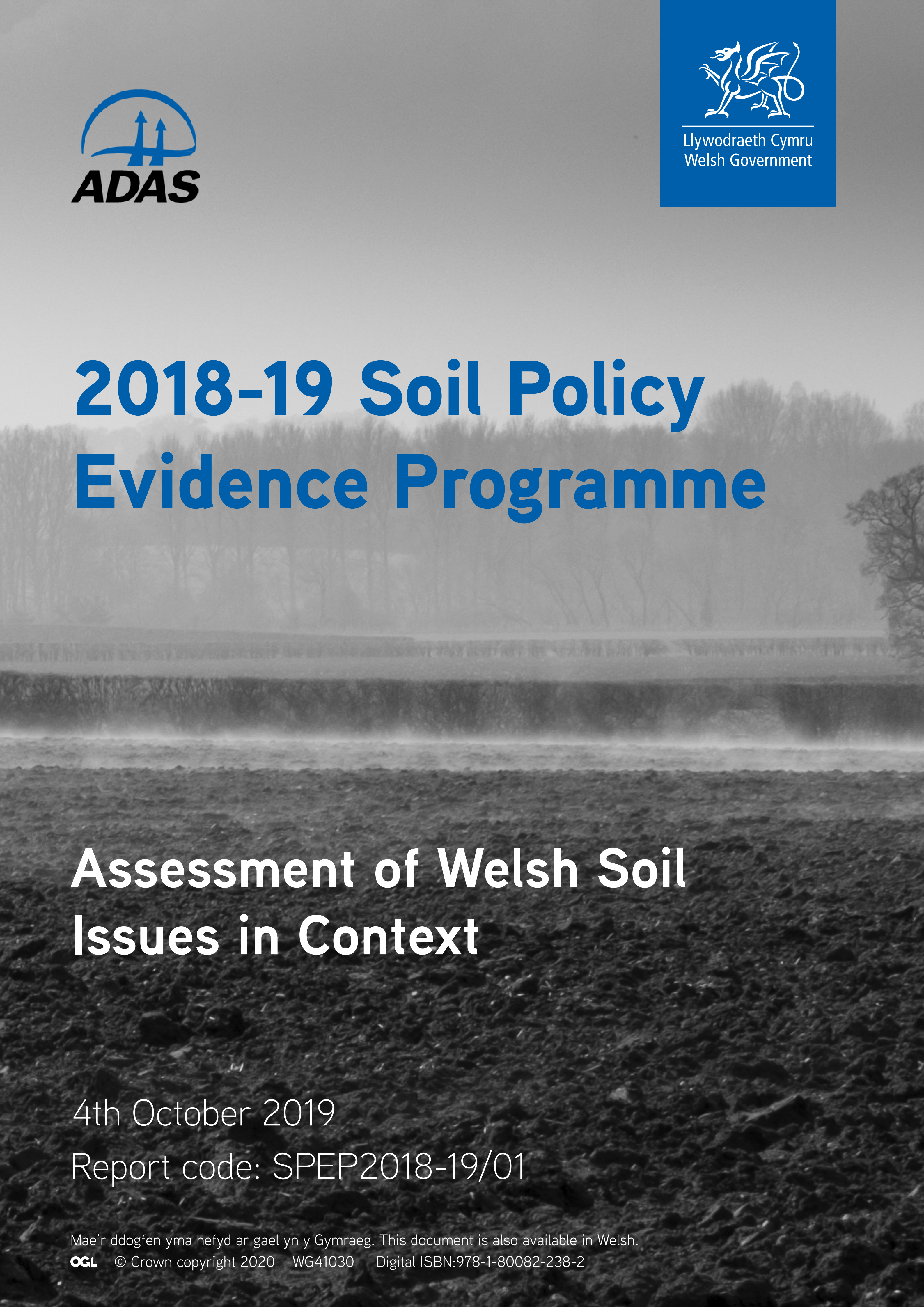

ADAS

Llywodraeth Cymru
Welsh Government

2018-19 Soil Policy Evidence Programme

Assessment of Welsh Soil Issues in Context

4th October 2019

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Assessment of Welsh Soil Issues in Context

Soil Policy Evidence Programme 2018-19/01

Submitted to:

Soil Policy & Agricultural Land Use Planning Unit

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Welsh Government

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Introduction

- Soil is the foundation of all terrestrial ecosystems and provides multiple ecosystem services; the most prominent of these being the provision of food and fibre, climate regulation and carbon storage, the regulation of water flow and quality and the support of both above and below ground biodiversity.
- Agricultural management is the major controllable factor influencing soil condition; 85% of the land area of Wales is utilised for agriculture. Another *c*.12% of the land area of Wales (284,000 ha) is woodland, of which 55% is coniferous.
- Grassland (permanent managed pasture and rough grazing), with significant variation in type (e.g. improved, natural or semi-natural) and management (e.g. stocking rate or cutting regime), accounts for more than 70% (1.3 million ha) of the utilised area and grass leys for another 8%. In comparison, arable land accounts for 13% (0.25 million ha) of the agricultural area and thus threats to arable land only affect a small part of the total agricultural land area. The dominance of grassland agriculture reflects the high altitudes, high rainfall, impeded drainage and extended duration of field capacity in many areas of Wales.
- Headlines such as '100 harvests left'[1], 'We can only ignore the soil crisis for so long'[2] and 'We're treating soil like dirt'[3], have bought the issues surrounding soil protection (and in particular topsoil and organic matter loss) to a wider audience. However, despite the alarmist nature of these headlines many refer to specific risks, for specific soils, in specific areas, e.g. organic matter and topsoil loss in the East Anglian Fens and many soils in Wales remain in good condition.

Threats to Welsh soils

- The most important threats to soil in Wales are listed below; the type of land use that is most affected by the threat is also identified:

  I. Climate change (arable, grassland and forest)
  II. Soil compaction (mainly arable, intensive grassland and forestry)
  III. Soil erosion (mainly arable)
  IV. Loss of soil organic matter (SOM) and loss of soil biodiversity (mainly arable)
  V. Soil loss to development/soil sealing (arable and grassland)
  VI. Soil contamination (arable and grassland).

- Soil degradation can occur as a result of a number of processes. Important threats to soil in Wales are, compaction, erosion, loss of organic matter and concurrent loss of soil biodiversity, soil loss to development and soil contamination; however, the distribution of these threats is varies across the country.
- The threat of any changes to land use as a result of Brexit are impossible to quantify at this stage.
- Climate change is likely to increase the threats to soils in Wales. E.g. increasing temperatures are predicted to speed up organic matter loss and changes in rainfall patterns (increased winter precipitation and decreased summer precipitation) and intensities are likely to increase risks of soil compaction and erosion.
- The extensively grazed grassland (e.g. where the total amount of nitrogen in organic manure applied, either directly by livestock or as a result of spreading is ≤100 kg N/ha) soils that

[1] https://www.fwi.co.uk/news/only-100-harvests-left-in-uk-farm-soils-scientists-warn
[2] https://www.telegraph.co.uk/news/earth/agriculture/farming/11838959/We-can-only-ignore-the-soil-crisis-for-so-long.html
[3] https://www.theguardian.com/commentisfree/2015/mar/25/treating-soil-like-dirt-fatal-mistake-human-life

predominate in Wales are generally at low risk of soil degradation and typically will have low rates of soil erosion and compaction, coupled with high organic matter contents and consequently high carbon storage. The main threat to intensively managed grassland soil is damage by heavy machinery (e.g. harvesters and manure spreaders), intensively/poorly managed grazing livestock and land use change, i.e. cultivation for arable and fodder production. In comparison, arable soils are much more vulnerable to a range of threats caused by cultivation practices that may compact soils, influence soil erosion rates and lead to reductions in organic matter content. The intensity of any threat to soils will be directly linked to soil, site and climatic factors.

- ***Climate Change:*** It is not yet clear how soils are responding to a changing climate, with much debate over whether measured declines in UK soil carbon concentrations over the last few decades are a result of climate change or other factors such as changes in land management or recovery from acidification. However, given the predicted increases in temperature and changes in the seasonality and magnitude of rainfall events, changes to soils and the services they provide are highly likely, particularly if land-use patterns also change.
- ***Compaction:*** Based on modelling assessments of soil wetness classes, it has been suggested that 25% of the total grassland area is liable to compaction from machinery damage or livestock. Compaction by livestock is strongly linked to the timing and intensity of grazing activities and the risks are much higher with wet soil and low plant density (i.e. in early spring and late autumn or early winter). In comparison, based on the same modelling assessments, it has been suggested that <5% of arable soil and <1% of forest soils in Wales are at significant risk of compaction, mainly from cultivation and harvest operations.
- ***Erosion:*** Large areas of Wales are assumed to have low erosion rates due to grassland land use and relatively low stocking rates (18% reduction in sheep and lamb numbers between 1998 and 2018), although this has not been quantified by measurements or observations. In comparison, although the number of dairy herds in Wales has decreased in recent years dairy cow numbers have increased, potentially suggesting increased stocking rates in some localised areas. Land use change is an important factor in soil erosion risk and significant decreases in erosion risk have been noted when fields have changed from winter cereals to permanent grass. This is because grassland soils generally have year round crop cover and so soil is not exposed to the erosive forces of water or wind, although the erosion risk will be higher during the reseeding phase.
- ***Soil organic matter (SOM):*** SOM accumulation is favoured by management systems, which add high amounts of biomass to soil, improve soil structure, enhance species diversity and minimise soil disturbance. Such high carbon input (e.g. litter and roots), low disturbance systems are typified by the grassland soils that predominate in Wales. Thus most soils in Wales will be at lower risk of SOM loss, although SOM loss may occur when grasslands are reseeded. Nevertheless, 'habitat soils' (defined as all habitats except woodlands, arable and improved grassland) in Wales, which include some organo-mineral, grassland soils have lost 1% soil organic carbon per year since 2007, possibly due to recovery from acidification or climate change. For the minority of soils in Wales that are in arable systems, the risk of SOM loss is significantly greater, as SOM loss is triggered by reduced accumulation or removal of OM (crop residues may not be returned to the soil so levels become depleted) and soil disturbance, which increases oxidation of soil organic matter.

Remediation of soil degradation

- Grazing or over-grazing by livestock is a major cause of grassland compaction. Measures to prevent compaction by livestock include: keeping livestock off wet fields, increasing the length of grazing rotations, providing multiple gateways and feeders/drinkers, regular moving of temporary feeders/grazers and limiting stocking rates.

- The key to controlling soil erosion by water is to maximise vegetation cover on sloping land. Improving rainfall infiltration into soils and minimising damage to soil structure will also reduce erosion risk. Permanent soil cover minimises erosion and hence grassland soils are often at low risk of water erosion.
- Best practice methods for SOM can be broadly grouped into the following categories: land use change (e.g. convert tillage land to permanent grassland), reduction in soil erosion (e.g. establish winter cover crops on spring cropping land), changes to tillage/cultivation practices (e.g. reduced or zero tillage) and increased organic matter additions/returns. There is a relationship between soil biodiversity and organic matter additions so that land management that increases or maintains soil organic matter levels is also likely to benefit soil biodiversity, although the relationship is not fully understood.

Regulation and policy

- A comprehensive soils policy should not just focus on preserving/improving the (physical, biological, chemical) condition of soils, but rather on enhancing the services they support. In addition, there should be benefits for the farmer in terms of increased production, lowering costs or financial reward. However, there are a number of challenges to regulating soil which mainly relate to: the establishment of baseline and/or target values for soil properties, the mismatch between the policy cycle and measurable changes in soil and the need to balance the ability of soils to provide a full range of ecosystem services at the local, regional and national scale
- To regulate soil effectively there is a need to establish both baseline and target values for soil that can be included in legislation and that are practical, measurable and enforceable. Soil quality indicators (SQIs) are often proposed to assess the delivery of soil ecosystem service. However, despite significant progress with interpreting indicator values, major scientific and practical issues remain to be addressed and as a result, SQI are difficult to include in regulation. Nevertheless, it is clear that policies that maintain or enhance SOM contents should result in multiple benefits in terms of climate change mitigation and the sustainability of agricultural systems.

Conclusions

- Most soils in Wales are at a low risk of degradation under current agricultural management, which is dominated by permanent grassland (i.e. grassland not ploughed for >5 years). The main threat to grassland soil under the current land use is soil compaction as a result of the use of heavy machinery and intensively/poorly managed grazing livestock. However, land use change, i.e. cultivation for arable and fodder production and climate change present further potential risks to grassland soils through changes in rainfall intensity/distribution and associated change in soil moisture regimes.
- For the minority of soils that are managed for arable cropping the main current threats are related to agricultural management and include compaction, erosion and the loss of soil organic matter. In common with grassland soils, climate change poses future risks to arable soils, which although not yet fully understood, could increase the risks from soil erosion, soil compaction and soil organic matter loss.
- There are a number of challenges associated with regulating soil, which mainly relate to: the establishment of baseline and/or target values for soil properties. Nevertheless, it is clear that policies that maintain or enhance SOM contents should result in multiple benefits in terms of climate change mitigation and the sustainability of agricultural systems.

1 Introduction

- Soil is an important natural resource that provides a range of vital ecosystem services. However, soil functions are vulnerable to a range of degradation processes and a number of threats to soils have been identified in Europe including erosion, compaction, loss of soil organic matter, sealing contamination and loss of biodiversity.

1.1 Objectives

- The objectives of this report were to understand and prioritise the specific threats to soils in Wales. In detail to:
    1. Identify and rank threats to soils in relation to soil type, location and farming enterprise
    2. Assess the practicality and cost/benefits of measures to prevent and remediate soil degradation
    3. Assess the challenges involved with regulating soils
    4. Identify policy options to maintain/improve soil quality
    5. Identify priorities to improve knowledge exchange and enable land managers to maintain/improve soil quality.

1.2 Land use

- In 2017, 85% of the land area of Wales was utilised as agricultural area (Wiseall, 2018) hence agricultural management is the major controllable factor influencing soil condition. Agricultural land is usually managed to produce grass for livestock or tilled to produce a range of crops.
- Welsh agriculture is dominated by grassland (permanent pasture and rough grazing) with significant variation in type (e.g. improved, natural or semi-natural) and management (e.g. stocking rate or cutting regime), which accounts for more than 70% (1.3 million ha) of the utilised area. In comparison, tillage accounts for 13% (0.25 million ha) of the area, 10% is common rough grazing (0.18 million ha) and the remaining 5% woodland or other land on agricultural holdings (Welsh Government, 2018a). Of the 246,000 ha of tilled land in 2017, 63% (*c*.154,000 ha) was grass under 5 years old and 37% (92,000) was in arable and/or horticulture production. Almost half of the tillage land (43,000 ha) was in Pembrokeshire and South Wales (Welsh Government, 2018b); more than 50% of the area of tillage crops was cereals, in particular wheat and barley (Figure 1).
- Woodlands cover approximately 12% of the land area of Wales (284,000 ha) and provide soil protection, timber, biodiversity as well as having amenity value. Coniferous woodland make up 55% of woodlands in Wales with the majority of coniferous woodland located on the poorer soils in upland Wales. However, in recent years new tree planting has been dominated by broadleaved tree species. The Woodland for Wales strategy aims to plant 2000 ha of additional woodland each year from 2020 to 2030 (Welsh Government, 2018d).

