacerbated by modern land management systems such as; the use of controlled traffic methods (tramlines) or where heavy machinery and livestock causes compaction thereby reducing the infiltration rate of rainfall and leading to greater runoff, which can entrain soil particles causing rill and gully erosion. If these soil particles reach a water course, they can cause damage to the aquatic ecosystem through siltation and delivery of potential pollutants such as P. Measurements on arable soils in England showed that tramlines represented the dominant pathway for surface runoff and transport of sediment, P and N from cereal crops with between 9 and 27% greater runoff from tramlines compared to land with no tramlines and carrying around 25 times more sediment (Silgram et al., 2010). This demonstrates that there is a close association between increased erosion, runoff and sediment transport and land management.

In many parts of Scotland, agricultural production depends on efficient artificial under-drainage, however, these drains can also provide a pathway for the delivery of sediment and nutrients (P and nitrate) to surface waters. Gooday et al. (2016) used an agricultural modelling framework to apportion pollutant emissions by delivery pathway for the UK. This modelling indicated that soil surface runoff and erosion pathways were particularly important for P, accounting for 74% in comparison to 41% for N in the form of nitrate (NO_3^-), where leaching processes are dominant. For P, the contributions from surface runoff and drain-flow pathways were 44% and 48%, respectively, with only a small amount due to leaching. Surface runoff was the dominant pathway for sediment transport (56%) followed by drain-flow and no losses due to leaching.

While soil compaction and structural degradation, either through the use of controlled traffic measures (tramlines) or through trafficking by heavy vehicles, can exacerbate the transport of pollutants to water ways through increased runoff and erosion, tramlines can be viewed as a specific pathway with specific costs and measures of alleviation and are reviewed separately within this report. The dominant pathway of diffuse pollution due to structural damage and trafficking is through increased erosion and sediment transport. Hallett et al. (2016) reported that runoff, erosion and nutrient losses were about ten times greater from soil structurally damaged parts of fields than within the fields or field margins (but tramlines were not specifically investigated).

Soil compaction and structural degradation

Soil structure is the aggregation of soil particles (sand, silt, clay and organic matter) into granules, crumbs or blocks and soil compaction is the physical degradation of this soil structure where the soil becomes denser with compressed pores and poor infiltration properties which can lead to increased runoff, erosion and waterlogging. Waterlogging can also lead to a reduction in soil physical strength and a breakdown of soil structure, further damaging the soil. Soil compaction has become increasingly common in agricultural systems, including forest silvo-culture (Ishaq et al., 2001; Nawaz et al., 2013). Soil compaction depends on the pressure applied through the weight of the machinery and the soil strength which is influenced by the texture, structure, organic matter content and water content. The wetter the soil and closer to field capacity, the greater the potential for compaction (Batey, 2009). Passes over the agricultural field of heavy machinery can cause increased compaction with every pass depending on the soil conditions, however, the initial pass or passes can cause the largest component of the damage (Bakker and Davis 1995; Hargreaves et al., 2019a; Koch et al., 2008).

While topsoil compaction can often be readily remedied through ploughing and growing of specific crops, subsoil compaction below the depth of ploughing often remains unseen and is more difficult to repair, however, it should be noted that many Scottish soils have naturally compacted subsoils which means they naturally have a greater risk of runoff and erosion. The soils at greatest risk of becoming compacted in the subsoil are those currently with porous soil structures that are exposed to heavy machinery or livestock. All soils have varying degrees of risk of compaction in the topsoil depending on soil wetness and amount of sand, silt or clay, however, organic matter in the soil also influences the water infiltration and moisture holding capacity as well as retaining soil structure, which can help reduce the susceptibility of soils to compaction.

• Key pollutants

Soil compaction and structural degradation themselves do not provide pathways for pollutants to move from land to surface waters, instead a compacted or damaged soil makes the transport of sediment and sediment-bound nutrients, pathogens and organic wastes more likely through increased runoff and/or increased erosion.

• Scale and extent of the problem

There are no national statistics on the amount of nutrient losses associated with structural degradation or the scale of the problem.

In 2016, Hallett et al. published a report of a systematic study of the structural condition of soils in 120 fields in four Scottish catchments (Ugie, South Esk, East Pow and Coyle). The catchments were selected to encompass a range of soils and land management practices (intensive arable, mixed farming and livestock production). The structure was assessed using a visual assessment technique (Visual Evaluation of Soil Structure (VESS)) (Ball et al., 2007 and 2015) which classifies topsoils (VESS) and subsoils (SubVESS) into one of five categories from good to poor. They found severe structural degradation in 18% of the topsoils sampled in 831 locations across the four catchments and 9% of subsoils.

Hallett et al. (2016) also found that nutrient losses (N and P) were about 10 times greater from areas with structurally degraded topsoils and from tramlines than either within field topsoils or from less trafficked field margins. As these results were from only six arable fields in two catchments, it is difficult to extrapolate these results more widely.

In a report to ClimateXChange, Lilly et al. (2018) stated that '*although there has been no systematic, wide-scale survey of the physical condition of Scottish soils, some useful evidence does exist*'. They cited work done for the National Soil Inventory of Scotland (NSIS) 2007-9 resampling (Lilly et al., 2012) and the East of Scotland Farm Survey (Baggaley et al., 2017), that, when combined, these datasets suggested 35% of the soils sampled had porosities below the level suitable for good root development leaving the crop vulnerable to drought stress and the land susceptible to increased runoff and erosion.

From the same report, Lilly et al. (2018) reported that there have been attempts to identify those soils susceptible to compaction, for example, Ball et al. (2000) and Soane et al. (1972). However, this does not represent an actual measure of compaction which remains lacking for much of the country.

In 2014, Lilly and Baggaley produced maps of the vulnerability of Scottish soils to topsoil and subsoil compaction. Again, like Ball et al. (2000) and Soane et al. (1972) these maps only allow an assessment of the potential extent of structural degradation in Scotland rather than the actual amount. The topsoil compaction risk maps for mineral soils were based on soil texture and inherent drainage class while the subsoil compaction made use of soil texture, packing density and climatic data. Table 1 shows the area covered by each risk class (low to high for mineral soils) and Figure 1 shows the distribution of the vulnerability of soil compaction in Scottish soils based on the phase 6 release of the soil map of Scotland (partial cover) (Soil Survey of Scotland Staff, 1970-1987). Note that the distribution of organic soils is shown but the topsoil compaction risk is for mineral soils only. This map shows that around 25% of the cultivated land in Scotland is at high risk of topsoil compaction which could exacerbate runoff of nutrients and sediment from land to waters.

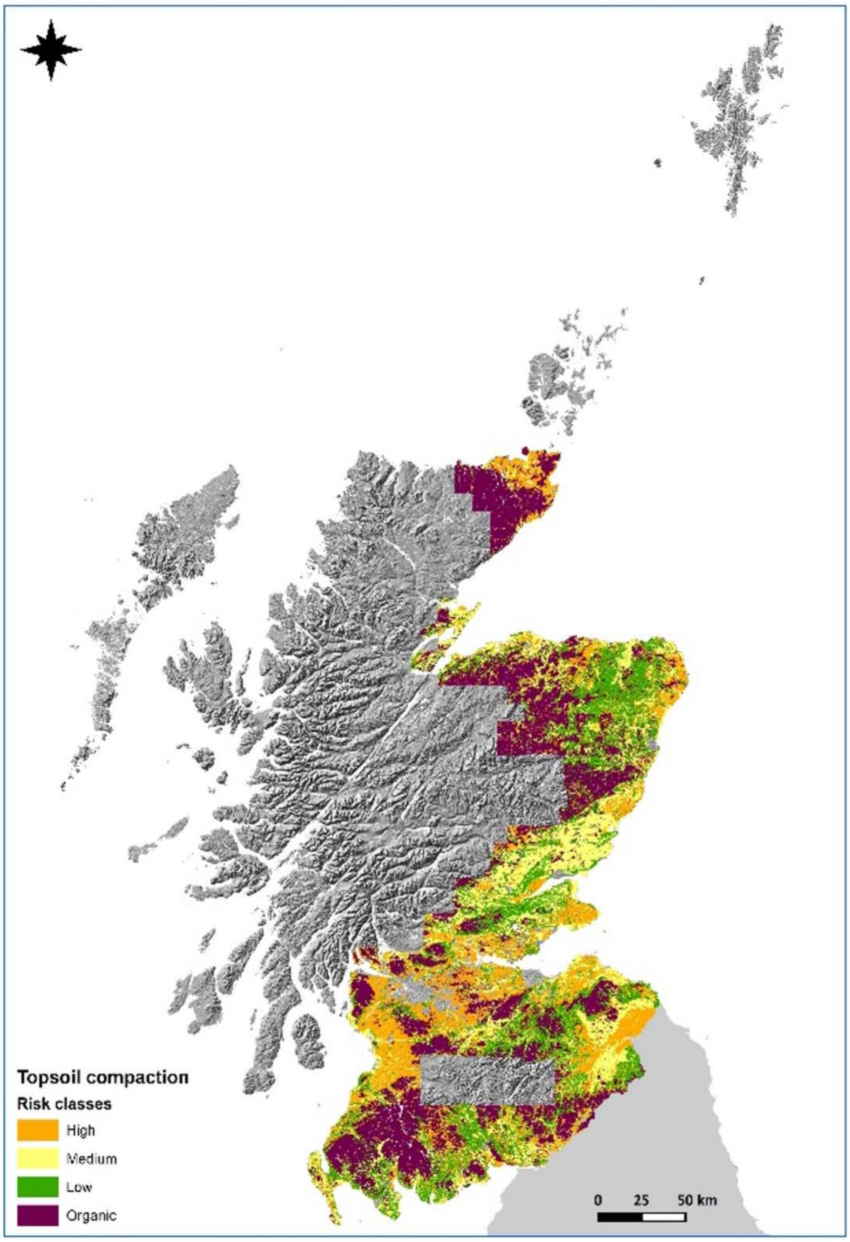


Figure 1. Map showing the distribution of compaction risk classes for mineral topsoils based on phase 6 of the soil map of Scotland (partial cover). Soils with organic surface horizons were not allocated to a risk class.

Table 1. The extent and proportion of land in each topsoil compaction risk class based on phase 6 of the soil map of Scotland (partial cover).		
Risk class	**Extent and proportion of land in each topsoil compaction risk class**	
	Area (km²)	*Area (%)
Low	6940	20
Medium	7160	21
High	8040	23
Organic topsoil‡	10490	31
Non-soil	1684	5

* Area as a proportion of phase 6 soil map of Scotland (partial cover);

‡ Soils with organic topsoils were not allocated to a topsoil compaction risk class.

However, the overall risk of topsoil becoming compacted depends both on its inherent susceptibility and the land use. Therefore, the topsoil compaction risk was adjusted by land use whereby, the proportion of grass to crop and the proportion of cereals to root crops over a 9-year period (2007-15) for which data were available (see Appendix 2).

Of the soils that are highly vulnerable or moderately vulnerable to topsoil compaction, 3214 km^2 and 1979 km^2 of these soils, respectively, are under low intensity, grassland systems, thereby reducing the likelihood of compaction. Around 372 km^2 of the land that is highly vulnerable to topsoil compaction has root crops in the rotation and an additional 1062 km^2 of land that is moderately vulnerable to topsoil compaction also has root crops in rotation making this land more susceptible to compaction.

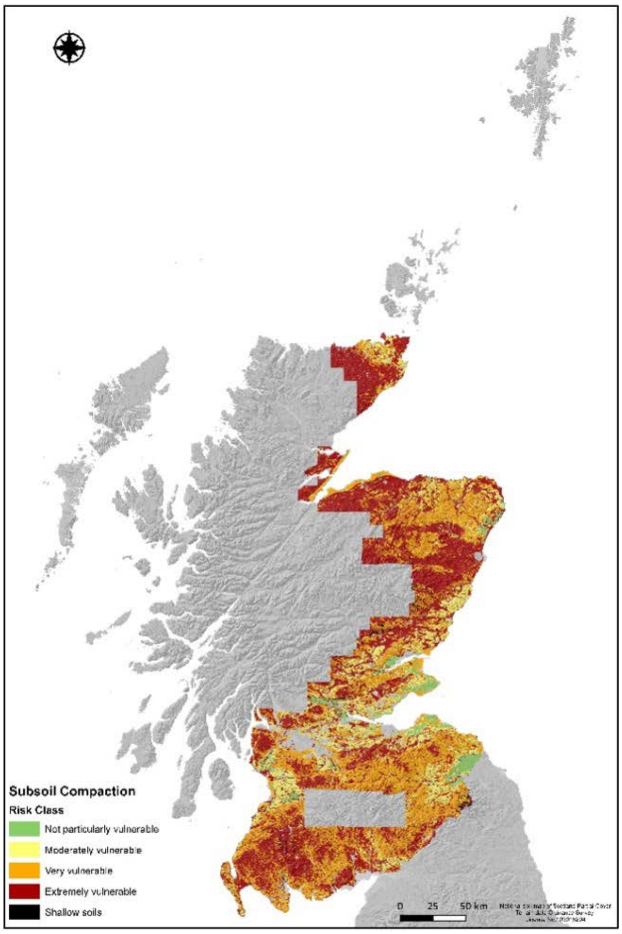
An important consideration in assessing the scale of the potential problems with subsoil compaction risk is that many of Scotland's soils have naturally compact subsoil. These soils will generally be classified as having low to moderate vulnerability as they are unlikely to be further compacted. Due to the slowly permeable nature of the subsoil, these soils generally have imperfect to poor natural drainage and, where cultivated, will normally have artificial drainage installed. The contribution of these soils to diffuse pollution is considered later in terms of drain-flow and erosion risk. The soils are widespread, and the compact subsoils extend to depth so there is little opportunity for ameliorating the compact subsoil. Figure 2 (below) shows the distribution of subsoil compaction risk (left), the subsoil compaction risk where the soils with naturally compacted subsoils have been masked out on the right (grey areas). The land classified as extremely vulnerable are largely organic soils. The soils most at risk of subsoil compaction are to be found in the Southern uplands, the North-east of Scotland and the north east part of the Midland Valley.

Table 2 shows the area of land in the various subsoil vulnerability classes. Around 80% of the land is shown as being very or extremely vulnerable with 14629 km^2 classed as extremely vulnerable (although approximately 400 km^2 of this are soils with an organic surface layer).

Table 2. Area and proportion of land in each of the subsoil vulnerability classes, based on phase 6 of the soil map of Scotland (partial cover).			
Subsoil vulnerability	**Area and proportion of land in subsoil vulnerability classes**		
	Area (km²)	Area (%)	Area (km²) of naturally compact subsoil
Not vulnerable	1112	3	1020
Moderately vulnerable	4801	14	2782
Very vulnerable	11921	35	1812
Extremely vulnerable	*14629	43	93
Shallow soils	170	1	-
Non soil	1682	5	-

*includes 400 km^2 of soils with organic surface layers.

Although these maps show the vulnerability of soils to compaction, they do not show the extent of any damage. They can, however, be used to target monitoring and mitigation strategies to those areas most at risk. The maps are available on Scotland's soils website (https://soils.environment.gov.scot/) where a user can zoom in to view the risk class at a field scale.



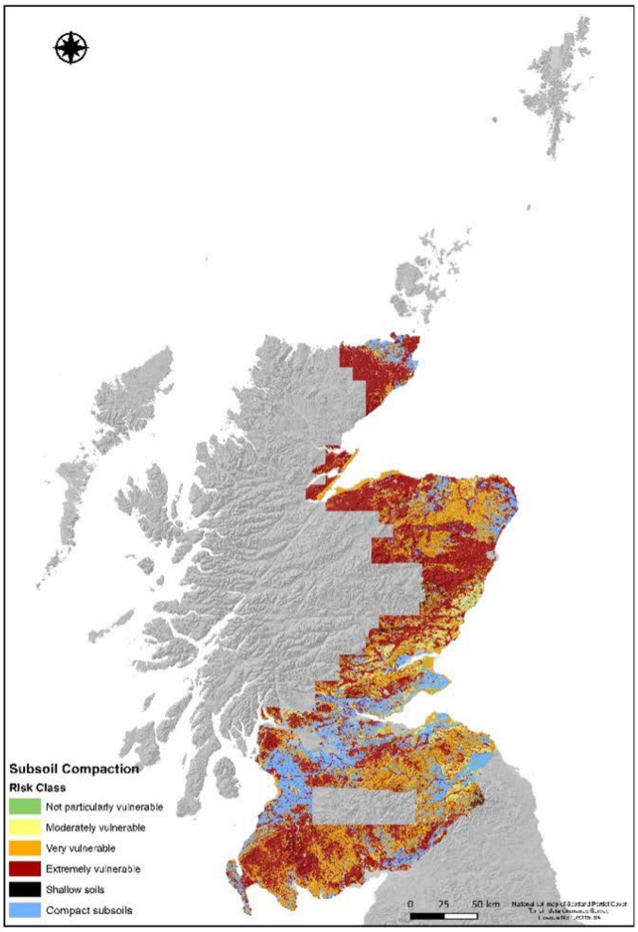


Figure 2. Map (left) showing the distribution of subsoil compaction risk classes based on phase 6 of the soil map of Scotland (partial cover). Map (right) shows the distribution of subsoil compaction risk classes based on Phase 6 of the soil map of Scotland (partial cover) with areas of soils with naturally occurring compacted layers masked out in blue and urban areas masked out in grey. © Crown copyright and database right (2020). All rights reserved. The James Hutton Institute, Ordnance Survey Licence Number 100019294.

• Practical preventative measures and solutions to prevent or minimise structural degradation

Practical measures to reduce soil structural degradation to minimise pollutant transport from land to waters include:

1. Reduced traffic in wet conditions and timing of cultivation. Restricting traffic to when the soil is close to or drier than field capacity would reduce the potential for compaction.
2. Maintain soil drains to reduce the number of days the soil exceeds field capacity.
3. Controlled traffic farming (CTF). However, while Controlled traffic measures that keeps vehicles to the same pre-set areas of a field has been shown to improve soil structure of the surrounding soil, the 'tramlines' can be sites where gullying is initiated during rainstorms or rapid snow melt.
4. Tramline disruption to help improve infiltration.
5. Reduce vehicle size and/or tyre pressure.
6. Reduced tillage or no tillage to limit movement of traffic across the field.
7. Increase tramline spacing.
8. Alleviation of compaction. Ploughing after the crop has been lifted will introduce structure back into the ploughed layer of the arable soil. However, tractor use may exacerbate subsoil compaction and add to plough pans which are much more difficult and costly to remediate.
9. Grow cover crops and use organic amendments to help alleviate compaction.
10. Reduce grazing in wet conditions.
11. Operational changes - include moving feeders and water troughs if necessary, to minimise the most severe soil structural damage; move or add gateways to reduce compaction damage and reduce potential runoff.
12. Matching soil type to crops and introducing grassland into cereal and root crop rotations.

A more detailed description of these measures is given below and the costs and level of reduction in soil structural degradation of these measures are discussed below and summarised in Table 3.

Reduced traffic in wet conditions and timing of cultivation

Soil compaction has become increasingly common in agricultural systems, including forest silvo-culture (Ishaq et al., 2001; Nawaz et al., 2013) and depends on the pressure applied through the weight of the machinery and the soil strength. The strength of a soil is influenced by the texture, structure, organic matter content and water content at the time of trafficking, the wetter the soil and closer to field capacity, the greater the potential for compaction (Batey, 2009). Although multiple passes over the field by heavy machinery can cause increased compaction with every pass (depending on the soil conditions), the initial pass can cause the largest component of the damage (Bakker and Davis, 1995; Hargreaves et al., 2019b).

Reducing traffic when the soil is close to field capacity would reduce the potential for compaction, this can be achieved by timing operations such as harvesting, silage baling and slurry application, however, some operations, especially root vegetable harvest, often occur at a time when the soil will be at field capacity or wetter (Batey, 2009). Installing or maintaining field drainage could help in the alleviation of soil water or restricting these crops to more freely draining fields with less clayey soils. Using maps of soil risk to compaction may help in deciding the cropping type.

Controlled traffic farming

Compaction is a common problem, as identified in Scotland (18% of topsoils in 4 catchment areas surveyed (Hallett et al., 2016)) particularly under combinable and root crops. In the past, this was often associated with plough pans (narrow bands of smeared and compacted soil) at the base of the topsoil. As the mass of tractors, harvesters, trailers and other machinery has increased, with axle loads in excess of 10 Mt now common, soil compaction can now be seen at greater depths and can extend to 0.6 m depth (Schjønning et al., 2015). Subsurface compaction risks increase with farm size and machinery weight and once it occurs, it can be difficult and expensive to alleviate (Jones et al., 2003). Although technologies are improving, techniques to loosen deep-seated compaction effectively and economically are not currently available (Batey, 2009).

Controlled traffic, that keeps vehicles to the same pre-set areas of a field with the use of tramlines, has been shown to improve soil structure and water movement and storage in Scotland in addition to giving substantial savings of fuel and time (CTF Europe; Cloy et al., 2016). Chamen et al., (2015) observed that infiltration increased by 84–400% in the absence of wheel compaction, which was coupled by an increase in plant available water supply. Similarly, McPhee et al. (2015) measured significantly greater water infiltration rates under controlled traffic farming systems in broccoli, particularly during winter months. For example, in 2010, the average water infiltration rate in the controlled traffic farming treatment was >180 mm/h, compared to 3 mm/h in the conventional treatment as a result of the increased soil bulk density, reduction and fragmentation of pores and the reduction in conventional tillage to alleviate the soil structure. These improvements in soil structure and water infiltration rate, and reductions in surface runoff, measured under controlled traffic farming in arable crops, have been confirmed by other researchers (McHugh et al., 2009; Tullberg et al., 2001). In Australia, controlled traffic and no-tillage have shown to have cumulative benefits to infiltration and yield production (Li et al., 2007). While we have no data on the area in Scotland being farmed with controlled traffic, there is anecdotal evidence of farmer interest in England where several recent farmer meetings (e.g., Groundswell) have included farmers speaking about their experiences with controlled traffic farming. Such systems may have potential in Scotland.

Alleviation of compaction

Compaction in arable soils can be easier to remedy than compaction in grassland soils. Ploughing after the crop has been lifted will introduce structure back into the ploughed layer of the arable soil. Where compaction is found on the surface, cross-tillage (tilling across earlier tillage activity) soon after its creation has been found to be an effective method of control (Batey, 2009). Where compaction occurs in the topsoil, the next tillage operation may be all that is required to loosen compacted areas. However, if compaction has occurred below the plough depth it is recommended that a subsoiler be used. Winged subsoilers ensure an even lift when subsoiling a large arable area (Cloy et al., 2016). Subsoil loosening operations need to be carried out under appropriate soil strength and water conditions, where they occur in the field – compacted soils should be sufficiently fragile to shatter as the loosening tine passes through or just below the compact layer (Batey, 2009).

A recent investigation of soil compaction in 75 fields (using VESS and SubVESS) under horticultural production across the UK, found that growers used a wide range of methods to try to improve soil structure across their farms. Cover cropping and organic amendments were most widely used, and many growers felt cultivations were an important tool for tackling soil structural issues, in particular, subsoiling to depth. Although conventional cultivation methods were popular with growers, five growers used reduced tillage methods within the rotation. Two growers, with rotations of cereals, onions, potatoes and salads, were specifically using reduced tillage methods and another used controlled traffic farming to improve soil structural conditions (AHDB Horticulture, 2017).

Maize growers are advised to avoid land of high erosion risk for growing maize (as farming operations causing soil compaction are likely to exacerbate erosion) and to sow an early maturing variety of maize so that harvesting can be carried out before the end of autumn. In addition, they are also encouraged to reduce the post-harvest erosion risk by establishing a winter-cover crop or by rough ploughing immediately after harvest, to prevent overwinter runoff and erosion; and subsoiling along the contour to improve soil infiltration and reduce runoff (Cloy et al., 2016; Jaafar, 2010). Elevated erosion risks are also associated with potato cultivation but new tied ridging technologies, that use soil walls or dams to bridge furrows, have been developed to reduce these risks (AHDB Potato Council, 2013; Vejchar et al., 2017), however, they are not commonly used as a result of the increased time and effort.

In grasslands, there are mechanical methods that can mitigate the effects of surface damage and are recommended to alleviate compaction. These methods fall into three main groups: i) aerators i.e., surface spikers or slitters working typically at a soil depth of 0 to 15 cm; ii) sward lifters working between 15 and 35 cm soil depth and iii) subsoilers working between 35 and 50 cm soil depth (Cloy et al., 2016). For sward lifting, the tines should be just below the lower compaction band (approximately 2 to 3 cm); if they are set to run through the compacted layer the problem could be made worse. Soil moisture content is also very important because if the ground is too dry it will be difficult to pull through the soil, but if too wet, channels will be formed with smearing and cutting of the sward (Cloy et al., 2016). In Scotland, it is rare that subsoils are sufficiently dry i.e., drier than the Plastic Limit (the limit at which soil moisture is reduced to allow the soil to stop acting like a plastic) to make them suitable for effective subsoiling.

• Costs associated with identified preventative measures and solutions

Table 3 summarises the actions, the cost to reduce or alleviate soil compaction and structural damage with an estimated level of reduction along with the practicality of the action. For more detail and information on each aspect see Appendix 4. The numbers in the left-hand column relate to those in the table in Appendix 4.

Table 3. Actions with cost implication, level of reduction (against not implementing the action) and practicality of implementing measures/actions to reduce or alleviate soil compaction and structural damage (based on Appendix 4 Table A4.1).

	Action	Cost of implementation[a]	Level of reduction	Practicality
2	If needed, move feeders and water troughs to reduce extensive soil damage	Low	High	Depending on water points this should be straightforward but could have cost implications to establish water points and could cause extra damage depending on how wet the field
3	Don't travel over fields in wet conditions or reduce access if unavoidable to reduce compaction	Low	Medium	If possible, reduce traffic depending on the weather conditions and the time of the year
4	Increase soil organic matter content (including chop and incorporate cereal stubble)	Low	Medium	Incorporate more crop residues and cover crops
7	Reduced cultivation – conservation tillage where appropriate	Low	Medium	Practical but potential increase in herbicide use, difficult to correct any soil compaction issues
8	No tillage – conservation tillage where appropriate	Low	Medium	Practical but potential increase in herbicide use
10	Timing of agricultural practices – keep off tramlines in winter	Low	Low	Should be done as often as possible depending on the field conditions
11	Use of VESS to detect compaction and soil structural degradation	Low	Low	Training maybe needed but easy to employ
12	Move gateways – add gateways to the field	Medium	High	Expense of new gates and could affect hedge rows
15	Change cropping from veg. to cereals or cereals/veg. crop to grassland	Medium	High	Practicality depends on crop rotation and farm type
16	Cultivate alternating strips of crops across the contour where practicable	Medium	Medium	Practicality depends on crop rotation and farm type
17	Strip grazing across the slope, starting at the highest point of the field	Medium	Medium	Needs extra fencing and labour to move the fences on a regular basis
18	Avoid wetter fields to reduce poaching and surface capping by reducing grazing in wet conditions	Medium	Medium	Needs to consider grazing rotation, weather and field condition
20	Cultivate across the slope - Re-align tramlines away from the steepest part of the slope	Medium	Medium	Needs consideration of the crop and machinery involved
23	Soil compaction alleviation in grassland soils and tramline disruption in arable crops	Medium	Low	Needs specialise equipment but easier to employ
27	Implementation of field drainage	High	Medium	Cost of implementation and the knowledge for a suitable scheme
32	Reduce vehicle size and/or reduced pressure tyres, use of flexi tyres	High	Low	Could help reduce machinery costs but increase fuel and labour costs
33	Increasing tramline spacing	High	Low	Needs suitable equipment to be available
34	Controlled traffic farming	High	Medium	Needs investment in technology and subscription to GPS systems, organisation of working widths for all traffic

[a] Colours indicate level of cost – green = low cost (<£250 or <£50/ha), yellow = medium cost (<£500 or <£150/ha) and red = high cost (>£500 or >£250/ha).

• Impacts on water quality if solutions were put in place

Clements and Donaldson (2002) showed that chisel ploughing was only effective at alleviating compaction when soil conditions allowed effective soil shattering, however, when effective, measured surface runoff of sediment losses from compacted soil shattered by chisel ploughing was typically only 10 m^3 ha^{-1}, whereas the runoff from compacted maize stubble averaged 433 m^3 ha^{-1}.

Hallett et al. (2016) found that nutrient losses (N and P) by runoff were about 10 times greater from areas with structurally degraded topsoils and from tramlines than from either within field or less trafficked field margins. As these results were from only six arable fields in two catchments, it is difficult to extrapolate more widely but the figures indicate that substantial reductions in pollutants reaching rivers and streams can be achieved.

As soil compaction can occur both within-field in general and specifically along tramlines, it is difficult to separate the impact of the two. Compaction can increase runoff and erosion and can be related to land use intensity. This report attempts to integrate land use intensity, erosion, runoff and compaction to assess the overall scale and extent of diffuse pollution due to compacted soil.

• Knowledge gaps and recommendations for future research

The extent of soil compaction in Scottish soils is unknown as there has still been no systematic survey to assess its extent (Lilly et al., 2018). Models of soil susceptibility and land use intensity can indicate where there is the greatest potential for damage to occur, but land use and land management can have a significant role in both preventing and remediating compacted soils. A systematic evaluation of the extent and severity of soil compaction would help in targeting mitigation strategies to alleviate soil compaction as there are still evidence gaps. While topsoil compaction is relatively easily remedied, subsoil compaction is generally more difficult to identify (some Scottish soils are naturally compact) and more costly to remediate. There is little knowledge on the direct impact of structural degradation, other than tramlines, on diffuse pollution in Scotland.

Tramlines

Tramlines are the undrilled unvegetated wheeled rows in many arable fields that over time can progressively become compacted. They are a major pathway for sediment and P transport via erosion by overland flow. Around 8,800 km^2 (11.2%) of Scotland is under arable production systems and these fields will have tramlines at some time. Figure 3 shows the distribution of arable land in Scotland. Tramlines have been attributed as being the causal factor of in-field erosion in 34% of fields surveyed (Chambers et al., 2000 in Withers et al., 2006). A UK based study has shown that tramlines increase runoff by 46%, generate a five-fold increase in sediment loss and four-fold increase in total P loss (Withers et al., 2006). However, there is no systematic survey of the contribution of tramlines to runoff or diffuse pollution in Scotland.

• Key pollutants

Sediment-bound (particulate) P and sediment eroding from arable fields has been identified as a principal contributor to ecological downgrading of water quality of lakes, and, more indirectly, of rivers in Scotland (Stutter et al., 2009). Particulate P is expected to be the primary P loss from agricultural fields due to runoff and soil erosion.

• Scale and extent of the problem

Tramlines, which are often oriented with the slope, are a key part of arable farming which accounts for just over 11% of Scotland (around 8800 km^2) and are known to be a preferential pathway for runoff and hence, erosion with much anecdotal evidence for rills and gullies to form from both new and old tramlines where the soil has become compacted and thus being a potential source of diffuse pollution. Hallett et al. (2016) showed that runoff from tramlines and damaged soils can be up to 10 times greater than runoff from uncompacted areas. Tramlines therefore, can be a major pathway and source for sediment and P transport via erosion by overland flow. Figure 3 shows the distribution of arable land in Scotland that is likely to have tramlines (often running with slope) at some time.

However, there is limited research on the extent of field pathways as sources of diffuse pollution losses from tramlines and wheelings, and Silgram et al. (2010 and 2015) highlighted the scarcity of data. Although, one study (Silgram et al., 2015) conducted over several years at multiple sites, including a Scottish site at the Balruddery farm of the James Hutton Institute, did find sediment losses of between 117 and 417 kg ha^{-1} and total dissolved P losses of between 0.01 and 0.065 kg ha^{-1} over a 2-year period in conjunction with conventionally managed tramlines.

Although there is little direct measurement of the amount of sediment lost or nutrients transported to rivers and streams, there are some reported observations that tramlines can enhance diffuse pollution. Davidson and Harrison (1995) observed tramline erosion during a rapid response survey in Strath Earn, south west of Perth, following 18 days of severe weather conditions in January 1993. In their survey, fields with the greatest likelihood of having erosion features were either ploughed (45% of ploughed fields) or in autumn cereals (78% of autumn cereal fields). Wade (1998) in a survey of 223 fields within 100 km^2 in North Fife, observed fields under winter cereal accounted for 77% of those fields observed to have some form of soil erosion and that rills were predominantly aligned by the direction of cultivation and were more severe in compacted tractor wheelings. Watson and Evans (2007) also found winter cereal fields in Mearns near Stonehaven, comprised 70-73% of all eroded fields and had some of the deepest gullies found in the area. Davidson and Harrison (1995) also reported runoff from two upslope pasture fields near Town Yetholm that was subsequently concentrated along tramlines, leading to the creation of a gully some 1.4 m deep and depositing 105 m^3 of sediment. Kirkbride and Reeves (1993) noted that up/down slope alignment of wheelings and furrows increased risk of erosion.

