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Soil erosion and compaction in Scottish soils: adapting to a changing climate

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Executive Summary

Sustainable soil management is a particular challenge as Scotland adapts to a changing climate, and has been highlighted by the Adaptation Sub-Committee, in its UK Climate Change Risk Assessment 2017. Soil compaction and erosion have been identified as being important, particularly in exacerbating flooding impacts and decreasing soil carbon storage.

This report collates the current state of confident knowledge for Scotland – what we know, what we don't know and what is under active debate.

Key findings

- Much of what we know about erosion rates on agricultural land in Scotland comes from a few, individual studies of erosion events, but there is a growing body of evidence that can be used to examine the role of land use (both current and historic), soil type and slope on erosion susceptibility. Other factors such as antecedent moisture content, ground cover and presence of tramlines also play a role, making it difficult to be certain when, or if, erosion will occur.
- Soil erosion models with sediment yield as an output seem to exaggerate the amount of soil loss and are difficult to validate, although they do offer a way to examine the relative changes in erosion rate under different land uses and changing climates.
- There is a link between soil compaction and erosion; soils that become compacted have a restricted capacity to store rainfall and generate overland flow more quickly than soils that are not compacted. This overland flow can then cause erosion.
- The greatest driver of soil compaction is machinery weight, which has been increasing over the past few decades, although using wide tyres, dual wheels and low pressure tyres can reduce the impact.
- We have a better understanding of field level effects with evidence gathered in Aberdeenshire following storm Frank (December 2015) suggesting erosion seemed more prevalent in areas that were more intensively managed.

Conclusion

We do not know the full extent of erosion or compaction in Scotland. Current models allow us to assess risk to help minimise impact but we need more information on the interaction between climate and soils (and compaction and erosion) to improve predictions of when, or if, a soil erodes or becomes compacted.

Climate change (including erratic weather patterns) along with changes in machinery and farming practices will increase the susceptibility of Scottish soils to erosion or damage by compaction. Development of avoidance and mitigation strategies requires an integrated approach that includes the multiple factors contributing to erosion and compaction risks.

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Soil erosion and compaction – why it matters

Soil erosion and compaction can have a large impact on run-off, water storage and water quality as well as adversely affecting crop production. Scotland's soils and climate make it susceptible to both erosion and compaction.

Soil erosion is part of a natural cycle where soil particles are removed from one part of the landscape and deposited elsewhere and occurs in both uplands and lowlands. However, the loss of organic matter and poor soil structure combined with extreme rainfall can increase the risk of erosion in agricultural land. This leads to run-off to streams and rivers, the loss of valuable topsoil, nutrients and crop productivity and the development of rills and gullies in fields.

The Scottish Government has prioritised sustainable soil management and the importance of improved soil condition (for example, The Scottish Land use Strategy, the Climate Change Adaptation Programme and the Climate Change Plan; Good Agricultural and Environmental Conditions) which, if implemented will go some way to reducing the risk of erosion on agricultural land.

Increased mechanisation has brought many benefits to farm business management, but some associated practices, for example the creation of 'tramlines' running up and down a slope can provide pathways for water to gather and flow leading to rill or gully erosion. Similarly, the production of fine seedbeds (particularly associated with high-value crops) means soil is more readily washed downslope or blown away in strong winds. There is also soil loss from the field when soil adheres to harvested root crops and is only removed at the packing houses.

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 infiltration (and increasing runoff and the risk of erosion) and decreasing the amount of oxygen in the soil, which in turn constrains good root establishment and crop growth. Compacted soils are more at risk of becoming waterlogged which can lead to an increase of nitrous oxide emissions (a powerful greenhouse gas) from cultivated land. 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) and natural processes, subsoil compaction below the depth of ploughing often remains unseen and is more difficult to repair.

Erosion was one identified as one of the main threats to Scotland's soils in the comprehensive 'State of Scotland's Soil Report' published in 2011 (https://www.sepa.org.uk/media/138741/state-of-soil-report-final.pdf). The report also identified that there was no systematic assessment of actual soil erosion in Scotland with studies limited to a few specific sites and often gathered in response to severe erosion events. Although some modelling of soil erosion has been done (Lilly et al., 2002 and 2009), the results are difficult to validate and the actual modelled results can be dependent on the spatial scale (resolution) of the available input data (Baggaley and Potts, 2017). The State of Scotland's Soils report also highlighted a similar lack of evidence on the extent of compaction within Scottish soils.

This paper

The aim of this paper is to collate the existing information, to outline the existing evidence and identify current knowledge in relation to the state of erosion and compaction in Scottish soils. We will review new data collected since 2011 from field, catchment and national studies, examining the key drivers of both erosion and compaction and assess likely future trends.

Since 2011, there have been a number of studies (Lilly and Baggaley, 2014; Hallett et al. 2016; Baggaley et al., 2017, Silgram et al., 2015, Lilly et al., 2011, Griffiths et al., 2015; SEPA Catchment walks and associated dataset) that have attempted to quantify or characterise the current state of both erosion and compaction in Scottish soils and to identify some of the key drivers in relation to land management.

Soil erosion in Scotland

What we know

Despite calls for a soil monitoring programme to assess the state of Scottish soils in the 2011 State of Scotland's soil report, there is still no systematic, national survey of erosion in Scotland. This is not unusual and many national and international scale erosion estimates are derived by modelling the interaction between a range of factors including soil type, slope, weather patterns and land management (Lilly et al., 2002; Kirkby, et al., 2008; Panagos et al., 2015; Borreli et al., 2018). A nationally applied soil erosion risk model developed by Kirkby et al. (2004) suggests annual erosion rates greater than the estimated natural rate of soil formation (Appendix 1). However, resampling of the National Soil Inventory of Scotland (2007-9) shows that there has been a statistically significant increase in topsoil thickness of cultivated soils rather than a decrease due to erosion. The same resampling also showed a decline in the concentration of soil organic matter in topsoils, perhaps indicating that the reason for the increase in topsoil thickness is due to deeper ploughing and mixing the carbon-rich topsoil with carbon-poor subsoils thereby offsetting any losses due to erosion.