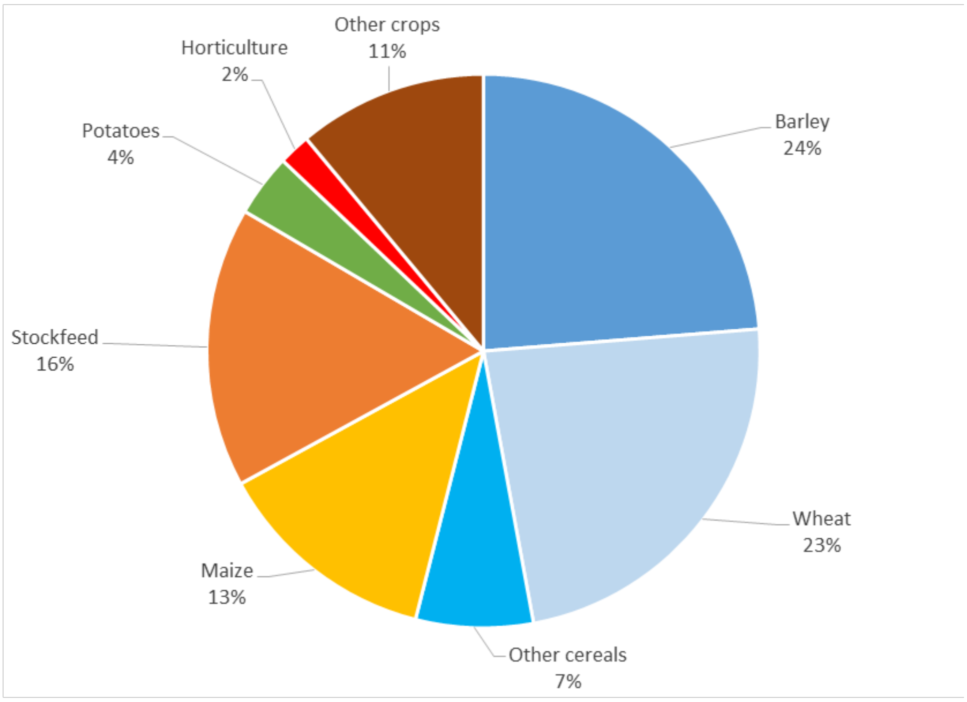


Figure 1. Tillage cropping in Wales (% of area in 2017)

- The optimal zones for agricultural production are related to both climatic and soil conditions. Local climate is strongly influenced by topography, aspect and altitudinal gradients in temperature and rainfall that lead to microclimatic variations. Of the total land area of Wales, 60% is more than 150 m above sea level, and 27% is more than 300 m above sea level (Russell *et al*., 2011), which will limit the potential for agricultural crop production. High altitudes, acid soils and impeded drainage limit tillage and grassland intensification over large parts of Wales. As a result, around 75% of land is classified as predictive ALC classes 3b, 4 and 5 (i.e. mainly unsuitable for arable cropping). Similarly, around 80% of the agricultural land in Wales has been designated under the Less Favoured Area (LFA) Directive (EU Directive 75/268/EEC of 28 April 1975). LFA land is characterised by challenging climatic limitations and shallow, stony and/or peaty soils with limited agricultural and forestry potential and below average economic returns (Armstrong, 2016). Of the total tillage land in Wales, 37,600 ha (43%) was designated as LFA (Welsh Government, 2018a).

1.3 Soil

- Soil conditions and land conditions are strongly influenced by climate (and altitude), vegetation, land use, the sediments or rocks from which they have developed and the underlying geology. Jenny (1941) suggested that soil development was controlled by five factors; parent material, climate, organisms, relief/topography and time.
- Soils fall into three main broad groups, i.e. organic, organo-mineral or mineral soils. Organic soils have an organic layer (comprised of decaying plant material) of at least 40 cm, organo-mineral soils have an organic layer of ≤ 40 cm and mineral soils are defined as having no organic layer.
- Most soils in Wales are mineral soil (*c*.80%) but there are also 426,211 ha of organo-mineral soils in Wales (17% of Wales), 65% of which is under grassland, the majority of which is unimproved rough or semi-natural grassland in upland regions (Figure 2). Only 1% of organo-mineral soils in Wales are under cropland; they also occur under forest and heathland. In comparison, there are 90,050 ha of peat in Wales, equivalent to about 4% of the land area, 75% is in upland areas and 25% in lowlands (Evans *et al.,* 2015).

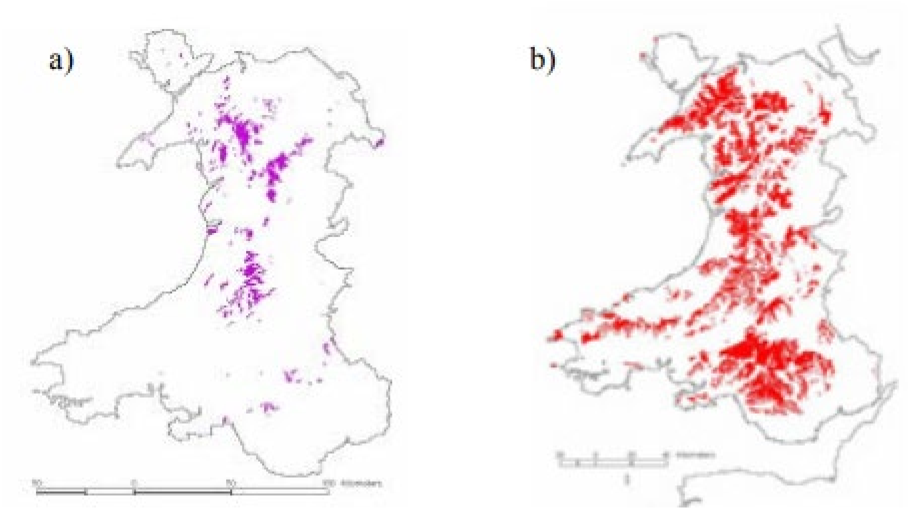


Figure 2. Distribution of a) peat soils and b) organo-mineral soils in Wales

- In England and Wales soil characteristics are defined at four levels (major group, group, sub-group and series) in a hierarchical system, general characteristics being used at the highest level to give broad separations and more specific ones at lower levels to give increasingly precise subdivisions (Hallett *et al*., 2017). There are 10 major soil groups (based on pedogenic characteristics) within the soil classification for England and Wales, all of which are present in Wales (Avery, 1980), Table 1. These are further divided into >60 groups, >80 sub-groups and 100s of series.

Table 1. Major soil groups in Wales

Major soil group	Land cover (%)	Description
Terrestrial raw soils	<0.1	Very young soils with only a superficial organo-mineral layer
Raw gley soils	0.2	Unripened young soils of saltmarshes
Lithomorphic soils	2.2	Shallow soils without a weathered subsoil
Pelosols	0.1	Clayey 'cracking' soils
Brown soils	30.2	Loamy, permeable soils with weathered subsoil
Podzolic soils	32.3	Acid soils with brightly coloured iron-enriched subsoil
Surface-water gley soils	24.7	Loamy and clayey seasonally waterlogged soils with impermeable subsoil
Ground-water gley soils	3.4	Soils associated with high seasonal groundwater
Man-made soil	0.4	Restored soils of disturbed ground
Peat soils	3.4	Soils in deep peat.
Unclassified land (urban)	3.0	

- To provide an overview of the soil texture, drainage, fertility, land cover, habitats, topsoil carbon, drainage and general cropping guidance 27 'soilscapes' have been described by Cranfield University. The 'soilscapes' were designed to provide 'extensive, understandable and useful soil data for a non-soil specialist'[4]. There is no direct relationship between the major soil

[4] http://www.landis.org.uk/soilscapes/soilguide.cfm

groups in Table 1 and the soilscapes in Table 2, the first classification forms part of an in-depth site specific assessment whereas the latter is intended to give a more broad overview.

- The predominant soilscapes in Wales (i.e. those with the largest % land cover) and their agricultural (cropping) characteristics are described in Table 2, below, with the full range of soils shown in Figure 3. Overall, there is a scarcity of high quality agricultural soils, with those considered to be the best and most versatile accounting for no more than 11% of Wales' land area (UK NEA, 2011).

Table 2. The main Soilscapes in Wales (Cranfield University, 2017)

Soilscape description	Land cover (%)	Suitability for cropping
Freely draining slightly acid loamy soils	24	Suitable for range of spring and autumn sown crops; under grass the soils have a long grazing season. Free drainage reduces the risk of soil damage from grazing animals or farm machinery. Shortage of soil moisture most likely limiting factor on yields, particularly where stony or shallow
Free draining acid loamy soils over rock	23	Land mostly steeply sloping and with restricted mechanised access; suited to grassland with potential for year round grazing
Slowly permeable seasonally wet acid loamy and clayey soils.	15	Mostly suited to grass production for dairying or beef; some cereal production often for feed. Timeliness of stocking and fieldwork is important, and wet ground conditions should be avoided at the beginning and end of the growing season to prevent damage to soil structure. Land is tile drained and periodic moling or subsoiling will assist drainage
Very acid loamy upland soils with a wet peaty surface	9	Some soils are capable of improvement to grassland but most only support rough grazing of low or moderate grazing value
Slowly permeable wet very acid upland soils with a peaty surface	8	Some soils are capable of improvement to grassland but most only support rough grazing of low or moderate grazing value. Grazing or trafficking during wet ground conditions should be avoided to prevent damage to soil structure

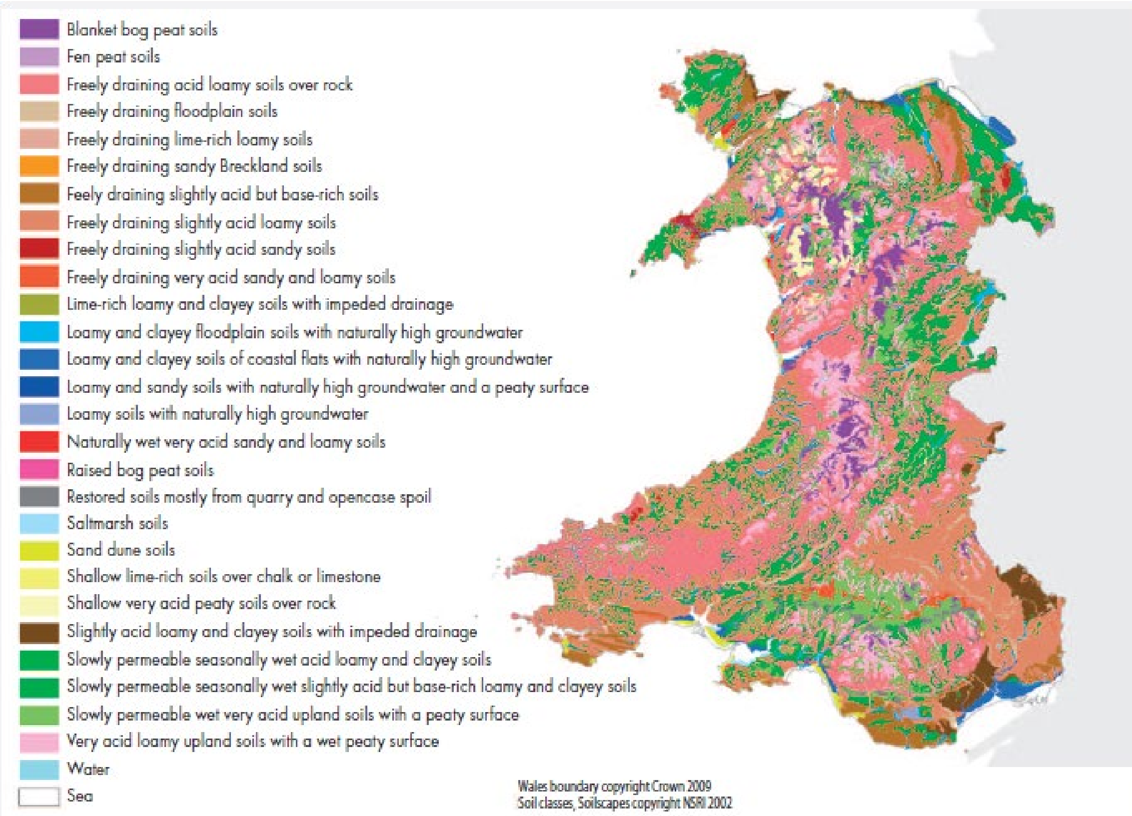
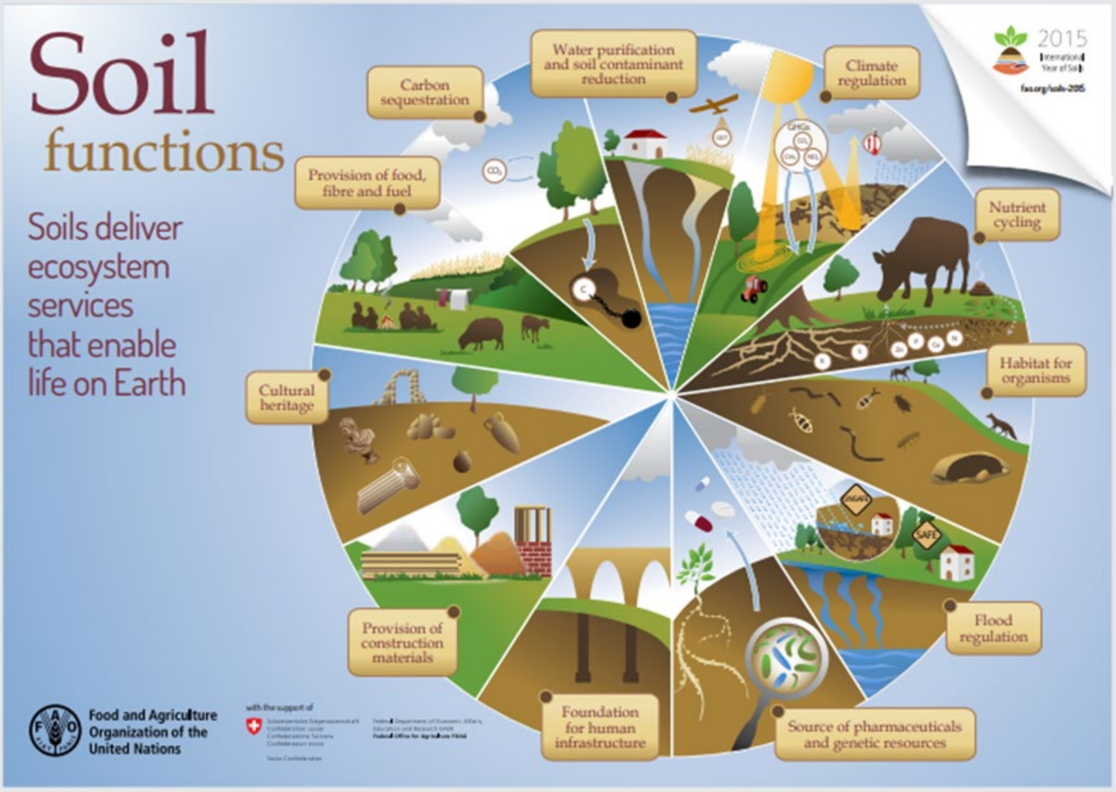


Figure 3. Soilscapes in Wales (Cranfield University, 2017).

2 Threats to Welsh Soils

- Soil is the foundation of all terrestrial ecosystems and provides multiple ecosystem services; the most prominent of these being the provision of food and fibre, climate regulation and carbon storage, the regulation of water flow and quality and the support of both above and below ground biodiversity (Figure 4). It is estimated that 95% of food is produced on soils (FAO, 2015).



Source: http://www.fao.org/resources/infographics/infographics-details/en/c/284478/

Figure 4. Soil functions.

- A well-functioning soil is essential for achieving 13 of the 17 UN Sustainable Development Goals (SDG) through the provision of ecosystem services such as the provision of food and fibre, flood mitigation and carbon storage (Figure 5).