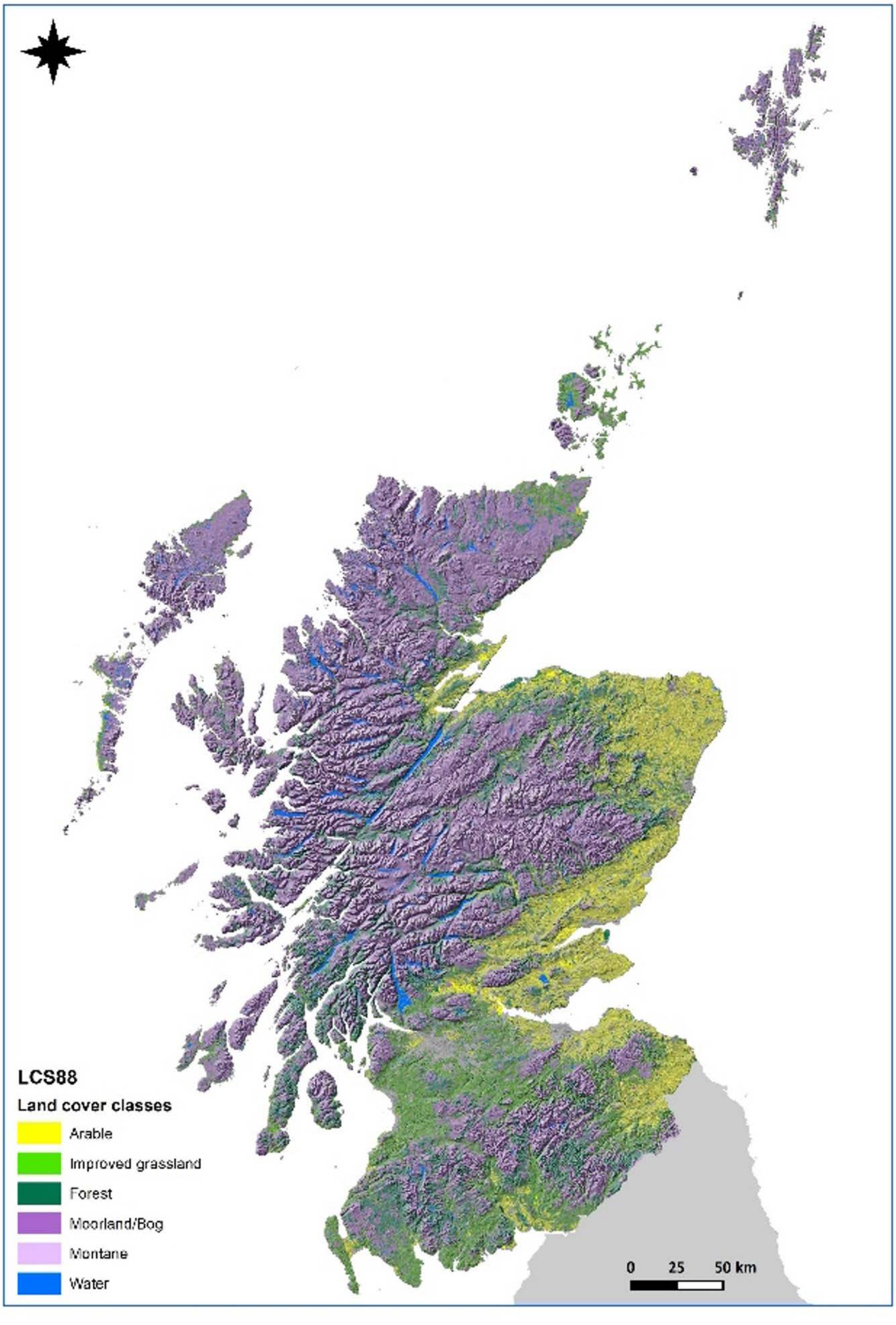


Figure 3. Land cover of Scotland (LCS88) map showing broad land cover classes. © Crown copyright and database right (2020). All rights reserved. The James Hutton Institute, Ordnance Survey Licence Number 100019294.

• Practical preventative measures and solutions to prevent or minimise losses of pollutants

The effectiveness of different tramline management mitigation options across a range of soil types (particularly clay soils) and weather conditions requires further research (Silgram et al., 2010 and 2015), however, there are indications from research by Bailey et al. (2013) that measures such as tramline disruption would be beneficial to reduce loss of pollutants (see Table 3.2.2).

Practical measures to reduce pollutant transport from land to waters from tramlines include:

- Reduced or no tillage and other regenerative agricultural practices that improve soil structure and infiltration.
- Load spreading/reduction through use of tyre flexibility, tyre tread, dual wheels.
- Tramline disruption using tines or harrow.
- Reshaping tramline to improve lateral runoff.
- Increasing distance between tramlines.
- Cultivate across the slope to re-align tramlines away from the steepest part of the slope
- Timing and limiting operations to avoid traffic when soil conditions are unsuitable, and avoiding surface broadcast of winter fertiliser applications (especially organic fertiliser).
- Delaying establishment of tramlines by postponing operations until the spring (introducing spring sowing).
- Drilling tramlines to provide limited vegetation cover.
- Consult models designed to assess impact of machinery on soil.

Based on limited evidence, recommendations for wheelings and tramline management may include looking at tyre tread patterns, correct inflation of tyres within design range, dual wheels, tyre flexibility and spreading the load from tractor to ground. Limited testing has been conducted in the UK and so more research is needed to determine the impact on the soil and how this would affect compaction and erosion via tramlines. Disrupting tramlines to 6 cm using a tine reduced runoff and leaving crop residues are another possible mechanism but little research has been done to show the effectiveness (Silgram et al., 2010). There is also a knowledge gap on the effect of avoiding cultivation and leaving tramlines vertically on a slope, but anecdotal evidence suggests that preferential flow down tramline channels on slopes increases surface runoff and soil erosion compared to cultivating horizontally which reduced flow.

Agricultural engineering is leading to frequent improvements in tyre and track design to improve traction and to minimise compaction. However, as mentioned earlier, these improvements are offset by the increasing mass of machinery. Alongside controlled traffic farming techniques, methods to limit compaction include: reduced tyre pressure (within the design range), use of dual wheels, rubber tracks and flotation tyres (Batey, 2009). Silgram et al. (2015) conducted a multi-year, multi-site study of the runoff from tramlines in autumn sown cereals that included data from a Scottish site at the Balruddery farm of the James Hutton Institute. From this, it was recommended that the use of correctly inflated very flexible tyres was the most practical and cost-effective way to reduce runoff associated with autumn wheelings of combinable crops. The commercially available very flexible XEOBIB tyres supplied by Michelin were the best available when the study started in 2009 (see Figure 4) and gave superior performance to earlier tyre designs. The tread pattern was similar in both tyre types, but the flexible casing of the new tyres allowed for a greater spread of the load. Other companies produce similar designs and there is a clear trade-off between tyre quality and cost. The cost of more modern flexible tyres may be higher than older conventional tyres, but long-running costs and benefits outweigh the starting cost. As noted above, tyre developments continue. Recently, Michelin have released a new range of very flexible tyres under the name EVOBIB (see Figure 4).

Figure 4. Photographs of a) the new EVOBIB and b) the older XEOBIB tyres. Note the block shapes in the centre of the tread in the new EVOBIB tyre and the spiked harrow used alongside the XEOBIB tyre for loosening the soil (courtesy of B. McKenzie).

These new tyres continue with the very flexible design but also have a significantly modified tread pattern, which it is hoped will act to limit runoff. To the best of our knowledge, no testing of these new tyres has occurred in the UK. A further likely advantage of these tyres is that they can be linked to tractor mounted compressors (now commonly available) allowing the tyre inflation pressure to be rapidly changed as the tractor moves from road to field. The intention is to improve safety with better tractor handling on the road while providing rapid adjustment to minimise compaction in the field.

Silgram et al. (2010) found that disrupted tramlines (shallow disruption to 6 cm depth using a tine) and areas without tramlines experienced less surface runoff than conventional or offset (areas where the crop sprayer was run over the emerging crop rather than running on the unseeded tramline area) tramlines. Crop residue chopping and incorporation helped reduce losses, but the absence or disruption of tramlines was most effective for reducing erosion and runoff. Silgram et al. (2015) also suggested increasing the distance between tramlines and avoiding overloading the axle and putting up and down tramlines on steep slopes.

Where possible, options to avoid cultivation and tramlines up and down slopes should be investigated. These options are likely to include using non-inversion tillage systems that can be enacted along the contour i.e., perpendicular to the slope.

Alongside the spiked harrow (see Figure 4), other suggestions by Silgram et al. (2015) included the use of a novel rotary harrow attached to the rear of the crop sprayer in autumn (see Figure 5). This harrow creates holes in the surface of the soil across the wheeling and increases water infiltration without affecting traction. The harrow is controlled from the tractor cab and has low draft requirement. Another suggestion was the use of a new type of surface roller, again attached to the rear of the tractor and used after autumn spraying. The roller creates a convex soil surface allowing surface water to flow to the sides, into the crop and not down the wheelings (Silgram et al., 2015).

Figure 5. Photograph of rotary harrow in operation. Note; the block of concrete is to provide the same weight as the spray equipment (courtesy of B. McKenzie).

Withers et al. (2006) assessed the contribution of tramlines to runoff, sediment and P loss under different soil and crop management strategies on a sandy loam hill slope (8% slope) site in Wiltshire, England, over two winters. They observed that cover cropping and across the slope tramlines reduced erosion and runoff, although young cereal seedlings in the tramlines were not effective at limiting runoff in the work done at the James Hutton Institute Balruddery farm. Up and down tramlines had 46% more runoff compared to untrafficked or ploughed areas. Late-drilled soils under traditional cultivation became capped following storm events (7.5 mm overland flow) whereas early-drilled soils under traditional and reduced cultivations had less than 2 mm of flow. New machinery capabilities that enable farmers to plough along contours will play a key role in the future for reducing erosion risks in Scotland. Indeed, a study in Bedfordshire by Melville and Morgan (2001) found that use of a contour grass strip was an effective approach for erosion control, especially at the bottom of slopes.

The Terranimo model (www.soilcompaction.eu) is a useful agricultural decision support tool for reducing soil compaction risks associated with machinery traffic, including tramlines, and thus is likely to assist in minimising erosion risk associated with compaction. The model was developed to help farmers make decisions about tyres and adjusting tyre pressures to minimise environmental impacts (Lassen et al., 2013). Thus, it is easy to use for farmers following click on choices about machinery etc. Inputs to the model are information about the machine being used including: tyre type and inflation pressure, the soil texture, bulk density and organic matter content and the soil water status. It simulates the stress distribution in the contact area and down into the soil as inflicted by a tyre with a certain wheel load and inflation pressure. Evaluation of the compaction risk is achieved by comparison to soil strength, which is also estimated by the model (Lassen et al., 2013). Elsewhere in Europe, it has been used in contracts that restrict the use of certain heavy machines by contractors and to inform farmer groups on benefits of selecting improved tyres. Recently, support from AHDB has allowed the model to link to the Scottish soils database and the continued support means this will extend to include soils information from England and Wales. The European partners aim to include responses to tracked machines (i.e., not just tyres) in the near future.

• Costs associated with identified preventative measures and solutions

Table 4 summarises the likely cost of implementing measures/actions, level of reduction and practicality relative to reduce runoff and erosion from tramlines. For more detail and information on each aspect see Appendix

4. The numbers in the left-hand column relate to those in Table A4.1 in Appendix 4.

• Impacts on water quality if solutions were put in place

In both the UK as a whole (McGonigle et al., 2012) and in Scotland (https://www.sepa.org.uk/regulations/water/diffuse-pollution/diffuse-pollution-in-the-rural-environment/), it is estimated that about 65% of surface waters do not comply with drinking water standards or good ecological status as defined by European Union's Water Framework Directive (European Parliament, 2000), with agriculture causing the greatest threat to compliance. Available evidence of improvements in water quality after implementation of practical mitigation is scarce but a selection of key findings are summarised below. It is important to note that the potential beneficial impacts on water quality of certain mitigation methods can be counterbalanced by the importance of remaining key transport pathways or hydrological processes, thus dampening catchment response to mitigation strategies (Silgram et al., 2015). For example, buffer strips can reduce runoff and erosion pollutant losses but not drain-flow or bed sediment remobilisation pollutant losses.

Impacts on water quality after implementing very flexible tyres, tramline disruption, minimum tillage, crop residue incorporation, alternative cultivation and beetle banks

A multi-year study of winter sown combinable crops at James Hutton's Balruddery research farm found that using either very flexible tyres, or tramline disruption using a spiked harrow, significantly decreased losses of sediment, N and P. Very flexible tyres reduced runoff by between 33% and 80% and removing tramline compaction using a spiked harrow reduced sediment losses between 76% and 98% (Lilly et al., 2018).

Table 4. Relative cost of implementing measures/actions, level of reduction and practicality to reduce runoff and erosion from tramlines (based on Appendix 4 Table A4.1).

	Action	Cost of implementation[a]	Level of reduction	Practicality
3	Don't travel over fields in wet conditions or reduce access if unavoidable wet conditions to reduce compaction	Low	Medium	If possible, reduce traffic depending on the weather conditions and the time of the year
7	Reduced cultivation – conservation tillage where appropriate	Low	Medium	Practical but potential increase in herbicide use, difficult to correct any soil compaction issues
8	No tillage – conservation tillage where appropriate	Low	Medium	Practical but potential increase in herbicide use
10	Timing of agricultural practices – keep off tramlines in winter	Low	Low	Should be done as often as possible depending on the field conditions
11	Use of VESS to detect compaction and soil structural degradation	Low	Low	Training maybe needed but easy to employ
15	Change cropping from veg to cereals or cereals/veg crop to grassland	Medium	High	Practicality depends on crop rotation and farm type
16	Cultivate alternating strips of crops across the contour where practicable	Medium	Medium	Needs decisions on crop types and the suitability of machinery available
20	Cultivate across the slope - Re-align tramlines away from the steepest part of the slope	Medium	Medium	Needs consideration of the crop and machinery involved
21	Use of green or cover crops (sown tramlines)	Medium	Medium	Cost implications but easy to implement
23	Soil compaction alleviation in grassland soils and tramline disruption in arable crops	Medium	Low	Needs specialist equipment but easy to employ
25	Grass boundaries or filter strip, especially at the bottom of slopes	High	High	Depends on slope of the farm fields and crops grown
27	Establish and maintain wetland areas and/or water retention ponds	High	High	Needs consideration in location and suitability of the fields
32	Reduce vehicle size and/or reduced pressure tyres, use of flexi tyres	High	Low	Could help reduce machinery costs but increase fuel and labour costs
33	Increasing tramline spacing	High	Low	Needs suitable equipment to be available

[a] Colours indicate level of cost – green = low cost (<£250 or <£50/ha), yellow = medium cost (<£500 or <£150/ha) and red = high cost (>£500 or >£250/ha).

Bailey et al. (2013) assessed the effectiveness of a range of diffuse pollution mitigation options (including tramline disruption) on silt, sand and clay soils using three contrasting English case study farms. A summary of findings for runoff, suspended sediment and total P reductions is presented in Table 5. Overall, their study found that tramline disruption appeared to have the greatest potential for reducing runoff, sediment and total P losses. This supports findings that tramlines, particularly in conventionally ploughed fields, are a major diffuse pollution transport pathway. Withers et al. (2006) found that tramline plots produced up to 46% more runoff, 5-fold more sediment loss and fourfold more P loss compared to plots without tramlines. D'Arcy and Frost (2001) estimated reductions in total P loss by soil erosion of 95% and 50% from converting arable to permanent grassland and switching from autumn to spring sowing, respectively, without specifically controlling tramline runoff.

D'Arcy and Frost (2001) estimated a lower reduction (20%) in total P loss by soil erosion from contour ploughing compared to reductions measured by Bailey et al. (2013). Clements and Donaldson (2002), however, found that an understorey of clover within the maize drilled across the slope reduced runoff by 40-90%.

Vejchar et al. (2017) compared surface water runoff and soil losses from potato cultivation with and without the application of a tied ridging system on a sloping field (8%) in the Czech Republic. The tied ridging system reduced runoff and soil losses by 78% and 88%, respectively. A similar approach has been successfully trialled at the James Hutton's Balruddery research farm where a 'Tied Ridger', normally used to create a series of dams between potato drills to help retain irrigation and rainwater on sloping fields, was used to create new field margins of ridges across the bottom of the most vulnerable fields and then sown with a wild grass seed mix.

• Knowledge gaps and recommendations for future research

There is limited research on diffuse pollution losses from tramlines and wheelings, especially Scottish research studies. Silgram et al. (2010 and 2015) highlighted the scarcity of data when outlining the effectiveness of different tramline management mitigation options across a range of soil types, cropping systems and weather conditions. Bailey et al. (2013) and Lilly et al. (2018) reported promising findings regarding mitigation of diffuse pollution from tramline disruption and use of very flexible tyres but recognised that further work is needed to evaluate alternative tramline management methods such as seeding tramlines and roller/tine configurations for different soil and site conditions.

Based on limited evidence, recommendations for wheelings and tramline management may include looking at tyre tread patterns, correct inflation of tyres within design range, dual wheels, tyre flexibility and spreading the load from tractor to ground. Limited testing has been conducted in the UK and so more research is needed to determine the impact on the soil and how this would affect compaction and erosion via tramlines. Disrupting tramlines to 6 cm, using a tine, reduced runoff and leaving crop residues are another possible mechanism but again there is limited research to show the effectiveness of this measure (Silgram et al., 2010). There is also a knowledge gap on the effect of avoiding cultivation and leaving tramlines vertically on a slope, but anecdotal evidence suggests that preferential flow down tramline channels on slopes increases surface runoff and soil erosion compared to cultivating horizontally which reduced flow.

Table 5. Summary of effectiveness of different mitigation options on silt, sand and clay soils (adapted from Bailey et al., 2013).

Mitigation option	% Reduction compared to control treatment		
	Runoff	Suspended sediment	Total P
Tramline disruption (silt)	95-97	98-99	97-99
Tramline disruption (sand)	69-88	75-96	72-95
Minimum tillage (sand)	66-81	94-98	92-97
Minimum tillage (clay)	36-62	47-62	34-52
Crop residue incorporation (sand)	24-50	40-43	34-50
Contour cultivation - plough (clay)	64-76	67-79	60-79
Contour cultivation – minimum tillage (clay)	73	45	48
Beetle bank - plough (clay)	45-91	37-94	32-97
Beetle bank – minimum tillage (clay)	64	16-81	9-74

Soil erosion in Scottish cultivated soils: scale of the problem and spatial distribution

Soil erosion is part of a natural cycle where soil particles are redistributed in the landscape by wind or water, it can be exacerbated by modern land management systems such as the use of controlled traffic methods (tramlines) or where machinery and livestock cause compaction, thereby reducing the infiltration rate of rainfall and leading to greater runoff, which can entrain soil particles causing rill and gully erosion. If these soil particles reach a water course, they can cause damage to the aquatic ecosystem through siltation and delivery of potential pollutants such as P.

Structural degradation and tramlines can add to the inherent susceptibility of Scotland's soils to both erosion and compaction. Recent work (Lilly and Baggaley, 2014) applied simple, transparent rule-based models to predict and map the soils susceptibility to erosion. The underlying soil map used in this work has been subsequently updated and new areas digitised allowing a greater land area to be assessed (34,314 km^2) which primarily covers the cultivated land in Scotland.

The soil erosion risk map (Figure 6) shows the risk of a bare soil being eroded by water under intense or prolonged rainfall (Lilly and Baggaley, 2014). The map was developed by combining the susceptibility to erosion based on soil texture and capacity to absorb rainfall with slope to determine how erosive the overland flow could be, with steeper slopes leading to faster runoff. Soils with mineral topsoils have been classified separately from those with organic (peaty) surface layers.

For mineral soils, the risk of soil erosion is shown in three main classes for soils with mineral topsoils: High (H),

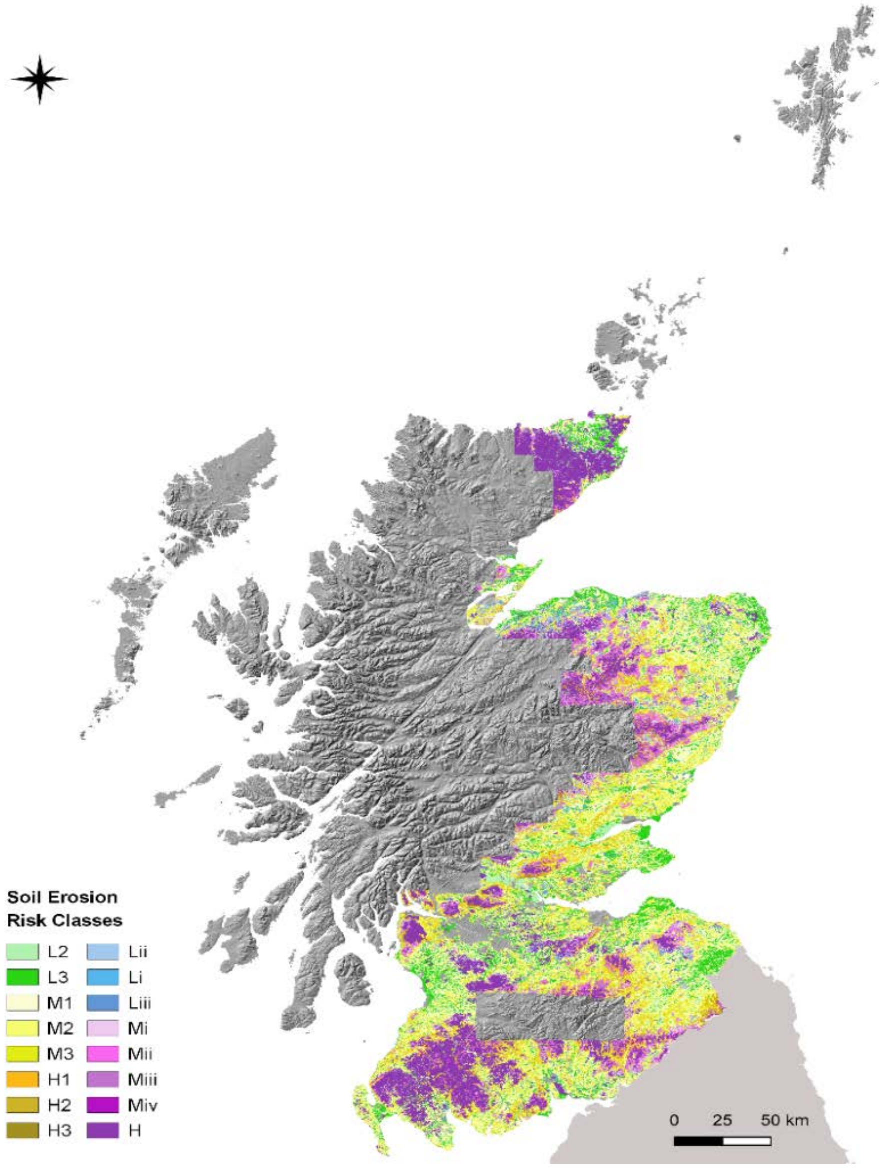


Figure 6. Map showing the distribution of soil erosion risk classes based on phase 6 of the soil map of Scotland (partial cover). Classes L2 to H3 showing increasing risk of erosion in mineral soils and Li to H show increasing risk of erosion in organic and organo-mineral soils.

Moderate (M) or Low (L), which are further subdivided in 3 sub-classes (H1/H2/H3; M1/M2/M3; L1/L2/L3), where subclass 1-3 represent increasing severity of risk. Organic soils (peats) are considered highly erodible so are always deemed to be at a high risk of erosion. Organo-mineral soils are less likely to erode and have four (4) sub-classes for moderate erosion risk (Mi/Mii/Miii/Miv) and three (3) for low erosion risk (Li/Lii/Liii) with subclasses i to iv representing increasing severity of risk. The soil erosion risk map is available at 50 m grid resolution and covers an area of 34,314 km², primarily the cultivated land and adjacent uplands in Scotland.

The extent of each erosion class based on phase 6 of the soil map of Scotland (partial cover) produced by Soil Survey of Scotland Staff (1970-1987) shows that the moderate erosion risk class for mineral soil (M1-M3) is by far the most extensive (46.6%) (Table 6).

Table 6. The area and proportion of each soil erosion risk class based on phase 6 of the soil map of Scotland (partial cover).

Inherent erosion risk class	Area and proportion of erosion risk class	
	Area km²	Cover %
Mineral soils Low (L2-L3)	4258	12.4
Mineral soils Moderate (M1-M3)	15983	46.6
Mineral soils High (H1-H3)	1718	5.0
Soils with organic surface layer	10605	30.9
Misc. (water, built up)	1749	5.1
Total	34314	100.0

Soil erosion and compaction can have a large impact on runoff, water storage and water quality as well as adversely affecting crop production. Although soil erosion is part of a natural cycle, certain land management features such as 'tramlines' (controlled traffic systems) running up and downslope can create preferential flow pathways where runoff can accumulate and cause erosion. The production of fine seedbeds (particularly associated with high-value, root crops) or structural damage caused by late-harvested root crops, such as potatoes, can also increase the risk of erosion in agricultural land. Soil compaction caused by the passage of heavy machinery or poaching by livestock reduces the infiltration of rain and snow melt into the soil and can cause the upper layers to become saturated leading to overland flow. Some land uses, such as grassland, can help protect the soil from eroding by providing a continuous cover throughout the year. To better assess the likelihood of erosion in Scottish cultivated soils, the inherent erosion risk shown in Figure 6 was modified by an index of land use intensity (Appendix 2) to reflect the land uses that could help protect from, or exacerbate, erosion.

The classification of crop and land uses to risk classes was based on a set of rules where grasslands (and rough grazings) were classified as low land use intensity because they provide a complete and continuous cover of soil, whereas land under root crops was classed as high intensity due to amount of cultivation, damage to soil structure and passage by heavy machinery. However, land under cereals was classed as moderate because these crop types represent an intermediate situation whereby there is adequate annual plant coverage and thus soil protection for part of the year, but cultivation practices may cause some degree of soil compaction, for example, the use of controlled traffic systems. A report by Baggaley et al. (2017) showed that land where potatoes had been grown was most at risk of eroding.

The intensity of land use was calculated using Integrated Administration and Control System (IACS) data from 2007 to 2015 (9 years). The number of years a field was under each crop risk class (Low, Moderate and High) was counted and then used to assess the land use intensity for each field under IACS during 2015 for the 9-year period. A 6-class land use intensity (LUI) assessment of increasing land use intensity for each field (LUI-1=Low -> LUI-6=High) was developed, based on the rules shown in Table 7. Further detail is given in Appendix 2 and the distribution of land use intensity classes is shown in Figure 7.

Table 7. Rules to classify fields into land use intensity classes (LUI) and percentage cover.

Land use intensity (LUI)	Rules to classify fields into land use intensity classes	Area (%)* of LUI class
LUI-1	Rough grazing was the dominant land use in most years	27
LUI-2	Improved grassland was the dominant land use in most years	37
LUI-3	Number of years in grass was greater than number of years in cereals and no root crops grown	8
LUI-4	Number of years in cereals was greater than number of years in grass and no root crops grown	18
LUI-5	Root crops grown in at least one of the 9 years	9
LUI-6	Root crops grown in at least 5 of the 9 years	1

* percentage of area covered by phase 6 soil map (34314 km²).

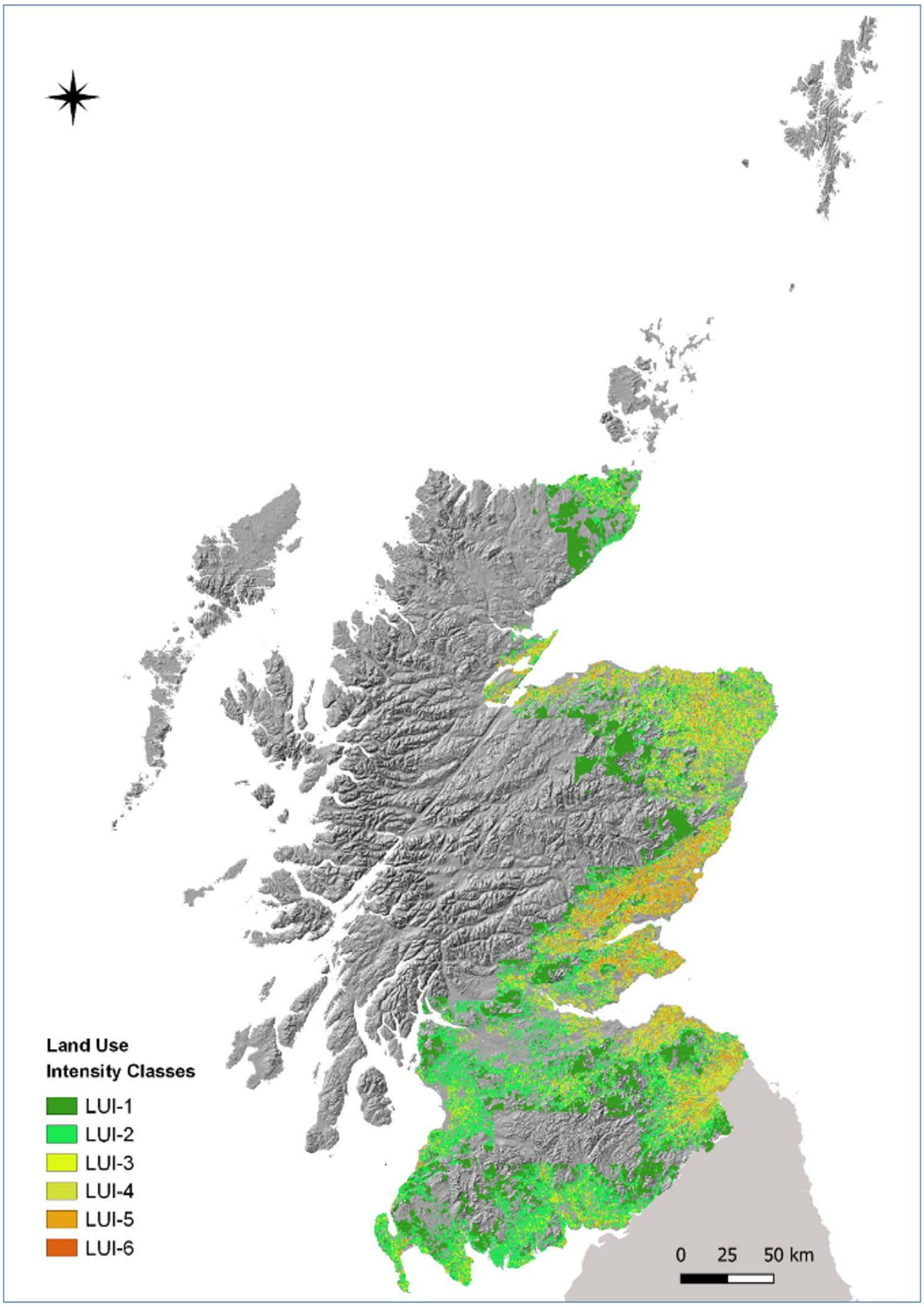


Figure 7. Map of land use intensity classes at 50 m grid resolution for the study area. © Crown copyright and database right (2020). All rights reserved. The James Hutton Institute, Ordnance Survey Licence Number 100019294.

The LUI was then used to modify the inherent soil erosion risk using the following rules:

- If land use intensity was LUI-1, LUI-2 or LUI-3 (predominantly grassland systems), then the soil erosion risk was lowered by one risk class.
- If land use intensity was LUI-4 (mixed arable with bare soil for some parts of the year), then the soil erosion risk was kept the same.
- If land use intensity was LUI-5 (root crops grown at least once in 9 years), then the soil erosion risk increased by one risk class.
- If land use intensity was LUI-6 (root crops grown in most of the 9 years), then the soil erosion risk increased by two risk classes.

Figure 8(a) shows the distribution of the land use-modified erosion risk classes and the difference between this and the unaltered erosion risk map (b). The main changes discernible between the maps are in the south and west where there is a greater preponderance of grasslands and in Angus and Strathmore where there are greater amounts of cereal and root crops grown. Overall, adjusting soil erosion risk by land use intensity resulted in 2437 km^2 more land classified as of low erosion risk, 2077 km^2 less of moderate risk and 360 km^2 less classified as of high erosion risk (Table 8).

Table 8. Area and proportion of each soil erosion risk class on mineral topsoil based on phase 6 of the soil map of Scotland (partial cover) after being modified by land use intensity. The difference between the area of map coverage and the total area of risk class is attributable to water, built up areas and other areas with no soil cover.

Soil erosion risk class	Inherent soil erosion risk		LUI-modified soil erosion risk		Difference	
	Area (km²)	Cover (%)	Area (km²)	Cover (%)	Area (km²)	Cover (%)
Low (L1-3)	4258	12.4	6695	19.5	+2437	+7.1
Moderate (M1-M3)	15983	46.6	13906	40.5	-2077	-6.1
High (H1-H3)	1718	5.0	1358	4.0	-359	-1.0

* percentage of area covered by phase 6 soil map (34,314 km²).