Many studies summarised in the 2011 State of Scotland's Soil Report were of localised events or at the field-scale. Davidson and Grieve (2004) summarised soil loss from individual, notable erosion events caused by excess rainfall. Up to 80 tonnes per hectare were eroded in one day's rainfall (Frost and Spiers, 1984) accompanied by severe gullying, but these are relatively rare and localised. Bowes (2010) assessed the erosion losses in three fields in eastern Scotland between October and December 2006. The fields had a history of erosion and although, in this case, some of the soil was redeposited at the bottom of the slope there was a net erosion loss of 92 tonnes of soil and severe gullying which followed the pattern of tramlines.

An extreme rainfall event in early 2016 (named as 'Storm Frank') saw 145mm of rain (more than twice the average for January) recorded in Aberdeenshire between 1st and 8th January. Baggaley et al. (2017) took the opportunity to survey 439 fields in the Ugie and South Esk catchments. Although some catastrophic erosion events were observed in Aberdeenshire during this storm, Baggaley et al., only observed erosion in 17 of these 439 fields, 4% of the fields. Of these, 16 were in the South Esk catchment and 14 had had a potato crop at least once within the preceding 8 years. 10 had 3 or more years of spring cereals, 10 had 3 or more years winter crops and only 2 had 3 or more years in grass in the preceding 8 years. Thus, where erosion had occurred, it seemed to be more prevalent in fields that were more intensively managed. The study also showed that having grassland as part of a rotation or maintaining stubble in fields appeared to decrease the risk of erosion perhaps indicating that suitable management can reduce the instances of erosion even under extreme circumstances. However, land use is not the only factor in determining whether a soil will erode; the texture of the soil, its ability to absorb rainfall and the slope all contribute making analyses of field observations complex.

Within the SEPA "Catchment Walk" data set SEPA staff observed 3808 breaches of General Binding Rules (GBRs) along the water courses in 11 catchments across Scotland (Figure 1). The majority (96%) of the breaches identified were of "significant erosion or poaching of land within 5 m of a water course" (GBR19a). Other breaches were of GBR20c, where land was not being cultivated in a way that minimises the risk to surface water.

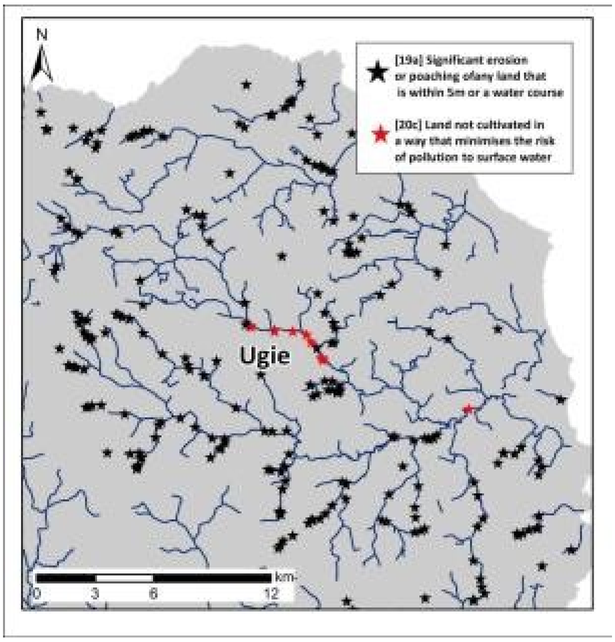


Figure 1: Example of SEPA catchment walk observation points in North east Scotland (unpublished data from SEPA).

The majority of the catchment walk observations were of bank erosion, poaching, flooding or where soil was entering rivers at unbridged vehicle crossing points (Figure 2). Only 29 incidences of in-field rill or gully erosion being recorded. As the vast majority of these observations were made along the stream network, they are more likely to record bank erosion rather than in-field erosion.

Figure 2: photos illustrating the types of GBR breaches recorded by SEPA staff

SEPA collated another data set with information derived from Farm Visits (Figure 3). This was a more targeted dataset had a more broad coverage across a number of Scottish catchments with less focus on land directly adjacent to water courses and more structured. Of the 790 observations, 681 recorded livestock poaching with 29 observations recorded as ‘Runoff in field’. The information collected in the Farm Visit provides the opportunity to better identify the potential causes of erosion, however, the data were not collected systematically but are targeted at known areas at risk of, or have, eroded in the past.

Fields	Observations
Wheel direction	Across slope
Crop land cover	Cereal/OSR
[illegible]	Erosion – non OSR
Erosion type	Gully/Rill
Sediment deposited	In source field
Tramlines	No
Vegetation cover	Partial
Cultivation method	Ploughed
Erosion cause	Runoff in field
Cereal cover	Winter
Erosion visible	Yes

Figure 3: Example of record from the Farm Visit dataset showing the data recorded at each site.

Within fields, tramline wheelings (or controlled traffic systems) are the narrow concave, unvegetated areas seen in arable fields that are used to restrict the passage of farm machinery to specific areas of the field to limit damage elsewhere. On sloping land these usually run up and down the slope. Work in England, supported by Defra, has revealed that these tramlines are a major transport pathway for surface water runoff and are associated with soil erosion (Silgram et al., 2015) particularly within winter sown cereals (and other combinable crops). The impacts of tramlines on runoff derived erosion and was found across soils with sandy, silty and clayey textures. While autumn spraying of cereals is an economic necessity, the unforeseen effects of autumn spraying include compaction of the soil along the tramlines and erosion associated with winter rainfall.

Scottish data from June 2016 showed that the total land area under cereal crops was 432,000 hectares with winter barley accounting for ~48,000 hectares, 11% of total cereal crop area, and wheat ~110,000 hectares (Scottish Government, 2017). 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 phosphorous loss (Withers et al., 2006). Managing tramline wheelings has highlighted that significant reductions in sediment and nutrient losses to water courses can be significantly reduced by up to 75% using 'very flexible', low ground pressure, tyres.