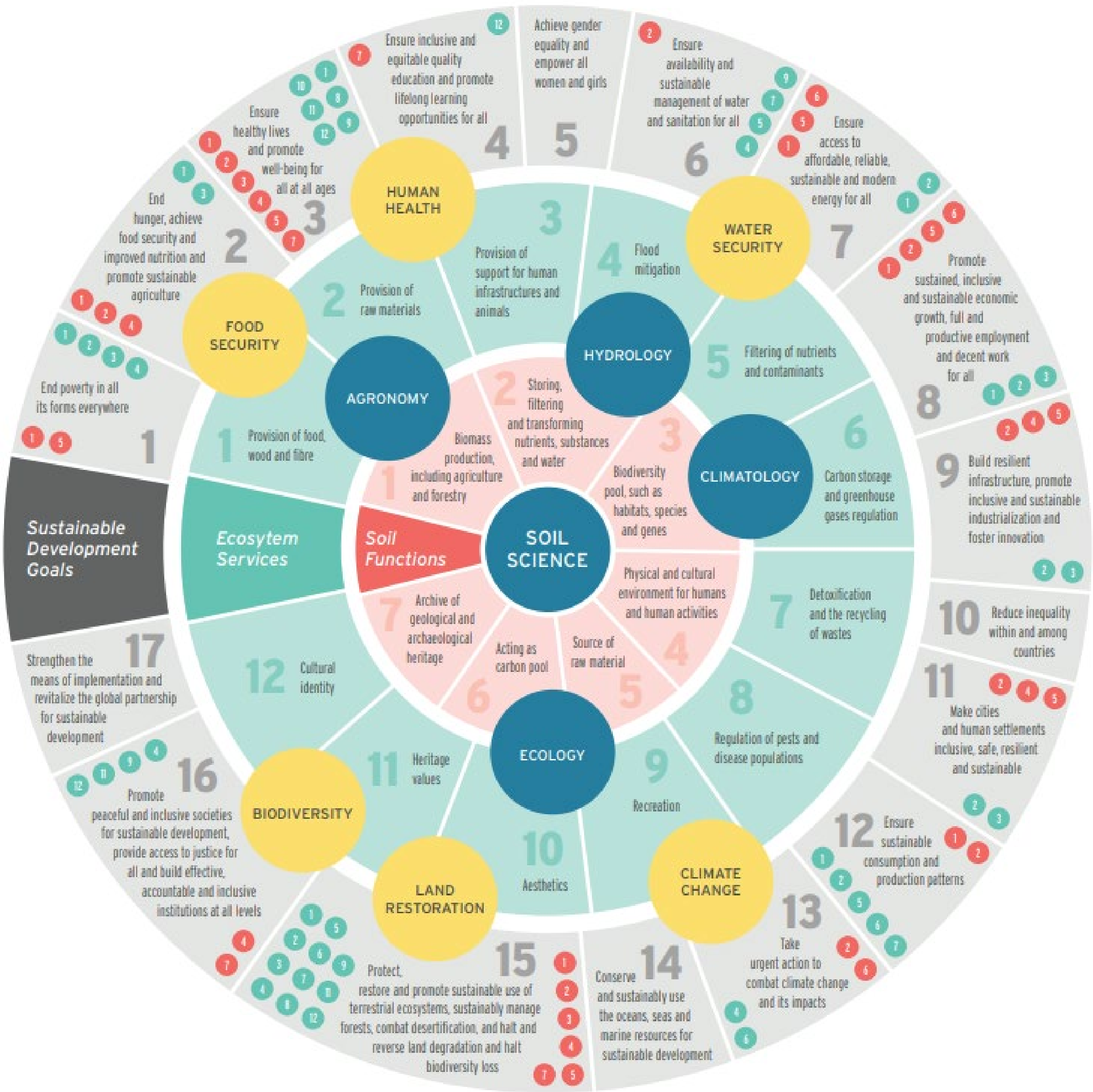


Figure 5. The significance of soils and soil science towards realisation of the UN sustainable development goals. Source: Keesstra *et al.*, 2016.

- Different soils deliver some ecosystem services more effectively than others, with lowland mineral soils under arable and grassland management important for food production, while deep peats in upland areas support semi-natural habitats and are arguably more important for carbon storage and climate regulation. However, the ability of soils to deliver these services is threatened by a number of degradation processes.
- High level pressures on soils can be broadly grouped into two categories – anthropogenic (i.e. caused by human activity) and climate induced change (Haygarth and Ritz, 2009).
- It is important to note that the main threats to soils will vary according to the type of land management (i.e. grassland v arable). Extensively, grazed grassland soils are generally at low risk of soil degradation and typically will have low rates of soil erosion and compaction, coupled with high organic matter contents. In comparison, arable soils are much more vulnerable to a range of threats caused by cultivation practices that may compact soils, influence soil erosion rates and lead to reductions in organic matter.

- Historically forests tended to have been planted on ground of poorer quality than agricultural land, for example, steep slopes or seasonally waterlogged soils, which may make them vulnerable to degradation (Forestry Commission, 2017). However, many forest soils have low and infrequent levels of disturbance so that the risks of which minimises potential damage. Planting, harvesting and brash management have the potential to cause soil erosion or compaction or loss of soil organic matter.
- In Wales, grassland agriculture predominates and thus most soils will be at low risk of degradation. The main threat to grassland soil is damage by intensively/poorly managed grazing livestock and land use change, i.e. cultivation for arable and fodder production. Inherent risks are associated with high rainfall and soil wetness resulting in restricted opportunities for cultivations. In addition, it has been reported that 40% of drains in arable and improved grassland are in need of repair and replacement (Emmett *et al.,* 2017), which also has implications for production and soil damage.
- The most important threats to soil in Wales are listed below; the type of land that is most affected by the threat is also identified:

I. Climate change (arable, grassland and forest)
II. Soil compaction (mainly arable, intensive grassland and forestry)
III. Soil erosion (mainly arable)
IV. Loss of soil organic matter (SOM) and loss of soil biodiversity (arable)
V. Soil loss to development/soil sealing (arable and grassland)
VI. Soil contamination (arable and grassland).

- Threats to soils in Wales are discussed in the following sections of the report in order of their importance to soils. Note that although compaction, erosion and loss of SOM are important threats to soil they mainly affect arable soils, which make up only a small proportion (13%) of the soils in Wales.

2.1 Climate change

- It is not yet clear how soils are responding to a changing climate, with much debate over whether measured declines in UK soil carbon (C) concentrations over the last few decades are a result of climate change or other factors such as changes in land management (Barraclough *et al*., 2015). However, given the predicted increases in temperature and changes in the seasonality and magnitude of rainfall events, changes to soils and the services they provide are highly likely, particularly if land-use patterns also change. This includes potential changes in soil carbon storage and greenhouse gas (GHG) emissions, soil structural stability, biodiversity and erosion, flooding and water regulation. Protecting this carbon store has been identified as a key means by which land management can contribute to climate change mitigation and resilience through increasing/maintaining OM.

2.1.1 Soil type

- Barraclough *et al*. (2015) reported that soil type influenced the impact of climate change on soil carbon content. For organo-mineral/mineral soils only 0-5% of the change in soil C could be predicted by climate. While, for organic soils, it was estimated that between 9-22% of changes in soil C content were related to changes in by climate. It was concluded that organo-mineral/mineral and organic soils under temperate conditions will respond differently to changes in climate. The authors suggested that higher rainfall would increase the carbon content of mineral soils. In contrast increases in temperature would have no impact on the C content of mineral soils but lead to reductions in C content of organic soils. Carbon concentration in mineral soils being weakly positively correlated with rainfall, but insensitive to temperature while C in organic soils is strongly negatively corrected with temperature.

- Climate change-related risk to soils include changes in field capacity period and start/end dates, change in ALC grade, loss of soil carbon/organic matter, compaction and erosion. The changes in soil functions resulting from climate change have been reviewed by Natural Resources Wales (2016b) and the summary table is reproduced below (Table 3).

Table 3. Changes in soil functions in response to climate change (Natural Resources Wales, 2016b).

Soil response to climate change	Key soil/landscape areas impacted	Type of response in Wales
Change in soil moisture, hydrological response and flooding of soils.	Slowly permeable soils	Duration of field capacity period not significantly changed across Wales in 2020 and 2050 but start and end date shifted (later onset of return to field capacity in Autumn).
	Change in water regime of wet organic (peat) or organo-mineral soils.	Potential soil moisture deficits (PSMD) are similar in 2020 to the baseline but increase by 2080.
	Other soils that may have restricted storage capacity.	Some evidence for a small reduction in the period of waterlogging in slowly permeable soils by 2080.
	Change in water-holding capacity in organic soils	As saturation period has not changed this could imply that there is limited hydrological buffering to events, increasing the susceptibility to run-off and flooding.
	Soils on sloping ground	Change in grade of agricultural land due to shift in climatic drought criteria.
	Shrink-swell (clay) soils in urban areas and infrastructure routes.	Human health impacts from less buffering of air temperature by soil (moisture) during extreme weather i.e. heatwaves. Landslides e.g. earthworks/embankment failures causing disruption to rail and road networks. Few soils cause shrink-swell subsidence and earthwork failures in Wales combined with low PSMD.
	Organic (peat) and organo-mineral soils.	Extreme events (drought): Increase risk of wildfires – peat loss and hydrophobicity (increased water run-off).
	Slowly permeable, waterlogged soils, including peats; coastal soils; grassland soils.	Soil protection of cultural heritage. Degradation of waterlogged soils in response to fluctuating rainfall pattern and lower water tables may expose some previously buried archaeological remains to air, impacting on preservation. Pollen record in peaty soils lost by oxidation in upper peat layers. Sea level rise resulting in loss or damage to archaeological remains. Higher river volume and increased frequency of flooding increasing soil erosion in heritage sites in estuarine areas. Poaching and machinery pressure damaging archaeological sites.
	Coastal soils	Coastal flooding from sea-level rise – soil loss and salinization impacts on soil function.

Change in soil carbon dynamics	Organic (peat) or organo-mineral soils. Declines in soil carbon related to climate	Declines in soil carbon related to climate change alone are small, although upland areas will experience greater amount of C loss through Particulate Organic Carbon, Dissolved Organic Carbon and CO_2. However, the UK CCRA17 Evidence Report166 has identified climate change risks to natural carbon stores and carbon sequestration, emphasising that upland and lowland deep peat soils represent Wales' largest terrestrial store of carbon
Change in soil erosion risk by water.	Fine sandy and silty soils; peat soils.	Grassland systems less vulnerable to erosion.
Soil biodiversity responses.	Potentially all soils but focus on soils with maximum change e.g. organic (peat) or organo-mineral soils.	Change in biological response as a result of drying previously saturated soils
Grassland productivity- induced change in soil structure e.g. increased grazing pressure impacts of livestock causing soil compaction.	Soils of improved and permanent grassland systems	Increase in grazing window means greater pressure on soils from livestock (compaction and associated erosion).

2.1.2 Location

- For Wales, the most recent decade (2008-2017) was on average 0.3°C warmer than 1981-2010 and 0.8°C warmer than 1961-1990. Most of the warmest years have been recorded since 1990 (Lowe *et al*., 2016). In the past few decades there has been an increase in annual average rainfall over the UK, the most recent decade (2008–2017) was 8% wetter than 1961–1990 and 3% wetter than 1981-2010. For Wales annual rainfall has increased by 4% from the 1961-1990 average and decreased by 0.5% from the 1981-2010 average (Lowe *et al*., 2016).
- Also of note is the run of recent wet summers; of the last ten summers from 2008 to 2017, only summer 2013 has seen a UK rainfall total below the 1981-2010 average. Thus, UK summers for the most recent decade (2008 to 2017) have been on average 20% wetter than 1961-1990 and 17% wetter than 1981-2010 (Lowe *et al*., 2016).
- Cranfield University (2016 – Defra SP1104), reported on UKCP09 scenarios which were based on models for three emission scenarios (low, medium and high). These scenarios suggested an increase in both winter and summer temperature from the 2020s to the 2080s, with all areas of Wales experiencing similar % increases in temperature. Overall, rainfall was not predicted to change but it was suggested that there would be a difference in the seasonal distribution of rainfall, with a decrease in summer precipitation and increase in winter precipitation. This difference was predicted to become spatially explicit by the 2080s. Greatest reductions in summer precipitation were apparent in the Gower, South Wales and the border regions and greater increases in winter precipitation in South Wales and the Llyn peninsula.
- More recently, UKCP18 has produced new projections of how climate might change in the UK over coming decades (Lowe *et al*., 2018). The regional climate projections are based on four 'Representative Concentration Pathways' (RCPs). RCPs are time-dependant projections of atmospheric greenhouse (GHG) concentrations based on assumptions about economic activity, population growth, energy sources and other socio-economic factors. The four RCPs together span the range of year 2100 radiative forcing values found in the open literature, i.e. from 2.6 to 8.5 watts per square metre (W/m^2):
    1. RCP2.6: low GHG concentration levels, radiative forcing peaks at 3 W/m^2 in around 2050, declining to 2.6 W/m^2 by about 2100
    2. RCP4.5: peak GHG by around 2100, followed by stabilisation. Radiative forcing peaks at 4.5 W/m^2.
    3. RCP6: peak GHG by around 2100, followed by stabilisation. Radiative forcing peak at 6 W/m^2
    4. RCP8.5: increasing GHG over time. Radiative forcing peaks at 8.5 W/m^2

- For the probabilistic projections, the maps show the 10, 50 and 90% percentile levels of change. The 50% level is the median change, and the 10% and 90% levels provide lower and upper estimates of the associated uncertainty ranges. The projections suggest that by 2080-2099, annual mean temperature will be 1-2 to 3-4°C higher than the baseline (1981-2000). Only for the RCP8.5 will there be any spatial variation in the annual temperature with greatest temperature increases predicted in south east Wales.
- For winter temperature, increases of 1-2 to 4-5°C are predicted by 2080-2099; with only the RCP4.5 scenario suggesting that there will be any spatial variation in temperature (lower temperature increases in west Wales (Pembrokeshire, Llyn peninsula and Anglesey) than in the rest of the country).
- For summer temperatures, increases of 1-2 to 5-6°C are predicted by 2080-2099 with all scenarios showing some spatial variation in temperature increases. Most scenarios suggest that the greatest increase in temperature will be in south east Wales (Figure 6).
- All scenarios suggest that annual rainfall will increase slightly in west Wales and remain at similar levels to the baseline in east Wales. Winter rainfall is expected to increase, compared to

the baseline, particularly around the coast. In comparison, summer rainfall is expected to decrease in relation to the baseline particularly in south and east Wales (Figure 7). By 2080-2099, rainfall will be about 20-40% less than the baseline.

- Cranfield University (2019) has applied the Agricultural Land Classification (ALC) climate interpolation routine to the UKCP18 scenarios to produce maps for average annual rainfall (AAR), average summer rainfall (ASR), median duration of field capacity days (FCD) and median accumulated temperature above 0°C January to June (AT0). For each parameter mapped data is shown for 2020, 2050 and 2080 for low, medium and high emission scenarios.
- For AAR, there is little noticeable change in either the distribution or amount of rainfall for Wales for any of the time period/emission scenario combinations (Figure 8). In comparison, for summer rainfall (ASR) in Wales there is a noticeable reduction in rain between time periods but little difference between low, medium and high emission scenarios (Figure 9). Similarly, to the UKCP18 predictions, the reductions in summer rainfall are most marked in the south and east of Wales.
- For the majority of Wales, field capacity days fall into the two highest categories (i.e. 223-279 days or >280 days) in all of the time period/emission scenario combination (Figure 10). However, the scenarios suggest that for some areas of Wales (e.g. the south east) there could be a reduction in field capacity days in 2050 and 2080 compared to 2020, particularly in the high emissions scenarios, reflecting the reduction in summer rainfall noted above.
- By 2050, the prediction maps show a noticeable increase in the accumulated temperature above 0°C for the low, medium and high emission scenarios, particularly in the south east of the country (Figure 11). In line with the UKCP18 predictions, by 2080, accumulated temperature has further increased and there is a noticeable difference in the low, medium and high emission scenarios, with the latter predicting the greatest increases in AT0.
- Cranfield University have also looked at the change in ALC grade resulting from the changes in climate parameters shown in Figures 8-12. The predicted changes suggest a reduction in the amount of ALC grades 1 and 2 land under all time period/emission scenarios, with an initial downgrade to ALC grade 3a/3b by 2050 and in some areas a further downgrade to ALC 4 by 2080 (Figure 12). The medium and high emissions scenario also suggest that some land that is currently ALC 3a/3b will be downgraded to ALC 4 by 2080, particularly in the high emissions scenario.

2.1.3 Farming enterprise

- Flooding, both coastal and inland has the potential to cause waterlogging of crops and soil erosion. These can lead to physiological impacts through loss of nutrients, and depending on the flood tolerance of the crop through prolonged waterlogging. If growing crops are underwater, impacts do not occur immediately but yield penalties can be evident if this is for a prolonged period of time (ADAS *et al*., 2014).
- Flooded soil is not passable by machinery which may affect crop and soil management operations. If land is particularly prone to flooding various adaptation measures are possible. This may include flood defences, changing land use to a crop which grows outside of times most prone to flooding (e.g. spring cropping) or changing land use to grazing/another use.
- Water stress through a lack of rainfall is a lower risk than flooding due to the relatively high rainfall in Wales (ASC, 2016). In addition, whilst drier summers will limit the potential yield of some crops the impacts are not likely to be less than in drier regions of the UK.
- However, for high value crops where available water is essential for yield and quality (e.g. potatoes and some fruit crops), restrictions on use for agricultural crops (in the form of irrigation) are likely to affect yields and quality. Conversely, whilst this presents a risk, in the context of the wider UK, Wales is not as water stressed as eastern regions (or other areas globally), potentially giving an opportunity for the expansion of sectors such as horticulture (ADAS *et al*., 2014).

- Extreme weather events (i.e. extended periods of intense rainfall) and shifts in land use/cropping patterns associated with climate change (i.e. increased ploughing out of permanent grassland) are factors that may increase erosion rates in the future.