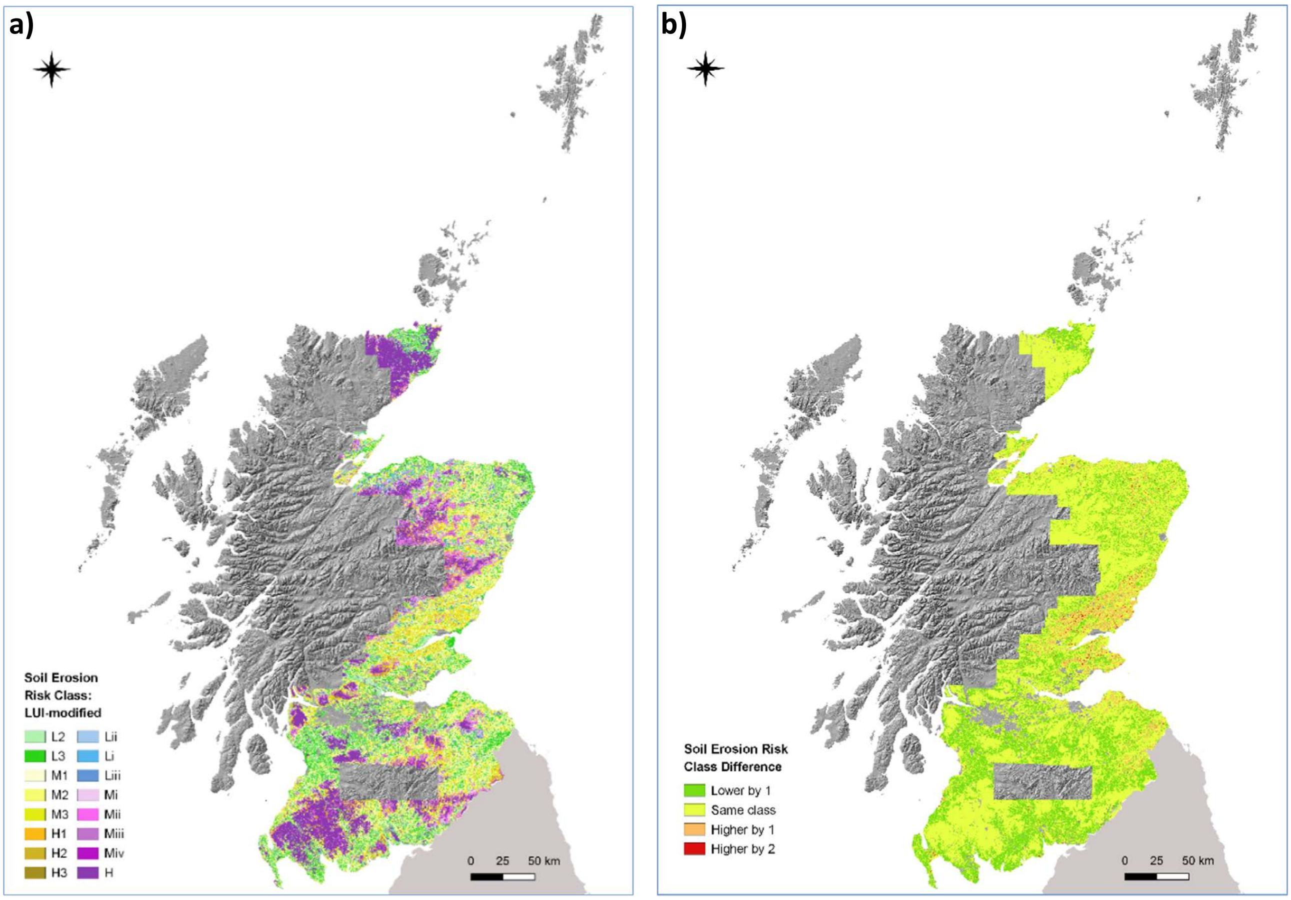


Figure 8. Map showing the distribution of a) soil erosion risk classes based on Phase 6 of the soil map of Scotland (partial cover) adjusted by the intensity of land use (LUI) and b) difference in classes between the LUI-modified and the original soil erosion risk map. Note this map also shows the erosion risk out with the area of IACS data which will be the same as the unaltered risk mapping.

The area of land under cultivation that is at risk of erosion due to both inherent features, such as slope and soil type and due to land management, that can lead to compaction and structural degradation was quantified and mapped to show the scale and extent of land likely to contribute to diffuse pollution. However, is it known that anthropogenically-induced erosion does not occur on all land in each year and erosion by overland flow can be sporadic and due to a combination of circumstances and timing. A recent report for the Scottish Government (Rickson et al., 2020), quantified the probability of erosion by overland flow occurring in any year on land in each erosion risk class for both mineral and peaty soils, for example, there is a 2% chance of a field in the low erosion risk class eroding in any given year (Table 9).

Table 9. Probabilities (%) of erosion occurring on land in each erosion risk class by soil type.

	Probability of erosion (%)	
	Mineral	Peaty
Low	2%	12%
Moderate	13%	12%
High	24%	31%

They also estimated erosion rates based on broad land-use categories that can be related to the land use intensity (LUI) classes (Table 10). By combining estimated erosion rates with probability of erosion occurring, the overall amount of sediment eroded can be calculated. By calculating the mean topsoil Total P concentration (mg kg^{-1}) by land use from the Scottish soils database (n=1927), we were able to estimate the mean annual amount of Total P lost in eroded sediment from the cultivated land area of Scotland as between 0.094 kg P ha^{-1} yr^{-1} for LUI-1 (rough grazing) to 0.65 kg P ha^{-1} yr^{-1} for LUI-6 (dominant crops are potatoes, maize and root vegetables) (see Table 11 and Appendix 2). Scaling to the area covered by the Phase 6 soil map, gives a total P loss in sediment of 581,697 kg yr^{-1} (see later where the relative contributions of both erosion and drain-flow are evaluated).

Table 10. Soil erosion rates (t ha^{-1} yr^{-1}) for each land use intensity class and soil.

Land use intensity classes	Soil erosion rates (t ha^{-1} yr^{-1}) by LUI class	
	Mineral soil	Soil with peaty surface layers
LUI-1	0.75	0.39
LUI-2	3.00	1.00
LUI-3 & LUI-4	2.40	5.00
LUI-5 & LUI-6	4.30	10.00

Table 11. Mean values and standard deviation (±) of P loss due to runoff and soil erosion (g P ha^{-1} yr^{-1}) for each land use intensity (LUI) class in the study area.

LUI class	P loss in sediment (g P ha^{-1} yr^{-1})	Standard deviation of P loss (g P ha^{-1} yr^{-1})
LUI-1	94.4	41.6
LUI-2	376.0	173.0
LUI-3	314.0	190.0
LUI-4	306.4	183.0
LUI-5	586.8	312.0
LUI-6	650.0	456.0

• Practical preventative measures for reducing diffuse pollution from soil erosion

Besides tramline management, there are other ways to reduce the movement of potential pollutants to waters. These include growing crops suitable for the soils and landform, use of grass margins and buffers to trap sediment and altering cultivation methods.

Suitable crops for the soil type

Converting root crops to arable land, arable land to grassland or introducing grass leys into arable rotations, especially on steeply sloping fields can be effective methods of controlling soil erosion (Defra, 2005). Winter cereals can take two months to achieve a crop cover of 30% (which should provide adequate cover) during which soils are susceptible to erosion, especially as winter months usually experience greater rainfall (Boardman, 2013) or as the evapotranspiration rates are less than during summer, whereas grassland has more than 50% of cover throughout the year, once the sward has developed after sowing. Previous work has shown that perennial ryegrass completely prevented water erosion on slopes up to 10-14° (Fullen, 1998; Jankauskas and Jankauskiene, 2000).

Understanding the workability (controlled by soil texture and climate) of soils is key to ensuring crops are grown in conditions that reduce damage to the soils. Soil texture is the defining aspect of the suitability for certain crops. Although the potential for soil damage is increased with the growing of potatoes in wet seasons, as there can be difficulties in the timing of seedbed preparation and harvesting (Finch et al., 2014).

Cover crop use, undersowing and retention of stubble

The protection of the soil surface is important as particulate pollutants are mobilised predominantly from the top 0-50 mm of soil (Seta et al., 1993). Cover crops help maintain soil cover during autumn and winter and are especially useful for helping mitigate erosion on high risk sloping land and preventing transfer of excess nutrients (McKenzie et al., 2017). Jaafar (2010) found that in general, straw mulching and the growing of cover crops were effective practices for erosion control on maize stubble fields. Additional costs associated with integrating cover crops into arable rotations in terms of: seed costs (unless volunteers are used), seedbed preparation, planting, destruction via spraying, cultivation or grazing, can be a concern, but are thought to be more cost-effective than other preventative measures.

Undersowing of crops also helps to buffer against soil erosion and can reduce mechanical damage to soil structure with an additional advantage of increasing organic matter (Schjønning and Rasmussen, 1989; Breland, 1995). The finer root systems retain the soil and help maintain soil structure at the surface, while the vegetation from the greater cover retains the surface roughness and buffers the rainfall (Breland, 1995).

Retention of stubble in the field after harvest helps protect the soil surface from rainfall events through the maintaining of surface roughness and reducing the potential of soil erosion. This is particularly important for sandy or silty soils that are more prone to erosion.

Conservation tillage

Farmers have reported their experiences with reduced tillage in a report of case studies which considered the barriers to the uptake of reduced tillage (Alskaf et al., 2019). Many UK farmers that are successfully using and advocating reduced tillage systems are members of Biodiversity, Agriculture, Soil and Environment (BASE) UK (http://base-uk.co.uk/). Success is based on improved soil health and reduction in establishment costs, though financial benefits may be delayed due to reductions in yield in the first or second seasons. UK farmers that have adopted conservation tillage report anecdotally improved water infiltration, aggregate stability, organic matter and worm numbers and retention of rainfall leading to better traffic-ability and growing conditions (Farming for a Better Climate (https://www.farmingforabetterclimate.org/); Soil Association, 2017). These improvements are attributed to the presence of residues and increased structural stability which enhances the continuity of vertical macroporosity between the surface and lower layers of soil (Soane et al., 2012). However, Soane et al. (2012) found that improved infiltration was not universally reported in the literature and that any pan or crust at the surface could dramatically reduce the infiltration rate. Good timing of field operations is important under no-tillage because compaction or wheel-ruts created in wet conditions when soils are close to field capacity, cannot be later easily remediated by tillage.

Scottish farmers that have successfully adopted reduced tillage practices report better timeliness due to the ability to establish a greater area in the limited time available. This is particularly important in wet seasons and may make some finer-textured soils more suited to reduced tillage (Morris et al., 2010; Soane et al., 2012; McKenzie et al., 2017). In Scotland, the benefit of decreased working time may be particularly beneficial for winter cropping regimes. Winter cropping regimes have the advantage of covering most of the soil over winter and preventing surface water erosion (McKenzie et al., 2017).

In terms of adoption of preventative measures such as conservation tillage, soil type is only likely to restrict its use where structure is particularly poor as in some silts and sandy soils with low organic matter (Arvidsson et al., 2014; Morris et al., 2010). For flexible or 'managed' systems of tillage, soil surface and structural conditions before crop establishment require investigation. Many Scottish farmers have reported problems using reduced tillage practices for spring barley. The 'managed' systems described by McKenzie et al. (2017), where choice of tillage system is flexible and varies according to specific conditions, such as soil conditions before tillage, preceding crop and amount and decomposition status of plant residues (Arvidsson et al., 2014), give suitable returns and perhaps offer a good means for adopting reduced tillage and no-tillage systems. The use of rotations, cover crops and controlled traffic farming, offer further opportunities to realize the full benefits of no-till (Soane et al., 2012).

Kouselou et al. (2018) compiled machine, soil and landform factors likely to influence the extent and severity of tillage erosion (which is an often-overlooked direct source of soil erosion and therefore nutrient loss). They demonstrated decreased severity of tillage erosion under reduced tillage systems and its elimination under no-till. Under reduced tillage, improved soil structure (Seehusen et al., 2017) and the presence of plant residues at the soil surface, that provide improved protection against water and wind erosion (Armand et al., 2009; Morris et al., 2010; Seehusen et al., 2017), are generally recognised as regular features in the research literature.

Contour farming or strip cultivation

Loss of soil and nutrients during cultivation and then afterwards from harvest, especially on a sloping field, can be controlled through the direction of cultivation and leaving areas (strips) of the field either in alternative crops or in grass. Strip cultivation or contour farming follows the contour of the field to help retain the soils on sloping fields by slowing the water movement across the surface and through the soil. The more open crops (maize or wheat) are alternated in strips with a more densely growing crop (peas or beans) or grassland. When this method has been employed for several years, it has shown a reduction in soil loss through erosion (Kell, 1938). In the US, studies have shown up to 10% greater yield for the crops grown in strips compared to a monoculture of just one of the crops (Francis et al., 1986) and reduced soil erosion on slopes up to 10% (Blanco-Canqui and Lal, 2010). Contour farming can help control soil erosion on steeper slopes but needs to be combined with other actions.

Buffer strips for preventing soil erosion and other means of capturing sediment

The interception of eroded particles in grass/buffer strips before transportation to nearby watercourses will improve water quality. The suspended sediment trapping efficiencies of buffer strips are often reported to be in excess of 50-90% depending on: slope length, vegetation density, buffer strip width, sediment particle size and the risk of channelisation (Silgram et al., 2015). Fiener et al. (2005) showed that detention ponds effectively trapped sediment and reduced sediment movement by between 54% and 85%, or by between 1.0 and 15.3 t ha^{-1} yr^{-1}. McKergow et al. (2003) demonstrated that the use of stream bank fencing to prevent poaching and direct excretion into water courses, reduced catchment particulate exports from > 100 kg ha^{-1} yr^{-1} to 10 kg ha^{-1} yr^{-1}.

A report by Defra (2005) recommended the establishment of grass margins/buffer strips, rural sustainable drainage systems and reductions in field size using new hedges and beetle banks as ways to control soil erosion (although changing/reducing field size may have negative consequences for farm business). Managing grass margins and beetle banks across the middle of fields can, however, be cost-effective ways to reduce soil erosion, especially in fields that have sloping ground, as the soil can be captured by the bank (SAC Consulting, 2002).

The use of carefully designed 3D buffer strips (buffers that work both below and above the ground), such as wooded and engineered buffers that are tailored to local conditions and needs, have recently been promoted as novel measures for reducing pollutant losses. Stutter et al. (2020) suggested that 3D buffers that used natural engineering principles could slow the flow of runoff and therefore reduce pollutant loss. The cost-effectiveness of these 3D buffer measures for mitigating pollution, however, has not been compared with other options.

Increased organic matter

Organic matter in the soil is an important component of the soil quality and influences the water infiltration and moisture holding capacity, soil structure, nutrient availability and the diversity of the microbiome. Larger residues of organic matter on the surface of the soil reduce raindrop disruption to the soil surface aggregates and prevent the soil sealing and encouraging surface runoff. The risk of compaction over the longer term, particularly in arable soils, is believed to be reduced through maintaining or increasing organic matter contents (Cloy et al., 2016).

Enhanced soil organic matter inputs to agricultural land can be achieved using livestock manures, in addition the incorporation of cereal straw back into the soil as a source of organic matter inputs. Cattle farmyard manure (FYM) can provide as much as 4 t ha^{-1} of organic matter to the soil when applied at a rate equivalent to 250 kg ha^{-1} of N (Bhogal et al., 2009). Cover crops and green manures increase the organic matter content and help retain nutrients over the winter period that would otherwise be lost through erosion and leaching leading to diffuse pollution.

Drain-flow

Drain-flow can be defined as the flow of water (and soluble pollutants) and fine particles from the field into a subsurface (artificial) drainage network (e.g., pipes) that most often connect to surface water or an open drainage ditch. The function of an artificial drainage system is to remove excess rainfall from the soil to extend the time the soil is in a good condition for growing crops, to allow agricultural machinery to work on the land and animals to graze without causing damage to the soil structure. Gramlich et al. (2018) reviewed the effects of artificial drainage on hydrology, nutrient and other pollutant losses from 195 articles and showed that total annual water-flows and peak water flows were generally increased, which usually resulted in a decrease in surface runoff and increasing subsurface runoff. The review also indicated a consensus in the literature of a reduction in surface erosion with the installation of artificial drains on all but the flattest sites (<2% slope). Overall, for total P (where losses are often dominantly of P bound to soil particles and delivered to watercourses via surface erosion) there was a reduction in total P loss where artificial drains are installed thereby reducing overland flow. However, for N losses, artificial drainage increased total N loss from mineral soils due to high losses of nitrate (NO_3^-) which has a weak sorption to soils. Early work suggested that very little soluble P is lost from soil in artificial drainage water because soluble P is only a small fraction of the total soil P (Fortune, et al., 2005; Johnston and Dawson, 2005). More recent work suggests that there are elevated concentrations of dissolved P in artificial drain waters compared to natural subsurface runoff due, in part, to the drained area receiving P fertiliser inputs; changes in soil redox conditions leading to P mobilisation (Menberu et al., 2017); due to the connection of the drainage system via preferential pathways leading to high P losses via drains (Beauchemin et al., 1998; King et al., 2015) and of P bound to fine soil particles and colloids (Chapman et al., 2001; Djodjic et al., 1999; Stamm et al., 1998).

Specific to Scottish conditions, Stutter and Richards (2018) obtained artificial drain water and soils from associated drained fields from 28 farms in Scotland. They found that grasslands differed from croplands with greater soil total P (TP) (mean of 0.709 mg P L^{-1}) and dissolved unreactive P (DUP) (organically complexed dissolved P; 0.036 mg P L^{-1}) in the drain waters. Conversely, cropland had greater drain water soluble reactive P to total dissolved P ratios (0.6 compared with 0.2 mg P L^{-1} for grassland), NO_3^- (6.9 mg N L^{-1}) and the cultivated soils had greater P associated with surface Fe and Al complexes.

Soluble reactive P concentrations did not differ between grassland and cropland drain waters (means of 0.032 and 0.021 mg P L^{-1}, respectively). The study found that soil test P (STP) with a range of 4-19 mg P kg^{-1} was a significant predictor of both total dissolved P (TDP) and DUP, these relationships were stronger in grassland soils and had more scatter in cropland soils. In addition, the cropland soils with least organic matter contents resulted in greater drain water concentrations of soluble reactive P (the form on which the P criteria for freshwaters are set under the Water Framework Directive (European Parliament, 2000)).

In summary, high concentrations of P can be delivered via artificial drains in some situations but the mean soluble reactive P concentrations found in Scotland and elsewhere were similar to the concentration thresholds between good and degraded status for UK rivers under the Water Framework Directive criteria. However, the appreciable dissolved unreactive P arising from drainage of pasture soils may also contribute to eutrophication. These results were used to inform the modelling of P transport through drains.

• Scale and extent of the problem

As stated, potential pollutants such as soluble P, P bound to small soil particles, and N can be rapidly transported to waters via the artificial drainage system installed in soils which are seasonally waterlogged. Many records of where field drains have been installed have been lost so their distribution has to be inferred. Lilly et al. (2012) estimated that almost all the soils in Scotland under cultivation that had inhibited natural drainage (that is, imperfect, poor or very poor drainage classes) did have such artificial drainage systems and this approach was adopted here. Information on which soils were likely to have artificial soil drainage was derived from the soil map of Scotland (partial cover) at 1:25,000 scale.

Combining the areas of imperfect, poor and very poor soil drainage from the soil map of Scotland (partial cover) and the polygons of cultivated fields from the 2015 IACS database, spatial analysis showed that approximately 6,687 km^2 are likely to have artificial (field) drains. This represents around 19.5% of the land covered by the phase 6 soil map of Scotland (partial cover) map (Figure 9) and around 52% of cultivated land, based on 2015 IACS fields and lying within the area covered by the soil map.

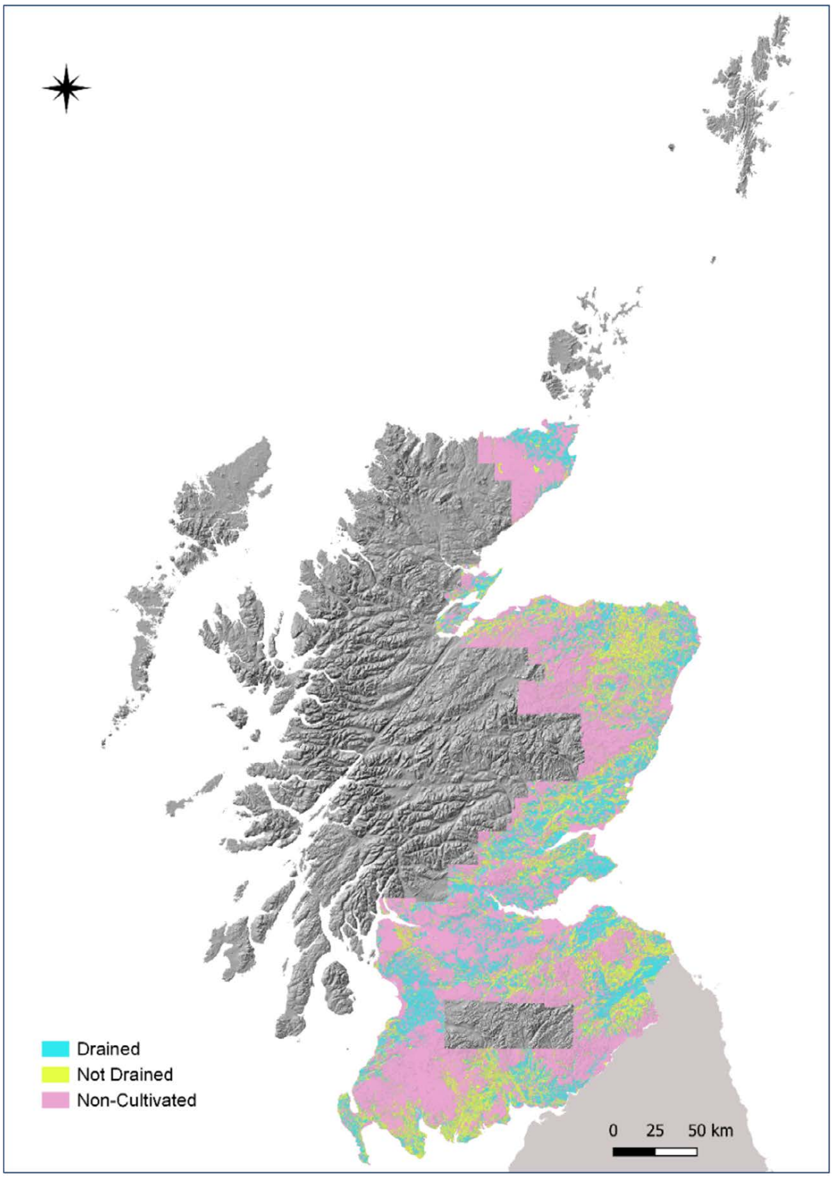


Figure 9. Map showing the area of land based on phase 6 of the soil map of Scotland (partial cover) that is likely to have artificial underdrainage systems in place. © Crown copyright and database right (2020). All rights reserved. The James Hutton Institute, Ordnance Survey Licence Number 100019294.

The movement of TP to artificial drains was estimated using published relationships linking agronomic P data (Modified Morgan's extraction) with TDP concentrations in drain-flow in Scottish agricultural catchments (Stutter and Richards, 2018), along with the assumption that each crop in the 2015 IACS dataset was at its target P status (see Table 3.4.1) and the known relationship between TDP and TP from the work by Stutter and Richards (2018). As there were no data on estimates of flow in the drains, it was assumed that all excess winter rainfall (October to March), as calculated from the monthly HadUK gridded precipitation for the 1981-2010 period (1 km^2 grid resolution, Met Office), contributed to drain-flow in those soils with imperfect or poor natural drainage and were likely to have a drainage system (Figure 10).

Table 12. Target P status by Modified Morgan's extractant for Scottish crops and grasslands taken from SRUC Technical notes. These values were similar to those found by Stutter and Richards (2018).

Land use	Target P by Modified Morgan's (MM) extractant (mg L^{-1})
Grass[1]	6.0
Cereals[2]	9.5
Potatoes and other root vegetables[2]	13.4

SRUC Technical notes [1]652 and [2]633 (SRUC TN652, 2013: SRUC TN 633, 2013).

This modelling allowed an estimate of the contribution of P in drain-flow for each land use intensity (LUI) to be made (Table 13), which can be directly compared to P losses by erosion (see later for more details of the modelling and comparison of P losses by erosion and drain-flow). There is an estimated total of 281631 kg P lost each year in drain-flow. As with P losses due to erosion, these values should be treated with caution given the inherent uncertainties in estimating drain-flow, rates and P concentrations within the field.

Table 13. Mean values and standard deviation (±) of P loss due leaching to drains for each land use intensity (LUI) class.

LUI class	P loss in drains (g P ha^{-1} yr^{-1})	Standard deviation of P loss in drains (g P ha^{-1} yr^{-1})
LUI-1	-	-
LUI-2	514	137
LUI-3	323	75
LUI-4	348	82
LUI-5	350	70
LUI-6	435	100

NB: No P leaching to drains was calculated for LUI-1 (rough grazing) because the LUI-1 area was not included in the assessment of the land likely to have been artificially drained.

As well loss of P, drain-flow can also carry N in the form of nitrate (NO_3^-) to surface and ground waters. An existing process-based NIRAMS model (Dunn, et al., 2004a &

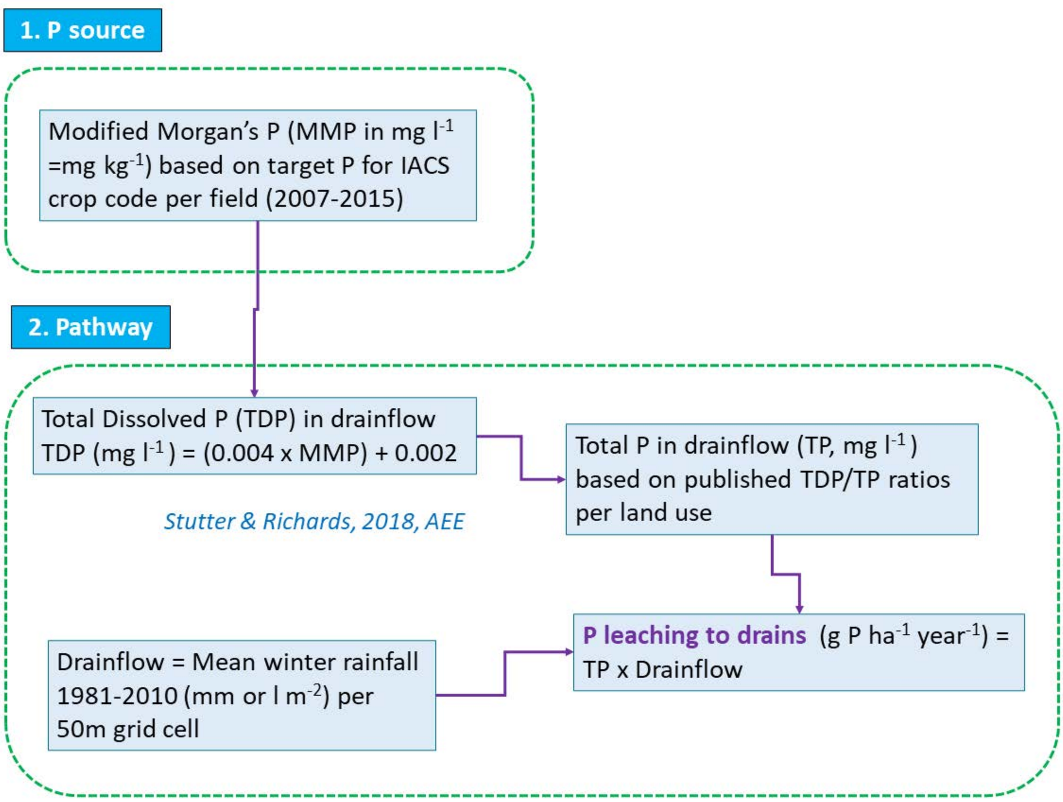


Figure 10. Flowchart of steps used to assess P loss due to leaching to drains.

2004b) dealt with N transport to streams and rivers and has been subsequently modified to predict leaching to groundwaters. In this section of the report we focus on N loss to surface waters through drain-flow.

A simple approach was taken to estimate the loss of N from the soil through drains. The method was based on combining annual rates of leachable N with the soil's infiltration capacity and follows the same procedure used by Lilly et al. (2001) in the development of a methodology for the designation of groundwater nitrate vulnerable zones. Leachable N was expressed as residual nitrogen (N) that is in excess of crop needs after crop harvest or at the end of the growing season. Average leachable N rates were calculated for IACS crop categories for the 2007-2015 period (Table 14). The amount of N likely to leach through was calculated as crop residual N multiplied by the inverse of the soil's Standard Percentage Runoff (SPR) converted to a proportion. SPR is a hydrological index derived from the Hydrology of Soil Types (HOST) classification (Boorman et al., 1995) and is also embedded within the erosion risk assessment. Soils with a low infiltration capacity (for example, soils with slowly permeable subsoils) have a limited capacity to allow N to infiltrate to drains.

Mean N leaching to drains was also found to increase with LUI class and ranged from 0.70 kg N ha^{-1} yr^{-1} for rough grazing to 53.41 kg N ha^{-1} yr^{-1} for root vegetables in rotation (Table 14).

Table 14. Mean and standard deviation (±) per land use intensity (LUI) class of rates of leaching to drains (kg N ha^{-1} yr^{-1}).

Land use intensity class	N leaching rate (kg N ha^{-1} yr^{-1})	Standard deviation of N leaching rate (kg N ha^{-1} yr^{-1})
LUI-1	0.70	0.87
LUI-2	16.39	10.77
LUI-3	31.61	9.14
LUI-4	36.58	8.26
LUI-5	39.88	9.23
LUI-6	53.41	15.45

Full details of the modelling approach to calculate P loss through drains, P loss by erosion and N leaching loss through drains are given later. Note that this modelling does not indicate the actual amount of P or N that reaches water courses, only that which is lost from a particular land area, for example, in the case of erosion, sediment may be deposited on more gentle slopes before reaching a water course. Comparison of P losses through drainage and erosion are also outlined later while Figure 11 shows the distribution of those losses. Losses to drains are greatest in the south and west and losses by erosion are greatest in the Strathmore/Angus area.

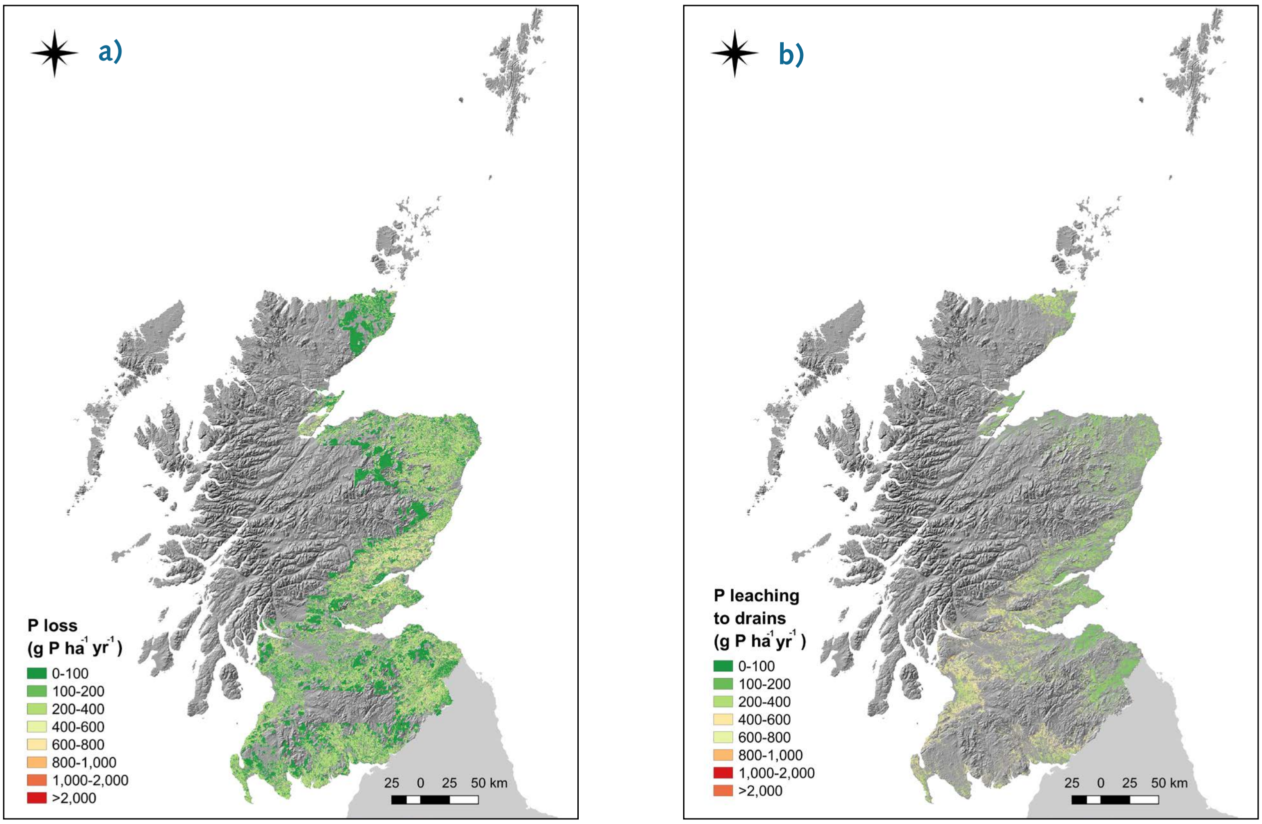


Figure 11. Distribution of P loss (g P ha^{-1} yr^{-1}) due to (a) surface runoff and soil erosion and (b) leaching to drains at 50 m grid resolution for the study area.