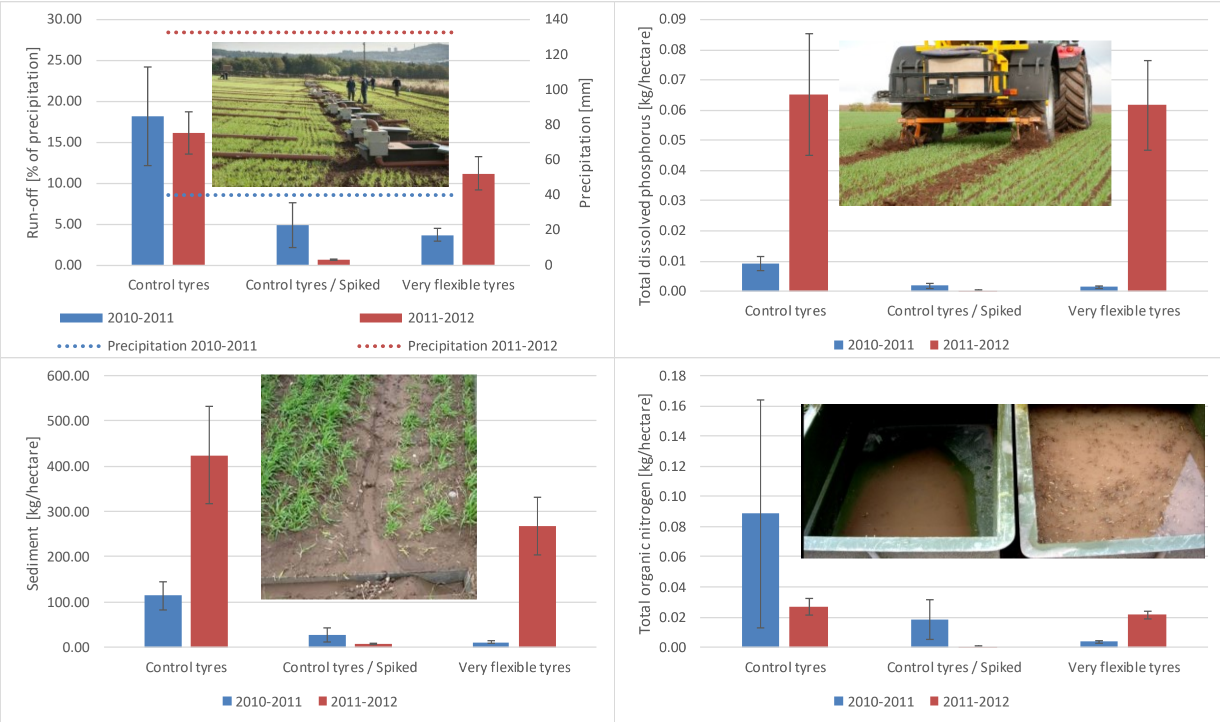
Other types of erosion can affect the sustainable use of agricultural land. For example, Fitton et al. (2016) published a national coastal erosion susceptibility model for Scotland. It should be noted however that there are some areas of Scotland at particular risk (e.g., the western isles) which have significant scientific and cultural importance. One area specifically is the machair landscape where the threat of costal erosion should not be ignored (Young, 2015).

Although erosion of soil by wind is less prevalent than erosion by water, there are few studies that have tried to quantify these losses or to identify the areas at greatest risk. One study, has investigated wind erosion on the machair soils. These areas are exposed to some of the highest mean wind-speeds in the UK with machair soil directly exposed as a result of cultivation or grazing (either by livestock or by rabbits) and therefore highly susceptible to erosion. The study found that soils nearer the coast are more susceptible to erosion (as indicated by lower wind abrasion resistance of the more siliceous) than those on the more calcareous parent material further inland. While organic matter concentrations are generally low in these sandy soils those with more organic matter are generally less erodible (Young et al., 2015).

Scottish tramlines case study

A multi-year study was established at Balruddery Farm, Perthshire, Scotland to investigate the impact of tramline management on erosion, runoff and nutrient loss within winter sown combinable crops. The site was situated on a 9° slope with a sandy loam textured soil. A variety of treatments were tested from the use of conventional tyres and very flexible tyres to sown tramlines and a tramline profiler to promote water infiltration by making the wheel track convex allowing water to shed to the side rather than run downslope.

The study simulated the use of a sprayer in the autumn with soil trafficked when soil was in a favourable condition, i.e. not under wet conditions that could lead to compaction. Data was collected after specific rainfall events with water sampled for chemistry within 48 hours of the event finishing.



- ❖ Results showed that using very flexible tyres reduced runoff by between 80% and 33%
- ❖ Removing compaction using a spiked harrow reduced sediment losses between 76% and 98%
- ❖ The use of either very flexible tyres, or a spiked harrow, significantly decreased losses of sediment, total organic nitrogen and total dissolved phosphorus

- ❖ Key outputs
  - Correctly inflated very flexible tyres, typically run with pressures of 50% when compared to conventional tyres, reduce compaction, surface runoff, sediment and nutrient loss
  - Sowing the tramlines has no consistent effect on tramline derived erosion
  - Rotary harrow may be more effective than very flexible tyres under certain conditions/circumstances
  - None of the treatments had any effects on wheelslip, fuel use or crop yield

What we don't know

Soil erosion models remain difficult to validate due to lack of data. They often predict sediment losses over an artificial land area represented by a regular grid cell whereas much of the erosion on cultivated land occurs as distinct, localised gullies and rills, where some of the sediment can be redeposited within the field rather than 'lost'.

Defra statistics (Silgram et al., 2015) show that across Great Britain arable soils with moderate slopes (4-5° - a large proportion of the 4.6 million hectares of cropped land) is at risk of tramline erosion. However, it is not known whether this also applies to Scottish soils or whether this area is constant or changing. Changes with potential to land use management may result from farm economics (cropping vs pastoral activities), cropping systems (winter vs spring cropping), and machinery changes (making cropping possible on steeper sloping land). Recent climate studies (Thompson et al., 2017) suggest that, for at least some parts of the UK, the chances of record winter rainfall are increasing. New climate projections are due in 2018 that may allow more detailed assessment of the impacts on erosion trends in response to these projections.