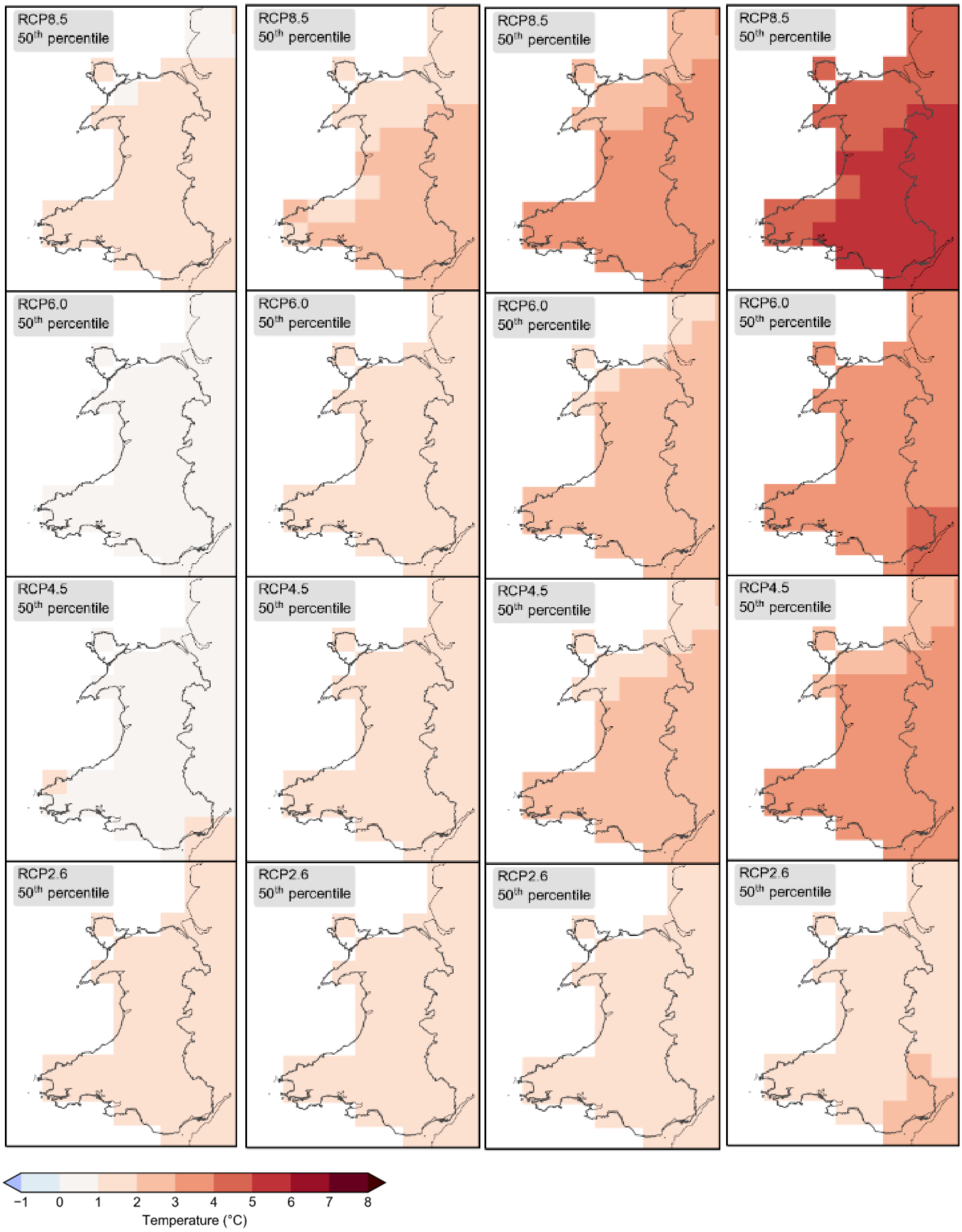


Figure 6. Summer mean temperature anomaly in Wales for four time periods (a. 2020-2039, b. 2040-2059, c. 2060-2076 and d. 2080-2099 50th percentile.

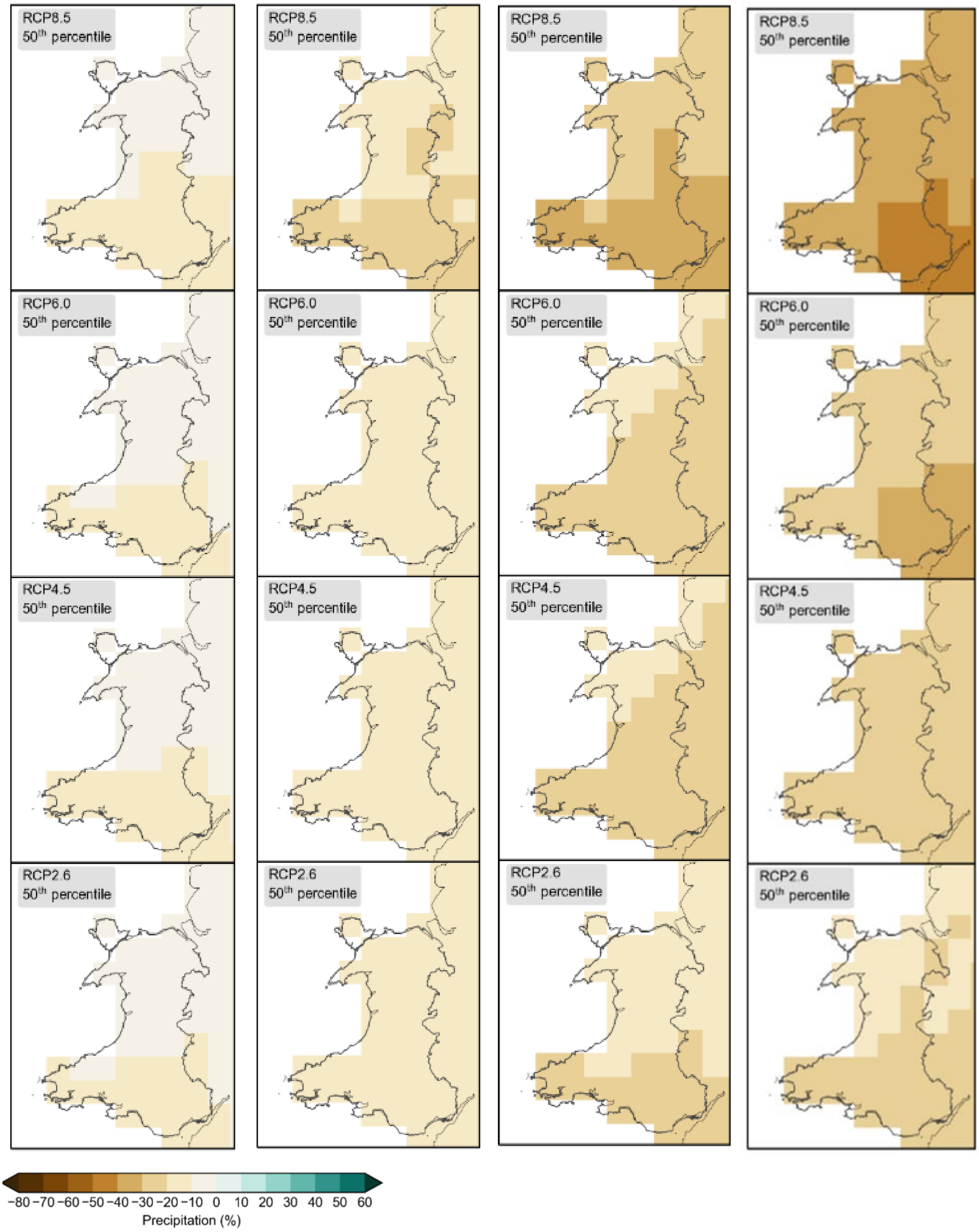


Figure 7. Mean summer rainfall (changes compared to 1981-2000 baseline) for four time periods (a. 2020-2039, b. 2040-2059, c. 2060-2076 and d. 2080-2099) for the 50th percentile.

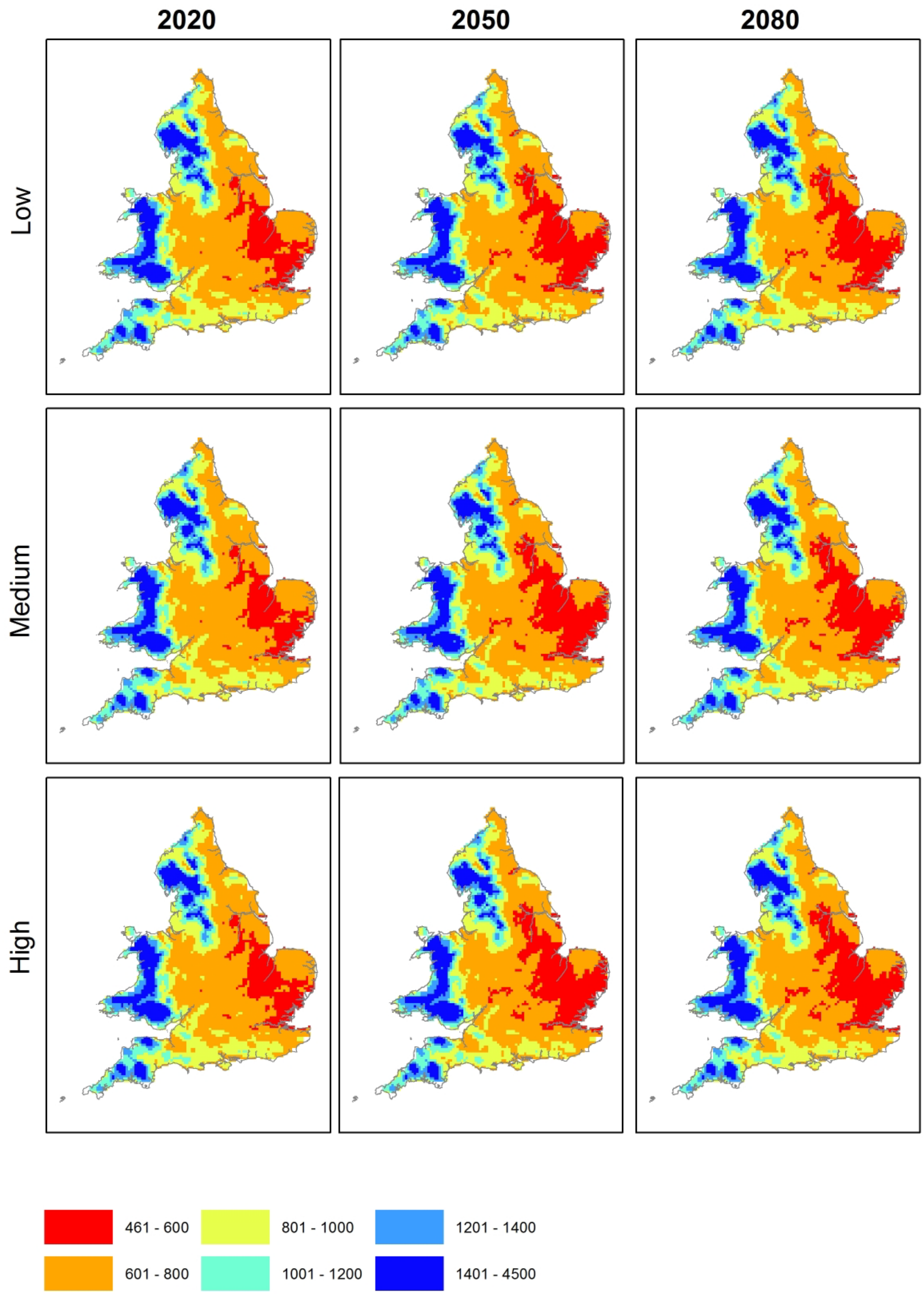


Figure 8. Average annual rainfall (mm) for 2020, 2050 and 2080 UKCP18 low, medium and high scenarios

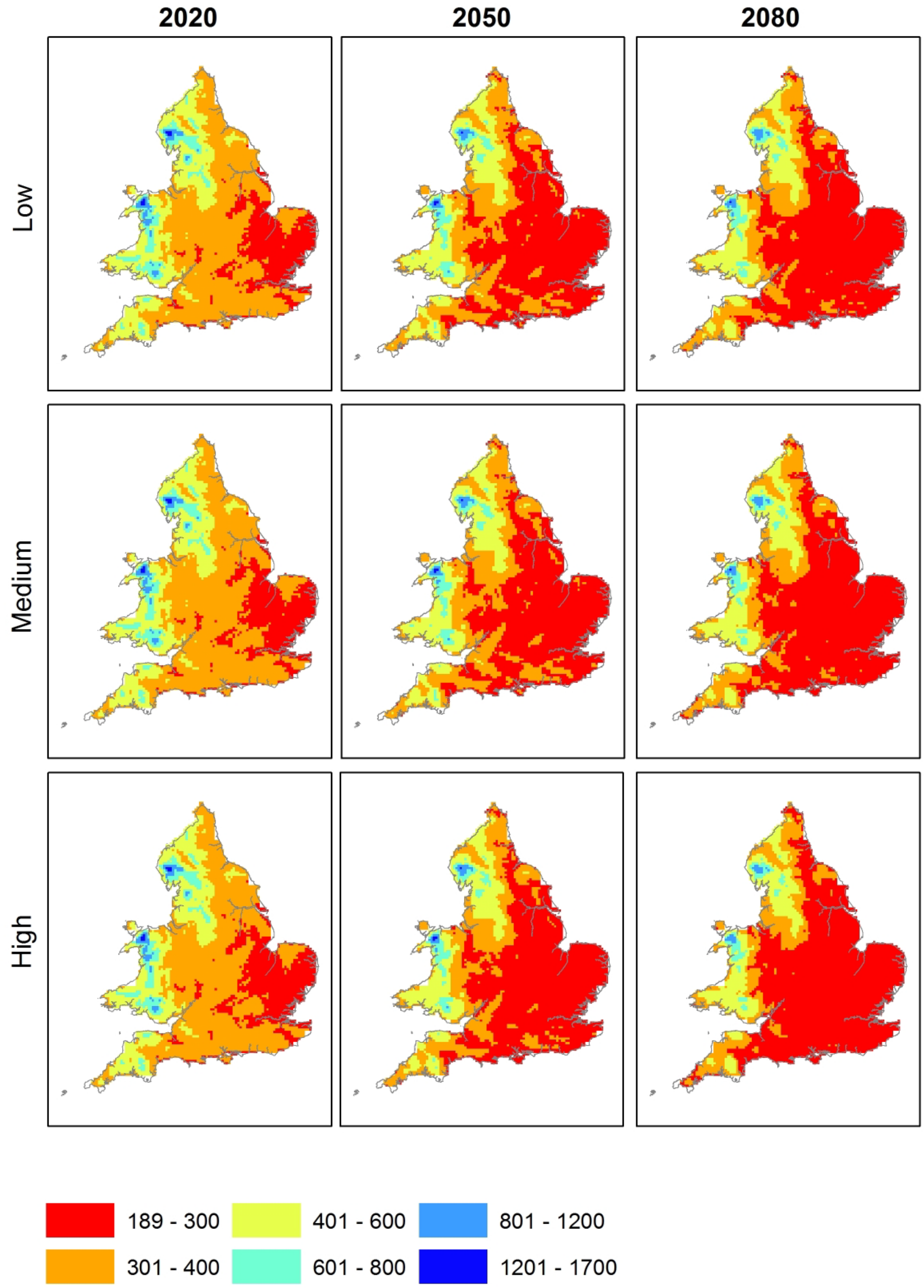


Figure 9. Average summer rainfall (mm) for 2020, 2050 and 2080 UKCP18 low, medium and high scenarios