• Practical preventative measures and solutions to prevent or minimise losses of pollutants

The following are general measures that can be taken to prevent or minimise pollutant losses from drain-flow and some examples will be covered in more detail.

1. Maintain functional field drainage by having them cleaned out by jetting and regularly clearing drainage ditches.
2. Drainage water management and treatment: have drains discharge onto buffer strips rather than directly to water courses or use of sustainable above ground drainage systems (swales, sediment traps and constructed wetlands).
3. Soil P levels should be maintained close to optimum extractable-P concentrations to avoid excess P and reduce P losses.
4. Using cover crops, avoiding surface broadcast of slurry through the winter or ensure use of slow-release P fertilisers.

Field drainage

The PEPFAA code and Farming and Water Scotland provide practical guidance for farmers in Scotland on how to minimise the risks of environmental pollution from farming operations (Reduce Diffuse Pollution Risks in Farming. Know the regulations. (farmingandwaterscotland.org)). Functional field drainage is important for achieving soil nutrient retention and minimising losses of pollutants but the requirement to maintain drainage was removed from cross compliance in 2015. Current practical guidance promotes the maintenance of functional field drainage to ensure continued benefit (Farm Advisory Service TN720, 2019). Guidance recommends that drainage outlets or outflows are kept clear and regularly inspected. Drains should be cleaned out by jetting and drainage ditches should be cleared regularly (AHDB, 2015; Cloy et al., 2016; SEPA (Supporting Guidance (WAT-SG-96) (sepa.org.uk) and PEPFAA (PEPFAA: Do's and Don'ts Guide 2005 - Soil protection and sustainability (everysite.co.uk)).

Field drainage systems may need to be better managed, but they cannot be removed. The effectiveness of land drains will decline due to collapse or blockages and maintaining or replacing them is costly and can, in many cases be beyond the financial capacity of the farm business. Due to cost, the majority of agricultural drainage in Scotland was installed using subsidies that are no longer available. Poorly designed or managed drainage systems are thought to exacerbate runoff and erosion risks. If a new drainage system is required, a thorough site and soil investigation is recommended. Current guidance also states that smaller lateral drains that act as interceptors on sloping land should run across the slope and the use of more expensive permeable infill in drains is recommended as it can prolong the drains use and help connect to mole drains (AHDB, 2015; Cloy et al., 2016). Improved drainage design has been suggested as a method for reducing nutrient losses but evidence available in the literature is still lacking. For example, King et al. (2015) reported that tile drain spacing was found to have little impact on P transport.

Options to mitigate artificial drainage transfers of nutrients

There are contradictory research findings and practical recommendations for minimising diffuse pollution losses from drain-flow. For example, Cuttle et al. (2016) suggested 'allowing field drainage systems to deteriorate' as a method for mitigating diffuse pollution. Also, Kleinman et al. (2015) stated that dredging of drainage ditches should not be recommended because of the disturbance it causes and its potential to increase the erosion of banks. Regarding artificial drainage systems, tile drainage has been reported to decrease P loss associated with surface runoff (McDowell et al., 2001) but a review by King et al. (2015) highlighted that high P concentrations are often found in tile drains, where soils are prone to preferential flow and/or in drainage systems with surface flow inlets.

The loss of NO_3^- via artificial drainage is a key delivery route to tackle. This has been tried via controlled drainage, whereby, control structures (e.g., valves on drains) reduce drainage in certain circumstances (e.g., when no trafficking of the field is required in winter) to induce a higher water table zone of denitrification (reducing NO_3^- in subsurface runoff, although potentially increasing gaseous N losses). The valves are then opened fully during cultivation periods (Randall and Goss, 2008). Another mitigation action for N is the technique of passively (via control box structures) allowing tile drain water to be discharged onto the surface of suitable soils (that have enough organic matter to promote denitrification) in wet buffer zones (Jaynes and Isenhart, 2019). A further design of a wet buffer zone is reported by Zak et al. (2019), with integrated buffer zones (IBZ), whereby, artificial drains are cut back from direct delivery to the watercourse. The water discharges instead into a small linear wetland parallel to the natural stream with nutrient uptake into a zone of tree rooting and via sedimentation of particles into an overspill filtration bed.

Mitigation of subsurface P flow to watercourses

Researchers have consistently found that topsoil and subsoil texture, P-sorption capacity and P saturation need to be taken into consideration during fertiliser management practices. To avoid excess P and reduce P losses, soil P levels should be maintained close to optimum extractable-P concentrations from fertiliser recommendations (Andersson et al., 2015; Bergstom et al., 2015; Kleinman et al., 2015; SRUC TN668, 2015; Johnston & Dawson, 2005). Christianson et al. (2016) devised the '4R approach' for managing nutrients - applying the right nutrient source at the right rate, right time and right place. Kleinman et al. (2015) suggested that use of tillage in fine textured clay soils that brings subsoil to the surface, increases P sorption capacity and that tillage breaks up macropores and disconnects flow pathways between surface soils and tile drains thus minimising subsurface P losses. Other practices have been recommended specifically for mitigating subsurface P flow to watercourses (Hart et al., 2004; King et al., 2015; Kleinman et al., 2015), these include:

i. The use of carefully designed drainage ditches to remove excess water from agricultural fields.

ii. Stabilisation of banks by vegetation.

iii. Drainage water management and treatment (e.g., using drainage filter or buffer strips).

iv. Using cover crops.

v. Constructed wetlands.

vi. Liming clay soils.

vii. Using slow-release P fertilisers such as direct-application phosphate rock (DAPR) instead of soluble P fertilisers.

Practices in the field, as well as at the field edge, can affect diffuse pollution pathways via artificial drainage. With the ubiquitous nature of drainage in agriculture in the UK it remains that any source controls at the field scale, for example, accurate use of fertilisers aiming to match crop offtakes informed by soil testing, will limit the pathway of N and P via subsurface drainage. In especially problematic areas of high N and P concentrations, and/or sensitive waterbodies, edge-of-field options, for example, drain water interception and removal from direct connections to watercourses, could additionally be used.

Sustainable drainage systems

Duffy et al. (2016) recently produced a practical guide for Scottish farmers and landowners seeking to use above ground drainage systems (Rural Sustainable Drainage Systems) that act as physical barriers to trap pollutants and reduce diffuse pollution. Examples include: sediment traps and sediment trap bunds, swales, ponds and constructed farm wetlands (Duffy et al., 2016).

• Costs associated with identified preventative measures and solutions

Table 15 summarises the likely benefits, the pathways addressed, the practicality of implementing these measures/actions and the cost. For more detail and information on each aspect see Appendix 4. The numbers in the left-hand column relate to those in Table A4.1 in Appendix 4.

	Action	Cost of implementation[a]	Level of reduction	Practicality
4	Increase soil organic matter content (including chop and incorporate cereal stubble)	Low	Medium	Incorporate more crop residues and cover crops
5	Suitable crop for the soil texture and slope	Low	Medium	Needs consideration on drilling and current crop rotation
6	Adopt and use fertiliser plan	Low	Medium	Very practical and should be encouraged
7	Reduced cultivation – conservation tillage where appropriate	Low	Medium	Practical but potential increase in herbicide use, difficult to correct any soil compaction issues
8	No tillage – conservation tillage where appropriate	Low	Medium	Practical but potential increase in herbicide use
9	Leaving land in stubble and/or crop residues	Low	Medium	Benefits to this management straightforward to employ
11	Use of VESS to detect compaction and soil structural degradation	Low	Low	Training maybe needed but easy to employ
15	Change cropping from veg. to cereals or cereals/veg. crop to grassland	Medium	High	Practicality depends on crop rotation and farm type
21	Use of green or cover crops	Medium	Medium	Cost implications but easy to implement
22	Undersown spring cereals	Medium	Low	May have cost implications if extra machinery is required
23	Soil compaction alleviation in grassland soils and tramline disruption in arable crops	Medium	Low	Needs specialist equipment but easy to employ
25	Grass boundaries or filter strip, especially at the bottom of slopes	High	High	Depends on slope of the farm fields and crops grown
26	Cultivate soils in the spring not autumn, including slurry and manure incorporation	High	Medium	If suitable to the crop rotation and access to manure and slurry
27	Establish and maintain wetland areas and/or water retention ponds	High	Medium	Needs consideration in location and suitability of the fields
28	Implementation of field drainage	High	Medium	Cost of implementation and the knowledge for a suitable scheme
30	Agro-forestry	High	Medium	Cost implications and consideration of suitable fields

Table 15. Benefits and the practicality of implementing measures/actions and the cost to reduce or alleviate transport of potential pollutants through artificial drainage systems (based on Appendix 4, Table A4.1).

[a] Colours indicate level of cost – green = low cost (<£250 or <£50/ha), yellow = medium cost (<£500 or <£150/ha) and red = high cost (>£500 or >£250/ha).

• Impacts on water quality if solutions were put in place

Artificial drainage improvements

Contradictory findings for mitigating diffuse pollution via artificial drainage systems have been reported for the impacts on water quality resulting from practical recommendations or improvements. For example, Haygarth et al. (1998) found that subsurface movement, not in association with artificial drains, can decrease P loss by as much as 30% but Nash et al. (2015) reported an 80% reduction in P from clay-pan soils that were managed using tile drainage vs free subsurface drainage. Interestingly, King et al. (2015) also found that tillage had minimal impacts on reducing P loss to tile drains. Williams et al. (2015) studied the effect of tillage on P losses from artificial drains and found that the incorporation of surface applied fertilisers into soils reduced the risk of P losses through tile drains and there is more discussion of tillage practice effects in the review by Gramlich et al. (2018). Hence, there are trade-offs in the transfers of P to drains via macropores where no-till situations exist compared with the action of conventional ploughing that disrupts macro-pores, and hence, connectivity. Quantifying trade-offs of tillage management (no-till, strip till, conventional tillage) on P sources and P transport in artificial drainage is necessary to define the correct mix of practices (Kleinman et al., 2015).

The use of carefully designed integrated buffer zones for mitigating nutrient losses has been found to be effective for both N and P loss mitigation, including via the artificial drainage pathways (Zak et al., 2019). Feyereisen et al. (2015) found that replacing open surface drain inlets with blind or gravel inlets reduced the total suspended sediment and P losses to surface waters.

• Knowledge gaps and recommendations for future research

The relationship between land drainage and diffuse pollution should be fully characterised. The important role of land drainage in supporting modern agriculture in Scotland is little researched but, due to high installation and maintenance costs, a decline in the effectiveness of land drainage can be expected which may prompt a change in policy as yield and profitability decline. It will be important to fully understand the role of land drains to ensure that any policy changes do not exacerbate diffuse pollution issues. Lilly et al. (2012) suggested that there is a need for a national scale assessment of the extent and condition of current drainage in Scotland, similar to studies undertaken in England and Wales. Further, there is a need to fully characterise the relationship between land drainage and diffuse pollution to inform best practice and policy development. As a first step towards filling the knowledge gap with regards to the state of agricultural drainage systems in Scotland, it would be useful to consider gathering basic drainage information during the IACS census exercise.

More research is needed to evaluate models that look at the P transport to and into drainage systems (Kleinman et al., 2015). Dils and Heathwaite (1999) found that field drains were effective conduits for P export from agricultural catchments and recommended that controlling P loss from agricultural sources depended on better understanding of surface and subsurface transport pathways. The scarcity of drainage P information has been identified as a critical gap in scientific understanding (Christianson et al., 2016). Bol et al. (2018) hypothesised that climate change could increase the amount of P available from the soil and recognised the need for better understanding and ability to predict effects of climate change on P flux. There are key knowledge gaps in the understanding of nutrient losses from artificial drainage compared to losses from natural drainage. The available literature that Gramlich et al. (2018) were able to draw on in their review of the effects of artificial drainage on nutrient losses was limited. Regarding this current report, the literature concerning drainage in the UK comprised ~20 studies, but these were dominantly of drainage effects on peat (i.e., of limited agricultural capacity) and half of these were prior to 1980. Drainage design and longevity is another area that merits investigation as contradictory findings have been reported. Feyereisen et al. (2015) recommended further investigation into the longevity of blind and gravel inlets.

Leaching

While the movement of solutes to drains can be considered as leaching, it is also the flow or infiltration of water and both soluble and insoluble pollutants down through the soil profile into groundwater. The range of pollutants includes agro-chemicals, phenols, pathogens. Perhaps the most prevalent pollutant in terms of diffuse pollution from land-based activities is NO_3^-. Nitrate is soluble and does not readily bind to soil surfaces and so is relatively easily transported to groundwaters and then to surface waters. Nitrate vulnerable zones (NVZs) were introduced in Scotland in 2002/3 to protect surface waters and ground waters by reducing diffuse pollution from NO_3^-. The areas designated were based on surface water catchments and covered around 14% of Scotland.

• Scale and extent of the problem

The introduction of NVZs was intended to reduce the pollution of surface and groundwaters by NO_3^- from agricultural activities through a series of regulations designed to control the timing and amount of organic and inorganic fertiliser applied to land. Initially, four NVZs were designated covering around 14% of Scotland (Moray/Aberdeenshire/Banff and Buchan; Strathmore/Fife; Lothian and Borders; Lower Nithsdale). While there was some land removed from the NVZs in 2016, new areas were added (now approximately 11% of Scotland).

The current land area under NVZ regulation is shown in Figure 12.

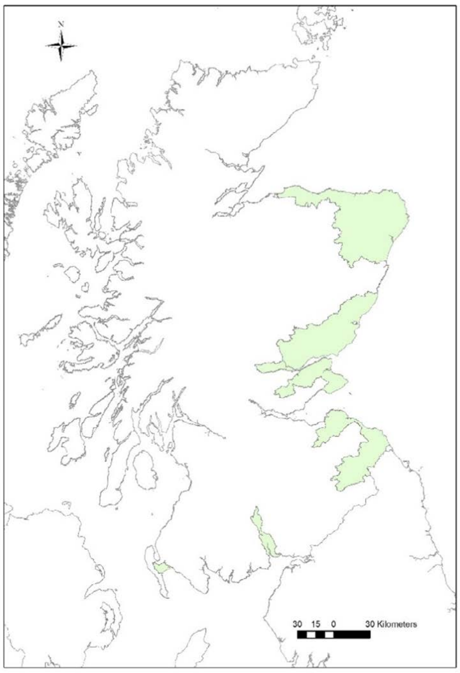


Figure 12. Distribution of current (2020) Nitrate Vulnerable zones in Scotland. © Crown copyright and database right (2020). All rights reserved. The James Hutton Institute, Ordnance Survey Licence Number 100019294.

• Practical preventative measures and solutions to prevent or minimise losses of pollutants

The NVZs were designed to limit the amount of NO_3^- concentrations in surface and groundwaters to <50 mg L^{-1} and there are already regulations in place to limit the movement of NO_3^- to surface and groundwaters (European Parliament, 2000).

• Costs associated with identified preventative measures and solutions

Table 16 summarises actions that can be taken to provide likely benefits, the pathways addressed, the practicality of implementing these measures/actions and the costs. For more detail and information on each aspect see Appendix 4. The numbers in the left-hand column relate to those in Table A4.1 in Appendix 4.

• Impacts on water quality if solutions were put in place

Water quality has improved to the extent that the area of land initially designated as NVZ and been reduced and only 6 of the 403 groundwater bodies monitored by SEPA are classed as poor due to the NO_3^- concentration (https://www.sepa.org.uk/data-visualisation/water-classification-hub).

• Knowledge gaps and recommendations for future research

There is a considerable body of work on the leaching of NO_3^- to groundwater and subsequent impacts on surface water. This coupled with an extensive monitoring network and regulations on the timing and amount of N fertiliser that can be applied within the areas designated as Nitrate Vulnerable, would suggest there are few gaps in our knowledge and limited scope for future research. In the case of more complex P leaching processes, however, more research is needed.

Hotspots

In this review, hotspots are areas of land with specific land management features (e.g., feeding troughs, gateways) that result in the application and concentration of pollutants that can be rapidly released in association with runoff or drainage.

Agricultural land use (e.g., livestock) and land management decisions (e.g., grazing intensity) influence the presence of feeders, water troughs and gateways in fields with livestock. These features are landscape 'hotspots' representing high risk areas for nutrient loss to water where applied nutrients are rapidly released in association with runoff or drainage (Withers et al., 2006).

Table 16. Actions and the practicality of implementing measures/actions and the cost to reduce or alleviate leaching of N to groundwaters outwith current NVZ regulations (based on Appendix 4, Table A4.1).

	Action	Cost of implementation[a]	Level of reduction	Practicality
2	If needed, move feeders and water troughs to reduce extensive soil damage	Low	High	Depending on water points this should be straightforward but could have cost implications to establish water points and could cause extra damage depending on how wet the field
6	Adopt and use fertiliser plan, including timings of application and liming	Low	Medium	Very practical and should be encouraged
9	Leaving land in stubble and/or crop residues	Low	Medium	Benefits to this management straightforward to employ
10	Timing of agricultural practices – keep off tramlines in winter, if possible	Low	Low	Should be done as often as possible depending on the field conditions
13	Beetle Banks	Medium	High	Has cost implications and needs consideration of field
15	Change cropping from veg to cereals or cereals/veg crop to grassland	Medium	High	Practicality depends on crop rotation and farm type
18	Avoid wetter fields to reduce poaching and surface capping by reducing grazing in wet conditions	Medium	Medium	Needs to consider grazing rotation, weather and field condition
21	Use of green or cover crops	Medium	Medium	Cost implications but easy to implement
26	Cultivate soils in the spring not autumn, including slurry and manure incorporation	High	Medium	If suitable to the crop rotation and access to manure and slurry
28	Implementation of field drainage	High	Medium	Cost of implementation and the knowledge for a suitable scheme
31	Establish new hedges	High	Low	Cost of implementation

[a] Colours indicate level of cost – green = low cost (<£250 or <£50/ha), yellow = medium cost (<£500 or <£150/ha) and red = high cost (>£500 or >£250/ha).

Areas of nutrient 'hotspots' which are of moderate soil erosion risk include: livestock feeding, watering, sheltering and access points and outdoor pig rearing areas.

Areas around gates can become compacted due to traffic being concentrated in these areas leading to runoff and sediment transport.

• Scale of the problem

There was a scarcity of information about 'hotspot' diffuse pollution pathways. Vulnerable areas receiving fertiliser and slurry applications and fields containing livestock with feeders, water troughs and gateways are seen as 'hotspot' risks, but other less obvious hotspots include the mobilisation of particulate P from drainage ditches during heavy flow, particularly where the ditches have P bound to iron-rich sediments (Baken et al., 2016).

• Practical preventative measures and solutions to prevent or minimise losses of pollutants

Identification of individual land management 'hotspots' where intervention measures can be taken is the most promising means of reducing total pollutant loads. Examples are provided below:

Cultivation near water courses

Care must be taken when cultivating soils close to water courses as risks of soil loss are increased. The Water Environment (Controlled Activities) (Scotland) Regulations 2011, as amended, contain Diffuse Pollution General Binding Rules which state that there must be no cultivation within 2 m of the top of the bank of any surface water. Therefore, a buffer strip of 2 m must be left uncultivated (ploughing the field within 2 m and then only sowing seed starting 2 m into the field would not comply with these rules) (SEPA, https://www.sepa.org.uk/regulations/water/diffuse-pollution/diffuse-pollution-in-the-rural-environment/).

Animal movements near water courses

Livestock trampling banks of water courses either when grazing and gaining access to drinking water or moving from field to field is a cause of vegetation loss from the banks and through poaching, subsequent soil erosion. This leads to increased transport of the soil particles into the water course and associated nutrient pollution. Livestock standing in the water can also increase perturbation and add further N and P through their dung and urine. Fencing along the banks of the water course prevents access and if animals need to be moved through the stream, then a suitable bridge with fencing at either side for safety should be used.

Livestock and grazing management practices, equipment and field access

One way of reducing diffuse pollution 'hotspots' is for less intensive grazing by reducing stock numbers. Effective grazing rotations and reducing the length of the grazing season, thereby avoiding autumn and winter trampling and poaching, was found to result in three times greater water infiltration (Stavi et al., 2011). Reducing grazing times in wet fields would also prevent soil structural damage, although this would incur an extra feeding cost if the animals were housed or as a result of less efficient use of the grassland on wetter fields. Another additional cost could be from increased slurry being spread from the extra housing of the animals. Reducing profit on the farm is not practicable for the majority of farmers, although making sward management less intense with more reliance on grass/clover swards to replace the fertiliser costs with biologically fixed N and increased forage protein would be beneficial. A reduction in replacement rates in dairy farms would also result in less animals kept on farm.

Other effective livestock management practices for reducing 'hotspots' of localised compaction and surface runoff include moving feeders and water troughs if necessary, managing field corners, moving/adding gateways to fields, reducing stocking rates and strip grazing across the slope (Bailey et al., 2013; Cuttle et al., 2016).

Farming and Water Scotland provide information and guidance for farmers to help reduce diffuse pollution risks from rural land use, including information about grant schemes (see Farming and Water Scotland and Scottish Government websites). This initiative helps farmers comply with regulations such as minimum legal working distances from water courses and encourages use of grass margins, fencing off livestock from rivers and streams and the use bridges for animal movements across streams.

• Costs associated with identified preventative measures and solutions

Table 17 summarises the likely benefits, the pathways addressed, the practicality of implementing these and related measures/actions and the cost. For more detail and information on each aspect see Appendix 4. The numbers in the left-hand column relate to those in Table A4.1 in Appendix 4.

Table 17. Additional actions, cost of implementation, level of reduction and the practicality of implementing measures/actions to reduce or alleviate the effects of hotspots (based on Appendix 4, Table A4.1).

	Action	Cost of implementation[a]	Level of reduction	Practicality
1	No cultivation within 2 m of a water course	Low	High	Easy to implement
2	If needed, move feeders and water troughs to reduce extensive soil damage	Low	High	Depending on water points this should be straightforward but could have cost implications to establish water points and could cause extra damage depending on how wet the field
3	Don't travel over fields in wet conditions or reduce access if unavoidable to reduce compaction	Low	Medium	If possible, reduce traffic depending on the weather conditions and the time of the year
11	Use of VESS to detect compaction and soil structural degradation	Low	Low	Training maybe needed but easy to employ
12	Move gateways – add gateways to the field	Medium	High	Expense of new gates and could affect hedge rows
13	Beetle Banks	Medium	High	Has cost implications and needs consideration of field
18	Avoid wetter fields to reduce poaching and surface capping by reducing grazing in wet conditions	Medium	Medium	Needs to consider grazing rotation, weather and field condition
19	Fence off livestock from rivers and streams	Medium	Medium	Cost of fencing and contractors but easy to implement
23	Soil compaction alleviation in grassland soils and tramline disruption in arable crops	Medium	Low	Needs specialist equipment but easy to employ
24	Remove management of field corners	Medium	Low	Needs consideration in relation to the crop being grow
25	Grass boundaries or filter strip, especially at the bottom of slopes	High	High	Depends on slope of the farm fields and crops grown
27	Establish and maintain wetland areas and/or water retention ponds	High	Medium	Needs consideration in location and suitability of the fields
29	Use bridges for animal movements across streams	High	Medium	Cost of bridges would be high but would help maintain banks and herd foot health
30	Agro-forestry	High	Medium	Cost implications and consideration of suitable fields

[a] Colours indicate level of cost – green = low cost (<£250 or <£50/ha), yellow = medium cost (<£500 or <£150/ha) and red = high cost (>£500 or >£250/ha).

• Impacts on water quality if solutions were put in place

The localised and often transient nature of hotspots makes it difficult to assess what impact they currently have on water quality and remain as a gap in our knowledge. Cuttle et al. (2016) estimated the effectiveness of various mitigation measures on N and P diffuse pollution using seven different model farm scenarios. Estimates of reduced 'hotspots' N and P losses are summarised in Table 18. For further information see Appendix 4 and Table A4.2.

• Knowledge gaps and recommendations for future research

There was a scarcity of information about 'hotspot' diffuse pollution pathways. Management strategies for preventing and minimising diffuse pollution need to identify 'hotspots' where pollutants are rapidly released into watercourses. Vulnerable areas include those receiving fertiliser and slurry applications and fields containing livestock with feeders; water troughs and gateways are seen as 'hotspot' risks, but other hotspots include the mobilisation of particulate P from drainage ditches during heavy flow (Baken et al., 2016). Given the temporal nature of hotspot contribution to diffuse pollution there is a case for also considering 'hot moments'.

Pathways of diffuse pollution summary

- **Soil type, climate, landscape characteristics and land management contribute to diffuse water pollution.**
- **Arable soils in England showed that tramlines represented the dominant pathway for surface runoff and transport of sediment, P and N from cereal crops. This is also likely to be the case for Scotland.**
- **Drains provide a pathway for the delivery of sediment and N and P to surface waters but the dominant pathway of diffuse pollution is through erosion and sediment transport. This erosion and sediment transport is increased and exacerbated by damage to soil structure and trafficking.**
- **One of the key causes of poor soil structure is compaction caused by trafficking along tramlines, therefore structural degradation and tramlines contribute to losses of N and P from Scottish agricultural soils.**
- **Reducing traffic when the soil is close to field capacity would reduce the potential for compaction, this can be achieved by considering the timing of operations.**
- **Use of controlled traffic farming (CTF) has been shown to improve 'untrafficked' soil structure and water movement and storage in Scotland but tramlines (which are necessary for CTF) are a dominant pathway of diffuse pollution.**
- **Alleviation of topsoil and subsoil compaction is recommended, with ploughing for arable crops as well as amendment of the soil through increased organic matter, tied ridging with potatoes and surface spiking and sward lifting in grasslands.**

Table 18. Summary of effectiveness of different mitigation options on hotspot N and P losses (based on estimations from Cuttle et al., 2016). Taken from Appendix 4, Table A4.2.

Mitigation option	N loss reductions	P loss reductions
Avoid applying manure at high-risk times	1-12 kg N ha^{-1}	manure P 25% clay loam soils 50% sandy loam soils
Construct bridges for livestock crossings of rivers and streams	0-1 kg N ha^{-1}	soil P 50% manure P 1%
Fence off watercourses from livestock	0-1 kg N ha^{-1}	soil and manure P 50%
Avoiding applying manure to high-risk areas	0-1 kg N ha^{-1}	manure P 40%
Reduce livestock numbers	10-25 kg N ha^{-1} dairy 3-5 kg N ha^{-1} beef	soil, manure and fertiliser P 18-35%
Move livestock feeders and troughs	0-1 kg N ha^{-1}	soil and manure P 15%
Move gateways	No effect	7.5%
Placement of manure heaps away from watercourses and drains	0-1 kg N ha^{-1}	manure P 4%

- **Alleviation of subsoil compaction is more costly and difficult.**
- **Reduction of tramlines and aligning them across the slope, reduced or no tillage, spreading of machinery loads as evenly as possible over a larger tyre diameter, use of correctly inflated very flexible tyres, delaying of tramline establishment and use of buffer strips (3D buffers recently shown to be promising) all can reduce the effect of tramlines on pollutant and sediment transport.**
- **The use of either very flexible tyres, or tramline disruption using a spiked harrow, has been shown to significantly decrease losses of sediment, N and P from Scottish soils under winter sown combinable crops.**
- **Up and down tramlines were shown to increase surface runoff from Scottish soils by around 50% compared to untrafficked or ploughed areas.**
- **Improvements in water quality were shown for a range of vulnerable English soils after the use of the following mitigation options: tramline disruption, minimum tillage, crop residue incorporation, contour cultivation and beetle banks.**
- **Conservation tillage systems are beneficial to soil and water quality but choice of tillage system should be flexible depending on specific conditions such as soil surface and structural conditions before crop establishment, preceding crop and amount and decomposition status of plant residues.**
- **The use of rotations, cover crops and CTF offer opportunities to realize the full benefits of no-till.**
- **Reducing the source of nutrient loss by employing nutrient management plans, growing suitable crops for the soil type, retention of stubble, contour farming and controlling the out-flow of field drains before they reach a water course need to be considered.**
- **Use of Nitrate Vulnerable Zones, control of cultivation and animal movements close to water courses help control N leaching but further research is needed to address P leaching.**

Assessing the relative contribution and spatial distribution of diffuse pollution pathways for P and N

Phosphorus loss

Assessments of P loss due to the surface pathways, subsurface pathways and artificial drains were a) combined to produce an assessment of total P export from both pathways for the study area (phase 6 of the soil map of Scotland (partial cover)) (Figure 13a,b) compared the relative importance of each pathway of P diffuse pollution; this was done only for an area identified as likely to have been drained where values for both pathways were calculated (Figure 13b).

Based on Table 19, mean P loss due to runoff and soil erosion ranged from 94.4 g P ha^{-1} yr^{-1} for LUI-1 (rough grazing) to 650 g P ha^{-1} yr^{-1} for LUI-6 (dominant crops are potatoes, maize and root vegetables). These values are comparable to published results of P loss from different land uses (D'Arcy and Frost, 2001) and indicate that intensive cultivation methods can pose a greater risk for P diffusion pollution due to runoff and soil erosion. Conversely, permanent grassland systems (LUI-2) were found to have the greater mean values of P leaching to drains compared to arable land with cereals (LUI-3 and LUI-4) and potatoes and other root vegetables and maize (LUI-5 and LUI-6), despite having the lowest soil P status (expressed by modified Morgan's P) (Table 19). This was because of incoming rainfall and subsequently estimated drain-flow in grassland systems being greater than in other cultivated land, as result of grasslands being located at higher altitudes therefore receiving greater total precipitation. Grassland systems also had higher mean P loss due to runoff and soil erosion than arable land with cereals (LUI-3 and LUI-4) due to the slightly higher erosion rate estimated for grasslands on mineral soil (Table 19). This estimate comes from a recent report on the cost of soil erosion in Scotland (Rickson, et al., 2020) and was based on observations most likely from reseeded pasture in England and likely to over-estimate the erosion rate on grassland. Total P export was highest for the more intensive land uses (LUI-5 and LUI-6) and lowest for areas of rough grazing (LUI-1), but P export from improved grassland was greater than in cereals, due mainly to the greater contribution from P leaching through drains in grasslands.

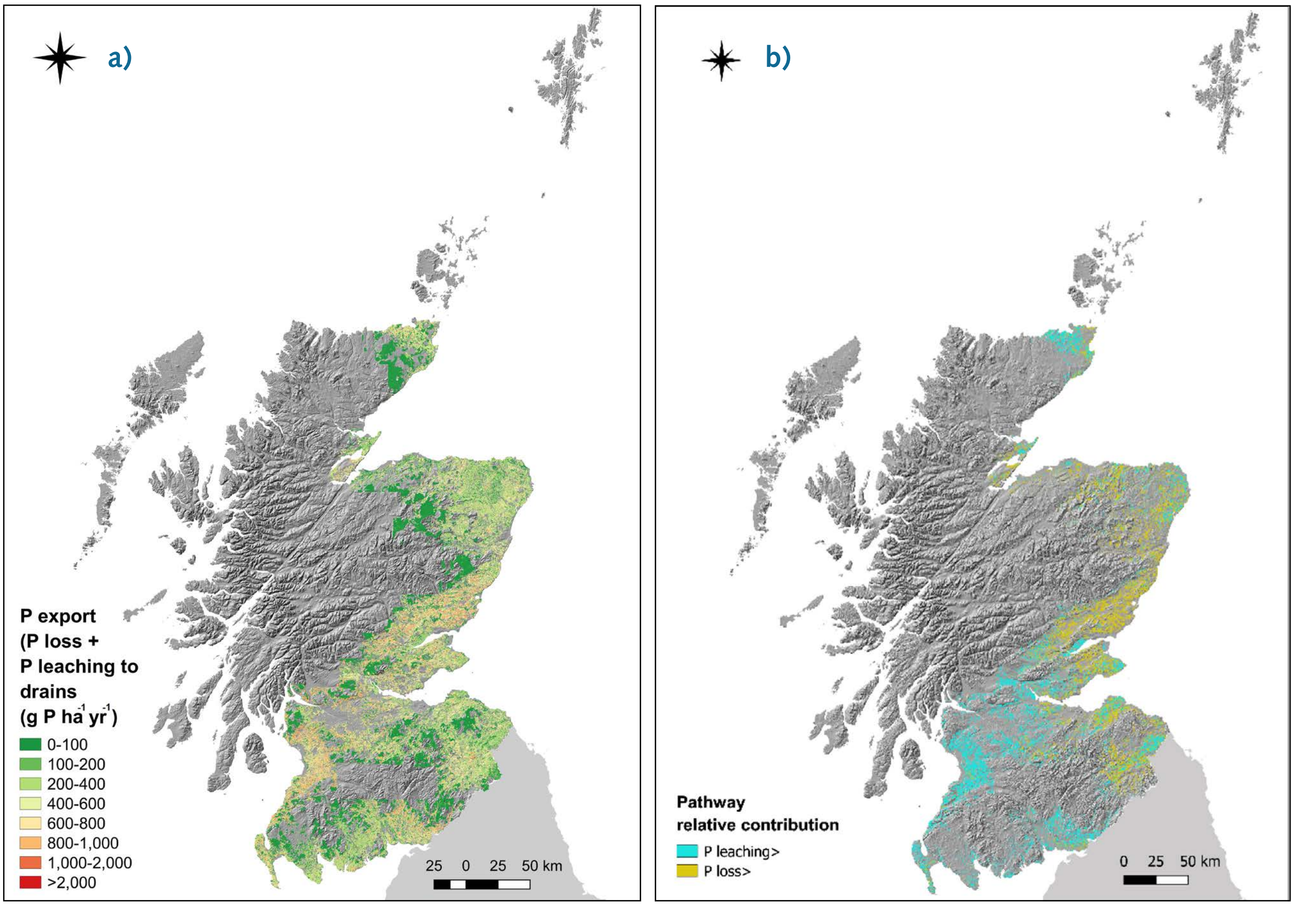


Figure 13. Maps at 50 m grid resolution of a) P export (g P ha^{-1} yr^{-1}) as the sum of P loss from the surface and subsurface pathways and b) relative importance of P pathways of diffuse pollution; blue areas indicate where values of P leaching to drains are greater than values of P loss due to runoff and soil erosion.