Understanding areas susceptible to erosion is critical and recently produced erosion risk maps for much of the cultivated land in Scotland will be made available on Scotland's Soils website. While these maps show the risk of erosion, the study in the Ugie and South Esk catchments has shown that risk does not always translate to actual losses and that suitable land management practices can help mitigate soil erosion. In those catchments, 86% of the fields were classed as being at moderate risk of erosion and 6% at a high risk with a greater proportion at high risk within the Ugie. Land use and land management also have a role to play in mitigating the erosion risk.

There are many identified consequences of erosion, both on-site and off-site. Most of these relate to the loss of sediment and nutrients from one place and their deposition elsewhere. In the last few years there has been a growing awareness in Scotland that in addition to the movement of mineral and nutrient components of the soil there may also be redistribution of organic matter and soil biota. The consequences of these changes for soil function and ecosystem services are poorly understood.

Doetterl et al. (2012) identified that the majority of Europe's cropland is situated on gently rolling landscapes and that significant soil and carbon erosion has been observed affecting at least 50 million ha. Similar rolling topographies are common for Scotland' cropping areas. Eroding agricultural soils may act as sinks or sources of atmospheric carbon and nitrogen depending on whether soil organic matter is exposed during soil transport or buried when sediment is deposited. However, Dungait et al. (2013) concluded that we still do not fully understand how these changes affect the storage and release of greenhouse gases in eroding arable soils.

Scottish Government funded research shows broadleaf weeds within and around the edges of cropped land contributes to multiple ecosystem services and biodiversity. These benefits include supporting pollinators but there are also benefits associated from seeds in the soil seedbank. These include food for insect herbivores and a potential role in soil aggregation. Lewis et al., (2013) considered the significance of soil erosion for arable weed seedbank biodiversity and noted likely restructuring of the seedbank in response to preferential movement of seeds of different species. Similarly, the redistribution of soil fauna by erosion can be important in transferring nematodes between fields with damaging consequences for crops but may also be important for changing the functioning of soil food-webs (Baxter et al., 2013). How selective the erosion processes are in the redistribution of any of the soil carbon, microbiota, soil fauna or weed-seeds is not known but there is a need to broaden investigations of erosion beyond sediment and nutrient detachment, translocation and deposition.

Trends

In general, the greater the proportion of arable cropping in a catchment, the greater the increase in suspended sediment load (Lilly et al., 2009). There was also a strong geographical distribution with catchments draining into the Moray Firth showing an increase in suspended sediment, whilst those catchments in the central belt showing a decrease. The Harmonized Monitoring Scheme (HMS), which provides long-term data on suspended sediments in many Scottish rivers, shows that while some rivers have shown an increase in suspended sediment loads through time, others have shown a decrease.

It remains difficult to predict future trends in soil erosion in cultivated land. There is considerable uncertainty in the UKCP09 climate change predictions (this may change with the release of the UKCP18 dataset) particularly for the western seaboard, although most predictions agree that there will be increased rainfall over eastern Scotland during the winter months. This increase in rainfall is likely to increase the erosion losses if current land use patterns remain the same. However, there is an increasing awareness of the detriment to the soil resource, water quality and sustainability that may mean farmers and land managers adopting novel methods to limiting erosion from their land. One relatively simple approach is retaining stubble in fields previously sown to spring cereals, shown to help reduce erosion. Other mitigation strategies, such as adherence to policies like Cross Compliance (Good Agricultural and Environmental Condition) and the Water Framework Directive, should also help to minimise soil erosion in the future.

Other vulnerable soils include eroded or bare peat, when drier summers may make these soils less able to absorb the greater autumn rainfall predicted, leading to increased run-off and increased erosion. Where significant cracking develops in these peat soils, infiltration may increase, causing a sudden rise in pore water pressure leading to failure and landslides.

Soil compaction in Scotland

Soil compaction occurs when an external mechanical stress from equipment or livestock exceeds the mechanical stability of soil (Bailey et al., 1996) and is considered a serious threat to soil quality, especially in highly managed agricultural systems. Topsoil compaction refers to damage to the ploughed layer of soil, while subsoil compaction refers to damage of the soil layers below the plough depth. Because subsoil compaction is both persistent and expensive to remediate, it is usually viewed as a more severe threat to soil quality than topsoil compaction.

Soil compaction generally leads to soils becoming less porous and more dense and within agriculture is typically caused by mechanical damage to soil. This damage decreases the water storage and aeration in the soil, limiting root growth and leading to decreases in crop yield (Bengough et al., 2011), increases in emissions of greenhouse gases (Ball et al., 1999), increased vulnerability of crops to diseases (Batey, 2009), and decreased water infiltration into the soil resulting in accelerated run-off and an increased risk of soil erosion. Soil compaction also causes increases in management costs (Chamen et al., 2003).

Although many of Scotland’s cultivated soils have naturally compact subsoils (which means they naturally have a greater risk or runoff and erosion), the soils at greatest risk of becoming compacted in the subsoil are those currently with good, porous soil structure 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.

What we know

Although there has been no systematic, wide-scale survey of the physical condition of Scottish soils, some useful evidence does exist in the National Soil Inventory of Scotland (NSIS) 2007-9 resampling (Lilly et al, 2011) and the East of Scotland Farm Survey (Griffiths et al., 2015). Soil cores taken from over 50 commercial arable fields in east Scotland (Griffiths et al., 2015) just after autumn harvest showed that there was sufficient damage to the soil structure in a third of the samples to inhibit root growth due to limited pore space for the roots to grow into. A similar set of soil cores taken during the resampling of the NSIS (2007-9) in early spring showed a similar proportion of soils with poor soil structure (see Appendix 2). In total, by combining the two datasets, 35% of the soils sampled were below the level suitable for good root development leaving the crop vulnerable to drought stress.