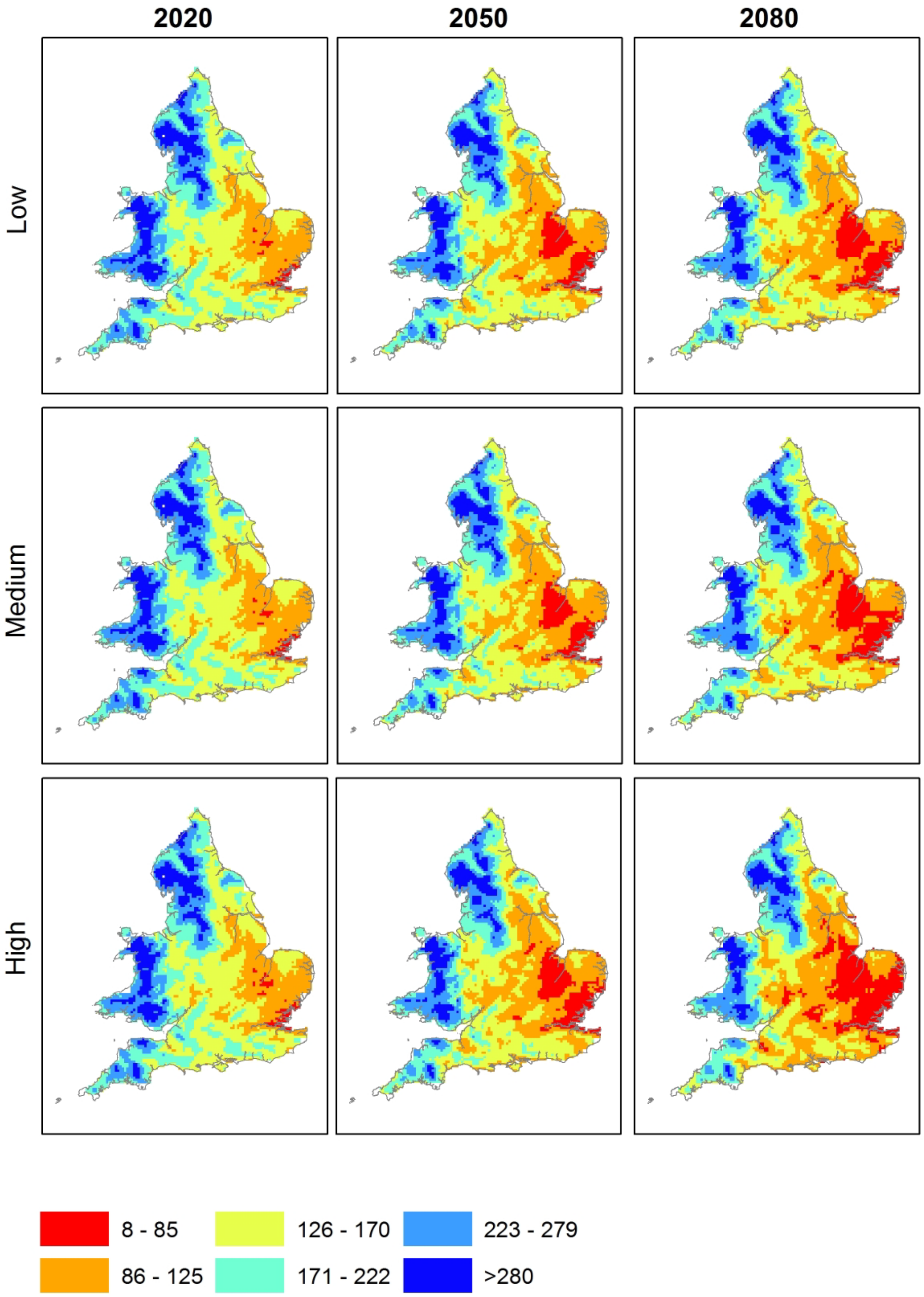


Figure 10. Median duration of field capacity (days) for 2020, 2050 and 2080 UKCP18 low, medium and high scenarios.

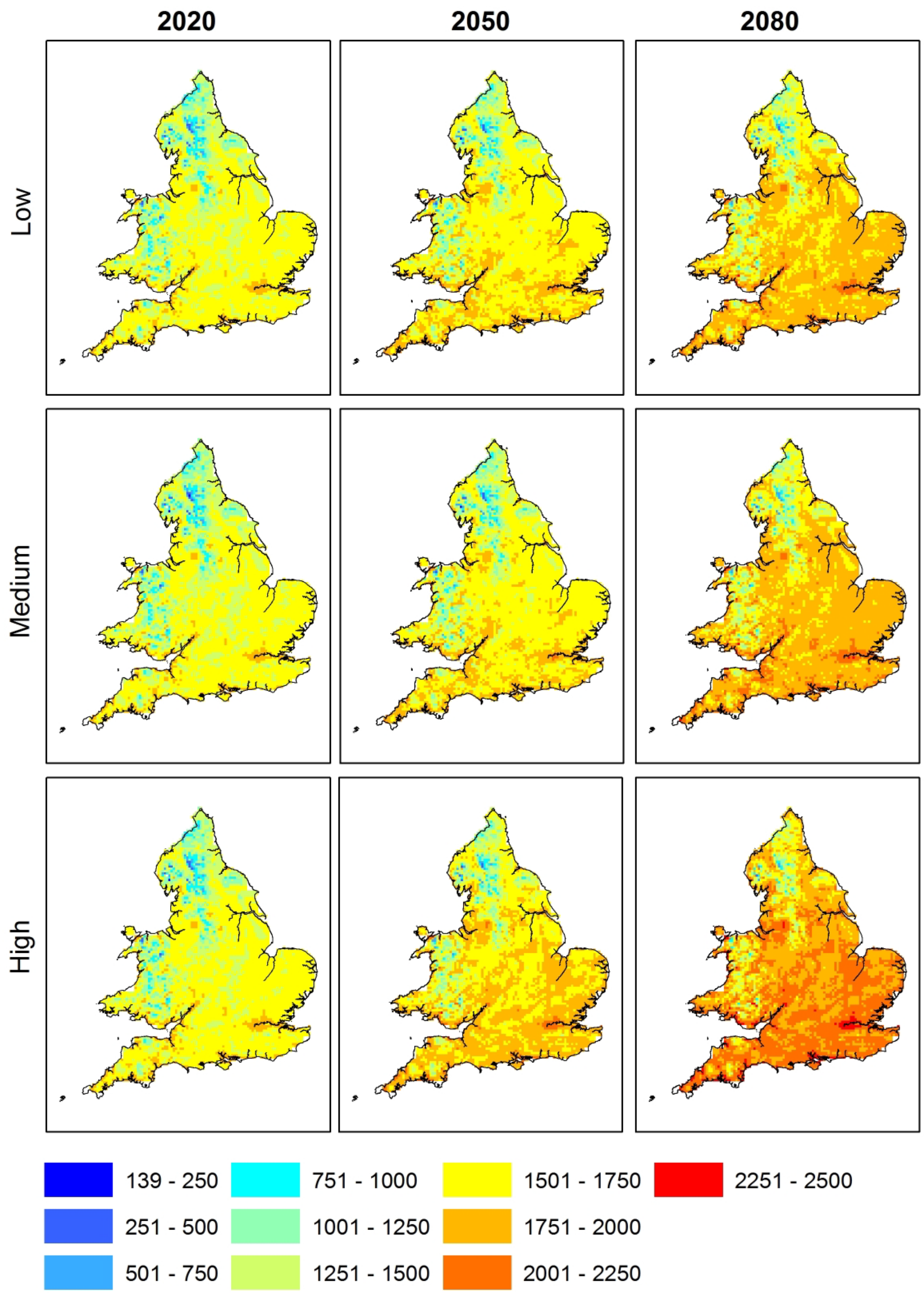


Figure 11. Median accumulated temperature above 0°C from January to June for 2020, 2050 and 2080 UKCP18 low, medium and high scenarios.

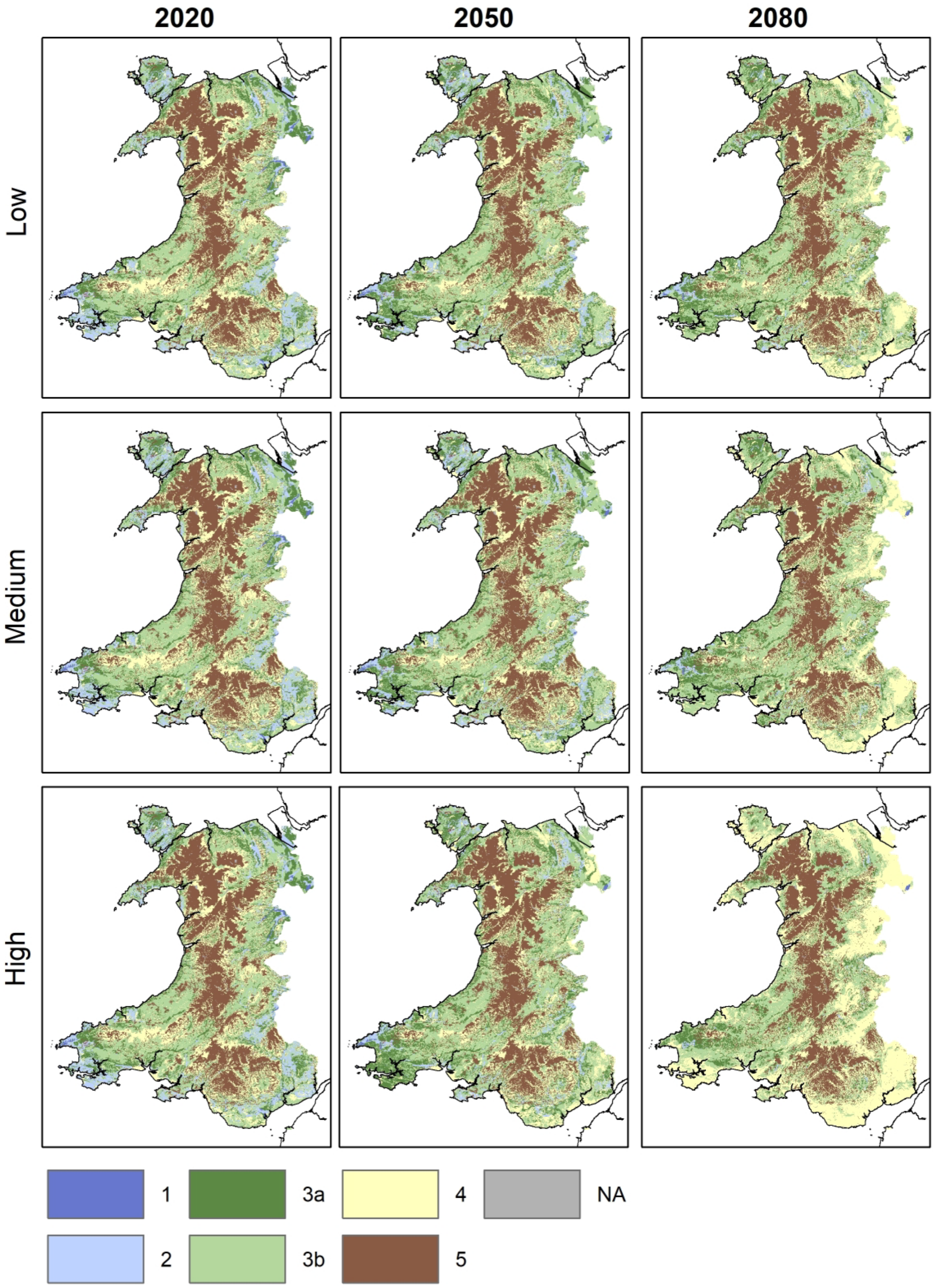


Figure 12. Agricultural Land Classification class for 2020, 2050 and 2080 UKCP18 low, medium and high scenarios.

2.2 Compaction

- Soil compaction is the physical reduction in volume of soil due to a compressive force. Compaction usually occurs when machinery or livestock travel on soils that are not strong enough to withstand their weight. The problem is increasing due to the increasing size and weight of field machinery; between 1960 and 2010, wheel loads from machinery increased by almost 600% (Schjønning *et al*., 2018). In addition, the increased use of contractors, may lead to more field operations being carried out under unsuitable conditions as the farmer is no longer in control of the timing of the fieldwork or the machinery that is used.
- Soils are particularly vulnerable to compaction when wet. Compaction can cause a significant deterioration in soil structure, reducing the number and connectivity of soil pores and increasing bulk density. This has a direct impact on a number of key soil physical and biological processes, notably water infiltration, gaseous exchange, root access and soil faunal activity, with implications for crop productivity, water quality, flood management and biodiversity. Increases in runoff and erosion from compacted fields result in higher nutrient and sediment loads in water courses, while reduced infiltration rates increase the risk of flooding.
- In most cases, measures to alleviate or prevent compaction would be expected to increase crop production and enhance other soil functions, but there are clear conflicts between the need to establish and harvest crops in restricted timing windows and the need to avoid compaction (Sagoo and Newell Price, 2019).

2.2.1 Soil type

- Soil texture and moisture content are important factors controlling the risk of compaction with soils with high clay content more vulnerable to compaction when wet. Also, soils containing low levels of organic matter are generally more susceptible to compaction (Arvidsson *et al*., 2003).
- The effect of soil moisture on structural damage is greater than any effect likely to be due to differences in tractor weight, tyre size or ground pressure (Davies *et al*., 1972), and moisture content changes of the order of 2 to 3% can have profound effects on soil damage due to changes in soil consistency relative to certain thresholds. The way that a soil responds to an applied load or cultivation changes at critical moisture contents or consistency states known as the:
    - Shrinkage limit: below which soil bulk strength is not particularly high (due to lack of water and therefore low surface tension forces and low film cohesion) but clod and aggregate strength is very high (due to attractive forces associated with the clay fraction), and working the soil will simply rearrange clods/aggregates with no structural damage
    - Lower plastic limit: above which clod strength is low and bulk strength is high and soil moisture content is adequate for the water to behave like a lubricant and the risk of structural damage increases with water content
    - Upper plastic limit: above which the soil is in the 'liquid' state, has almost no strength, is readily puddled (compacted) and can be virtually impossible to work.
- Soils are most workable at moisture contents within the friable range between the shrinkage limit and the lower plastic limit, with bulk shear strength increasing and clod shear strength decreasing rapidly with moisture content (Spoor, 1975; Figure 13). At the shrinkage limit end of the friable range, the risk of structural damage is very low and soil can be cultivated with minimal energy requirement.

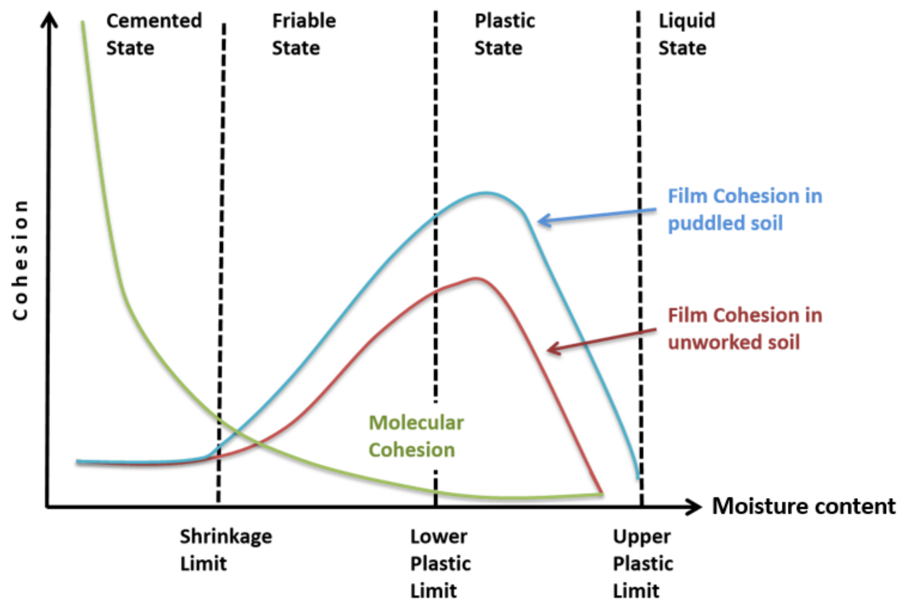


Figure 13. Variation in cohesion with moisture content (Source: Spoor, 1975).

- When soil is in a plastic state (between the lower and upper plastic limits) soil clod and bearing strength declines, resulting in increased wheel slip, rolling resistance and sinkage/compression. The risk of structural damage increases with soil moisture content to a ‘sticky point’ where bulk shear strength falls and soil sticks to cultivation machinery (Spoor, 1975), resulting in significant:
  - Puddling, the mechanical process whereby wet soil aggregates are disrupted and some clay is dispersed; and
  - Smearing, localised spreading and smoothing of soil by sliding pressure

- Not all soils have these consistency states. Lighter soils with less than 18% clay content will only reach the lower plastic limit at a relatively high moisture content and the lightest soils will not reach a plastic state or have a ‘sticky point’ due to lack of clay content and related adhesion forces.
- The effects of working land therefore relate to the load applied and the soil moisture content (relative to the plastic state) at the time of working. When soil is in a friable state it is in the optimum state for cultivation. Nevertheless, soil compaction through compression can still occur especially as soil moisture approaches the lower plastic limit, as coarser pores (i.e. greater than 0.05 mm) are still mainly air-filled and able to reduce in volume (Spoor, 1975). Thus, soils at field capacity (start of drainage) are prone to compaction.
- Clay and medium soils tend to be at greatest risk of structural damage due to the longer periods of time during which the soil is in the plastic state following prolonged or heavy rainfall. Heavy soils also have lower bearing strength when wet and are therefore more susceptible to compaction during trafficking, grazing and cultivation than soils with a lower clay content (Holman *et al*., 2003).
- Soils also differ in terms of the proximity of field capacity to the lower plastic limit. For example, some clay and medium soils that are above their lower plastic limit at field capacity need several days without rainfall before they can be cultivated (Davies *et al*., 1972). By contrast, many sandy soils are not plastic and do not have a lower plastic limit. Recently cultivated soils

that are mechanically weak are also more liable to damage than a well-structured soil in stubbles or under grassland.