The statistics for P loss due to runoff, soil erosion and P leaching to drains were calculated using P values of individual 50 m grid cells in the study area and in the area likely to have been artificially drained, respectively. No P leaching from drains was calculated for LUI-1 (rough grazing) because the LUI-1 area was not included in the assessment of the land likely to have been artificially drained.

P loss due to runoff and soil erosion for almost 90% of the study area ranged from 15 to 650 g P ha^{-1} yr^{-1} (Table 19). Extreme P loss values of above 2000 g P ha^{-1} yr^{-1} covered a small area of just 3.81 km^2 where land use intensity and respective soil erosion rates were high (LUI-5 and LUI-6) and the soil was peat, thus had the highest probability of soil erosion occurrence (Tables 20 and 21). This is most likely to be the result of spatial inconsistencies caused by the combination of the land use intensity and soil erosion risk datasets and led to P loss values that were considered to be unrealistic. P leaching to drains was found to be between 200 to 400 g P ha^{-1} yr^{-1} for more than half of the area likely to have been drained. Overall, total P export for almost half of the study area was found to be between 15 to 400 g P ha^{-1} yr^{-1}, with only 1.6% of the area being above 1200 g P ha^{-1} yr^{-1}.

Table 19. Mean values and standard deviation (±) of P loss due to runoff and soil erosion, P leaching to drains (on land likely to be drained) and combined P export (g P ha^{-1} yr^{-1}) for each Land Use Intensity (LUI) class.

LUI class	P loss (g ha^{-1} yr^{-1})	P leaching to drains (g ha^{-1} yr^{-1})	P export (g ha^{-1} yr^{-1})
LUI-1	94.4 ± 41.6	-	94.4 ± 41.6
LUI-2	376 ± 173	514 ± 137	601 ± 304
LUI-3	314 ± 190	323 ± 75	483 ± 240
LUI-4	306.4 ± 183	348 ± 82	489 ± 251
LUI-5	586.8 ± 312	350 ± 70	767 ± 386
LUI-6	650 ± 456	435 ± 100	808 ± 524

Table 20. Areal extent (in km²) and percentage covers (%, in brackets) of P range classes for P loss due to runoff and soil erosion, P leaching to drains and combined P export.

P range classes (g ha^{-1} yr^{-1})	P loss mapped area in km² (%)	P leaching to drains mapped area in km² (%)	P export mapped area in km² (%)
15 - 200	8414 (44.1)	16 (0.2)	6611 (34.6)
200 - 400	3756 (19.7)	3606 (54.9)	2601 (13.6)
400 - 600	4955 (26.0)	2192 (33.4)	3707 (19.4)
600 - 800	1555 (8.1)	748 (11.4)	2696 (14.1)
800 - 1200	326 (1.7)	2 (0.0)	3163 (16.6)
1,200 – 1,600	53 (0.3)	0 (0.0)	242 (1.3)
> 1,600	25 (0.1)	0 (0.0)	63 (0.3)

The assessment of P pathways relative importance showed that P leaching to drains was greater than P loss due to runoff and soil erosion for 55% of agricultural land likely to have been drained, but there were differences between land uses (Table 21). P leaching to drains was the most important pathway of P diffuse pollution in permanent grasslands (74% of total grassland area), but runoff and soil erosion contributed more to P diffuse pollution in 84% of the area covered by root vegetables in rotation (LUI-5 and LUI-6). In arable land with cereals, relative pathway importance was slightly greater for runoff and soil erosion than for leaching to drains. It seems clear that different pathways are dominant in different land uses requiring a targeted approach to mitigation.

Table 21. Areal extent (in km²) and percentage covers (%, in brackets) of pathways of diffuse P pollution per land use intensity (LUI) class.

Land use intensity (LUI) classes	Greater: P loss due to runoff & soil erosion	Greater: P leaching to drains
LUI-2	806 (26)	2283 (74)
LUI-3	442 (54)	370 (46)
LUI-4	926 (52)	864 (48)
LUI-5	771 (83)	153 (17)
LUI-6	38 (88)	5 (12)
Total Area	2982 (45)	3675 (55)

Overall, the methodology for quantifying P export from agricultural land and for assessing the relative importance of different pathways of P diffuse pollution is based on a robust scientific understanding of P transport mechanisms and on recent and best-available scientific evidence. However, due to the complexity of modelling processes related to P transport, there is a substantial degree of uncertainty in the results and therefore need to be treated with caution. For example, the range of soil erosion rates for different land uses is quite wide and this may lead to overestimations or underestimations of P loss for different land uses, while data used for assessing dissolved and total P concentrations in drain-flow come from a limited number of samples and studies in Scotland. Finally, there are important gaps in our knowledge of where drains have been installed, their performance and capacity, thus we can only make assumptions for their location and the volume of water that goes through them annually. However, despite all the uncertainties mentioned, the results of this assessment clearly indicate that intensive land management practices increase the risk of soil compaction and soil erosion that can cause P diffuse pollution and subsequently affect the quality of receiving watercourses. In addition, this analysis highlighted the importance of leaching to artificial drains as a pathway to diffuse pollution in cultivated soils with imperfect or poor natural drainage, especially for permanent grassland systems and for cereals. Contrary to sediment-bound P lost due to runoff and erosion, drains facilitate direct connectivity to adjacent watercourses and an important fraction of total P in drains is in dissolved form. Thus, the impact of P leaching to drains on watercourses could be more direct and immediate than P locked in sediments, transported to river systems through runoff and erosion, that then needs to be released to have any impact on water quality.

Nitrogen leaching to drains

The method used for assessing potential N leaching was based on combining annual rates of leachable N with the soil's infiltration capacity (Figure 14). Leachable N was expressed as the residual nitrogen (N) that is in excess of crop needs after the crop has been harvest or at the end of the growing season (Lilly et al., 2001) and was based on broad crop categories derived from the Agricultural and Horticultural Census (Table 22). In the modelling we have assumed that the crop will utilise the available N during the growing season such that the N losses are predominantly during the winter months. These categories were translated to IACS crop categories and mean leachable N rates were calculated for the 2007-2015 period and were assigned to each 50 m grid cell of the agricultural area likely to have been artificially drained.

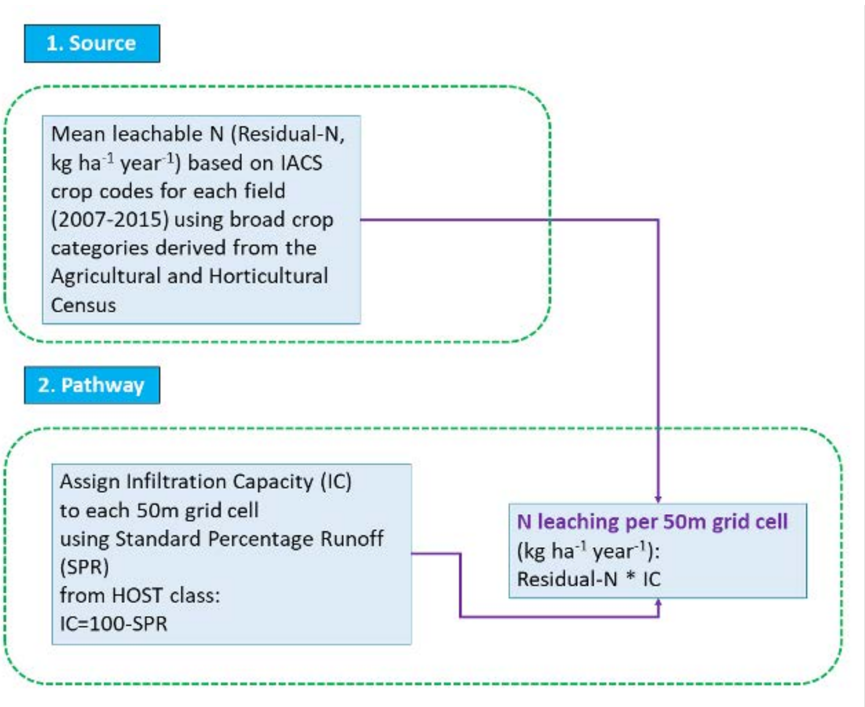


Figure 14. Flowchart of steps used to assess N leaching in the area of each 50 m grid cell.

Contrary to P, there is no numeric relationship that links leachable N rates with N concentrations in drain systems in Scotland. Therefore, we used a process-based approach whereby the amount of N likely to leach from the soil (to drains or groundwaters) is dependent on the soil's infiltration capacity (IC), i.e., the proportion of annual incoming rain that goes through the soil and is not lost to surface runoff. IC was calculated as the inverse of the soil's Standard Percentage Runoff (SPR) and converted to a proportion rather than a percentage. SPR is a hydrological index that indicates annual surface runoff capacity of soils and have been assigned to Scottish soils using the Hydrology of Soils Types (HOST) classification (Boorman et al., 1995). The rationale for this approach was that more dense, wetter soils with lower IC will pose a lesser risk of diffuse pollution as N (most likely in the form of NO_3^-) will not have the capacity to quickly infiltrate the soil and reach the drainage system. The spatial distribution of N leaching within the area of interest is shown in Figure 15.

Table 22. Potential leachable N (kg N ha^{-1} yr^{-1}) for broad crop categories derived from the Agricultural and Horticultural Census.

Crop categories	Leachable N (kg N ha^{-1} yr^{-1})
Set-aside and fallow	100
Cereals	50
Oilseed rape (including linseed)	70
Potatoes	90
Peas and other outdoor vegetables for human consumption	110
Fodder beet	90
Brassicas for stockfeeding	70
Fruits	85
Grass for mowing	75
Grass for grazing under 5 years old	50
Grass for grazing 5 years old and older	15
Rough grazing	1
Woodland	1
Semi-natural vegetation	1

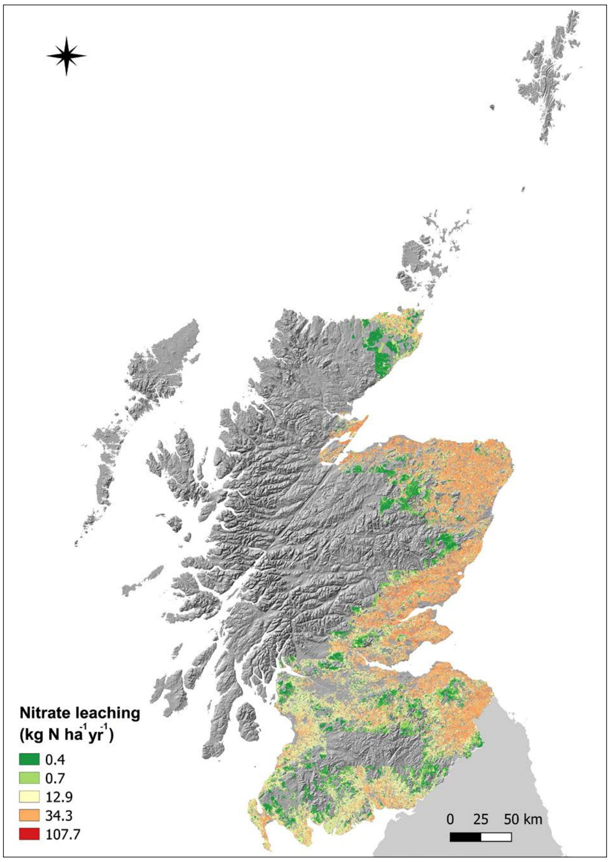


Figure 15. Map of N leaching rates (kg N ha^{-1} yr^{-1}) at 50 m grid resolution for the study area. © Crown copyright and database right (2020). All rights reserved. The James Hutton Institute, Ordnance Survey Licence Number 100019294.

Mean leachable N for the 2007-2015 period was found to increase with land use intensity (LUI) and ranged from just 1.27 kg N ha^{-1} yr^{-1} for rough grazing to 77.39 kg N ha^{-1} yr^{-1} for root vegetables in rotation (Table 23). Mean infiltration capacity was similar for almost all LUI classes and ranged from around 65% to 69%, except for LUI-1 that had mean infiltration of around 54%, indicating the presence of rough grazing in denser and wetter soils. Finally, mean rates of N leaching to soil were also found to increase with LUI class and ranged from 0.70 kg N ha^{-1} yr^{-1} for rough grazing to 53.41 kg N ha^{-1} yr^{-1} for root vegetables in rotation (Table 23).

Summary and comparison of relative contributions

With the caveats around the modelling of P losses by erosion and through drains in mind, a comparison of the relative difference between the amount of P lost can be made by land use intensity class (Table 23). An estimated 582 t P are lost by soil erosion annually and 282 t P are estimated to be lost through drain-flow. While it appears that losses by erosion are double that of the loss through drains, there are additional potential pollutant losses of N in drain water and groundwaters that may reach the river to take into account when considering relative contributions to diffuse pollution. Additionally, while drain water almost always enters rivers and streams through drainage ditches, eroded sediment may be trapped by buffer strips or be deposited in-field. Additionally, losses through drains only occur where the land is imperfectly, poorly or very poorly drained whereas soil erosion by overland flow can occur almost anywhere. Table 24 shows the comparison of P losses by erosion and through drains and Table 25 shows the same but only for the land area that is likely to be drained.

Table 23. Mean and standard deviation (±) values per land use intensity (LUI) class of mean leachable N for the 2007-2015 period (kg N ha^{-1} yr^{-1}), infiltration capacity (IC, %) and rates of N leaching (kg N ha^{-1} yr^{-1}).

Land use intensity class	Mean leachable N (kg N ha^{-1} yr^{-1})	Infiltration capacity (%)	N leaching rate (kg N ha^{-1} yr^{-1})
LUI-1	1.27 ±1.32	53.99 ±13.94	0.70 ±0.87
LUI-2	24.73 ±14.68	65.41 ±12.92	16.39 ±10.77
LUI-3	46.41 ±9.83	67.91 ±12.45	31.61 ±9.14
LUI-4	53.99 ±7.54	67.83 ±12.40	36.58 ±8.26
LUI-5	58.92 ±7.51	67.69 ±13.12	39.88 ±9.32
LUI-6	77.39 ±15.03	68.89 ±13.78	53.41 ±15.45

Table 24. Annual estimated relative losses of P through soil erosion and drain-flow for the area covered by the phase 6 soil map or Scotland (partial cover).

Land use intensity	P loss by erosion (kg)	P loss through drains (kg)	Total P loss (kg)
LUI-1	48605.6	--	48605.6
LUI-2	266820.5	158922.6	425743.1
LUI-3	48583.6	26189.8	74773.4
LUI-4	104525.6	62230.8	166756.4
LUI-5	105308.6	32383.2	137691.7
LUI-6	7853.3	1905.0	9758.4
Total	581697.2	281631.4	863328.7

Table 25. Annual estimated relative losses of P through soil erosion and drain-flow for the area of Scotland likely to have artificial drainage systems.			
Land use intensity	**P loss by erosion (kg)**	**P loss through drains (kg)**	**Total P loss (kg)**
LUI-1	155.2	0.0	155.2
LUI-2	108356.7	158922.6	267279.3
LUI-3	23838.2	26189.8	50028.0
LUI-4	52118.0	62230.8	114348.8
LUI-5	58285.2	32383.2	90668.4
LUI-6	3089.6	1905.0	4994.6
Sum	245842.9	281631.4	527474.3

A more detailed description of the methods used to determine P (and N) loss is given in Appendix 3.

Relative contribution and spatial distribution summary

- **An index of land use intensity (LUI) was developed to identify the spatial distribution of management and cultivation practices to assess management impacts on diffuse pollution risk.**
- **P loss due to runoff and soil erosion across Scotland have been estimated for combined soil erosion and LUI classes.**
- **P leaching to drains was greater than P loss due to runoff and soil erosion for 55% of agricultural land likely to have been drained.**
- **P leaching to drains was the most important pathway of P diffuse pollution in permanent grasslands (74% of total grassland area), but runoff and soil erosion contributed more to P diffuse pollution in 84% of the area covered by root vegetables.**
- **For P loss from arable land with cereals, relative pathway importance was slightly greater for runoff and soil erosion than for leaching to drains.**
- **Surface runoff and erosion are the principal source of P loss in cultivated, drier soils while P loss through drains is the dominant pathway in improved grasslands on wetter soils.**
- **Mean leachable soil N was found to increase with land use intensity.**

Use of Visual Evaluation of Soil Structure (VESS and SubVESS) to identify soil structural degradation and assess diffuse pollution risks

Visual evaluations of soil which can be carried out relatively simply and rapidly, clearly have a role in selecting the most appropriate measures and solutions for preventing or minimising loss of pollutants. The current Visual Evaluation of Soil Structure (VESS) system was developed specifically for identifying soil structural degradation and has been shown to detect major structural differences in unflooded *vs* flooded soils (see Figure 16).

Figure 16. Grassland soil photographs from a) an unflooded site with good friable soil structure with high porosity (VESS score Sq 2) and b) a flooded site that experienced prolonged waterlogging resulting in poor soil structure with Fe oxide mottles and low porosity (VESS score Sq 5). These Dumfriesshire soils were silty

clay loams and sites were 300 m apart. Photographs were taken in winter 2011.

The topsoil and subsoil visual evaluation of soil structure (VESS and SubVESS) methods provide a holistic assessment of current aggregate conditions and macroporosity and allow soil management decisions aimed to improve or maintain soil structural quality (Ball et al., 2007, 2015, 2017; Emmet-Booth et al., 2016; Guimarães et al., 2011). The simple five-point index scoring systems with 'traffic-light' colour schemes, developed using Scottish agricultural soils, are accessible to nonexperts (Ball et al., 2007; Emmet-Booth et al., 2016). Clearly defined scoring frames and photographic keys used in VESS and SubVESS help to minimise subjective errors, but Kraemer et al. (2017) questioned the usefulness of the current VESS system. Guimarães et al. (2011) modified the original system by Ball et al. (2007), due to its subjectivity and a need for an application for soils with different moisture contents (Ball et al., 2007) and textures (Askari et al., 2013; Guimarães et al., 2013). Recent research has highlighted that subjectivity is a modest limitation to methods such as VESS and SubVESS (Guimarães et al., 2017; Mueller et al., 2009). Guimarães et al. (2013) also found that soil texture (comparison of clay and sandy-loam soils) did not cause different VESS results and indeed Mueller et al. (2013) were able to make accurate assessments of soil structural quality in heavy soils with >30% clay content using visual methods. It can be argued that soil structure is a generic indicator of soil quality and although soil type may influence the actual estimate of soil structural quality, the application of the estimate (for example, in highly degraded soils) in terms of soil function is largely independent of soil type. The only exceptions are peaty and sandy soils that have poorly developed structures (Ball et al., 2017). Research has confirmed that reliable and appropriate VESS scores can be consistently identified by a range of different users/practitioners and that different operators typically find very similar scores (Askari et al., 2013; Guimarães et al. 2011, 2017; Emmet-Booth et al., 2018). To link VESS to soil management decisions, multiple samples are preferable especially where taken by more than one operator (Ball et al., 2017).

Here we review evidence for the potential use of VESS and SubVESS scores to identify soil structural degradation and assess diffuse pollution risks under different scenarios (e.g., sloping arable fields with different soil types). Soils with overall (whole block) scores Sq 1 to 2.9 do not require changes in management but Sq≥ 4 relate to poor, degraded structures that require improvement. From Sq 3 to 3.9 the soil structure shows less porosity and more smooth surfaces on aggregates that are larger (up to 10 cm) and are more subangular. Scores in this range of intermediate quality are unlikely to severely affect soil function but need to be monitored to guard against further degradation with improvement suggested where considered necessary. VESS scores compiled for a range of contrasting Scottish agricultural soils under different management scenarios have been collated and assessed, these findings confirmed the VESS scoring system interpretations were reliable and that they have the ability to detect compaction alleviation (e.g., sward lifting compacted grassland). While VESS alone should not guide soil management, soils with scores of Sq ≥4 have poor structure and generally require direct intervention to improve soil quality. An overall score of Sq3 should be monitored more frequently to ensure future management does not result in further damage. Note that a block or layer of Sq 3.5 will contain some soil of score Sq 4 (Ball et al., 2017). If these are close to the soil surface, then they are likely to pose a greater risk of diffuse pollution from surface runoff and erosion, especially in sloping arable fields. Ideally, we recommend that the validity of such thresholds to inform soil management for preventing soil runoff and erosion is supported by other soil quality data such as increased bulk density, resistance to penetration, reduced macroporosity, reduced infiltration rates or other visible features such as evidence of waterlogging (Ball et al., 2017).

Overall, the VESS and SubVESS methods enable semi-quantitative information and good judgement of appropriate, good, moderate or poor states of soil structure for extension and monitoring (Shepherd, 2000; Ball and Douglas, 2003; Ball et al., 2007; McKenzie, 2001). Several authors have shown correlations between VESS and SubVESS with other soil physical measurements, indicating that these methods can reveal differences between land use types and management options (Batey et al., 2015). Building on recent work by Ball et al. (2017), using other available Scottish agricultural soil datasets compiled from SRUC and JHI field assessments, VESS scores were found to be related to a range of relevant soil physical and water retention/flow properties, as summarised in Table 26. Hallett et al. (2016) also found encouraging agreement between compaction risk mapping and VESS scores measured in the field. This study involved assessments of VESS scores in farmers' fields from 800 locations across four catchments in winter 2015-2016. Good soil structure was considered as VESS ≤ 2 and was found for about 60% of topsoils sampled. However, severe soil structural degradation (VESS ≥ 4) was found in 17% of topsoils within the cultivated areas of the fields. Greater topsoil physical degradation was found after harvest of potatoes and carrots. At the untrafficked field edges (taken as a reference for good soil quality), only 5% of topsoils were severely degraded, giving evidence of soil structural degradation induced by farming practice within the main fields. Often the consideration of both topsoil VESS and subsoil SubVESS scores may suggest appropriate management interventions. These management interventions could be mechanical such as restorative tillage or subsoiling if soil conditions are suitable. Also, the application of gypsum or lime (calcium-based) is often recommended to improve aggregation and internal drainage (Ball et al., 2017). Indeed, Bergstrom et al. (2015) found that using lime to improve the structure of clay soils could reduce P losses. This review acknowledges that many slowly permeable soils are naturally compacted (c.20% of mineral soils are naturally 4 or 5 on SubVESS scale) and appropriate management options are recommended bearing this in mind. Whether VESS and SubVESS scores are **natural,** or the result of human impact may not be known but management should avoid risks of structural deterioration. In these cases, such changes in management may be long term and could include adoption of management interventions such as crop rotations, with more abundant or deep penetrating root systems, or practices that increase concentrations of soil organic matter (Ball et al., 2017).

Use of VESS Summary

- **Visual Evaluation of Soil Structure (VESS) and subVESS can be used to assess the structural damage of soils and their susceptibility to erosion and nutrient loss.**
- **Agreement between VESS assessments and compaction risk mapping in Scotland.**
- **VESS and subVESS scores of 3 need to be monitored to ensure no further deterioration of soil structure.**
- **VESS and subVESS scores of 4 and 5 require direct intervention to restore soil structure and prevent potential erosion or nutrient losses.**
- **Greater topsoil physical degradation was found after harvest of potatoes and carrots.**

Conclusions

Diffuse pollution problems resulting from Scottish agricultural soils are heavily dependent on soil conditions

Table 26. Relationships via linear regression or correlation between VESS scores (Sq) and soil physical properties (revised using available Scottish soil data/adapted from Ball et al., 2017).

Soil property	Soil textures/types	Relationship (y = soil property, x = Sq score)	Significance (t-test for regression)	Source
Tensile strength	Clay	$y = 194.48x – 12.353; R^2=0.77$	* $P < 0.05$	Guimarães et al. (2011)
Tensile strength	Sandy	$y = 69.451x – 64.613; R^2 = 0.65$	* $P < 0.05$	Guimarães et al. (2011)
Bulk density	Clay	$y = 0.1209x + 0.8865; R^2 = 0.51$	* $P < 0.05$	Guimarães et al. (2013)
Bulk density	Sandy loam	$y = 0.189x + 0.7914; R^2 = 0.62$	* $P < 0.05$	Guimarães et al. (2013)
Air permeability	Clay	$y = -2.6078x + 12.655; R^2= 0.34$	** $P < 0.01$	Guimarães et al. (2013)
Air permeability	Sandy loam	$y = -3.9507x + 19.168; R^2 = 0.24$	** $P < 0.01$	Guimarães et al. (2013)
Penetration resistance	Clay	$y = 0.6383x + 0.4446; R^2 = 0.65$	* $P < 0.05$	Guimarães et al. (2013)
Penetration resistance	Sandy loam	$y = 0.5187x + 0.0408; R^2 = 0.72$	* $P < 0.05$	Guimarães et al. (2013)
Unsaturated hydraulic conductivity	Sandy loam	$y = -0.476x + 0.18; R^2 = 0.41$	* $\alpha = 0.02$	Moncada et al. (2014)
Air-filled porosity	Silt loam	Correlation, $R^2 = 0.59$	*** $P < 0.001$	Munkholm et al. (2013)
Mean weight diameter of aggregates	Silt loam	$y = 0.422x + 0.572, R^2 = 0.47$	** $\alpha = 0.01$	Moncada et al. (2014)
Bulk density	Scottish Silty clay loam	$y = 0.146x + 0.62; R^2 = 0.97$	*** $P < 0.001$	Hargreaves et al. (2019b)
Bulk density	English Sandy loam	$y = 0.068x + 1.03; R^2 = 0.37$	* $P < 0.05$	Hargreaves et al. (2019b)
Bulk density	Scottish (predominantly sandy)	$y = 0.1204x + 0.8622, R^2 = 0.26$	** $P < 0.01$	Unpublished SRUC and JHI data
Bulk density	Scottish Silty clay loam to silty clay	Correlation, $R^2 = 0.66$	*** $P < 0.001$	Unpublished University of Aberdeen data
Shear vane	Scottish (predominantly sandy)	$y = 22.602x + 15.816, R^2 = 0.70$	** $P < 0.01$	Unpublished SRUC and JHI data
Penetration resistance	Scottish Silty clay loam to silty clay	Correlation, $R^2 = 0.53$	** $P < 0.01$	Unpublished University of Aberdeen data
Saturated hydraulic conductivity	Scottish Silty clay loam to silty clay	Correlation, $R^2 = - 0.48$	** $P < 0.01$	Unpublished University of Aberdeen data

[a]Note that; for other Scottish soil data non-significant correlations were found between VESS and penetration resistance ($R^2 = 0.49$), water stable aggregates ($R^2 = 0.01$), infiltration rates ($R^2 = 0.12$) and air-filled porosity ($R^2 = 0.15$).

(presence of compaction, sloping land, whether there are drains), management practices (cropping decisions, such as spring vs winter cropping, livestock production) and climate (wet winters and heavier, intense periods of rain in summer). It is well established that compaction is an important driver of soil erosion as a pathway for diffuse pollution and that compaction can have a large impact on runoff, water storage and water quality as well as adversely affecting crop production.

The drainage status and infiltration capacity of soils are properties that can change under different soil types and poor management practices and therefore it is more difficult to quantify the contribution of drainage systems to diffuse pollution in agriculture. The structural stability of soils represents a decisive factor for susceptibility of soil to runoff and erosion. Review findings confirmed that the intensification of agricultural practices results in degradation of soil structure and that visual evaluations of soil which can be carried out relatively simply and rapidly, clearly have a role in selecting the most appropriate measures and solutions for preventing or minimising loss of pollutants.

The assessment of P diffuse pollution pathways relative importance showed that P leaching to drains was greater than P loss due to runoff and soil erosion for 55% of agricultural land likely to have been drained (which is around 17% of the land area covered by phase 6 soil map), but there were differences between land uses. P leaching to drains was the most important pathway of P diffuse pollution in permanent grasslands (in 74% of total grassland area), but runoff and soil erosion contributed more to P diffuse pollution in 84% of the area covered by root vegetables in rotation. In arable land with cereals, pathway relative importance was slightly greater for runoff and soil erosion than for leaching to drains.

In this review we conclude that the major agricultural N and P diffuse pollution pathways identified for most of the cultivated land in Scotland (based on the digital soil map (partial cover)) are runoff and erosion exacerbated by compaction and land use. Runoff and erosion contributed an estimated 582 t P yr^{-1}. A further 282 t P yr^{-1} were estimated to be lost through drains which may have a greater impact on the aquatic ecosystem as the water drains directly into the drainage network. Management of nutrient losses to drainage waters and performance of management techniques is site specific and depends on land management, tillage and cropping decisions as well as the maintenance of drains. Soil and particle erosion are the greatest risk to the wider environment, particularly for P. The amount of P lost by leaching to drains (a few kg of P per hectare) is negligible for farmers, in terms of economic value, although the environmental consequence is still significant (Johnson and Dawson, 2005; Fortune et al., 2005). Therefore, recommendations for land management techniques that mitigate pollutant ‘leaching’ to drains and groundwater via soil pore water is likely to be high cost but low yielding in terms of reducing risk of diffuse pollution to the wider environment. This may lead to greater impacts such as further compaction of soil which would increase surface runoff. Leaching is also an important pathway for N pollution from agriculture. However, erosion of soil and particles is a significant source of P through surface runoff.

A summary of cost-effective actions and their level of reduction identified from this review is shown in Table 27 (adapted from Appendix 4, Table A4.1). The colours indicate level of cost where green = low cost (<£250 or <£50 ha^{-1}), yellow = medium cost (<£500 or <£150 ha^{-1}) and red = high cost (>£500 or >£250 ha^{-1}). Actions that are already part of the General Binding Rules, which have a low implementation cost but high level of reduction of erosion include ‘not cultivating within 2 m of a water course’ and ‘moving feeders and water troughs if necessary to minimise the accumulation of pollutants in these hotspot areas’. Actions which are of medium cost of implementation with high levels of reduction include: ‘moving gateways or adding gateways to the field to alter livestock and machinery access points’, ‘incorporate beetle banks’ and ‘changing the cropping cereals to grassland or if this is not possible, avoid damaging crops like potatoes and maize or consider spring instead of winter crops’, although the latter option may not be practicable depending on the farm business or enterprise. Finally,

Table 27. Summary of ‘traffic-lighted’ management costs and levels of reduction and practicality (based on Appendix 4, Table A4.1).

	Action	Cost of implementation	Level of reduction	Practicality
1	No cultivation within 2 m of a water course	Low	High	Easy to implement
2	If needed, move feeders and water troughs to reduce extensive soil damage	Low	High	Depending on water points this should be straightforward but could have cost implications to establish water points and could cause extra damage depending on how wet the field
3	Don’t travel over fields in wet conditions or reduce traffic in wet conditions to reduce compaction	Low	Medium	If possible, reduce traffic depending on the weather conditions and the time of the year
4	Increase soil organic matter content (including chop and incorporate cereal stubble)	Low	Medium	Incorporate more crop residues and cover crops

Table 27. Summary of 'traffic-lighted' management costs and levels of reduction and practicality (based on Appendix 4, Table A4.1).

	Action	Cost of implementation	Level of reduction	Practicality
5	Suitable crop for the soil texture and slope	Low	Medium	Needs consideration on drilling and current crop rotation
6	Adopt and use fertiliser plan, including timings of application and liming	Low	Medium	Very practical and should be encouraged
7	Reduced cultivation – conservation tillage where appropriate	Low	Medium	Practical but potential increase in herbicide use, difficult to correct any soil compaction issues
8	No tillage – conservation tillage, where appropriate	Low	Medium	Practical but potential increase in herbicide use
9	Leaving land in stubble and/or crop residues	Low	Medium	Benefits to this management straightforward to employ
10	Timing of agricultural practices – keep off tramlines in winter	Low	Low	Should be done as often as possible depending on the field conditions
11	Use of VESS to detect compaction and soil structural degradation	Low	Low	Training maybe needed but easy to employ
12	Move gateways – add gateways to the field	Medium	High	Expense of new gates and could affect hedge rows
13	Beetle banks	Medium	High	Has cost implications and needs consideration of field
14	Establish in field buffer strips	Medium	Reduces nutrient loss	Reduces surface water/soil runoff and soil erosion
15	Change cropping from veg to cereals or cereals/ veg crop to grassland	Medium	High	Practicality depends on crop rotation and farm type
16	Cultivate alternating strips of crops across the contour where practical	Medium	Medium	Needs decisions on crop types and the suitability of machinery available
17	Strip grazing across the slope, starting at the highest point of the field	Medium	Medium	Needs extra fencing and labour to move the fences on a regular basis
18	Avoid wetter fields to reduce poaching and surface capping by reducing grazing in wet conditions	Medium	Medium	Needs to consider grazing rotation, weather and field condition
19	Fence off livestock from rivers and streams	Medium	Medium	Cost of fencing and contractors but easy to implement
20	Cultivate across the slope - Re-align tramlines away from the steepest part of the slope	Medium	Medium	Needs consideration of the crop and machinery involved
21	Use of green or cover crops	Medium	Medium	Cost implications but easy to implement
22	Undersown spring cereals	Medium	Low	May have cost implications if extra machinery is required
23	Soil compaction alleviation in grassland soils and tramline disruption in arable crops	Medium	Low	Needs specialist equipment by easier to employ
24	Remove management of field corners	Medium	Low	Needs consideration in relation to the crop being grow
25	Grass boundaries or filter strip, especially at the bottom of slopes	High	High	Depends on slope of the farm fields and crops grown
26	Cultivate soils in the spring not autumn, including slurry and manure incorporation	High	Medium	If suitable to the crop rotation and access to manure and slurry
27	Establish and maintain wetland areas and/or water retention ponds	High	Medium	Needs consideration in location and suitability of the fields
28	Implementation of field Drainage	High	Medium	Cost of implementation and the knowledge for a suitable scheme
29	Use bridges for animal movements across streams	High	Medium	Cost of bridges would be high but would help maintain banks and herd foot health
30	Agro-forestry	High	Medium	Cost implications and consideration of suitable fields
31	Establish new hedges	High	Low	Cost of implementation
32	Reduce vehicle size and/or reduced pressure tyres, use of flexi tyres	High	Low	Could help reduce machinery costs but increase fuel and labour costs
33	Increasing tramline spacing	High	Low	Needs suitable equipment to be available
34	Controlled traffic farming	High	Medium	Needs investment in technology and subscription to GPS systems, organisation of working widths for all traffic

'adding in grass boundaries, margins or filter strips at the bottom of slopes or in-field buffers' is of high cost with a high level of reduction.