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 (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 (classes 4-5) in 18% of topsoils and 9% of subsoils. As a proportion of these sites were examined after an extreme rainfall event (Storm Frank) and unprecedented rainfall in December 2015 to February 2016, the study may have over-estimated the extent of degraded soils.

To date there have been few attempts to map the geographical extent of compaction risk. A vulnerability map of subsoil compaction for Europe was prepared by Jones et al. (2003) using a simple classification system which was adapted and implemented at a more fine resolution for much of the cultivated land in Scotland (Lilly and Baggaley, 2014) where there is existing digitised map cover at 1:25 000 scale (Figure 4).

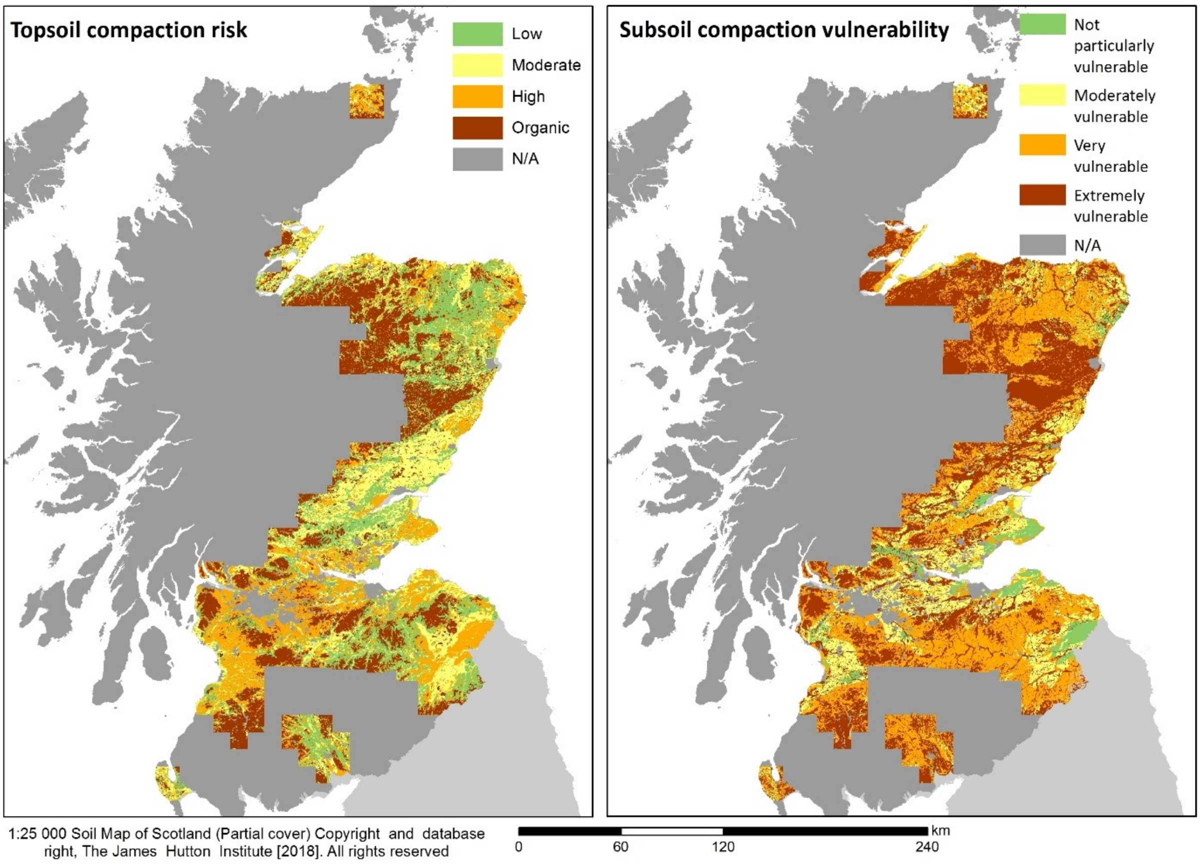


Figure 4: Topsoil and subsoil compaction risk for much of the cultivated land in Scotland based on digitised 1:25 000 scale soil maps –Soil Map of Scotland (partial cover).

As with erosion, there have been attempts to identify those soils susceptible to compaction, for example, Ball et al. (2000) examined 156 cultivated sites, primarily in eastern Scotland, and found many soils to be susceptible to compaction based on measurements of maximum dry bulk density. In Soane et al. (1972) 58 of these agricultural soils were analysed for compactability, however, this does not represent an actual measure of compaction which remains lacking for much of the country.

Troldborg et al. (2013) developed a model for assessing the risk of soil compaction and applied this to identify the distribution of the compaction risk across Scotland using data from NSIS (1978-88). They found that the vulnerability to compaction generally was high, especially in the wetter southern parts of Scotland. They also demonstrated the seasonal effects on compaction risk with soils being more vulnerable to compaction during autumn (and winter), when the soils are more likely to be wet and where exposure to heavy farm machinery is more likely. The advantage of the developed model is that it allows for combining available data from standard soil surveys and land use databases with qualitative expert knowledge and explicitly accounts for uncertainties in the assessment of the risk.

What we don't know

There are limited data available on soil compaction in Scotland and a systematic study of the extent and wider implications of soil compaction in Scotland has not been carried out to date. It is therefore not possible to provide a quantitative assessment of the current state at the national scale. However, surveys of farmers across Scotland have identified drainage and soil compaction as the greatest threats that soils face in Scotland, and there are widespread concerns about compaction, especially due to the harvesting of root vegetables (Munday, 2013; Soane, 1987).

More advanced models to predict compaction risk exist. Horn et al. (2005) assess the risk of soil compaction by comparing the mechanical strength of soils (as calculated using regression equations to predict certain soil properties using data from soil surveys) with the actual stresses exerted by agricultural machinery. If the stress exerted by machinery exceeds the mechanical strength of soil, then the soil is at risk of compaction. Horn et al. (2005) use this methodology to map the compaction risk across all of Europe. Although such a method in principle can be applied anywhere, it is questionable whether the regression equations for German soils as used in Horn et al. (2005) can be applied in countries like Scotland, where soil types and the climatic conditions are different. Beyond this model there is typically not enough information available for Scottish soils to use the more advanced models, and these do not describe soil compaction well because of difficulties in interpreting data (Gregory et al., 2006) and the complexities of the mechanical behaviour of soil.