- Around 40% of soils in Wales are considered wet, slowly permeable or have high groundwater (Cranfield University, 2016) and potentially vulnerable to compaction. In addition, in the GMEP farm practice survey it was reported that 40% of drains in arable and improved grassland were in need of repair or replacement. Wet soils are particularly vulnerable to compaction by machinery and livestock poaching (Emmett *et al.,* 2017).
- However, there is no data on vulnerability or resilience of specific soil or land use types to soil compaction for Wales.

2.2.2 Location

- Maps of the estimated probability of soil compaction in England and Wales have been produced by Cranfield University (2011) for Defra Project CTE0946 but are limited in terms of both accuracy and sensitivity (Figure 14). Nevertheless the maps indicate areas of Wales at low to high risk of soil compaction probably due to the dominance of grassland soils. In addition, large areas of Wales exist where the probability of soil compaction is unknown.

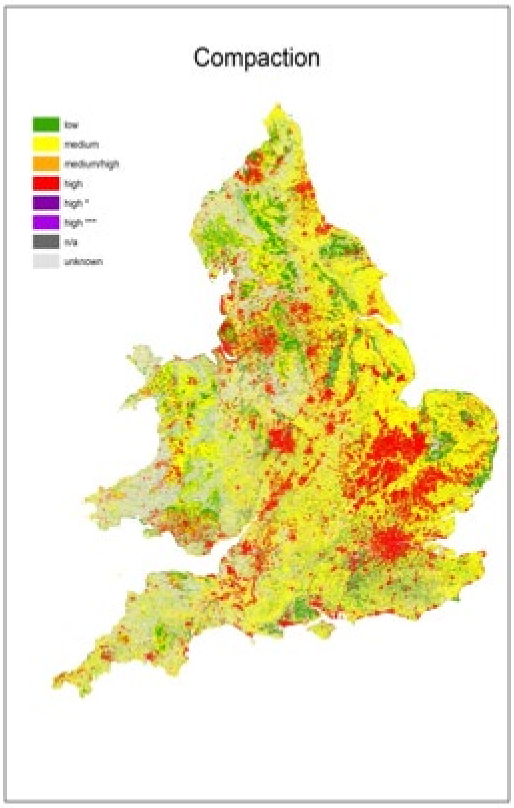


Figure 14. Probability of soil degradation by soil compaction in England and Wales (Source: Cranfield University, 2011).

2.2.3 Farming enterprise

- Compaction affects farm operations by reducing opportunities for access and increasing the risk of further soil degradation associated with mechanical cultivations and livestock trampling (Batey, 2009).

- Horticulture, intensive arable and improved grassland are most at risk of soil compaction, although the risk level varies by soil type (Table 4).

Table 4. The relative risk of compaction in each land use and soil type category (Source: Cranfield University, 2011. Defra Project CTE0946)

Land use	**Soil types**			
	Clay	**Silt**	**Sand**	**Peat**
Urban	H	H	H	H
Horticulture	H	L	H	M
Arable intensive	H	L	H	M
Arable extensive	H	L	M	M
Grassland improved	H	L	H	H
Grassland unimproved	M	L	M	M
Rough grassland	M	L	M	M
Forestry	H	L	M	M
Woodland	L	L	L	L
Wildscape	L	L	L	L

Note: H = high probability of soil degradation; M= moderate probability of soil degradation; L = low probability of soil degradation

- Extrapolating data from Graves *et al*. (2015), it has been suggested that 25% of the total grassland area in Wales is liable to agricultural compaction (Cranfield University, 2016). This is associated with machinery operations (e.g. slurry spreading or grass harvesting) or livestock poaching (particularly around gateways and feeding/drinking areas). Climate change scenarios that result in extended grazing seasons, may provide opportunities for longer outdoor grazing in winter, which may increase the risks of soil compaction by livestock. For soils in arable and horticultural production, it has been suggested that only 4% of the area was at risk of agricultural compaction (Cranfield University, 2016) mainly from cultivation and harvest operations.
- Frequent trafficking with heavy machinery increases the risks of soil compaction. In arable systems, soil compaction at harvest time can result from the use of heavy machinery, sometimes in 'wet' field conditions. Compaction is often more likely to occur when harvesting crops such as maize, potatoes and sugar beet as they are harvested in late summer early autumn later and generally under wetter field conditions and require a lot of heavy machinery (Defra, 2005). The heavy machinery used to form ridges for potato crop establishment also pose a risk of soil compaction, especially as the operations are carried out in early spring. (Anderson and Johnson, 2013).
- In horticultural systems, the pressures of late harvesting and establishment schedules to meet market requirements often lead to some soil structural damage. For example, a survey of 75 fields, covering a range of horticultural crops identified soil compaction in 70% of annual crops and 60% of perennial crops (Sagoo and Newell Price, 2019).
- In grassland systems the two main causes of compaction are machinery damage and compaction from livestock. Grassland vehicle trafficking can be double the intensity of vehicle traffic in an arable system (Cranfield University *et al*., 2007) but can be minimised by appropriate timings of vehicle operations where practically possible. Compaction by livestock is strongly linked to livestock density and is much higher with wet soil and low plant density.
- Grassland compaction is highly relevant for Wales, with more than 90% of its managed agricultural land under permanent or temporary grassland. Newell Price *et al*. (2012) reported soil structural condition on 300 grassland sites across England and Wales and concluded that 10-15% of fields were in poor structural condition and 50-60% in moderate condition; notably

the poor soil conditions were not restricted to improved grasslands; semi-improved grassland soils were also affected. The authors suggested that between 500,000 and 750,000 hectares of grassland in England and Wales could be in poor physical condition and 2 to 3 million hectares in moderate condition. Soils with higher organic matter contents were less at risk of compaction whilst the risks of compaction were shown to increase with machine size and the number of machinery passes.

- Anthony *et al*. (2012) carried out a survey of 120 sites in Wales to compare sites in Tir Gofal with those outside for a range of parameters. They noted that was evidence of soil damage at 23% of improved grasslands but that only 3% of the sampled sites had average soil bulk density above trigger values for soil compaction (1.3 g/cm^3 for mineral soils and 1 g/cm^3 for peat soils). Similarly, a GMEP survey in 2014 also found that most samples were below the bulk density trigger values suggesting a low level of soil compaction (Emmett *et al*., 2015).

2.3 Erosion

- Accelerated soil erosion, by water, wind, cultivation or livestock, can have serious implications not only for the provision of food and fibre (due to a loss of productive topsoils), but also impacts on water flow and quality (due to increased sediment loads and nutrient enrichment) as well as carbon storage (due to removal of C-rich topsoils). In Wales, the 'off site' effects of sediment and nutrients on water quality can far exceed any loss of productive capacity. In lowland areas, light arable soils are often at the greatest risk of erosion, whilst in uplands, thin soils and deep peats are the most sensitive soil types (Evans, 1990). The dominance of medium textured soils and permanent vegetative cover (i.e. grassland) across much of lowland Wales, would indicate a relatively low risk to soil erosion. However, in the uplands, shallow organo-mineral soils can be particularly vulnerable.
- The factors that influence the vulnerability of land to soil erosion have been reviewed extensively in the literature. Risk factors include the intensity, duration and timing of rainfall events; the physical, biological and chemical properties of soils; the length, gradient and form of slope; the type of vegetation/crop on the land and its stage of development; and the type and timing of land management practices (Knox *et al*., 2015). In particular, soils become more erodible and more likely to crust as levels of organic matter fall and aggregate stability is reduced (Boardman, 2013).
- Evans (1980) suggested that soils with a less than 2 % organic carbon content (c.3.5 % organic matter content) can be considered erodible. However, it should be noted that some soils with very high organic contents, particularly peats, are highly susceptible to wind and water erosion. Furthermore, the role played by organic matter depends on its origin. For example, organic matter from farmyard manure contributes to aggregate stability, while peat has very low aggregate stability.
- Erosion can occur as a result of water, wind, tillage, co-extraction with root vegetables and farm machinery and human and animal impact (from recreation and grazing) (Knox *et al*., 2015). Of the four types of erosion, erosion by water is the most extensive. Erosion is often episodic occurring predominately after specific land management practices that cause high levels of soil disturbance and/or after heavy rainfall.

2.3.1 Soil type

- In Wales water-induced erosion is more likely to be widespread than wind erosion (Owens *et al*., 2006). It occurs most frequently on sloping land with bare soil or sparse crop cover where the soil is weakly structured and has a fine sandy or coarse silty texture. The risk is greatest during periods of heavy rainfall when the soil has become saturated and surface soil structure broken down by the impact of raindrops. Soil erosion can destroy crops in localised areas or bury them under deposited sediment downslope.

- Factors affecting erodibility include soil texture (in particular the very fine sand and silt content) which lack cohesion. Soil topsoil textures dominated by sand and silt are more vulnerable to soil loss than those with a higher clay content (Evans, 1990). Silt sized particles are the most vulnerable to detachment by raindrops (Poesen, 1985 cited by Knox *et al*., 2015). Smaller particles (clays) are more resistant to detachment because of cohesion, and larger particles (sands) are resistant because of mass/weight.
- In general, clay soils have the lowest risk of soil erosion and organo-mineral/peat soils the highest risk (Table 5).
- Other factors affecting erodibility include soil shear strength. As soil shear strength increases, detachment decreases exponentially. Soil moisture content, organic matter content, soil chemistry and the stability of aggregates also determine the susceptibility of soil to erosion (Knox *et al*., 2015).
- In arable systems, the vulnerability to erosion is influenced by topsoil texture. However, there is no direct evidence of erosion rates or frequency on arable sites in Wales specifically, and sandy and silty soils have small spatial extents in Wales (Cranfield University, 2016).
- Wind erosion usually only affects sandy and light silt soils which are uncommon in Wales. Average soil loss in Wales by wind erosion is 0.12 t/ha per year compared to the UK where it is 1.03 t/ha per year. Wind erosion mainly affects sandy and peaty soils in arable production and has been reported to account for soil loss of 2.6 t/ha year from arable farms in East Anglia. This is due to a combination of the lack of crop cover during winter/early spring on many arable soils and the open landscapes (large fields without boundaries are more susceptible to wind erosion) (Boardman, 2013).

Table 5. The relative risk of erosion in each land use and soil type category (Source: Cranfield University, 2011. Defra Project CTE0946)

Land use	Soil types			
	Clay	Silt	Sand	Peat
Urban	L	H	H	n/a
Horticulture	L	H	H	H
Arable intensive	L	H	H	H
Arable extensive	L	M	H	H
Grassland improved	L	M	M	H
Grassland unimproved	L	M	M	H
Rough grassland	L	M	M	H
Forestry	L	L	L	M
Woodland	L	L	L	M
Wildscape	L	L	L	M

Note: H = high probability of soil degradation; M= moderate probability of soil degradation; L = low probability of soil degradation

2.3.2 Location

- The predominance of sloping land in Wales and high rainfall are two important factors that increase the risk of erosion by water in some areas of Wales. In comparison to water erosion, the area of Wales affected by wind erosion is small and has declined in recent years compared to 1950s and 1960s (Boardman, 2013) reflecting improvements in soil management practices.
- Modelled soil erosion rates by water have been estimated on the basis of the Revised Universal Soil Loss Equation (RUSLE) (European Soil Data Centre, 2012[5], Borrelli *et al*., 2017). Overall reported water erosion rate in the UK in 2012 was 2.07 t/ha, compared to 3.71 t/ha for Wales

[5] http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=aei_pr_soiler&lang=en

(average for the EU-28 is 2.40 t/ha). About 7% of land in Wales is susceptible to high rates of erosion (>11 t/ha) (average of the EU-28 is 6%).

- However, it is widely recognised that models such as RUSLE tend to overestimate soil losses as they do not take into account soil conversation measures (Keizer *et al*., 2016), although they do provide an indication of relative risk. In comparison estimates of rates of erosion from survey-based methods predict lower rates, e.g. sheet wash erosion on slopes can be 0.1-0.3 t/ha/year (Evans *et al*., 2017).
- Soil formation rates (by weathering) in Europe under current conditions are estimated to vary between 0.3 and 1.2 t/ha/year (Verheijen *et al*., 2009). For the UK, Evans *et al*. (2019) measured soil formation rates of 0.026 to 0.084 mm/year at an arable site and 0.053 to 0.096 mm/year at a forest site. At such slow rates of soil formation, soil losses exceeding 1 t/ha/year can be considered irreversible and unsustainable within a time span of 50-100 years (Jones *et al*., 2004; Verheijen *et al*., 2009).

2.3.3 Farming system

- Large areas of Wales are assumed to have low erosion rates due to grassland land use, although this has not been quantified by measurements or observations (Cranfield University, 2016). However, land use change is an important factor in soil erosion risk and significant decreases in erosion risk have been noted when fields changed from winter cereals to permanent grass (Boardman *et al*., 2017). This is because grassland soils have year round crop cover and so soil is not exposed to the erosive forces of water or wind. Also increased organic matter levels in grassland soils help bind soil particles into aggregates to improve soil structural stability. However, high stocking densities, outdoor over wintering of stock and associated impacts can cause compaction and poaching which may promote runoff and erosion.
- Soil is most vulnerable to erosion when soil cover is sparse, especially when intensive rainfall is more common (Knox *et al*., 2015). Crops such as maize, sugar beet and potatoes are prone to soil erosion because they tend to be established in late spring and harvested in late autumn leaving bare soil over winter. For example, maize is planted about 0.8 m apart and takes up to three months to provide an adequate crop cover so the risk of soil erosion is high. In contrast, oilseed rape typically provides ground cover soon after sowing in later summer reducing the risk of erosion (Table 6).
- In addition, soil may be extensively disturbed during crop establishment (e.g. bed forming or ridging for potatoes) or during harvesting (e.g. sugar beet). Sensitivity to erosion is also increased by the removal of stones from soils e.g., de-stoning for potato cultivation.
- Additions of organic matter (e.g. manure additions or the incorporation of crop residues), will improve soil structural resilience and reduce susceptibility of soils to erosion.

Table 6. Risk of erosion in soils drilled to different crops (modified from Knox *et al*., 2015).

Crop	Risk of erosion
Hop	1 field in 6
Maize	1 field in 7
Sugar beet	1 field in 7
Potatoes	1 field in 10
Market garden	1 field in 14
Bare soil/fallow	1 field in 21
Kale	1 field in 24
Short term Grass ley (<3 years)	1 field in 32
Peas	1 field in 38
Spring cereals	1 field in 34
Winter cereal	1 field in 42
Field beans	1 field in 71
Oilseed rape	1 field in 100

- The risk of water-driven soil erosion is expected to be higher with projected increases in the frequency and intensity of heavy rainfall events due to climate change, but there are no Wales-only studies available.
- Land management responses to changing climate (e.g. cultivation of steeper slopes; expansion cropping systems that leave bare soil over winter) may increase erosion risks further in the future.

2.3.4 Upland erosion

- The reviews of soil erosion in Wales (Boardman, 2013; Evans, 1990) indicate that soil erosion in Wales is mainly attributable to upland erosion processes. Although the extent and rate of this erosion has not been quantified a recent review by Tye *et al*. (2019) suggested that photo/satellite image could be used to identify where erosion was occurring. This could be linked to land use factors.
- Grazing and trampling by high numbers of livestock have been implicated in the erosion of peat and other upland soils (Natural England, 2009a). In the uplands, overgrazing by sheep and footpath use expose the soil and contribute significantly to erosion risk (McHugh *et al*. 2002). Also, moorland gripping when combined with grazing has been implicated in the increased risk of flash flooding and related erosion due to diminished water retention (Natural England, 2009a).
- Upland burning (controlled or uncontrolled) will also lead to an increase in bare soil (Glaves *et al.,* 2013). Where this is grazed before vegetation is well established erosion rates may increase. A study by Kinako and Gimingham (1980) of two upland sites in Scotland noted that erosion reached a maximum within eight months of a burn, with stability restored after 15-20 months. The authors noted that habitat deterioration though soil erosion was least where vegetation recovery was most rapid.
- Recently it has been suggested that under grazing can be a significant factor in increasing the risk of uncontrolled burning in the uplands[6]. This is as a result of the loss of natural firebreaks created by areas of densely grazed vegetation and increases in the areas of scrub and bracken, which combine to increase the risk and extent of fires. Appropriate stocking density on the uplands will mediate both erosion and fire risks.