Recommendations for preventing diffuse pollution

Knowledge gaps

- This review highlighted that effective land drainage and nutrient management is a fundamental part of modern agriculture but our current evidence of the relationships between specific Scottish agricultural drainage systems that contribute to diffuse pollution, as well as, the location, condition, functioning and flow volumes of these artificial drain systems is limited.
- More research is needed across all pathways. There are also many other knowledge gaps, particularly being able to identify diffuse pollution 'hot spots' in fields within Scottish catchments and our understanding of the impacts of recommended mitigation measures on water quality (as well as gathering more evidence linking VESS scores with water quality degradation).
- There is still uncertainty in erosion rates for soil and land use combinations, in particular the erosion rate for grasslands is likely to be overestimated.
- It is recommended that future research efforts focus on gathering further evidence for the effectiveness of practical diffuse pollution mitigation measures. All measures that have been investigated provide reduced diffuse pollution benefits with cost of implementation being the only potential drawback. More novel measures such as improved drainage design, alternative tramline and wheelings management options and 3D buffer strips should be tested further.
- Further research should be directed towards understanding and comparing the proportion of diffuse pollutants attributed to leaching, soil and particle erosion and surface runoff, particularly connectivity between source and waterbody.
- This review has found that all mitigation measures researched offer reductions in diffuse pollution. Overall, encouraging more farmers and land managers to use recommended practical mitigation measures identified here (focussing on pathways identified as being most important) is essential and indeed this is one of the next tasks within this CREW-funded diffuse pollution project.
- Based on this review, there is insufficient research or scientific understanding of mitigation measures, such as, compaction remediation, tramline and wheelings management, drainage management and treatment methods to definitively identify the methods that would have a cost effective or environmentally positive impact in **all situations and all Scottish soil types and climate**. However, useful UK-relevant research that has been conducted, such as detailed field investigations in England, appear to show that the measures outlined in this report can make a difference.
- Many of the most cost effective and high-level reduction practical measures identified are already included in environmental legislation i.e., 2 m safe working distance from waterways, timing fertiliser (inorganic and organic) applications to avoid periods before heavy rainfall, not applying on frozen or waterlogged land but additional measures need to be promoted more widely in the future to meet water quality targets.

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Appendices

Appendix 1: Drivers of diffuse pollution from agricultural soils

Soil properties and soil management decisions are drivers of diffuse pollution from agricultural soils that influence the pathways by which agricultural pollutants enter the water environment. Key drivers of relevance to each of the specific pathways of diffuse pollution are summarised below:

• Drivers of soil compaction/structural degradation and tramline pathways

Land management, tillage practices and cropping decisions

The combination of land management, tillage practices and cropping decisions influence soil structure. The growing of crops on land with unsuitable soil types such as those which are too fragile to resist the erosive energy of rainfall, runoff and snow melt, or more marginal land with steep slopes > 15% can be a key driver of soil erosion (Jaafar, 2010; Farm Advisory Service TN720, 2019). The rate, intensity and location of soil erosion is strongly influenced by slope, soil type, climate and land management practices (Lilly and Baggaley, 2014).

Tillage erosion occurs on sloping land where there is preferential movement downslope, particularly when ploughing is done up and down the slope (Lindstrom et al., 1992). Problems occur when soil particles are redistributed in response to the force applied by tillage and gravity on slopes. Tillage erosion has been studied extensively internationally (Lal, 1993; Busari et al., 2015; Wingeyer et al., 2015) however, it has been poorly documented in Scotland, which is surprising given the apparent high proportion of arable land in Scotland that is sloping (Farm Advisory Service TN720, 2019). In Scotland over the period 2015 to 2016, 90% of the cultivated landscape is cultivated by conventional inversion tillage compared to only 4% of the land not being tilled and 6% being managed through reduced or conservation tillage (Scottish Government, 2016).

Inappropriate timing of agricultural practises relates to ploughing and harvesting land during winter periods or under wet conditions. Ploughing and harvesting using heavy machinery can cause soil compaction and destroy soil structure. Soil compaction can be caused by the passage of heavy machinery or poaching by livestock reducing the number of large pores in the soil. This restricts water and decreases the amount of oxygen in the soil, which in turn constrains good root establishment and crop growth. Waterlogging can also lead to a reduction in soil physical strength and a breakdown of soil structure further damaging the soil. While topsoil compaction can be readily remedied through ploughing (potentially with a consequent loss of soil organic matter) in arable crops and sward lifting in grassland along with natural processes, subsoil compaction below the depth of ploughing often remains unseen and is more difficult to repair. Late sowing in the autumn and delayed harvesting in the late autumn or winter periods will increase the risks of soil erosion. Both situations will leave the land with a lack of ground cover to protect the soil surface from rainfall impact. Bare soil, exposed to raindrop impact, is at risk of forming crusts that restrict water entry to the soil and thus increase runoff. Exposure of bare soil surfaces to winter rainfall is also likely to result in the development of rills and gullies, and these will increase the rate of on-site soil erosion (Jaafar, 2010). Around 13% of soil on cultivated land in Scotland is left bare over winter compared to 42% which is covered with plant residues and stubbles and equally 42% under winter crops (Scottish Government, 2016). Quantified examples of the different pollution loads arising from poor land-use decisions (rather than agricultural pollution incidents) are given in Table A1.1 (taken from D'Arcy and Frost, 2001) which emphasizes the importance of N losses relative to P losses from the soil structural degradation/compaction pathway.

Table A1.1. Examples of variation in off field pollutant losses resulting from soil structural degradation associated with different land-uses where land-use decision determines the probable diffuse pollution load[a] (taken from D'Arcy and Frost, 2001).

Land use	Estimated total P loss (kg ha^{-1} y^{-1})	Estimated N losses (% of annual N application)
Permanent grass	0.10	5
Autumn sown cereals	0.65	12
Potatoes	0.80	20
Brassicas	0.65	20
Oil seed rape	0.65	30

[a]Nutrient loss coefficients, based on catchment studies of arable fields by Johnes (1996).

Before the 1970s, most agricultural land in the UK was used for the growing of spring-sown barley and winter wheat and the production of grass for cattle and sheep. However, since the 1970s increasing areas of arable land have been autumn-drilled for winter cereals, in response to the better yields (ADAS, 2007). The crop cover provided by winter cereals is low throughout the winter period and exposes the soil surface to heavy rainfall, which can create rills and gullies within the fields. Late harvest and wide row crops like potatoes and maize are more prone to erosion than cereals. Soil degradation from potato cultivation is well known due to excessive tillage and destoning operations (AHDB Potato Council,

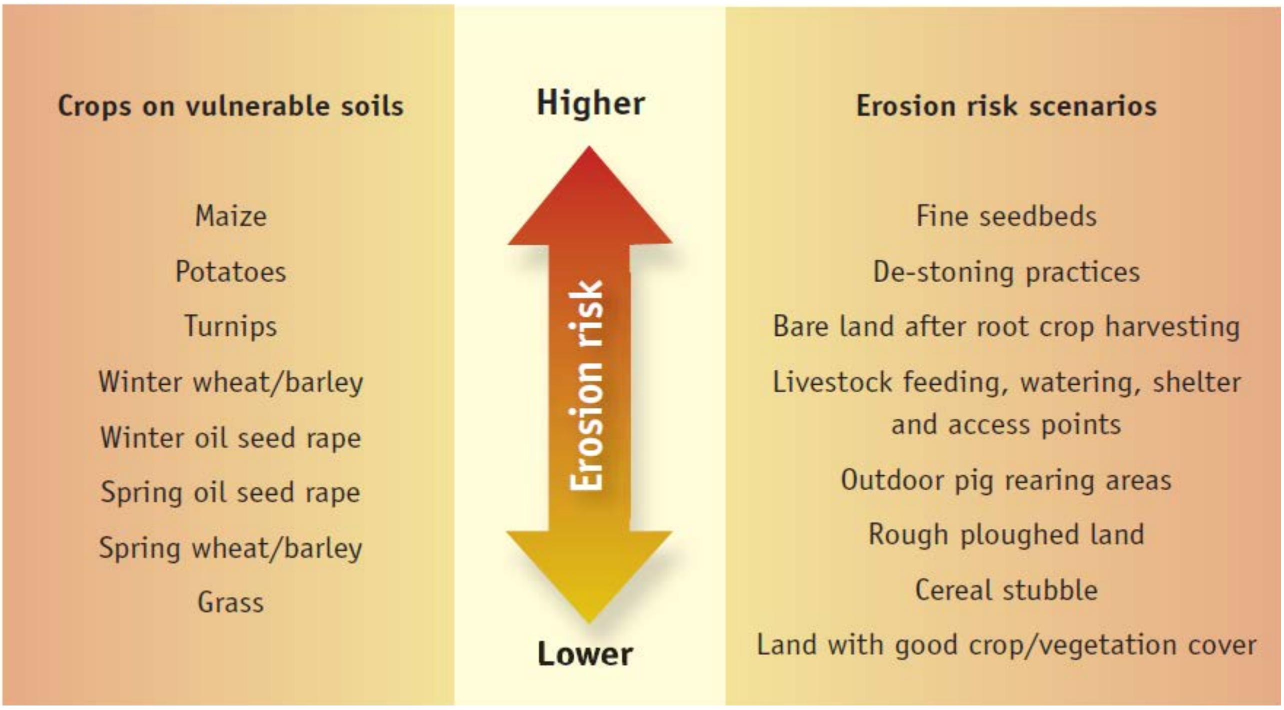

Figure A1.1. Soil erosion risks associated with the growth of different crop types on vulnerable soils and a range of erosion risk scenarios (taken from Cloy et al. (2016) - original source Defra (2005)).

2013) and in recent years, maize growing in the UK has become a major environmental issue due to its association with bare soil during the late autumn or winter period, which frequently coincides with periods of heavy rain (Jaafar, 2010). Defra (2005) advised avoiding growing high risk crops such as maize, potatoes and turnips in high risk scenarios as a way of reducing soil erosion risks (Figure A1.1). The highest erosion risk scenarios are fine seedbeds, de-stoning practices and bare land after root crop harvesting. Low risk crops include spring wheat and barley, and grass and the low risk erosion scenarios include fields with cereal stubble and land with good crop/ vegetation cover.

Susceptibility of soils to runoff and erosion and naturally compacted soils

Soil erosion is the result of three physical processes – the detachment of soil particles from a soil mass, the transport of these particles away from the point of detachment and the deposition of these particles. Detachment occurring in small channels or rills is the result of the forces of flowing water while detachment in the nearly level areas between rills is the result of raindrop impact. The type of erosion occurring, rill or interrill, is determined by soil properties such as texture, organic matter contents, the degree of aggregation and aggregate stability (Young, 1984; Withers et al., 2006).

Poorly structured and compacted soils are associated with an increased risk of runoff and erosion, leading to soil and nutrient losses to watercourses (Alaoui et al., 2018; Batey, 2009; Bhogal et al., 2019; O'Connell et al., 2007; Soane and van Ouwerkerk, 1995) but soil texture and organic matter content may override the influence of poorer soil structure (Cloy et al., 2015). The intensive use of well-drained, sandy and coarse loamy soils in the UK was found to produce surface slaking and a loss of aggregation resulting in increased surface-water runoff from fields that should naturally absorb winter rainfall (Palmer and Smith, 2013). The intensification of agricultural practices commonly results in compaction and degradation of soil structure (e.g., loss of aggregation, decreased diversity of pore sizes and increased bulk density). For soils experiencing the same climatic conditions and the same vegetation cover, well loosened soils have a much higher capability for water storage than compacted soils of the same soil type (Batey, 2009).

Tramlines running up and downslope and the production of fine seedbeds (particularly associated with high-value, root crops) can increase the risk of soil erosion in agricultural land leading to runoff to streams and rivers. Hallett et al. (2016) used the visual evaluation of soil structure (VESS and SubVESS) methods (Ball et al., 2007, 2015, 2017; Guimarães et al., 2011) to assess topsoil and subsoil degradation and found that runoff, erosion and nutrient losses were about 10 times greater from structurally degraded parts of fields such as tramlines than either within the field or at less trafficked boundaries. There is surprisingly limited research on diffuse pollution losses from tramlines and wheelings, but they are a primary transport pathway for surface runoff as they encourage the build-up and channelling of runoff, especially on sloping land (Withers et al., 2006).

Chambers and Garwood (2000) reported that they were associated with 33% of erosion events, particularly during heavy rainfall. Findings from UK field experiments have demonstrated that tramlines, especially on sloping land, are a major source of sediment and nutrient transport (Silgram et al., 2015). Lewis et al (2013) and Lewis (2014) established that in addition to being pathways for nutrient and sediment transport, tramlines were similarly associated with the movement of weed seeds across and from arable fields.

This review acknowledges that many slowly permeable soils have naturally compacted subsoils (c.20% of mineral soils are naturally 4 or 5 on SubVESS scale). Note that GIS analyses of soil datasets allowed identification of where naturally compacted soils are likely to occur to allow more targeted advice to farmers and land managers. The appropriate management options are recommended bearing this in mind.

• Drivers of drain-flow and leaching pathways

Soil conditions

The ability of water and solutes to move through soil influences the drain-flow and leaching pathways. Preferential flow through the soil occurs via cracks, macropores and biopores and drains create preferential flow pathways, so fertiliser bypasses the topsoil and subsoil 'buffers' (King et al., 2015; Kleinman et al., 2015). Soil texture and organic matter content also influence drainage. If drainage is impeded by poor soil physical conditions, the water transport rates to drains decrease, while waterlogging and overland flow increase, leading to greater peak flow and water quality degradation (Wheater and Evans, 2009). Magette et al. (2007) devised a methodology for field hydrological risk assessment for rapid nutrient loss to watercourses. They classed 'waterlogged fields and excessively drained soils' as being high risk, 'imperfectly drained soils' as moderate risk and 'moderately or well-drained soils' as low risk.

Current understanding of agricultural drainage systems in Scotland

The presence or absence of natural or artificial drainage systems determines the importance of drain-flow and leaching pathways. Agricultural land in Scotland has been drained using various methods since the 1700s, with major investment carried out from the 1950s to 1980s encouraged by grant schemes. Currently, the majority of drainage schemes are between 20 and 50 years old with some schemes up to 100 years old (Farm Advisory Service TN720, 2019). Artificial drains represent significant man-made subsurface pathways for diffuse pollution (Withers et al., 2000). King et al. (2015) found that P losses in tile drains were related to high rainfall and high flow events and cooler, wetter months of the non-growing season. Poorly designed or managed drainage systems can exacerbate runoff and erosion risks but there is very little accurate knowledge of existing agricultural drainage systems at both a national and farm level. There is very little, if no, records of current drainage activity in Scotland with most of the understanding based on anecdotal evidence from observations and discussions with drainage contractors. The majority of work carried out currently would be repairs to existing systems with any larger schemes limited to works adjacent to the installation of new linear infrastructure such as roads, pipelines and cable routes.

Lilly et al. (2012) highlighted the importance of effective agricultural drainage systems for mitigating climate change since emissions of the potent greenhouse gas nitrous oxide (N_2O) are promoted by wet soil conditions and therefore emissions are likely to be more prevalent in wetter soils that receive N fertilisers. The relationship between land drainage and diffuse pollution is however more complex as their presence is often the only reason that land can be farmed profitably and therefore drains promote the use of fertilisers and other potential pollutants such as pesticides and herbicides. In addition, land drainage reduces natural rainwater retention that can prevent or limit the loading of surface water from contaminated runoff. The role of land drainage in diffuse pollution cannot be clearly defined as it varies between situations and over time. In addition, it is thought that estimates of the extent and area of naturally imperfectly and poorly drained soils in Scotland, used by Lilly et al. (2012), may have been underestimated.

Artificial drainage and pollution losses from agricultural land

Artificial soil drainage covers extensive areas where productive improved grassland and arable cropping is desired on soils otherwise restricted in natural drainage, or in landscape positions prone to high water tables. The drainage seeks to lower water tables and bypasses the natural slow drainage of the soil matrix and any impermeable layers present to aerate upper soil horizons for root functioning. Hence, artificial drainage has the potential to dramatically alter the natural surface vs subsurface pathways of soil drainage, increase water drainage rates and total fluxes of water and contaminants, expose soils to wet and dry cycling and organic matter mineralisation and to connect new contaminant source areas to watercourses. Despite being extensive, there remains a limited number of studies on how artificial drains alter overall pollutant losses compared to natural drainage in controlled, or before and after studies on intensified agricultural land (Gramlich et al., 2018). Similarly, mitigation actions to control fluxes of nutrients and other pollutants from artificial drains are not widely practiced or reported and this is especially problematic since artificial drainage passes under other forms of mitigation at the land surface such as conventional vegetated buffer (or filter) strips, as the drains are designed to end at and discharge directly into watercourses.

Artificial land drainage effects on nutrient losses

Gramlich et al. (2018) provide an extensive review of the effects of artificial drainage on hydrology, nutrient and other pollutant losses, with focus on European climates. The review covers water flows, soil erosion, N, P and plant protection products. The synthesis from a review of 195 articles shows (with +, / and – indicating the number of individual studies supporting increased fluxes, no effect, or decreased fluxes, respectively) that total annual water flows were increased (27+ : 1-) and that peak water flows were generally increased (23+ : 15-) and this involved decreasing surface runoff and increasing subsurface runoff. The mechanisms of enhanced flows were found to vary with: topography, soil characteristics, drainage design, precipitation regimes and soil management, since competing processes exist. Whilst the action of drains in lowering the water table increases soil storage of rain volume, it is generally thought that the accelerated water velocity towards drain outlets is a key factor. Also, surface runoff may occur through infiltration excess and saturation excess surface runoff and the effect of drains in reducing cases of saturation excess lead overall to drains being a major factor in change from surface to subsurface runoff pathways in drained land. On flat land where surface runoff was negligible anyway, this may have limited effect, but where gentle to moderate slopes were associated with surface soil erosion and co-transport of particle-bound contaminants, the effects of drainage on pollutant losses were greater. Hence, Gramlich et al. (2018) found consensus in the literature of a reduction in surface erosion with artificial drain installation (18-) on all but the flattest sites (<2% slope). The effect of this pathway change on soil nutrients was found to be variable: for total P (where losses are often dominantly of P bound to soil particles and delivered to watercourses via surface erosion) there was a reduction (12- : 1/ : 1+). A similar benefit was found for plant protection products where many of these chemicals, like P, strongly bind to soil particles (3- : 1/). However, for N losses artificial drainage increased total N loss for mineral soils (16+ : 1-) and organic soils (8+). This occurs due to high losses of nitrate (NO_3^-) (with weak sorption to soils) resulting from enhanced N mineralisation and reduced denitrification rates in drained soils combined with the accelerated drainage pathway and increased water fluxes. In contrast, ammonium (NH_4^+) does bind to soil surfaces and was found to be generally reduced in artificially drained systems (in part, also via conversion to NO_3^-).

Concentrations, fluxes and forms of phosphorus via artificial drainage

Johnston and Dawson (2005) argued that very little soluble P is lost from soil in drainage water because soluble P is only a small fraction of the total soil P. Fortune, et al. (2005) investigated P losses in artificial field drainage waters, using $CaCl_2$ measurement of P as an indicator of P leaching losses. They concluded that the amount of P lost by leaching was equal to a few kg of P per hectare – negligible amounts for a farmer in terms of economic value but significant from an environmental perspective.

The review of P losses via drainage by Gramlich et al. (2018) recognised difficulties in the studies that compared artificially drained and naturally drained areas concerning the forms of P contributing to overall losses. Whilst the reduction in particulate P from surface runoff was a dominant effect of artificial drainage, many studies shows elevated concentrations of dissolved P in drain waters compared with natural subsurface runoff. The factors noted in this were that (i) artificially drained areas received greater P fertiliser inputs than comparative naturally-drained areas since they were brought into agricultural condition, (ii) that drains affected the soil redox conditions and led to P mobilisation (Menberu et al., 2017), also (iii) for soils with a high store of available P the connection of this to drainage via preferential pathways led to high P losses via drains. The effect of artificial drainage behaving as an extension of natural soil macropores is very important in P losses via subsurface pathways (Beauchemin et al., 1998; King et al., 2015). As well as losses via P leaching in soils of high soil test P (STP, Modified Morgan's extraction) but low soil P sorption capacity (e.g., sandy soils), the macropore and artificial drainage pathways are capable of high transfer rates of P bound to fine soil particles and colloids (especially prevalent in clay soils) under conditions of even high P sorption status (Chapman et al., 2001; Djodjic et al., 1999; Stamm et al., 1998). *Since literature indicates that nutrient losses from drain-flow pathways are higher than those from leaching pathways, the former pathway will receive most attention in this review.*

With specific respect to Scottish conditions, Stutter and Richards (2018) gained one-off and seasonal artificial drain water and soils from associated drained fields from 28 farms in Scotland. Overall, the range in total P in unfiltered samples was 0.013-4.589 mg P L^{-1} and for filtrate total dissolved P was 0.017-0.295 mg P L^{-1}. Grasslands (n=11) differed from croplands (n=17) with greater Total P (mean of 0.709 mg P L^{-1}), dissolved unreactive P (organically complexed dissolved P; 0.036 mg P L^{-1}) in the drain waters and greater total P and C:P ratios in the soils. Conversely, cropland had greater drain water soluble reactive P to total dissolved P ratios (0.6 compared with 0.2 mg P L^{-1} for grassland), NO_3^- (6.9 mg N L^{-1}) and the cultivated soils had greater P associated with surface

Fe and Al complexes. Soluble reactive P concentrations did not differ between grassland and cropland drain waters (means of 0.032 and 0.021 mg P L^{-1}, respectively). The study found that STP (range 4-19 mg P kg^{-1}) was a significant predictor of both total dissolved P (TDP) and dissolved unreactive P, these relationships were stronger in grassland soils and had more scatter in cropland soils. It was also found that the cropland soils with lowest organic matter content resulted in greater drain water concentrations of soluble reactive P (the form on which the P criteria for freshwaters are set under the Water Framework Directive).

The drain water P concentrations gained from the Scottish survey may be compared with those from other international studies: In England, Heathwaite and Dils (2000) found pasture soils had soluble reactive P and dissolved unreactive P concentrations of 0.02 and 0.01 mg P L^{-1}, respectively, whilst in Sweden, Ulén et al. (2016) reported 0.19 and 0.53 mg P/L, respectively, for pastures. For Danish grazing land, Andersen et al. (2016) reported TDP concentrations generally <0.1 mg P L^{-1} but ~15% of sites had concentrations between 0.1 – 0.4 mg TDP L^{-1}. In the U.S., Williams et al. (2015) showed 0.06-0.14 mg TDP L^{-1} from several cropland fields. In summary high concentrations of P can be delivered via artificial drains in some situations but the mean soluble reactive P concentrations found in Scotland and elsewhere were similar to the concentration thresholds between good and degraded status for UK rivers under the Water Framework Directive criteria. However, the appreciable dissolved unreactive P arising from drainage of pasture soils may also contribute to eutrophication.

• Drivers of hotspots pathways

Agricultural land use (e.g., livestock) and land management decisions (e.g., grazing intensity) influence the presence of feeders, water troughs and gateways in fields with livestock. These features are landscape 'hotspots' representing high risk areas for nutrient loss to water where applied nutrients are rapidly released in association with runoff or drainage (Withers et al., 2001). Areas of nutrient 'hotspots' which are of moderate soil erosion risk (Figure A1.1) include livestock feeding, watering, sheltering and access points and outdoor pig rearing areas.

Appendix 2: Development of an assessment of land use intensity

The current soil erosion risk map is based on the inherent erosion susceptibility, but this can be exacerbated through a wide variety of land management practices, including livestock grazing and cultivation practices, that can lead to soil compaction, presence of anaerobic layers, poor drainage and erosion. These soil management factors depend on cropping systems and directly affect the ability of water to infiltrate with greater runoff leading to soil erosion and loss of sediment-bound P from fields.

In order to take account of how land use can both help mitigate erosion and increase the risk, we adjusted the inherent soil erosion risk using an assessment of land use intensity in order to take account of the effect of different cultivation methods and crop characteristics on the susceptibility to soil erosion and potential for diffuse pollution.

To do this, we assigned crop risk classes to all crop types and land uses present in Scotland based on the list of Integrated Administration and Control System (IACS) codes. A simplified and generic version of this list is given in Table A2.1. Similar crop risk classification schemes have been proposed and used successfully in other P-modelling and P-risk assessment applications (Balana et al., 2012). Also, this particular approach has been recently used in a project for SEPA, which developed a framework for Red-Amber-Green (RAG) assessments to establish the relative P pollution risk for watercourses in Scotland in response to the application of P-rich materials to land (Gagkas et al., 2019). A detailed list of crop risk classes based on IACS codes is given in the Appendix 5.

The classification of crop and land uses to risk classes was based on a set of rules:

- Grasslands were classified as low crop risk because they provide a complete and continuous cover of soil by vegetation that provides sufficient protection against soil erosion due to the stabilizing capacity of the grass's rooting system.
- Crop risk was assumed to be high in land used for root vegetables and potatoes because this land is often left bare during the vulnerable autumn-winter periods and also due to the greater risk of soil compaction and soil aggregate instability caused by the use of heavy machinery and seed-bed preparation.
- For cereals, it was assumed that a field's crop risk class is moderate because these crop types represent an intermediate situation whereby there is adequate annual plant coverage and thus soil protection for part of the year, but cultivation practices may cause some degree of soil compaction, for example, the use of controlled traffic systems. Although winter cereals are assumed to be more susceptible to soil erosion than spring cereals, we assigned the same crop risk class to both in order to avoid over-complicating the crop risk assessment.

Table A2.1. Rules to classify fields into land use intensity classes (LUI) and percentage cover (also shown as Table 7).

Land use intensity (LUI)	Rules	Area (%)*
LUI-1	Rough grazing was the dominant land use in most years	27
LUI-2	Improved grassland was the dominant land use in most years	37
LUI-3	Number of years in grass was greater than number of years in cereals and no root crops grown	8
LUI-4	Number of years in cereals was greater than number of years in grass and no root crops grown	18
LUI-5	Root crops grown in at least one of the 9 years	9
LUI-6	Root crops grown in at least 5 of the 9 years	1

* percentage of area covered by phase 6 soil map (34,314 km^2).

To develop a classification of land use intensity, the crop risk classes were first assigned to the dominant (i.e., with higher areal coverage) crop within individual fields within the IACS database for each of the years from 2007 to 2015 (nine years in total). Table A2.2 shows how the various land use intensity classes vary annually. This dataset was then filtered to include only the 2015 IACS fields (latest available data) to produce a single GIS layer for mapping purposes.

Table A2.2. Proportions (%) of IACS fields per Crop Risk class for the period 2007 – 2015.

Year	Crop risk class		
	Low	Moderate	High
2007	78.6	20.1	1.3
2008	79.1	19.7	1.2
2009	77.6	21.0	1.3
2010	79.2	19.0	1.8
2011	80.2	18.1	1.7
2012	80.1	18.2	1.7
2013	82.5	16.1	1.3
2014	83.0	15.7	1.3
2015	83.1	15.6	1.3

The number of years for each crop risk class (Low, Moderate and High) was counted and then used to assess the land use intensity for each 2015 field during the 9-year period. A 6-class assessment of increasing land use intensity (LUI) for each field (LUI-1=Low -> LUI-6=High), based on the following rules:

- If all years had a Low crop risk, then the field was given a LUI-1 class or a LUI-2 class depending on whether rough grazing or improved grassland was the dominant land use for most years, respectively.
- If number of years with Low crop risk > years with Moderate crop risk and there were no years with a High crop risk, then the field was given a LUI-3 class.
- If number of years with Moderate crop risk > years with Low crop risk and there were no years with a High crop risk, then the field was given a LUI-4 class.
- If at least one year had a High crop risk, then the field was given a LUI-5 class.
- If number of years with High crop risk > years with Low or Moderate crop risk, then the field was given a LUI-6 class.

Adjustment of soil erosion risk by land use intensity

The soil erosion risk map was adjusted using the land use intensity (LUI) classification for the areas covered by the 2015 IACS dataset. This adjustment was done only for areas with mineral topsoils under cultivation, including rough grazing. This resulted in a modified erosion risk map at 50 m grid resolution. The adjustment of soil erosion risk by land use intensity at each 50 m grid cell was performed using the following rules:

- If land use intensity was low (LUI-1 or LUI-2) or lower moderate (LUI-3), then the soil erosion risk was lowered by one risk class.
- If land use intensity was upper moderate (LUI-4), then the soil erosion risk was kept the same.
- If land use intensity was lower high (LUI-5), then the soil erosion risk increased by one risk class.
- If land use intensity was upper high (LUI-6), then the soil erosion risk increased by two risk classes.

The rules for adjusting soil erosion risk by land use intensity are given in Table A2.3.

Overall, adjusting soil erosion risk by land use intensity resulted in 2,437 km^2 more classified as of low erosion risk, 2,077 km^2 less of moderate risk and 360 km^2 less classified as of high erosion risk (Table A2.4). Figure 4 shows the distribution of the erosion risk classes adjusted for land use intensity and the areas where there was a change in the original soil erosion risk map after the adjustment by land use intensity. The addition of land use intensity means that land in the south and west, where grassland is the dominant land, has less chance of eroding, while more intensively managed land in the North East, Strathmore and Angus is more prone to soil erosion. Other changes in erosion risk are less discernible at the scale of map shown.

Table A2.3. Rules for the adjustment of soil erosion risk based on land use intensity (note: there are no areas with soil erosion risk class: L1).

Soil erosion risk classes	Land use intensity				
	LUI-1/LUI-2	LUI-3	LUI-4	LUI-5	LUI-6
L2	L1 (Low)	L1 (Low)	L2 (Low)	L3 (Low)	M1 (Moderate)
L3	L2 (Low)	L2 (Low)	L3 (Low)	M1 (Moderate)	M2 (Moderate)
M1	L3 (Low)	L3 (Low)	M1 (Moderate)	M2 (Moderate)	M3 (Moderate)
M2	M1 (Moderate)	M1 (Moderate)	M2 (Moderate)	M3 (Moderate)	H1 (High)
M3	M2 (Moderate)	M2 (Moderate)	M3 (Moderate)	H1 (High)	H2 (High)
H1	M3 (Moderate)	M3 (Moderate)	H1 (High)	H2 (High)	H3 (High)
H2	H1 (High)	H1 (High)	H2 (High)	H3 (High)	H3 (High)
H3	H2 (High)	H2 (High)	H3 (High)	H3 (High)	H3 (High)

Table A2.4: Area and proportion of each soil erosion risk class on mineral topsoil based on phase 6 of the soil map of Scotland (partial cover) after being modified by land use intensity. The difference between the area of map coverage and the total area of risk class is attributable to water, built up areas and other areas with no soil cover.