Trends

A proportion of the sites examined by Hallett et al. (2016) prior to an extreme rainfall event (Storm Frank) and unprecedented rainfall in December 2015 to February 2016 were revisited (42 in total) to examine the impact of the prolonged storm in which Aberdeenshire recorded 145mm of rain (more than twice the average for January) between 1st and 8th January. Hallett et al. reported a 46% increase in the number of topsoils with poor soil structure following this event illustrating the impact that wetter winters and more storms could have on Scottish soils.

The greatest driver of soil compaction is machinery weight. Over the past few decades, agricultural machinery in Europe has considerably increased in power (Kutzbach, 2000) and hence in weight (according to Goering et al. (2003)). It is generally recommended that a tractor is ballasted at 60-70 kg per kW of engine power, meaning that the problem of soil compaction is likely to increase. The trends of increasing weight and power of agricultural machinery are related to an increasing demand of intensified agricultural production for food and biofuels, while reducing the need for manpower and allow for fewer tractor passes on fields. Machinery continues to increase in weight, with some harvesting equipment for root crops used in Scotland weighing 40 tonnes. As machinery weight increases, greater stresses are transmitted deeper into the soil profile. The stresses exerted by machinery can be reduced by increasing the contact area of wheels with the soil, which can be achieved by reducing the inflation pressure, increasing the number of wheels (e.g. using a dual or tandem wheel configuration) or using tracks rather than wheels (Keller and Arvidsson, 2004). However, due to the multi-pass effect, a tandem axle construction is likely to be less efficient in avoiding high levels of compaction compared to wide tyres and dual wheel arrangement. An increasing number of wheel passes in the same track has been shown to increase the risk of subsoil compaction (Alakukku, 2003; Schjonning and Rasmussen, 1994). See also the Scottish tramlines case study above

Information on agricultural machinery weight and management practices in Scotland has not been collated, but it is likely to show a similar trend to those seen in other countries. In Denmark, wheel loads greater than 3–4 tonnes are considered likely to cause persistent compaction in the subsoil. As such loads are common, particularly on larger farms, all managed soils are therefore considered to be at risk of subsoil compaction. The machinery involved in large scale mechanised agriculture is continually evolving but is largely common across most western European countries. Terranimo® is a computer model that predicts the risk of compaction by farm machinery under realistic operating conditions. It is designed as a tool for advisors and farmers. It has been used in regulating when access to land should be granted to contractors or to specify which types of machinery should not be used. It is currently being evaluated for Scottish conditions where stone and gravel content of Scottish arable soils is generally high and so there is a need for further testing of the soil deformation responses in stony soils.

Soil water content is another major driver in the risk of soil compaction and is strongly dependent on the climate. The climate change predictions for Scotland (UKCP09) suggest more erratic and wetter weather conditions in future, with a greater number of extreme rainfall events that produce large amounts of precipitation. The key trends of the long-term climate change projections for the UK are hotter and drier summers and with typical winters/autumns being milder and wetter. Overall, this is expected to make it much more difficult for farmers in Scotland to plan and carry-out field operations when soils are dry enough (i.e. less than field capacity) to minimise the risk of soil compaction. Cooper et al. (1997) predicted a marked reduction in workable days because of climate change and this is already being noticed by farmers who find it difficult to schedule cultivation, spraying and harvesting operations because of weather. Good timing of management operations is considered to be essential to protect soil vulnerable to compaction (Ball et al., 1997). In addition, contractors are increasing being used on farms, presenting a further challenge of less flexibility in timing operations and the associated risk of trafficking soil in unsuitable conditions.

Overall, predicting any future trends in soil compaction is associated with large uncertainty given the lack of information on the current state of soil compaction in Scotland. It remains uncertain what the amount of damage caused by different land management practices under different environmental conditions.

Conclusion

Much of what we know about erosion rates on agricultural land in Scotland comes from a few, individual studies of erosion events. There is, however, a growing body of evidence that can be used to examine the role of land use (both current and historic), soil type and slope on erosion susceptibility. Other factors such as antecedent moisture content, ground cover and presence of tramlines also play a role, making it difficult to be certain when, or if, erosion will occur.

Soil erosion models with sediment yield as an output seem to exaggerate the amount of soil loss and are difficult to validate, although they do offer a way to examine the relative changes in erosion rate under different land uses and changing climates. Recently published rule-based erosion risk maps identify areas susceptible to erosion and that need careful management to minimise soil loss. However, there is a tendency to focus on small high risk areas whereas larger areas of medium risk may contribute more to sediment loss.

Evidence suggests that Scottish soils have become compacted to the point that root growth could be restricted or inhibited leading to losses in yield. The extent of this compaction is unknown but models suggest that a large proportion of Scotland’s soils are at a moderate to high risk of becoming compacted. There is a link between soil compaction and erosion; soils that become compacted have a restricted capacity to store rainfall and generate overland flow more quickly than soils that are not compacted. This overland flow can then cause erosion.

The greatest driver of soil compaction is machinery weight, which has been increasing over the past few decades, although using wide tyres, dual wheels and low pressure tyres can reduce the impact. New field-scale models that predict the risk of compaction are being tested for Scottish conditions. Soil water content is a key determinant in whether a soil will and more weather may shorten the window of opportunity for cultivation under ideal soil conditions leading to increased compaction.

We do not know the full extent of erosion or compaction in Scotland. Current models allow us to assess risk to help minimise impact but we need more information on the interaction between climate and soils (and compaction and erosion) to improve predictions of when, or if, a soil erodes or becomes compacted.