[6] https://www.fwi.co.uk/news/rewilding-will-lead-bigger-wildfires

- Erosion can also occur due to recreational pressure from walkers, cyclists etc.; albeit this is usually confined to small well-defined areas recreation-induced erosion can still be significant in sensitive areas (Natural England, 2009b; 2009c).

2.4 Soil organic matter

- Soil organic matter (SOM) has been defined as any material produced originally by living organisms (plant and animal) that is returned to the soil and goes through the decomposition process (Bot and Benites 2005).
- SOM plays a central role in soil quality and functioning by providing a food source and habitat for the soil biological community thereby driving nutrient cycling. It is also a central component of soil aggregation and the maintenance of soil structure and water relations. Indeed, loss of SOM (due to changes in management, land-use and climate) is seen as one of the most important threats facing UK soils (Defra, 2009; Dobbie *et al.,* 2011). Changes in SOM are linked to changes in many other soil functions (Figure 15).
- The majority of soil ecosystem services are largely driven by biological processes, underpinned by SOM decomposition. Organic matter provides a food source and habitat for the soil biological community, drives the cycling of nutrients within soils and is a central component of soil aggregation and the maintenance of structure and water relations (Tisdall and Oades, 1982). It is therefore key to the maintenance of soil biophysical and chemical properties as well as being an important C store. Organic carbon (SOC) is the primary constituent of soil organic matter (SOM), on average 58% of organic matter by weight in soils is carbon (Post *et al*., 2001).
- Generally, soil organic matter increases with rainfall and clay content (Verheijen *et al*., 2005). However, no critical or threshold levels of SOC have been identified and this is most likely to be a reflection of the many possible ways that SOC interacts with the soil, water and plant system (Newell Price *et al*., 2015). Nevertheless, losses of SOM have been associated with a loss in soil quality and function; and reduced resistance and resilience to poor soil management. SOM can be lost from the soil system via microbial respiration during decomposition or via water or wind erosion. Although these are natural processes, they can be accelerated by human intervention e.g. tillage or removal of vegetative cover. Declines in SOM in both mineral and peat soil can also effect the vulnerability of soils to erosion and soil compaction and have negative effects on soil biodiversity (Figure 15).

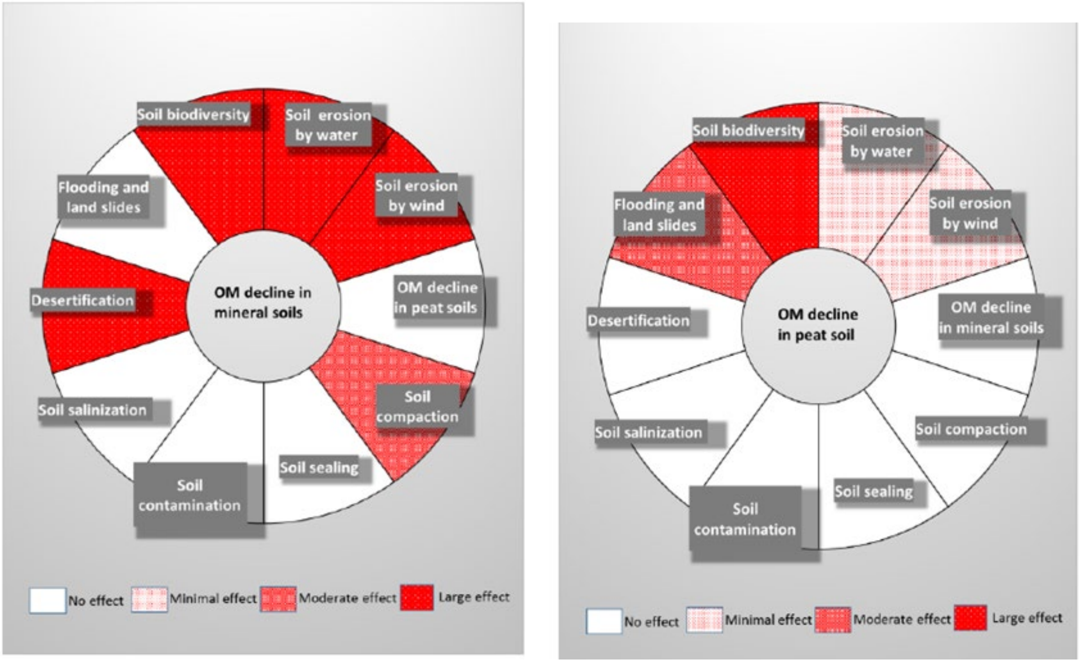


Figure 15. Effects of decline in soil organic matter (OM) in mineral and peat soils on other soil threats. Red is negative effect. (Source: Stolte *et al*., 2016)

- According to Lal (2004) high SOM accumulation is favoured by management systems, which add high amounts of biomass to soil, cause minimal soil disturbance, improve soil structure, enhance activities and species diversity and strengthen mechanisms of element cycling. Such low disturbance, high carbon input (e.g. litter and roots) and SOM content are typified by the permanent and rough grazing grassland soils that predominate in Wales (>80% of agricultural land) and woodland soils (c.12% of Wales). Thus most soils in Wales will be at low risk of SOM loss.
- For the minority of soils in Wales that are in arable systems (including grasslands <5 years old), the risk of SOM loss is significantly greater, as SOM loss is triggered by soil disturbance, which increases oxidation and by reduced accumulation or removal (crop residues may not be returned to the soil so levels become depleted). It has been estimated for Europe that conversion to arable crops causes a depletion of SOC stock, of around 1-1.7 t C ha-1 y-1 (Freibauer *et al*., 2004).

2.4.1 Soil type

- Krull *et al.* (2004) noted that the importance of soil organic matter to carry out certain functions in the soil will vary with soil type. For example, the need for soil organic matter to provide cation exchange capacity and improve water holding capacity is most important in sandy soils. On the other hand, the need for soil organic matter to provide a food and energy source for the microbial population is needed in all soils, regardless of soil texture.
- Soil organic matter tends to increase as the clay content increases. This increase depends on two mechanisms. First, bonds between the surface of clay particles and organic matter retard the decomposition process. Second, soils with higher clay content increase the potential for aggregate formation (Bot and Benites 2005). In addition, coarse sandier soils are better aerated and the presence of oxygen results in more rapid decay of organic matter. Thus, for mineral soils, under the same land management (e.g. intensive arable) the risk of OM loss is greater in sand soils than in clay or silt soils.
- Peats organo mineral and shallow soils are the most vulnerable in terms of rate of loss of soil organic matter over time (National Soils Resources Institute, 2004).

- Mineralization or oxidation of peat soils is a main cause of reduction of organic matter stocks (Van den Akker *et al*., 2016). Several factors are responsible for a decline in soil organic matter and many of them relate to human activity: drainage, cultivation and conversion to arable land, liming, fertilizer use/nitrogen (Kechavarzi *et al*., 2010) causing rapid mineralization of organic matter. The main driver for the reclamation and drainage of peat soils in the past was socio-economic demands for increased food production. Currently, many peat soils, particularly in the uplands (75% of peat soils) are subject to a range of designations (e.g. NNRs-National Nature Reserves, SSSIs-Sites of Special Scientific Interest) which will influence the range of management options that are applicable in those areas (Evans *et al.* 2015).

Table 7. The relative risk of organic matter decline in each land use and soil type category (Source: Cranfield University, 2011. Defra Project CTE0946)

Land use	**Soil types**			
	Clay	**Silt**	**Sand**	**Peat**
Urban	H	H	H	H
Horticulture	H*	H*	H***	H
Arable intensive	H*	H*	H***	H***
Arable extensive	M	M	M	M
Grassland improved	M	M	M	H
Grassland unimproved	L	L	L	
Rough grassland	L	L	L	L
Forestry	L	L	L	L
Woodland	L	L	L	L
Wildscape	L	L	L	L

Note: H = high probability of soil degradation; M= moderate probability of soil degradation; L = low probability of soil degradation. *, **and *** indicate that although high in all soil textures differences between soil textures can be recognized with * being smallest and *** being largest changes.

2.4.2 Location

- Bradley *et al*. (2005) estimated the Welsh soil carbon stock to be 340 Mt, a large proportion of which is sequestered in upland organic soils. More recently it has been estimated that the total soil carbon stock in Wales is 410 Mt (Russell et al., 2011; Natural Resources Wales, 2016b) of which 157 Mt is in peat soils and 57 Mt in forest soils (Natural Resources Wales, 2016b).
- Modelled estimates of European SOC stock suggest that NE Europe (including Wales) had a higher SOC (80-250 t C/ha) content than the Mediterranean and some areas of northern Europe (<40 t C/ha). Most of the highest European values (>250 t C/ha) correspond to peatland (Figure 16). Alonso *et al.* (2012) also highlighted the importance of natural and semi-natural habitats as stores of SOC; although this review was for England, these habitats will also be important stores of SOC in Wales (Table 8).

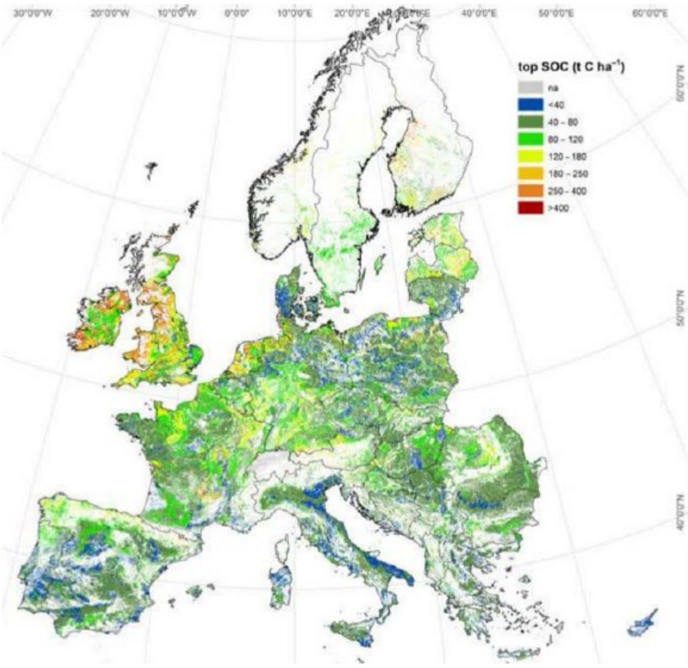


Figure 16. Soil organic carbon in the topsoil (0-30 cm) of European agricultural soils (Source: Lugato *et al*., 2014).

Table 8. Carbon stock average estimates by broad habitat (Source: Alonso *et al*., 2012).

Habitat	**Carbon stock in soils (t C/ha)**	**Carbon stock in vegetation (t C/ha)**
Dwarf shrub heath	88	2
Acid grassland	87	1
Fen, marsh and swamp	76	?
Bog	74	2
Coniferous woodland	70	70
Broad leaf, mixed & yew wood	63	70
Neutral grasslands	60	1
Improved grasslands	59	1
Arable and horticulture	43	1
Coastal margins	48	?

2.4.3 Farming enterprise

- Loss of organic carbon or organic matter from soils is related to the balance of inputs and decomposition dynamics of C in soil systems. Typically grasslands and woodlands are associated with high rates of OM accumulation; rotational grassland will have less OM than permanent grassland due to soil disturbance from periodic ploughing.
- Land use change, particularly the removal of permanent vegetative cover (e.g. deforestation or ploughing grasslands for arable cultivation) can have a major impact on SOM levels. When forest or permanent grassland is changed to arable cropland then above ground inputs of organic matter to the soil are significantly reduced as crops are removed when harvested.
- Land use change is as one of the most important threats facing Welsh soils. This is because of the large proportion of permanent grassland (almost two-thirds of the land area of Wales is

grassland) and the area of organo-mineral soils in Wales, whose shallow organic layers can be particularly vulnerable to changes in land use (Bol *et al*., 2011).

- The most vulnerable land use to loss of topsoil OM is upland peat followed by upland heath/grass moor (Cranfield University, 2016). Recent new analysis of the loss of topsoil-C in the 'habitat' category between 2007 and 2016 reported by the GMEP showed that the reported change was driven by trends in upland habitats, in particular the change for dwarf shrub to grass-dominated habitats (Alison *et al.,* 2019a).
- Cranfield University (2016) noted that there was conflicting evidence from two national monitoring programmes (Countryside Survey CS + Glastir Monitoring and Evaluation Programme - GMEP and the National Soil Inventory - NSI) for soil carbon change in topsoil in Wales. The NSI reports losses in soil carbon from 1978 to 2007 whereas the CS and GMEP reported no change. A review by Kirk *et al*. (2011), eliminated several potential reasons for the differences between the samplings (i.e. statistical effects, sampling or analysis methodology, sampling design or site re-location) but found no definitive reason for the difference.
- More recent soil samples taken for the Glastir Monitoring and Evaluation Programme (GMEP), between 2012 and 2016 also indicated no change in topsoil carbon for Wales (Emmett *et al*., 2017). As the sampling and analytical methodology used for topsoil in GMEP was identical to that used in Countryside Survey these datasets were combined to look for long-term national trends as well as providing a robust baseline for assessing future impacts of Glastir payments (Figure 17). GMEP data showed that soil carbon has been stable in improved land (arable and horticulture and improved grassland) for 30 years, decreased in habitat land (all habitats except woodlands, arable and improved habitats) and increased in woodland (broadleaved, mixed and coniferous) (Figure 17 and Table 9).Disaggregation of the GMEP data by Alison *et al*. (2019a) showed that the decline in SOC in habitat land was mainly confined to upland areas where acid grasslands were the predominate habitat type.
- As noted by Cranfield University (2016) there is no Welsh specific data for the SOM content of arable land, although data for England and Wales suggest that this has decreased (Reynolds *et al*., 2013; Bellamy *et al*., 2005).

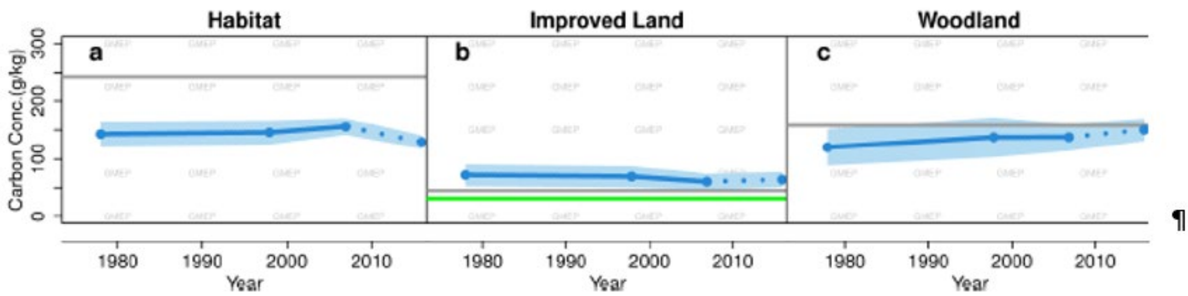


Figure 17. Long term trends in topsoil carbon concentration (g/kg; 0-15cm) at Countryside Survey sites in Wales for Habitat, Improved Land and Woodland categories. Countryside Survey data is indicated by a solid line and GMEP by a dotted line. The grey line is the CS Great Britain average 1978- 2007 and the green lines indicates minimum threshold levels.

Table 9. Long term trends in carbon (g/kg LOI) in topsoil (0-15cm) condition.

Land type	Countryside survey			GMEP			In scheme compared to average
	1978	1998	2007	2013-16	Overall	Latest	
Improved land	71.6	69.0	60.2	63.7	=	=	=
Habitat	143	146	156	130	=	-	=
Woodland	120	137	137	150	+	=	=
Wales	105	108	108	108	=	=	=

Significant differences over data series and latest period are indicated by: + significant increase; - significant decrease; = no change. Significant differences between land in the scheme compared to all Wales is also shown.