Soil erosion risk class	Soil erosion risk		LUI-modified soil erosion risk		Difference	
	Area (km²)	Cover (%)	Area (km²)	Cover (%)	Area (km²)	Cover (%)
L2	275	0.8	1732	5.3	+1457	+4.5
L3	3983	12.2	4963	15.2	+980	+3.0
M1	6559	20.1	6155	18.9	-404	-1.2
M2	6017	18.5	4965	15.2	-1052	-3.2
M3	3407	10.5	2786	8.6	-621	-1.9
H1	1306	4.0	1058	3.3	-248	-0.8
H2	338	1.0	262	0.8	-76	-0.2
H3	74	0.2	38	0.1	-35	-0.1

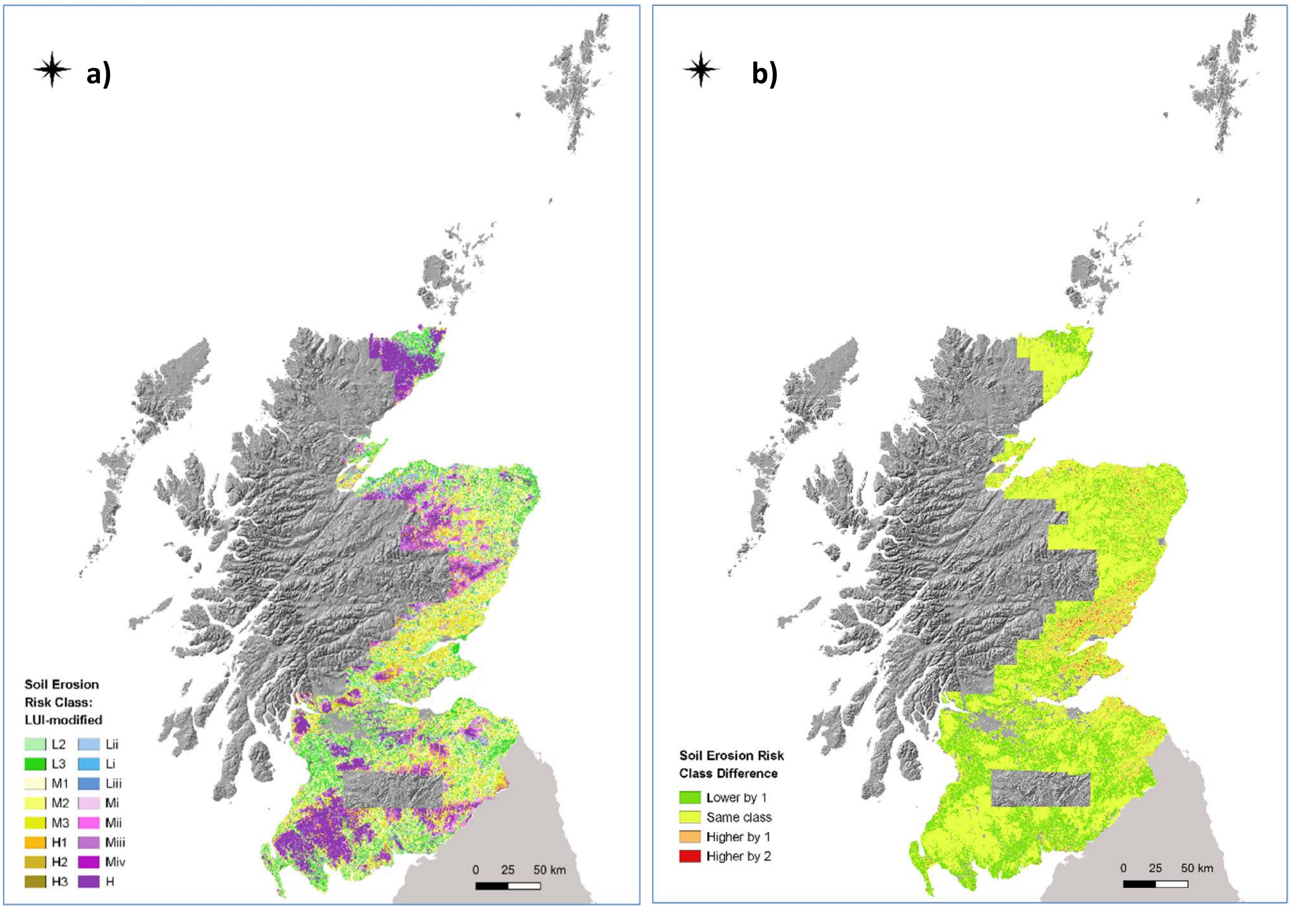

Figure A2.2. Map showing the distribution of a) soil erosion risk classes based on phase 6 of the soil map of Scotland (partial cover) adjusted by the intensity of land use (LUI) and b) difference in classes between the LUI-modified and the original soil erosion risk map. Note this map also shows the erosion risk out with the area of IACS data which will be the same as the unaltered risk mapping. © Crown copyright and database right (2020). All rights reserved. The James Hutton Institute, Ordnance Survey Licence Number 100019294.

Appendix 3: Detailed methodology for assessing the relative contribution and spatial distribution of diffuse pollution pathways for P and N

Introduction

The assessment was developed using linkages between the conceptual understanding of different pathways of diffuse pollution and data and relationships from relevant research findings. The assessment related to the particulate and soluble forms of phosphorus (P) and to soluble N. The assessment followed the approach of the Source-Pathway-Receptor (SPR) model by calculating appropriate values for quantifying pollutant source and export for the main diffuse pollution pathways: surface flow pathway that relates to particulate P loss in sediment due to runoff and soil erosion by overland flow, leaching of P through the artificial drainage system in agricultural soils with imperfect, poor or very poor natural soil drainage and loss of N.

The individual steps of the assessment were used to produce an estimate of pollutant export for each pathway at each 50 m grid cell of cultivated land (including rough grazing for the runoff and soil erosion pathway) within the extent of the Phase 6 of the soil map of Scotland (partial cover). With regards to P, the assessment produced harmonized estimates of P loss for the two pathways (in g P per ha per year) that were combined to estimate a) total P export for the extent of the study area and b) relative importance of each pathway within the area assessed as likely to have been artificially drained. For N, only potential losses from the soil were assessed using estimates of residual N (N excess of crop demand).

Phosphorus (P)

Surface flow pathway

Loss of particulate P due to surface runoff and soil erosion was estimated by combining soil total phosphorus (TP) with soil erosion rates and sediment yields as shown in Figure A3.1.

P-source was calculated as mean soil TP for the 2007-2015 period using crop information from IACS data and soil TP information for different vegetation types from the Scottish Soils Database (SSD) profiles. The SSD vegetation types were linked with aggregated crop categories from IACS data for each year and an average was calculated for the 9-year period; this approach was selected because it reflected the effect of crop rotation on soil P content. All crop categories were found in mineral soil, with the exception of rough grazing that was also be found in peaty soil. Mean soil TP values calculated for each aggregated crop category were the following:

Rough grazing = 940.3 mg kg^{-1} (peaty soil)/ 1016.8 mg kg^{-1} (mineral soil);

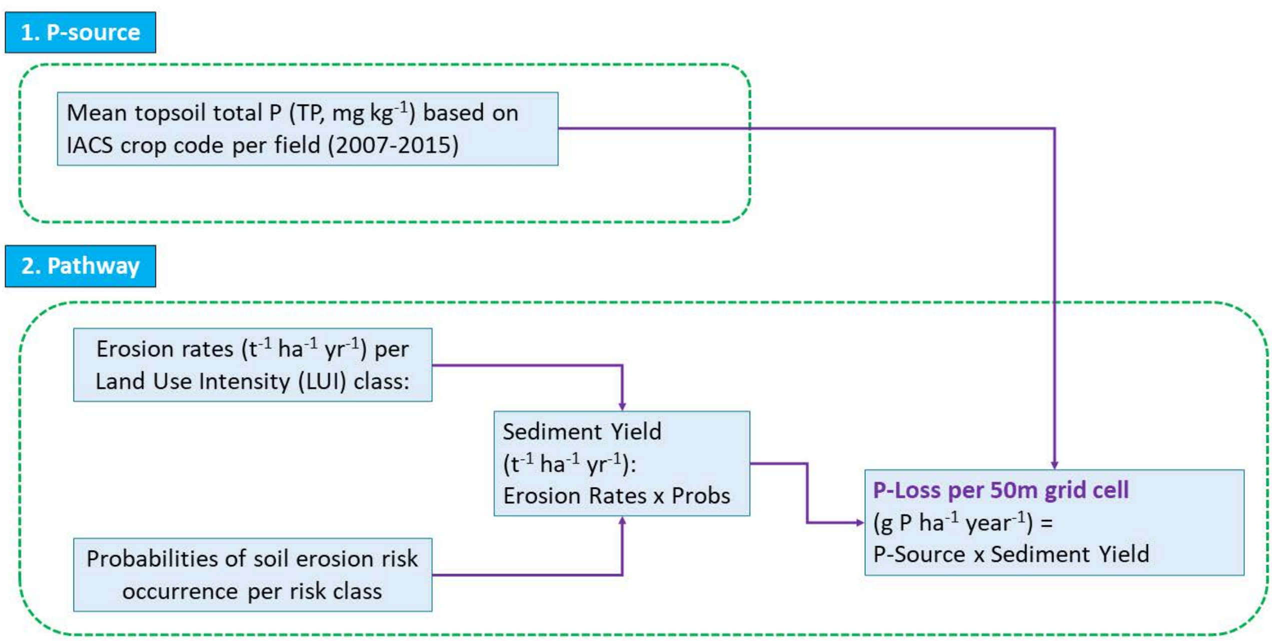

Figure A3.1. Flowchart of steps used to assess particulate P loss due to runoff and soil erosion in the area of each 50 m grid cell.

Permanent grassland = 1132.2 mg kg^{-1};

Cereals = 1237.1 mg kg^{-1};

Potatoes, root vegetables and maize = 1450.7 mg kg^{-1}.

Sediment yields were calculated by combining soil erosion rates with probabilities of occurrence of soil erosion that have been recently developed for Scotland (Rickson et al., 2020). Soil erosion rates were assigned to the Land Use Intensity (LUI) classes developed using the IACS crop information (Figure A3.2) and depending on whether the soil was mineral or peaty (Table A3.1 and 10).

Table A3.1. Soil erosion rates (t ha^{-1} yr^{-1}) by land use intensity class and soil type.

Land use intensity classes	Soil erosion rates (t ha^{-1} yr^{-1})	
	Mineral soil	Soil with peaty surface layers
LUI-1	0.75	0.39
LUI-2	3.00	1.00
LUI-3 & LUI-4	2.40	5.00
LUI-5 & LUI-6	4.30	10.00

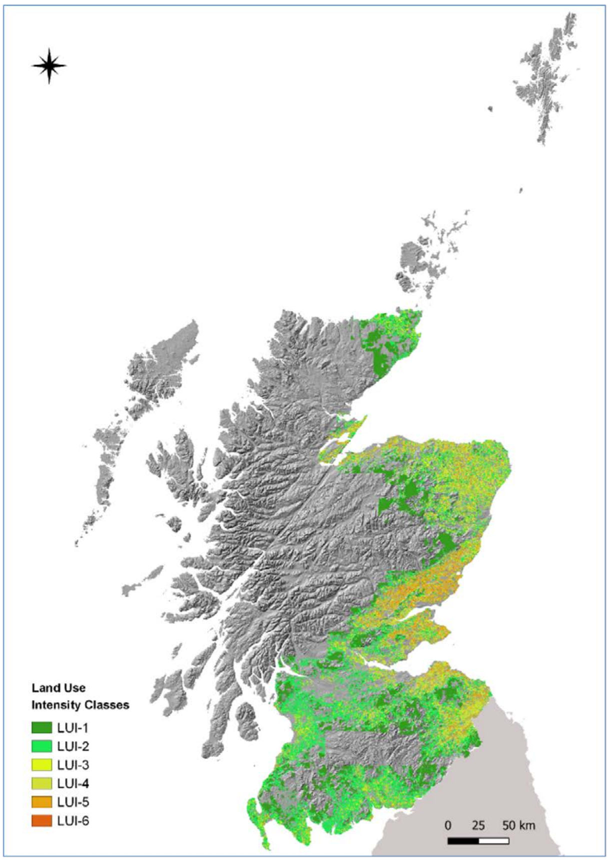

Figure A3.2. Map of land use intensity classes at 50 m grid resolution for the study area. © Crown copyright and database right (2020). All rights reserved. The James Hutton Institute, Ordnance Survey Licence Number 100019294.

Probabilities of soil erosion occurrence were estimated using information from a report for the Scottish Government (Rickson et al., 2020) where the probability of erosion by overland flow occurring in any year on land in each erosion risk class for both mineral and peaty soils was quantified, for example, there is a 2% chance of a field in the low erosion risk class eroding in any given year (Table A3.2 and 9).

Table A3.2. Probabilities (%) of erosion occurring on land in each erosion risk class by soil type.

Soil erosion risk class	Probability of erosion (%)	
	Mineral	Peaty
Low	2%	12%
Moderate	13%	12%
High	24%	31%

Soil TP and sediment yield values at each 50 m grid cell were then combined to produce an estimate of P loss due to surface runoff and soil erosion at each 50 m grid cell (area of 0.25 ha). The spatial distribution of P loss within the study area is shown in Figure A3.3.

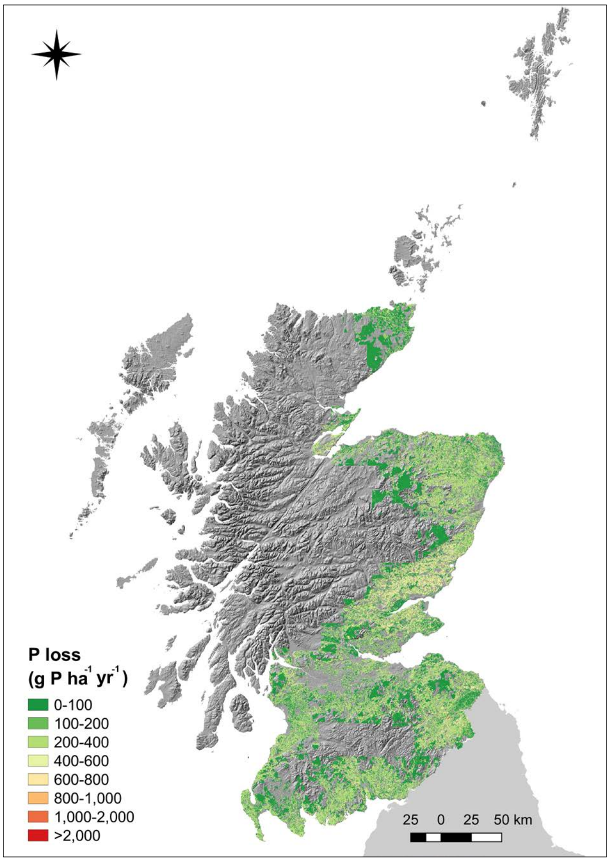

Figure A3.3. Map of P loss (g P ha^{-1} yr^{-1}) due to surface runoff and soil erosion at 50 m grid resolution for the study area. © Crown copyright and database right (2020). All rights reserved. The James Hutton Institute, Ordnance Survey Licence Number 100019294.

Subsurface flow pathway

Leaching of total P (TP) to artificial drains was estimated using published relationships linking agronomic P data with P concentrations in drain-flow in Scottish agricultural catchments (Figure A3.4). Recent research has identified a strong link between agronomic P in the form of modified Morgan's P (MMP) and total dissolved P (TDP) in experiments in agricultural drain systems in Scotland (Stutter and Richards, 2018). Therefore, the basis for the assessment of P leaching to drains was the relationship between MMP and TDP, expressed using a linear regression equation shown in Figure A3.4, and the ratios of TDP to TP in drain-flow, as found in sampled water from drains in grassland and cultivated systems in Scotland. Based on data from Stutter and Richards (2018), TP in drainwater is 3.02 times TDP in grassland systems and 1.95 times TDP in other cultivated land.

In order to make them comparable to estimates of P loss due runoff and soil erosion, TP concentrations in drainwater (mg L^{-1}) were converted to g of P using water flow in drains. Due to the absence of consistent estimates of flow in Scottish drain systems, we used an assumption based on expert opinion that all incoming winter rainfall in agricultural soils with imperfect or poor natural drainage should be diverted to artificial drain systems at an annual period. Mean annual winter (October to March) rainfall was calculated from monthly HadUK gridded precipitation for the 1981-2010 period (1 km^2 grid resolution, Met Office). In the absence of a national dataset of soil P status, the assumption was used that all cultivated soils were in target P within the area identified as likely to have been artificially drained in Scotland. MMP values for different land uses were used from relevant Technical Notes (TN) published by SRUC, which when compared were found to be similar and within the range of measured MMP in soil samples from the study by Stutter and Richards (2018) for the same land uses. The MMP values used were the following:

Grassland = 6 mg L^{-1} (TN652) (SRUC, 2013a);

Cereals = 9.5 mg L^{-1} (TN633) (SRUC, 2013b);

Potatoes (and other root vegetables) = 13.4 mg L^{-1} (TN633) (SRUC, 2013b).

The above MMP values were assigned to the IACS crop information and mean annual MMP values were calculated for the 2007-2015 period at each 50 m grid cell within the study area.

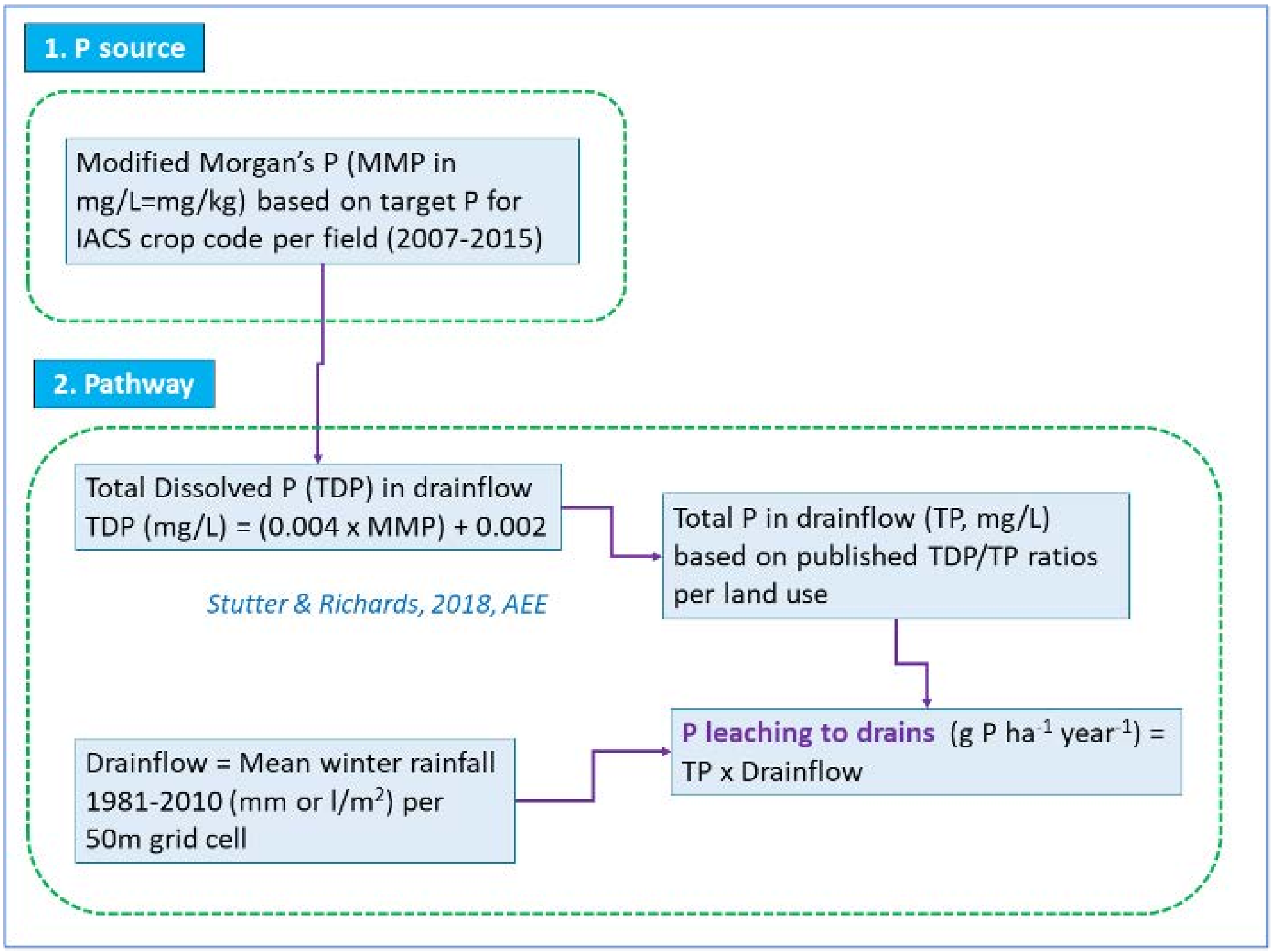

Figure A3.4. Flowchart of steps used to assess P loss due to leaching to drains in the area of each 50 m grid cell.

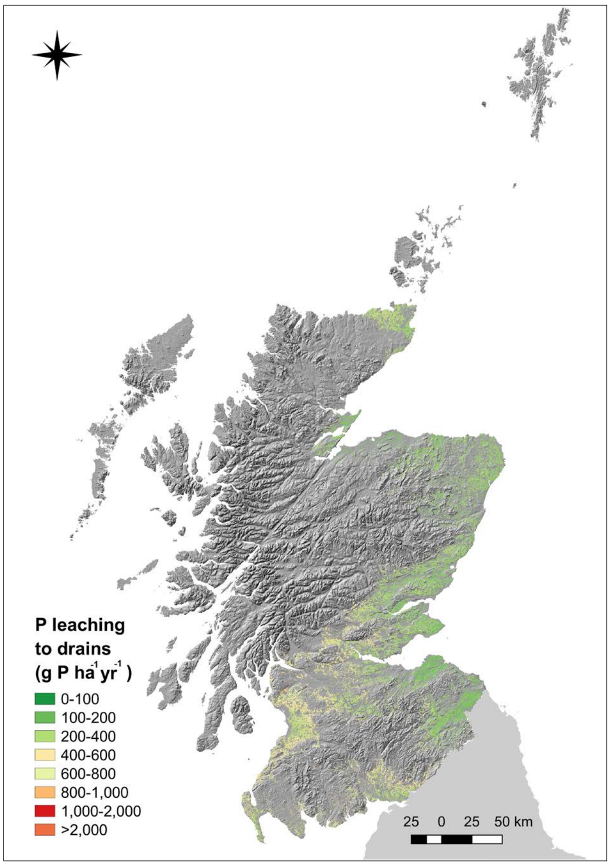

Figure A3.5. Map of P loss (g P ha^{-1} yr^{-1}) due to leaching to drains at 50 m grid resolution for the study area.

Calculated TP concentrations for different land uses and estimates of drain-flow were then combined to produce an estimate of P leaching to artificial drain systems at each 50 m grid cell. The spatial distribution of P leaching to drains within the study area is shown in Figure A3.5.

P export and relative importance of P pathways of diffuse pollution

Assessments of P loss due to the surface and subsurface pathways were a) combined to produce an assessment of total P export from both pathways for the study area (Phase 6 of the soil map of Scotland (partial cover)) (Figure A3.6a) and b) compared to assess the relative importance of each pathway of P diffuse pollution; this was done only for the area identified as likely to have been drained where values for both pathways were calculated (Figure A3.6b).

Based on Table A3.3, mean P loss due to runoff and soil erosion ranged from 94.4 g P ha^{-1} yr^{-1} for LUI-1 (rough grazing) to 650 g P ha^{-1} yr^{-1} for LUI-6 (dominant crops are potatoes, maize and root vegetables). These values are comparable to published results of P loss from different land uses (D'Arcy and Frost, 2001) and indicate that

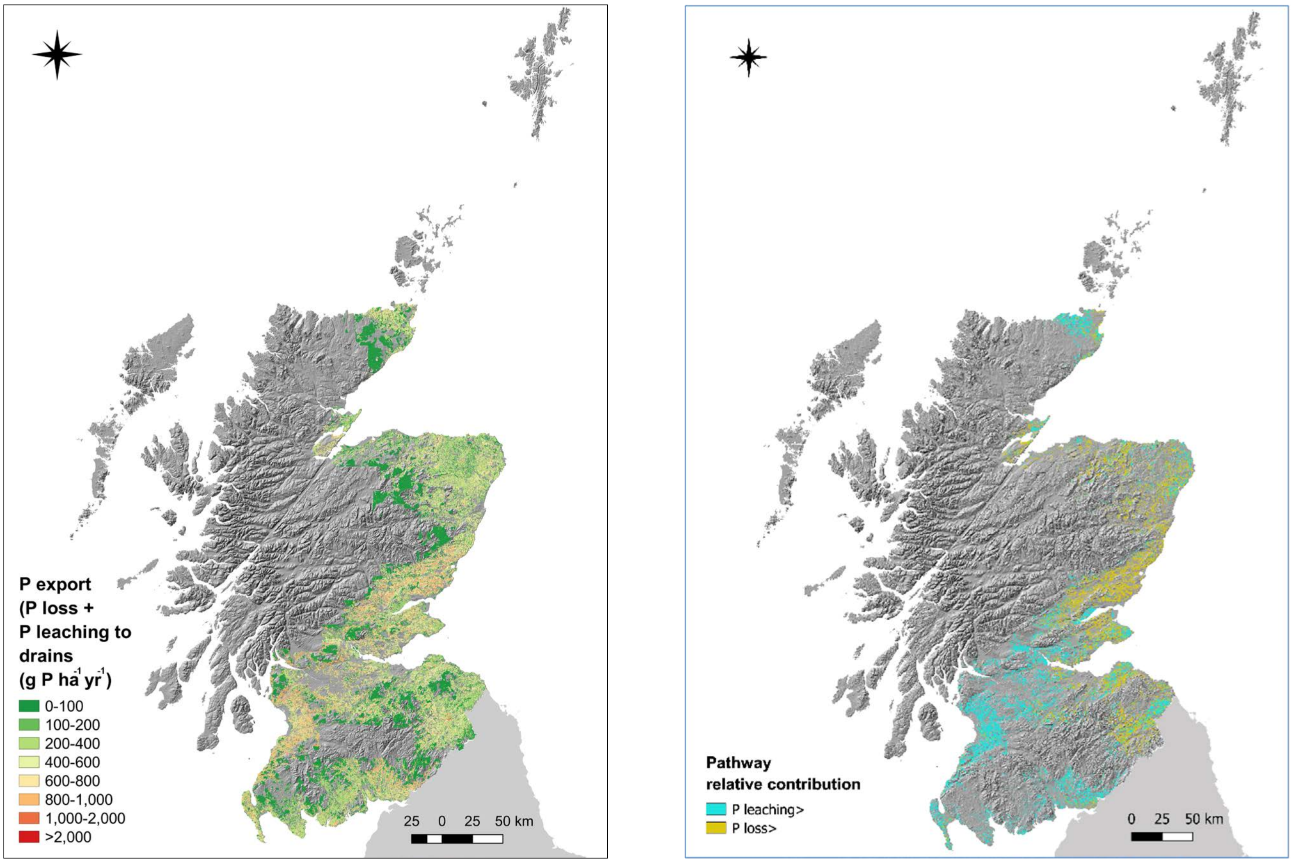

Figure A3.6. Maps at 50 m grid resolution of a) P export (g P ha^{-1} yr^{-1}) as the sum of P loss from the surface and subsurface pathways and b) relative importance of P pathways of diffuse pollution; blue areas indicate where values of P leaching to drains are greater than values of P loss due to runoff and soil erosion.

intensive cultivation methods can pose a great risk for P diffuse pollution due to runoff and soil erosion. On the other hand, permanent grassland systems (LUI-2) were found to have the greater mean values of P leaching to drains compared to arable land with cereals (LUI-3 and LUI-4) and potatoes and other root vegetables and maize (LUI-5 and LUI-6), despite having the lowest soil P status (expressed by modified Morgan's P) (Table 11). This was because incoming rainfall and subsequently estimated drain-flow in grassland systems was greater than in other cultivated land, as result of grasslands being located at higher altitudes receiving greater precipitation totals. Grassland systems also had higher mean P loss due to runoff and soil erosion than arable land with cereals (LUI-3 and LUI-4) due to the slightly higher erosion rate estimated for grasslands on mineral soil (Table 10). This estimate comes from a recent report on the cost of soil erosion in Scotland (Rickson, et al., 2020) and was based on observations most likely from reseeded pasture in England and likely to over-estimates the erosion rate on grassland. Total P export was highest for the more intensive land uses (LUI-5 and LUI-6) and lowest for areas of rough grazing (LUI-1), but P export from improved grassland was greater than in cereals, due mainly to the greater contribution from P leaching in grasslands. Statistics for P loss due to runoff and soil erosion and P leaching to drains were calculated using P values of individual 50 m grid cells in the study area and in the area likely to have been artificially drained, respectively. No P leaching was calculated for LUI-1 (rough grazing) because the LUI-1 area was not included in the assessment of the land likely to have been artificially drained.

P loss due to runoff and soil erosion for almost 90% of the study area ranged from 15 to 600 g P ha^{-1} yr^{-1} (Table A3.4). Extreme P loss values of above 2000 g P ha^{-1} yr^{-1} covered a small total area of just 3.81 km^2 where land use intensity and respective soil erosion rates were high (LUI-5 and LUI-6) and the soil was peat, thus had the highest probability of soil erosion occurrence. This was found to be the result of spatial inconsistencies caused by the combination of the land use intensity and soil erosion risk datasets and led to P loss values that were unrealistic because peat in Scotland is unlikely to be cultivated for cereals and root vegetables. P leaching to drains was found to be between 200 to 400 g P ha^{-1} yr^{-1} for more than half of the area likely to have been drained. Overall, total P export for almost half of the study area was found to be between 15 to 400 g P ha^{-1} yr^{-1}, with only 1.6% of the area being above 1,200 g P ha^{-1} yr^{-1}.

The assessment of P pathways relative importance showed that P leaching to drains was greater than P loss due to runoff and soil erosion for 55% of agricultural land likely to have been drained, but there were differences between land uses (Table A3.5). P leaching to drains was the most important pathway of P diffuse pollution in permanent grasslands (in 74% of total grassland area), but runoff and soil erosion contributed more to P diffuse pollution in 84% of the area covered by root vegetables in rotation (LUI-5

Table A3.3. Mean values and standard deviation (±) of P loss due to runoff and soil erosion, P leaching to drains and combined P export (g P ha^{-1} yr^{-1}) for each Land Use Intensity (LUI) class.

LUI class	P loss (g ha^{-1} yr^{-1})	P leaching to drains (g ha^{-1} yr^{-1})	P export (g ha^{-1} yr^{-1})
LUI-1	94.4 ± 41.6	-	94.4 ± 41.6
LUI-2	376 ± 173	514 ± 137	601 ± 304
LUI-3	314 ± 190	323 ± 75	483 ± 240
LUI-4	306.4 ± 183	348 ± 82	489 ± 251
LUI-5	586.8 ± 312	350 ± 70	767 ± 386
LUI-6	650 ± 456	435 ± 100	808 ± 524

Table A3.4. Areal extent (in km^2) and percentage covers (%, in brackets) of P range classes for P loss due to runoff and soil erosion, P leaching to drains and combined P export.

P range classes (g ha^{-1} yr^{-1})	P loss mapped area in km^2 and (%)	P leaching to drains mapped area in km^2 and (%)	P export mapped area in km^2 and (%)
15 - 200	8414 (44.1)	16 (0.2)	6611 (34.6)
200 - 400	3756 (19.7)	3606 (54.9)	2601 (13.6)
400 - 600	4955 (26.0)	2192 (33.4)	3707 (19.4)
600 - 800	1555 (8.1)	748 (11.4)	2696 (14.1)
800 - 1200	326 (1.7)	2 (0.0)	3163 (16.6)
1,200 – 1,600	53 (0.3)	0 (0.0)	242 (1.3)
> 1,600	25 (0.1)	0 (0.0)	63 (0.3)

Table A3.5. Areal extent (in km²) and percentage covers (%, in brackets) of pathways of diffuse P pollution per Land Use Intensity (LUI) class.

Land use intensity (LUI) classes	Greater: P loss due to runoff & soil erosion	Greater: P leaching to drains
LUI-2	806 (26)	2283 (74)
LUI-3	442 (54)	370 (46)
LUI-4	926 (52)	864 (48)
LUI-5	771 (83)	153 (17)
LUI-6	38 (88)	5 (12)
Total Area	2982 (45)	3675 (55)

and LUI-6). In arable land with cereals, pathway relative importance was slightly greater for runoff and soil erosion than for leaching to drains.

Overall, the methodology for quantifying P export from agricultural land and for assessing the relative importance of different pathways of P diffuse pollution is based on a robust scientific understanding of P transport mechanisms and on recent and best-available scientific evidence. However, due to the complexity of modelling processes related to P transport, there is a substantial degree of uncertainty in the results and therefore need to be treated with caution. For example, the range of soil erosion rates for different land uses is quite wide and this may lead to overestimations or underestimations of P loss for different land uses, while data used for assessing dissolved and total P concentrations in drain-flow come from a limited number of samples and studies in Scotland. Finally, there are important gaps in our knowledge of where drains have been installed, their performance and capacity, thus we can only make assumptions for their location and the volume of water that goes through them annually. However, and despite all the uncertainties mentioned, the results of this assessment clearly indicate that intensive land management practices increase the risk of soil compaction and soil erosion that can cause P diffuse pollution and subsequently affect the quality of receiving watercourses. In addition, this analysis highlighted the importance of leaching to artificial drains as a pathway to diffuse pollution in cultivated soils with imperfect or poor natural drainage, especially for permanent grassland systems and for cereals. Contrary to sediment-bound P lost due to runoff and erosion, drains facilitate direct connectivity to adjacent watercourses and an important fraction of total P in drains is in dissolved form. Thus, the impact of P leaching to drains on watercourses could be more direct and immediate than P locked in sediments, transported to river systems through runoff and erosion, that needs to be released to have any impacts on water quality.