Appendix 1: Soil erosion risk models

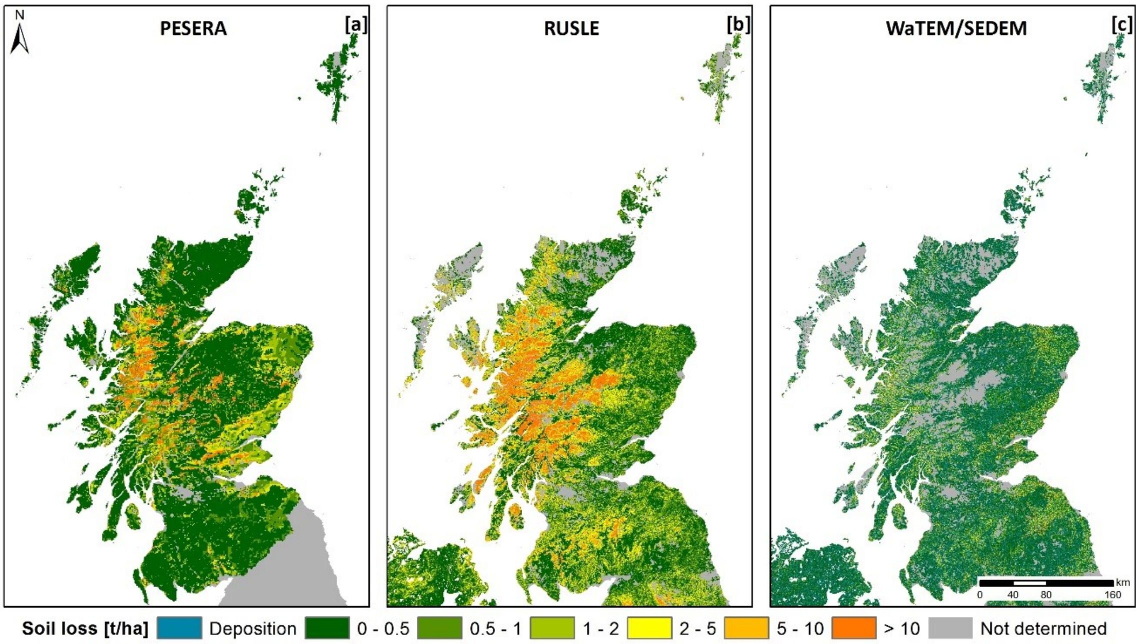


Figure 5: Soil erosion risk models

Sediment loss predicted by (a) the PESERA erosion risk model (1971-2000 climate data), (b) by the Revised Universal Soil Loss Equation (RUSLE) and (c) by the WaTEM/SEDEM model which is a combination of RUSLE, a transport and a sediment model and. Note that the sediment losses have not been validated.

Several soil erosion models have been developed to predict soil losses from Scottish soils by water erosion. Three of these have been developed for application at the European scale (Kirkby et al.,2004; Panagos et al., 2015; Borrelli et al., 2018). The models by Panagos et al., (2015) and Borrelli et al., (2018) use only European scale soils data to model the water erosion in Scotland (Figure 5 b and c) while the model developed by Kirkby et al. (2004) shown on the left (Figure 5 a) was applied to Scottish soils data by Lilly et al (2009). None of the models have been validated against actual erosion rates, but the model by Kirkby et al. (2004) based on national soil and climate data suggests annual erosion rates of less than one tonne per hectare per year for the majority of Scotland under 1971–2000 rainfall patterns and land uses although the model predicts greater losses for the arable areas of eastern Scotland (more than two tonnes per hectare per year). The other two models give similar predictions. These predicted losses are greater than the estimated natural rate of soil formation of 0.3-1.4 t per hectare per year or a soil loss of 0.03-0.14 mm per year assuming a dry bulk density of 1 g/cm3 (Verheijen et al., 2009). The key issue with all these types of models is that there is insufficient measured data of soil losses to validate them though they can give guidance on where the greatest risk of erosion may be.

Appendix 2: Evidence of compaction

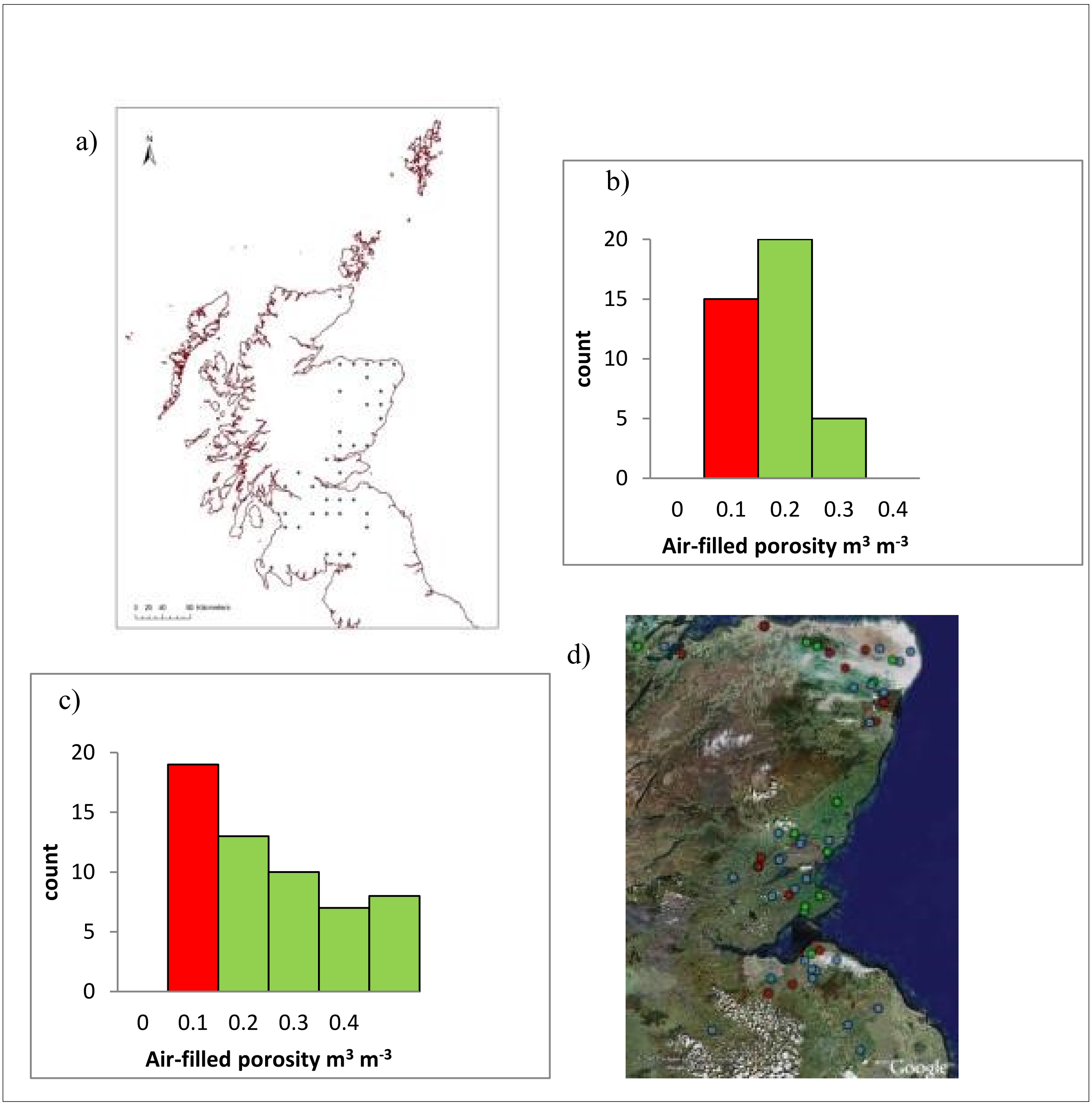


Figure 6: Evidence of compaction from the National Soil Inventory of Scotland 2007-9 resampling and the East of Scotland Farm Survey.

a) the distribution of cultivated soils from the NSIS (Lilly et al, 2011) for which air-filled porosity was calculated
b) the frequency distribution of NSIS air-filled porosity values (air-filled porosity m^3 m^{-3})
c) the distribution of cultivated soils from the East of Scotland arable farm survey (Griffiths et al., 2015) for which air-filled porosity was calculated
d) the frequency distribution of East of Scotland arable farm survey air-filled porosity values.

NB: Air-filled porosity values <0.1 m^3 m^{-3} are considered to restrict root growth.

Appendix 3: Some relevant literature on soil compaction

Soil compaction has been extensively researched over the years and the processes associated with compaction are broadly understood. Generally, compaction occurs when an external stress from machinery or livestock exceeds the mechanical stability of soil.

The mechanical stress on soil caused by machinery is mainly driven by machinery weight, but also depends on the number of machinery passes, tyre configuration, inflation pressure and tyre dimensions. The mechanical stress is usually described in terms of axle loads, wheel loads or ground contact pressures (Alakukku et al., 2003) and various studies have recommended limit values based on these measures to avoid soil compaction (e.g., Danfors, 1994; Horn and Fleige, 2009; Spoor et al., 2003). Axle load is often considered the main cause of subsoil compaction, while topsoil compaction is related to ground contact pressure (Hamza and Anderson, 2005); however, this generalisation has been challenged in a number of studies (e.g., Ansorge and Godwin, 2008; Keller and Arvidsson, 2004) and questions the establishment of an axle load limitation as proposed by e.g. Danfors (1994). The mechanical stresses from machinery can be reduced by decreasing machinery weight, number of passes and/or increasing the contact area of wheels with the soil. The wheel contact area can be increased by reducing the inflation pressure, increasing the number of wheels (e.g. using a dual or tandem wheel configuration) or using tracks rather than wheels (e.g., Bailey et al., 1996; Keller and Arvidsson, 2004). However, due to the multi-pass effect, a tandem axle construction is likely to be less efficient in avoiding high levels of compaction compared to wide tyres and dual wheel arrangement. An increasing number of wheel passes in the same track has been shown to increase the risk of subsoil compaction (e.g., Schjonning and Rasmussen, 1994; Wiermann et al., 2000). Studies have also shown that trampling-induced soil compaction mainly is restricted to the upper 20 cm of the soil profile, depending on animal weight and livestock density, while stresses induced by heavy agricultural machinery can extend much deeper and cause subsoil compaction.

Various factors and properties control the vulnerability of soil to compaction. Soil water content is a major factor influencing the risk of soil compaction with most dry soils being less prone to compaction, while wet soils can be highly susceptible to compaction. The soil water status strongly depends on climate and how quickly the soil allows for water to drain away. Properties such as previous stress history and bulk density (Keller & Arvidsson, 2007), content and type of organic matter (Soane et al., 1990; Zhang et al., 2005), texture (O'Sullivan et al., 1999) and soil structure (Horn & Fleige, 2009) are also known to control the susceptibility of soils to compaction. Most of these properties also regulate the capacity of soil to recover from compaction either through subsequent cultivation or the inherent resilience under natural weathering (Gregory et al., 2007). However, it should be noted that the literature contains conflicting conclusions on how some of these soil properties affect compaction susceptibility, reflecting the complexity and the wide differences in the soils analysed in the different studies as well as differences in the methods and compaction indicators used.

The microtopography of the soil surface is an important indicator of compaction caused by the passage of tyres or tracks of individual or multiple vehicles. That microtopography may also indicate likely flow paths for water run-off associated with decreased infiltration resulting from the compaction. The quantification of soil surface condition in the field can be by different methods. These include traditional mechanical pin-meters that have low accuracy and are very labour intensive. Alternatively, laser scanners that while having high-accuracy (< 1 mm resolution) are expensive and require rigid frameworks to anchor the equipment – restricting use for multiple machine passes. A Moiré technique has recently been developed and tested in Scotland (McKenzie et al., 2016) showing to demonstrate changes in soil microtopography resulting from single and multiple passes of a typical commercial tractor. This method uses a standard camera and battery-powered projector on simple tripods.

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