N leaching

The method used for assessing N leaching from soil was based on combining annual rates of leachable N with the soil's infiltration capacity (Figure A3.7). Leachable N was

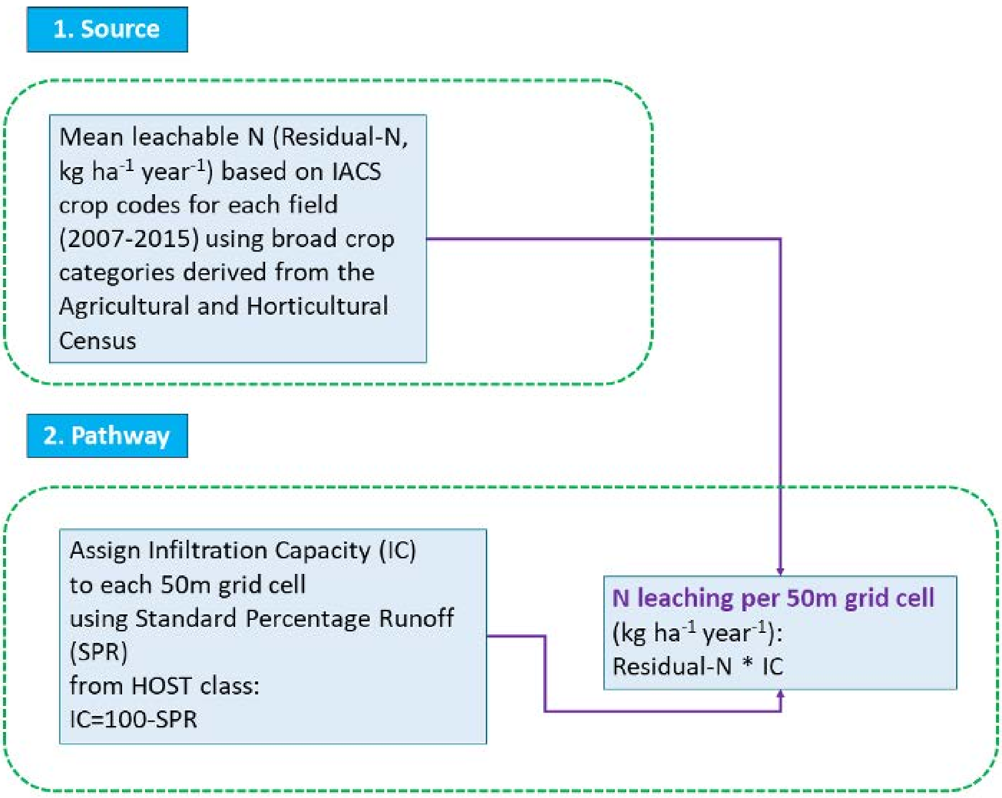

Figure A3.7. Flowchart of steps used to assess N leaching to drains in the area of each 50 m grid cell.

expressed as residual nitrogen (N) that is in excess of crop needs after crop harvest or at the end of the growing season and was based on broad crop categories derived from the Agricultural and Horticultural Census (Table A3.6). There is an assumption that during the growing season there is no excess N available for leaching. These categories were translated to IACS crop categories and mean leachable N rates were calculated for the 2007-2015 period and were assigned to each 50 m grid cell of the agricultural area likely to have been artificially drained.

Contrary to P, there is no numeric relationship (to our knowledge) that links leachable N rates with N concentrations in drain systems in Scotland. Therefore, we used a process-based approach whereby the amount of N likely leach to the soil is dependent on the soil's infiltration capacity (IC), i.e., the proportion of annual incoming rain that goes through the soil and is not lost to surface runoff. IC was calculated as the inverse of the soil's Standard Percentage Runoff (SPR), a hydrological index that indicates annual surface runoff capacity. SPR values have been assigned to Scottish soils using the Hydrology of Soils Types (HOST) classification (Boorman et al., 1995). The rationale for this approach was that wetter soils with lower IC will pose a lesser risk of diffuse pollution as N will not have the capacity to quickly infiltrate the soil and reach the drainage system. The spatial distribution of N leaching to drains within the area of interest is shown in Figure A3.8.

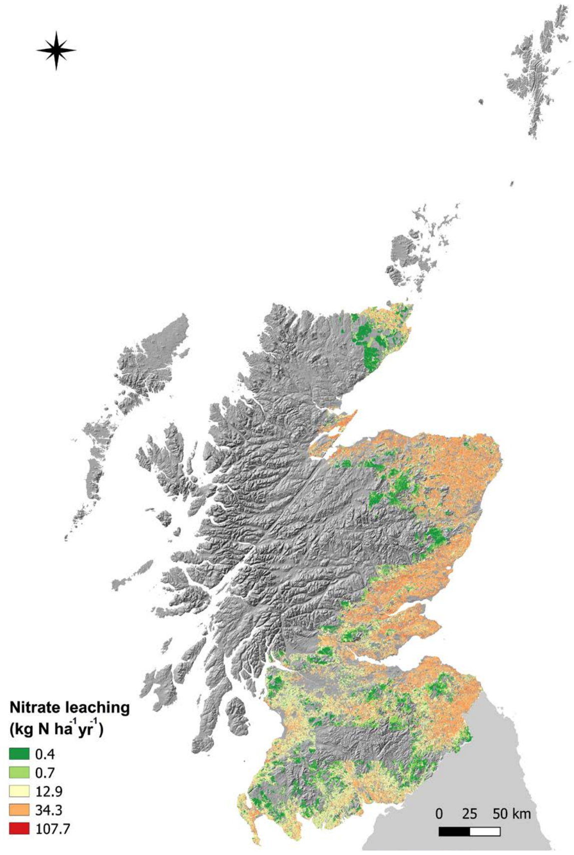

Figure A3.8. Map of N leaching to drains (kg N yr-1) at 50 m grid resolution for the study area. © Crown copyright and database right (2020). All rights reserved. The James Hutton Institute, Ordnance Survey Licence Number 100019294.

Mean leachable N for the 2007-2015 period was found to increase with land use intensity (LUI) and ranged from just 1.27 kg N ha^{-1} yr^{-1} for rough grazing to 77.39 kg N ha^{-1} yr-^{1} for root vegetables in rotation (Table A3.7). Mean infiltration capacity was similar for almost all LUI classes and ranged from around 65% to 69%, except for LUI-1 that had mean infiltration of around 54%, indicating the presence of rough grazing in denser and wetter soils. Finally, mean rates of N leaching to soil were also found

Table A3.6. Leachable N (kg N ha^{-1} yr^{-1}) for broad crop categories derived from the Agricultural and Horticultural Census.

Crop categories	Leachable N (kg N ha^{-1} yr^{-1})
Set-aside and fallow	100
Cereals	50
Oilseed rape (including linseed)	70
Potatoes	90
Peas and other outdoor vegetables for human consumption	110
Fodder beet	90
Brassicas for stock feeding	70
Fruits	85
Grass for mowing	75
Grass for grazing under 5 years old	50
Grass for grazing 5 years old and older	15
Rough grazing	1
Woodland	1
Semi-natural vegetation	1

to increase with LUI class and ranged from 0.70 kg N ha^{-1} yr^{-1} for rough grazing to 53.41 kg N ha^{-1} yr-^{1} for root vegetables in rotation (Table 15).

Table A3.7. Mean and standard deviation (±) values per land use intensity (LUI) class of mean leachable N for the 2007-2015 period (kg N ha^{-1} yr^{-1}), infiltration capacity (IC, %) and rates of N leaching (kg N ha^{-1} yr^{-1}).

Land use intensity class	Mean leachable N (kg N ha^{-1} yr^{-1})	IC (%)	N leaching rate (kg N ha^{-1} yr^{-1})
LUI-1	1.27 ±1.32	53.99 ±13.94	0.70 ±0.87
LUI-2	24.73 ±14.68	65.41 ±12.92	16.39 ±10.77
LUI-3	46.41 ±9.83	67.91 ±12.45	31.61 ±9.14
LUI-4	53.99 ±7.54	67.83 ±12.40	36.58 ±8.26
LUI-5	58.92 ±7.51	67.69 ±13.12	39.88 ±9.32
LUI-6	77.39 ±15.03	68.89 ±13.78	53.41 ±15.45

Mean leachable N for the 2007-2015 period was found to increase with land use intensity (LUI) and ranged from 25.42 kg N ha^{-1} yr^{-1} for permanent grassland to 74.21 kg N ha^{-1} yr^{-1} for root vegetables in rotation (Table A3.7). Mean infiltration capacity was similar for all LUI classes and ranged from around 62% to 64%. This was expected since soil drainage in the area of interest was either imperfect or poor. Finally, N leaching was also found to increase with LUI class and ranged from 16.31 kg N ha^{-1} yr^{-1} for permanent grassland to 36.78 kg N ha^{-1} yr^{-1} for root vegetables in rotation (Table A3.7). These results indicate that N leaching to drains can be quite important in cultivated areas on soils of imperfect or poor drainage, especially in the more intensively managed land, and could pose a significant risk for water quality in the receiving watercourses. In freely draining soils the N is likely to be leached through the soil profile to the groundwater and is covered by the Nitrate Vulnerable Zone regulations.

Appendix 4: Management costs, with pathways, levels of reduction and practicality of implementation

Table A4.1. Detailed 'traffic lighted' management costs, with pathways, levels of reduction and practicality of implementation.

	Action	Cost of implementation[a]	Benefits	Pathway addressed	Level of reduction	Practicality
1	No cultivation within 2 m of a water course	Low	Reduced nutrient loss	Reduces soil erosion loss	High	Easy to implement
2	If needed move feeders and water troughs to reduce extensive soil damage	Low	Reduces nutrient loss, soil compaction and yield loss	Reduces surface water/soil runoff and soil erosion through drainage, leaching and from hotspots	High	Depending on water points this should be straightforward but could have cost implications to establish water points and could cause extra damage depending on how wet the field
3	Don't travel over fields in wet conditions or reduce access if unavoidable to reduce compaction	Low	Reduces soil compaction, reduces yield loss maintains drainage	Reduces surface water/soil runoff and soil erosion through drainage, tramlines and from hotspots	Medium	If possible, reduce traffic depending on the weather conditions and the time of the year
4	Increase soil organic matter content (including chop and incorporate cereal stubble)	Low	Helps with maintain soil structure and drainage, increases yield and soil health	Reduces wind blown and surface soil/water erosion through reduced compaction to drain-flow and leaching	Medium	Incorporate more crop residues and cover crops
5	Suitable crop for the soil texture and slope	Low	Reduces potential soil loss and increases yield	Reduces soil fine particle loss through drain-flow and leaching	Medium	Needs consideration on drilling and current crop rotation
6	Adopt and use fertiliser plan, including timings of application and liming	Low	Reduces fertiliser use, saves costs	Reduces diffuse pollution (especially P) through leaching	Medium	Very Practical and should be encouraged
7	Reduced cultivation – conservation tillage where appropriate	Low	Increases soil organic matter and soil stability, reduces labour costs and fuel use	Reduces soil surface runoff and wind erosion through increased drainage	Medium	Practical but potential increase in herbicide use, difficult to correct any soil compaction issues
8	No tillage – conservation tillage where appropriate	Low	Increases soil organic matter and soil stability, reduces labour costs and fuel use	Reduces soil surface water loss through runoff and drainage and soil wind erosion	Medium	Practical but potential increase in herbicide use
9	Leaving land in stubble and/or crop residues	Low	Increases soil organic matter and potentially yield, reduces fertiliser use	Reduces wind blown and surface soil/water erosion through drain-flow, leaching, tramlines and hotspots	Medium	Benefits to this management straightforward to employ
10	Timing of agricultural practices – keep off land in winter if possible	Low	Reduces soil compaction, reduces yield loss	Reduces surface water/soil runoff loss through tramlines, drainage and leaching	Low	Should be done as often as possible depending on the field conditions

	Action	Cost of implementation[a]	Benefits	Pathway addressed	Level of reduction	Practicality
11	Use of VESS to detect compaction and soil structural degradation	Low	Increased awareness of soil structural quality and associated yield and drainage benefits	Potential to reduce surface water/soil runoff and soil erosion through tramlines, drainage and leaching	Low	Training maybe needed but easy to employ
12	Move gateways – add gateways to the field	Medium	Reduces soil compaction and increases yield.	Reduces soil loss from the field, reduces surface water/soil runoff loss through tramlines and drainage	High	Expense of new gates and could affect hedge rows
13	Beetle banks	Medium	Reduces nutrient loss, increases pollinator diversity, increases carbon sequestration	Reduces surface water/soil runoff and soil erosion through drainage, leaching and hotspots	High	Has cost implications and needs consideration of field
14	Establish in field buffer strips	Medium	Reduces nutrient loss	Reduces surface water/soil runoff and soil erosion	High	Cost implications for reduced crop cover and therefore reduced yields
15	Change cropping from veg to cereals, or cereals/veg crop to grassland	Medium	Increases soil organic matter content and maintains soil surface structure	Reduces loss of fine soil particles and increases drainage through drain-flow, leaching and from tramlines	High	Practicality depends on crop rotation and farm type
16	Cultivate alternating strips of crops across the contour where practical	Medium	Reduces soil compaction, reduces nutrient loss and can increase yield	Reduces surface water and soil runoff loss through tramlines, drainage, leaching and hotspots	Medium	Needs decisions on crop types and the suitability of machinery available
17	Strip grazing across the slope, starting at the highest point of the field	Medium	Reduces nutrient loss and soil compaction, increases soil organic material	Reduces surface water/soil runoff and soil erosion through drainage, leaching and hotspots	Medium	Needs extra fencing and labour to move the fences on a regular basis
18	Avoid wetter fields to reduce poaching and surface capping and by reducing grazing in wet conditions	Medium	Reduces nutrient loss and soil compaction, maintains drainage and sward yield and density	Reduces surface water/soil runoff and soil erosion through drainage, leaching and hotspots	Medium	Needs to consider grazing rotation, weather and field condition
19	Fence off livestock from rivers and streams	Medium	Reduces nutrient loss and potential animal injury	Reduces soil loss and erosion through river bank damage and river pollution through animal dung and urine	Medium	Cost of fencing and contractors but easy to implement
20	Cultivate across the slope - Re-align tramlines away from the steepest part of the slope	Medium	Reduces soil compaction, reduces nutrient loss and can increase yield	Reduces surface water and soil runoff loss through tramlines	Medium	Needs consideration of the crop and machinery involved

Table A4.1. Detailed 'traffic lighted' management costs, with pathways, levels of reduction and practicality of implementation.						
	Action	Cost of implementation[a]	Benefits	Pathway addressed	Level of reduction	Practicality
21	Use of green or cover crops	Medium	Increases soil organic matter and potentially yield - reduces fertiliser use	Reduces wind and surface soil/ water erosion through drain-flow, leaching and tramlines (if sown)	Medium	Cost implications but easy to implement
22	Undersown spring cereals	Medium	Maintains soil organic matter	Reduces surface water and soil/ water runoff loss through drainage	Low	May have cost implications if extra machinery is required
23	Soil compaction alleviation in grassland soils and tramline disruption in arable crops	Medium	Increases drainage and potentially increases yield	Reduces surface water/soil runoff and soil erosion through tramlines and drainage	Low	Needs specialist equipment but easy to employ
24	Remove management of field corners	Medium	Increased soil organic material, reduced nutrient loss	Reduces soil surface erosion through reduced runoff, slowed drainage and reduces leaching	Low	Needs consideration in relation to the crop being grown
25	Grass boundaries or filter strips, especially at the bottom of slopes	Medium	Increases organic carbon in the soil, prevents soil loss	Reduces wind and surface soil erosion entering water courses, as well as fine particle soil loss through runoff, drainage, leaching and hotspots	High	Depends on slope of the farm fields and crops grown
26	Cultivate soils in the spring not autumn, including slurry and manure incorporation	High	Reduces nutrient loss and increases use efficiency, increases soil organic matter	Reduces wind and surface soil/water erosion through reduced runoff and drainage	Medium	If suitable to the crop rotation and access to manure and slurry
27	Establish and maintain wetland areas and/or water retention ponds	High	Increases carbon sequestration, reduces diffuse pollution	Reduces soil surface water/ soil runoff loss through drainage, leaching and hotspots	High	Needs consideration in location and suitability of the fields
28	Implementation of field drainage	High	Reduces nutrient and soil loss, helps retain soil structure	Reduces soil surface water/ soil runoff loss, can reduce leaching, reduces compaction	Medium	Cost of implementation and the knowledge for a suitable scheme
29	Use bridges for animal movements across streams	High	Reduces nutrient loss and potential animal injury	Reduces soil loss and erosion from trampling of banks and river margins, reduces contamination from animal dung and urine	Medium	Cost of bridges would be high but would help maintain banks and herd foot health
30	Agro-forestry	High	Increased carbon sequestration, reduced nutrient loss and increased animal welfare and yield	Reduces surface soil loss and soil erosion, additionally reduces drainage, leaching, especially from hotspots	Medium	Cost implications and consideration of suitable fields

	Action	Cost of implementation[a]	Benefits	Pathway addressed	Level of reduction	Practicality
31	Establish new hedges	High	Reduces nutrient loss, increases carbon sequestration	Reduces surface soil runoff through drainage and leaching and soil wind erosion	Low	Cost of implementation
32	Reduce vehicle size and/or use reduced pressure tyres, use of flexi tyres	High	Reduces soil compaction, reduces yield loss	Reduces surface water/soil runoff loss through tramlines, drainage and leaching	Low	Could help reduce machinery costs but increase fuel and labour costs
33	Increasing tramline spacing	High	Reduces soil compaction, reduces yield loss	Reduces surface water/soil runoff loss through tramlines and drainage	Low	Needs suitable equipment to be available
34	Controlled traffic farming	High	Reduces soil compaction and yield loss	Reduces surface water/soil runoff loss	Medium	Needs investment in technology and subscription to GPS systems, organisation of working widths for all traffic

Table A4.1. Detailed 'traffic lighted' management costs, with pathways, levels of reduction and practicality of implementation.

[a] Colours indicate level of cost – green = low cost (<£250 or <£50/ha), yellow = medium cost (<£500 or <£150/ha) and red = high cost (>£500 or >£250/ha).

Cuttle et al. (2016) estimated the effectiveness of various mitigation measures on N and P diffuse pollution using seven different model farm scenarios. The effectiveness of different mitigation options are summarised in Table A4.2. Note that many practical measures for mitigating diffuse pollution have been identified but tools such as the Defra-funded FARMSCOPER decision support tool (Gooday et al., 2014; ADAS, 2015) could offer the ability to assess diffuse pollutant loads on a farm as well as quantify the impacts of identified farm mitigation methods on these pollutants. This tool, which is continually being improved, was tested using two broad farm types in the Clun catchment (Shropshire) – upland grazing and lowland arable farms. As the FARMSCOPER model contains well over 100 practical mitigation measures and identifies the top five efficient and cost-effective measures for reducing diffuse pollution based on broad farm input data, this is a good source of mitigation measures that could be implemented in Scotland with modification to suit Scottish farm conditions.

Table A4.2. Summary of effectiveness of different mitigation options on N and P losses (based on estimations from Cuttle et al., 2016).			
Mitigation option	**N loss reductions**	**Reductions in P loss**	**Pathway**
Arable conversion to ungrazed grassland	>95% nitrate	50%	All
Spring cropping instead of winter cropping	10 kg N ha^{-1}	soil P 50% clay loam soils 70% sandy loam soils	All
Establishment of autumn cover crops	10-45 kg N ha^{-1}	soil P 25% clay loam soils 35% sandy loam soils	All
Use fertiliser recommendations and reduced fertiliser application rates	5 kg N $ha^{-1}y^{-1}$ arable 1-5 kg N $ha^{-1}y^{-1}$ dairy 2 kg N $ha^{-1}y^{-1}$ beef	fertiliser P 20%	All
Conservation tillage (compared with ploughing)	0-5 kg N ha^{-1}	soil P 5% clay loam soils	All
Cultivate across the slope	No effect on nitrate	soil P 25% clay loam soils 35% sandy loam soils	All
Alleviating compaction in grassland fields	Depends on the size of the compacted area and plant N-use efficiency	soil P 50% clay loam soils 70% sandy loam soils	Soil compaction and structural degradation
Tramline management	No effect on nitrate	soil P 25% clay loam soils 35% sandy loam soils	Tramlines
Establish and maintain constructed wetlands	5-15 kg N ha^{-1}	40%	Drain-flow and leaching
Allowing field drainage systems to deteriorate	5-30 kg N ha^{-1}	5%	Drain-flow and leaching
Avoid applying manure at high-risk times	1-12 kg N ha^{-1}	manure P 25% clay loam soils 50% sandy loam soils	Hotspots
Construct bridges for livestock crossings of rivers and streams	0-1 kg N ha^{-1}	soil P 50% manure P 1%	Hotspots
Fence off watercourses from livestock	0-1 kg N ha^{-1}	soil and manure P 50%	Hotspots
Avoiding applying manure to high-risk areas	0-1 kg N ha^{-1}	manure P 40%	Hotspots
Reduce livestock numbers	10-25 kg N ha^{-1} dairy 3-5 kg N ha^{-1} beef	soil, manure and fertiliser P 18-35%	Hotspots
Move livestock feeders and troughs	0-1 kg N ha^{-1}	soil and manure P 15%	Hotspots
Move gateways	No effect	7.5%	Hotspots
Placement of manure heaps away from watercourses and drains	0-1 kg N ha^{-1}	manure P 4%	Hotspots

Appendix 5: Classification of IACS crops and land uses into crop risk classes

Table A5.1. Classification of IACS crops and land uses into crop risk classes.

Short code	Land use description	Crop risk
ASSF	ARABLE SILAGE FOR STOCK FEED	Moderate
CMIX	ARABLE SILAGE FOR STOCK FEED	Moderate
AMCP	AROMATIC, MEDICAL AND CULINARY PLANTS	Moderate
ARTC	ARTICHOKES	High
ASPG	ASPARAGUS	High
BEAN	BEANS FOR HUMAN CONSUMPTION	Moderate
BPP	BEDDING AND POT PLANTS	High
BLB	BILBERRIES (AND OTHER FRUITS OF THE GENUS VACCINIUM)	High
BKB	BLACKBERRIES	High
BLR	BLACKCURRANTS	High
BOR	BORAGE	High
BSP	BRUSSEL SPROUTS	High
BW	BUCKWHEAT	Moderate
BFLO	BULBS/FLOWERS	High
CABB	CABBAGES	High
CALA	CALABRESE	High
CANS	CANARY SEED	Moderate
CARR	CARROTS	High
CAUL	CAULIFLOWER	High
COMM	COMMON GRAZING	Low
FALW	FALLOW	Moderate
FALW_5	FALLOW LAND FOR MORE THAN 5 YEARS	Moderate
FFS	FIBRE FLAX	Moderate
FB	FIELD BEANS	Moderate
BSFS	FLOWER BULBS AND CUT FLOWERS	High
OCS_B	FODDER BEET	High
GSB	GOOSEBERRIES	High
PGRS	GRASS OVER 5 YEARS	Low
TGRS	GRASS UNDER 5 YEARS	Low
GCM	GREEN COVER MIXTURE	Low
HZL	HAZELNUTS	Moderate
HS	HEMP	Moderate
OCS_K	KALE AND CABBAGES FOR STOCKFEED	High
LEEK	LEEKS	High
LETT	LETTUCE	High
LIN	LINSEED	Moderate
LINSEED	LINSEED	Moderate
LLO_ASSF	LLO-ARABLE SILAGE FOR STOCKFEED	Moderate
LLO_CMIX	LLO-ARABLE SILAGE FROM STOCK FEED	Moderate
LLO_AMCP	LLO-AROMATIC, MEDICAL AND CULINARY PLANTS	Moderate
LLO_ARTC	LLO-ARTICHOKES	High
LLO_BEAN	LLO-BEANS FOR HUMAN CONSUMPTION	Moderate

LLO_BPP	LLO-BEDDING AND POT PLANTS	High
LLO_BLB	LLO-BILBERRIES (AND OTHER FRUITS OF THE GENUS VACCINIUM)	High
LLO_BSP	LLO-BRUSSEL SPROUTS	High
LLO_BFLO	LLO-BULBS/FLOWERS	High
LLO_CABB	LLO-CABBAGES	High
LLO_CALA	LLO-CALABRESE	High
LLO_CARR	LLO-CARROTS	High
LLO_CAUL	LLO-CAULIFLOWER	High
LLO_FALW	LLO-FALLOW	Moderate
LLO_FB	LLO-FIELD BEANS	Moderate
LLO_OCS_B	LLO-FODDER BEET	High
LLO_PGRS	LLO-GRASS OVER 5 YEARS	Low
LLO_TGRS	LLO-GRASS UNDER 5 YEARS	Low
LLO_OCS_K	LLO-KALE AND CABBAGES FOR STOCKFEED	High
LLO_LEEK	LLO-LEEKS	High
LLO_LETT	LLO-LETTUCE	High
LLO_LIN	LLO-LINSEED	Moderate
LLO_MAIZ	LLO-MAIZE	High
LLO_MC	LLO-MIXED CEREALS	Moderate
LLO_NURS	LLO-NURSERIES	Moderate
LLO_NU_FS	LLO-NURSERY - FRUIT STOCK	Moderate
LLO_NU_OT	LLO-NURSERY - ORNAMENTAL TREES	Moderate
LLO_WDG	LLO-OPEN WOODLAND(GRAZED)	Low
LLO_OCS	LLO-OTHER CROPS FOR STOCK FEED	Moderate
LLO_ONU	LLO-OTHER NURSERY STOCKS	Moderate
LLO_OSFRT	LLO-OTHER SOFT FRUIT	High
LLO_OVEG	LLO-OTHER VEGETABLES	High
LLO_PEAS	LLO-PEAS FOR HUMAN CONSUMPTION	Moderate
LLO_PSTS	LLO-PISTACHIOS	Low
LLO_PEM	LLO-POSITIVE ENVIRONMENTAL MANAGEMENT	Low
LLO_PP	LLO-PROTEIN PEAS	Moderate
LLO_RAST	LLO-RAPE FOR STOCK FEED	Moderate
LLO_RASP	LLO-RASPBERRIES	High
LLO_RCG	LLO-REED CANARY GRASS	Low
LLO_RCG_E	LLO-REED CANARY GRASS ENERGY	Low
LLO_RGR	LLO-ROUGH GRAZING	Low
LLO_SCR	LLO-SCREE OR SCRUB	Low
LLO_SPOT	LLO-SEED POTATOES	High
LLO_STS	LLO-SHOPPING TURNIPS/SWEDES	High
LLO_STS_E	LLO-SHOPPING TURNIPS/SWEDES ENERGY	High
LLO_SRC_E	LLO-SHORT ROTATION COPPICE ENERGY	Low
LLO_SB	LLO-SPRING BARLEY	Moderate
LLO_SB_E	LLO-SPRING BARLEY ENERGY	Moderate
LLO_SO	LLO-SPRING OATS	Moderate
LLO_SOSR	LLO-SPRING OILSEED RAPE	Moderate
LLO_SW	LLO-SPRING WHEAT	Moderate
LLO_STRB	LLO-STRAWBERRIES	High
LLO_SL	LLO-SWEET LUPINS	High

LLO_SC	LLO-SWEETCORN	High
LLO_TSB	LLO-TREES, SHRUBS AND BUSHES	Low
LLO_TRIT	LLO-TRITICALE	Moderate
LLO_TURF	LLO-TURF PRODUCTION	Moderate
LLO_TSWS	LLO-TURNIPS/SWEDES FOR STOCK FEED	High
LLO_WPOT	LLO-WARE POTATOES	High
LLO_WPOT_E	LLO-WARE POTATOES ENERGY	High
LLO_WCC	LLO-WHOLE CROP CEREALS	Moderate
LLO_WBS	LLO-WILD BIRD SEED	Low
LLO_WB	LLO-WINTER BARLEY	Moderate
LLO_WO	LLO-WINTER OATS	Moderate
LLO_WOSR	LLO-WINTER OILSEED RAPE	Moderate
LLO_WOSR_E	LLO-WINTER OILSEED RAPE ENERGY	Moderate
LLO_WW	LLO-WINTER WHEAT	Moderate
LLO_WAF	LLO-WOODLAND AND FORESTRY	Low
LGB	LOGANBERRIES	High
MAIZ	MAIZE	High
MIL	MILLET	Moderate
MSC	MISCANTHUS	Low
MC	MIXED CEREALS	Moderate
NEWTRS	NEW WOODLAND (ELIGIBLE FOR SFPS)	Low
NF_IB	NON-FOOD SETASIDE - BARLEY FOR INDUSTRIAL USE	Moderate
NF_CRBE	NON-FOOD SETASIDE - CRAMBE FOR INDUSTRIAL USE	High
NF_SRC	NON-FOOD SETASIDE - FOREST TREES SHORT CYCLE	Low
NF_HEAR	NON-FOOD SETASIDE - HIGH ERUCIC ACID RAPESEED	Moderate
NF_IOSR	NON-FOOD SETASIDE - OILSEED RAPE FOR INDUSTRIAL USE	Moderate
NF_IOTH	NON-FOOD SETASIDE - OTHER CROPS FOR INDUSTRIAL USE	Moderate
NF_TSB	NON-FOOD SETASIDE - TREES SHRUBS AND BUSHES	Low
NF_IW	NON-FOOD SETASIDE - WHEAT FOR INDUSTRIAL USE	Moderate
NS_5S_FWS	NORMAL SETASIDE - 5 YEAR UNDER FWS	Low
NS_5S_WGS	NORMAL SETASIDE - 5 YEAR UNDER WGS	Low
NS_BF	NORMAL SETASIDE - BARE FALLOW	Moderate
NS_GCM	NORMAL SETASIDE - GREEN COVER MIXTURE	Low
NS_MU	NORMAL SETASIDE - MUSTARD	Low
NS_NRC	NORMAL SETASIDE - NAT REGEN (AFTER CEREALS)	Moderate
NS_NRO	NORMAL SETASIDE - NAT REGEN (AFTER OTHER CROPS)	Moderate
NS_SAS_W	NORMAL SETASIDE - NEXT TO WATERCOURSES, HEDGES, WOODS, DYKES AND SSSIs	Moderate
NS_OL	NORMAL SETASIDE - ORGANIC LEGUMES	Low
NS_OWN	NORMAL SETASIDE - OWN MANAGEMENT PLAN	Moderate
NS_P	NORMAL SETASIDE - PHACELIA	Low
NS_G	NORMAL SETASIDE - SOWN GRASS COVER	Low
NS_WBC	NORMAL SETASIDE - WILD BIRD COVER	Low
NURS	NURSERIES	Moderate
NU_FS	NURSERY - FRUIT STOCK	Moderate
NU_OT	NURSERY - ORNAMENTAL TREES	Moderate
NU_SH	NURSERY - SHRUBS	Moderate
OILSEED_RAPE	OILSEED RAPE	Moderate

WDG	OPEN WOODLAND (GRAZED)	Low
OCS	OTHER CROPS FOR STOCK FEED	Moderate
ONU	OTHER NURSERY STOCKS	Moderate
OSFRT	OTHER SOFT FRUIT	High
OVEG	OTHER VEGETABLES	High
PEAS	PEAS FOR HUMAN CONSUMPTION	Moderate
PSTS	PISTACHIOS	High
PRSL	PONDS, RIVERS, STREAMS OR LOCHS	Low
PEM	POSITIVE ENVIRONMENTAL MANAGEMENT	Low
PP	PROTEIN PEAS	Moderate
RASP	RASPBERRIES	Moderate
RRC	REDCURRANTS	High
RCG	REED CANARY GRASS	Low
RHB	RHUBARB	High
RGR	ROUGH GRAZING	Low
RYE	RYE	Moderate
SCR	SCREE OR SCRUB	High
SPOT	SEED POTATOES	High
SAAP_A	SETASIDE AGRICULTURAL PRODUCTION - ARABLE	Moderate
SAAP_F	SETASIDE AGRICULTURAL PRODUCTION - FORAGE	Moderate
SAAP_PROT	SETASIDE AGRICULTURAL PRODUCTION - PROTEINS	Moderate
SHAR	SHARED GRAZING	Low
STS	SHOPPING TURNIPS/SWEDES	High
SRC	SHORT ROTATION COPPICE	Low
SRC_E	SHORT ROTATION COPPICE ENERGY	Low
SOR	SORGHUM	Moderate
SB	SPRING BARLEY	Moderate
SO	SPRING OATS	Moderate
SOSR	SPRING OILSEED RAPE	Moderate
SOSR_E	SPRING OILSEED RAPE ENERGY	Moderate
SW	SPRING WHEAT	Moderate
STRB	STRAWBERRIES	High
SL	SWEET LUPINS	High
SC	SWEETCORN	High
SC_E	SWEETCORN ENERGY	High
TFRT	TOP FRUIT	High
TSB	TREES SHRUBS & BUSHES	Low
TRIT	TRITICALE	Moderate
TURF	TURF PRODUCTION	Moderate
TSWS	TURNIPS/SWEDES FOR STOCK FEED	High
WPOT	WARE POTATOES	High
WRC	WHITECURRANTS	High
WCC	WHOLE CROP CEREALS	Moderate
WBS	WILD BIRD SEED	Low
WB	WINTER BARLEY	Moderate
WO	WINTER OATS	Moderate
WOSR	WINTER OILSEED RAPE	Moderate
WOSR_E	WINTER OILSEED RAPE ENERGY	Moderate

WW	WINTER WHEAT	Moderate
WAF	WOODLAND AND FORESTRY	Low
WAFF_LMCMS	WOODLAND/FORESTRY WITH UNIQUE FIELD IDENTIFIER	Low

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