- The resilience of Welsh soils to loss of organic carbon/matter is not reported in the evidence explicitly. However, due to the cool, wet climate and predominance of grassland systems SOM losses from the majority of Welsh soils under current management are not expected to be high.
- Higher temperatures and reduced soil moisture are factors likely to reduce soil organic matter levels which may subsequently reduce, crop production, soil biodiversity and carbon storage. Soils of wetland habitats, such as peat bogs and fens, are particularly sensitive to changes in soil wetness; the degraded condition (e.g. through drainage, extraction or over-grazing) of the majority of these habitats increases the vulnerability of their soils.

2.5 Loss of soil biodiversity

- The decline in Soil Biodiversity - is generally considered as the reduction of forms of life living in soils, both in terms of quantity and variety (Jones *et al*., 2005). Wherever soil biodiversity decline occurs it can significantly affect the soils' ability to function normally and respond to perturbations and on the capacity to recover (Tibbett, 2016, Figure 18).

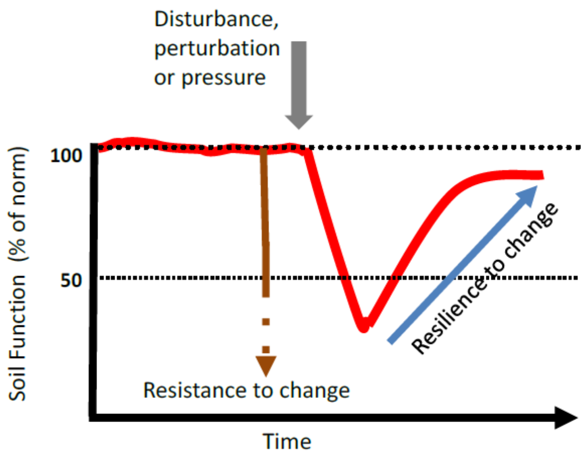


Figure 18. Schematic showing the effect of a perturbation on the resistance and resilience of soil function. Lower biodiversity is thought to lead to a soil with lower resistance to a perturbation and lower capacity to recover (Source: Tibbett, 2016).

- Soils provide a variety of habitats for a multitude of organisms of different size, physiological behaviour and ecosystem function, from bacteria and fungi for which the species richness and functional diversity is yet to be fully established, to larger species, such as earthworms, whose role has been more clearly defined. It is estimated that more than 1 in 4 of all living species in earth is a strictly soil-dwelling organism (Decaens *et al*., 2006). The diversity of soil types support a distinct diversity of below-ground biota and above-ground habitats.

- Whilst the link between soil biodiversity and ecosystem functioning is not well understood, it is clear that soil organisms play a fundamental role in the cycling and transformation of nutrients and organic compounds within soil (e.g. de Vries *et al*., 2013). Consequently, soil organisms are involved in delivering all the main supporting and regulating ecosystem services including food and fibre production, soil formation, flood risk management, water quality, climate control and waste and pollutant processing (Natural England, 2015).
- Decline in soil biodiversity is usually related to other deteriorations in soil quality and can be linked with other threats like erosion, organic matter depletion, contamination and compaction. In particular, there is a close link between soil biodiversity and SOM, although the relationship is not fully understood (Six *et al*., 2006).
- The majority of soils in Wales support grassland systems, where the threat of the loss of soil biodiversity is lower than in arable systems. Grassland systems are usually well supplied with organic matter/carbon (food/energy for soil organisms) and soils are generally undisturbed leading to a low risk of SOM loss or erosion. In contrast, the agricultural management that leads to a loss of soil biodiversity such as monoculture cropping, removal of residues, soil erosion and compaction are a threat to the small area of arable soils in Wales.

2.5.1 Soil type

- Soil organisms typically inhabit the pore spaces between soil particles the surface area of the pore space within a clay soil can be over 24,000 m^2 in just 1 g of soil, and this decreases with increasing proportions of silt and sand (Jeffrey *et al*., 2010). Consequently soils with increasing clay content can be expected to support a larger number of soil organisms, particularly micro-fauna (e.g. bacteria and fungi). Compacted soil is typically less biodiverse than undisturbed soil reflecting the reduced aeration and greater risk of waterlogging of compacted soil.
- Soils with a large and varied source of OM will generally support a wider variety of organisms due to it containing a range of substrates and nutrients (Jeffrey *et al*., 2010). Breure *et al.,* (2012) suggested that a more diverse soil community is also likely to be more resilient to change.
- Defra project CTE0946 (Cranfield University, 2011) suggested that the risk of soil biodiversity decline was mainly related to land use rather than soil type. Urban, horticulture and intensive arable systems had the greatest risk of soil biodiversity decline; only in forestry was the risk suggested to differ between soil types (Table 10). This was attributed to heavy metals from sewage sludge having a greater effect on soil biodiversity in forest soils with a higher OM content (i.e. clay and peat soils).

Table 10. The relative risk of soil biodiversity decline in each land use and soil type category (Source: Cranfield University, 2011. Defra Project CTE0946).

Land use	Soil types			
	Clay	**Silt**	**Sand**	**Peat**
Urban	H	H	H	H
Horticulture	H	H	H	H
Arable intensive	H	H	H	H
Arable extensive	L	L	L	L
Grassland improved	M	M	M	M
Grassland unimproved	L	L	L	L
Rough grassland	L	L	L	L
Forestry	M/H	L	L	M/H
Woodland	L	L	L	L
Wildscape	L	L	L	L

Note: H = high probability of soil degradation; M= moderate probability of soil degradation; L = low probability of soil degradation

- Climate change may affect soil biodiversity through changes in rainfall patterns and associated effects on soil moisture as well as changes to average temperatures, or through climate induced changes in SOM oxidation rate. Changes may favour different groups of organisms, e.g. bacteria over fungi and/or lead to changes in the species that make-up particular groups of organisms. However, quantifying the precise effects of climate change on soil biodiversity is not possible as current climate change models cannot predicts with any accuracy at this small scale (Jeffrey *et al.,* 2010).

2.5.2 Location

- There is a lack of data on the distribution, abundance and population for most soil dwelling organisms. Similarly, on habitat requirements. At the European scale the potential threats to soil biodiversity (land use change, intensive exploitation, invasive species, soil compaction, soil erosion, soil pollution and SOM decline) were combined to calculate a spatial index of risk level based on expert opinion (Jeffrey *et al*., 2010) (Figure 19).
- The risk map suggests, that parts of the UK are at particular risk of the loss of biodiversity, mainly due to intensive agriculture, invasive species and loss of SOM. For Wales, areas at high risk are confined to south west Wales and areas bordering England reflecting the higher proportion of arable production in these areas. Large areas of the Welsh uplands are mapped as having extremely low or no threats to soil biodiversity.
- There is no quantitative data on the vulnerability and resilience of Welsh soils to losses in soil biodiversity.

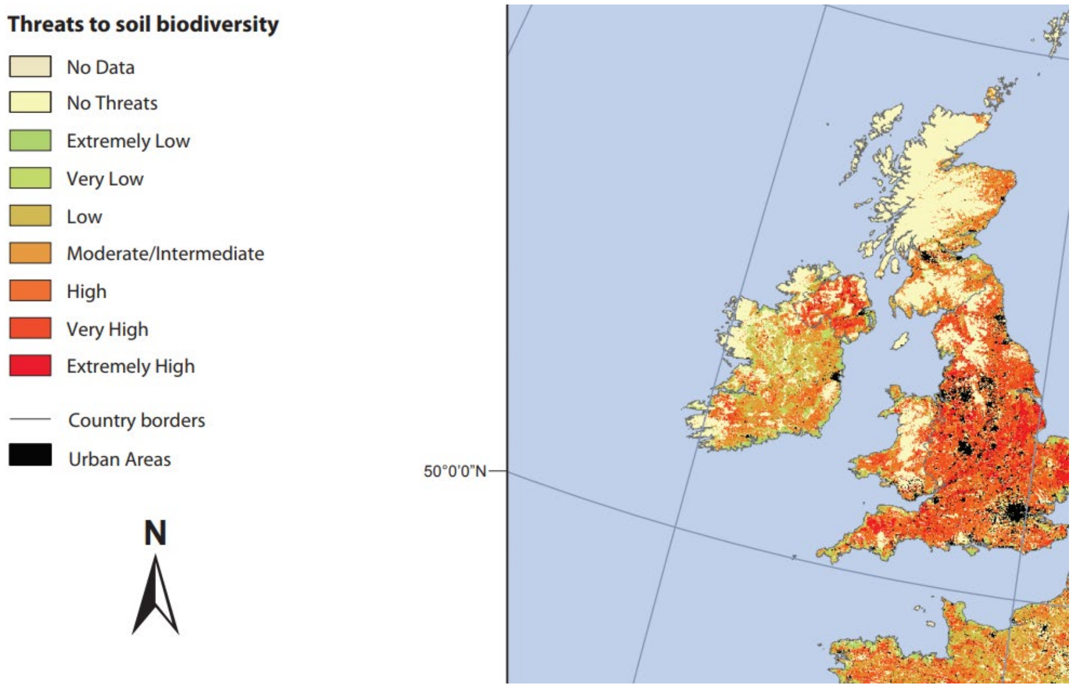


Figure 19. Threats to soil biodiversity in the UK. Potential threats were included in the calculation of the indicator: land use change/habitat disruption, intensive exploitation, invasive species, soil compaction, erosion, organic matter decline and pollution. Note: the map is an evaluation of the risk of soil biodiversity decline and does not represent the actual level of biodiversity (Source: Jeffrey *et al*., 2010).

2.5.3 Farming enterprise

- Changes in land management practice and land use can have large effects on soil biodiversity over relatively short-time scales. Agricultural land management practices, which reduce disturbance and increase and diversify organic matter inputs are most likely to benefit soil biota and their function (Natural England 2012).
- There is little evidence on trends in relation to soil biodiversity in Wales. Changes in soil biodiversity are likely to be related to i) land use change (both intensification/extensification), ii) loss of soil organic matter and/or iii) climate change (flooding and/or drought rather than changes in temperature). Reported low rates of change in land use and/or organic matter levels in Wales could infer little change in soil biodiversity.
- For Wales, GMEP data showed that total soil mesofauna (e.g. collembola or nematodes) numbers had declined on improved land and woodland to similar levels to those in 1998 (Emmett *et al*., 2017) (Figure 20; Table 11). A more detailed assessment of the data showed that the total number of mesofauna was lowest in land under arable and horticultural management and that improved grassland had lower mesofauna numbers than natural or acid grasslands (Figure 21). Species diversity tended to be higher where land use was extensively managed (e.g. unimproved grassland) (Figure 22).
- GMEP used eDNA methods to assess diversity of bacteria and fungi; in contrast to mesofauna data soil bacterial and fungal diversity was greatest in arable and horticultural soils and declined across the land intensification gradient (Figure 22), this was linked to the same trend in soil pH.

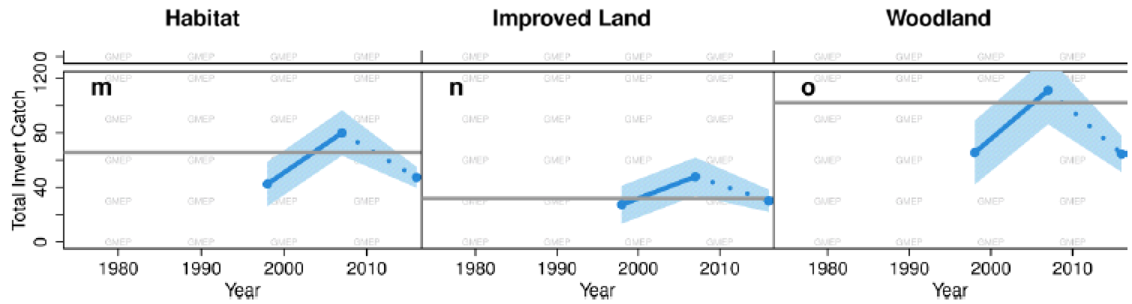


Figure 20. Long term trends in topsoil (0-15 cm) mesofauna numbers at Countryside Survey sites in Wales for Habitat, Improved Land and Woodland categories. Countryside Survey data is indicated by a solid line and GMEP by a dotted line. The grey line is the CS Great Britain average 1978- 2007.

Table 11. Long term trends in soil biota (numbers) in topsoil (0-15 cm).

Land type	Countryside survey			GMEP			In scheme compared to average
	1978	1998	2007	2013-16	Overall	Latest	
Improved land		27	50	30	=	-	=
Habitat		43	80	47	=	-	=
Woodland		65	111	64	=	-	=
Wales		41	70	43	=	-	=

Significant differences over data series and latest period are indicated by: + significant increase; - significant decrease; = no change. Significant differences between land in the scheme compared to all Wales is also shown.

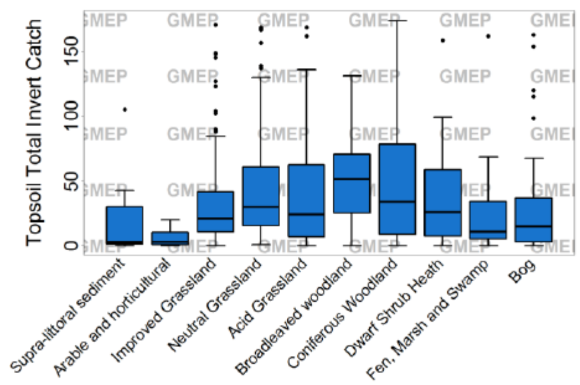


Figure 21. Topsoil mesofauna numbers in a range of habitats. Most productive habitats are on the left and the least productive on the right (George *et al.*, 2019).

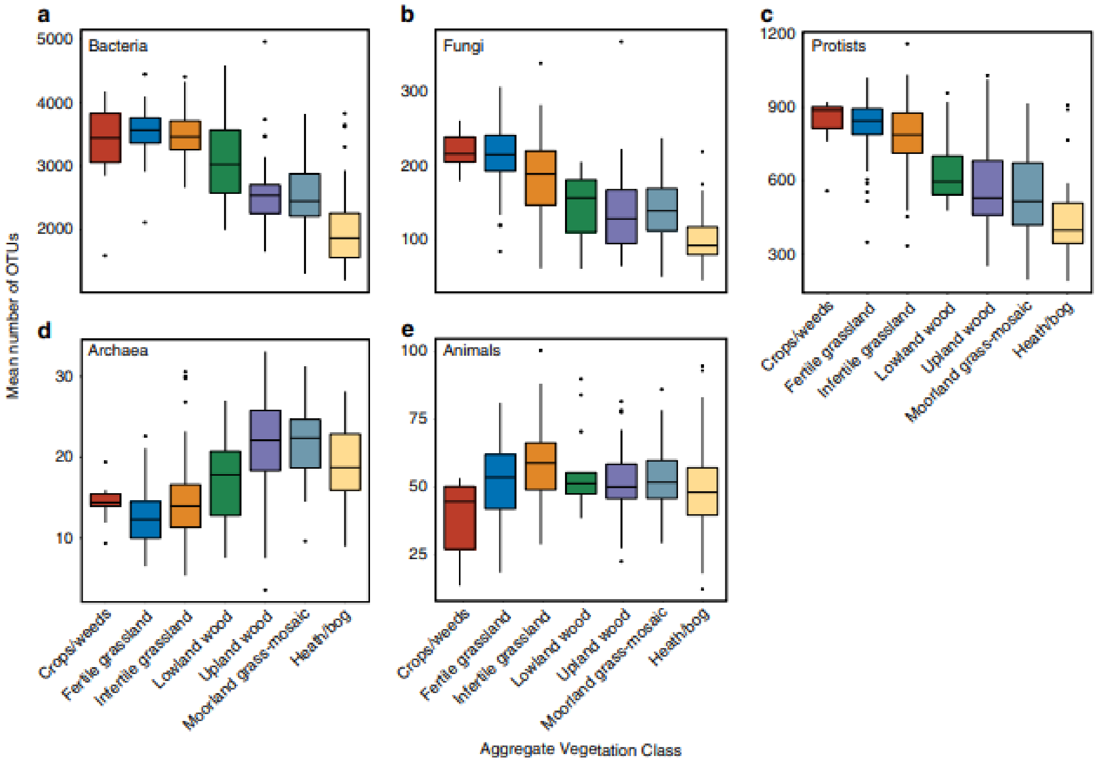


Figure 22. Topsoil bacteria, fungi, protist, archaea and soil animal species diversity in a range of habitats. Most productive habitats are on the left and the least productive on the right (George *et al.*, 2019).

2.6 Loss of soil to development

- Given that grassland makes up the majority of land cover in Wales development is most likely to affect food, fodder and fibre production (Cranfield University, 2015). Besides the loss of productivity and habitat, the other major impact of development is on the role of soil in water regulation. Poor construction practices during development can also lead to further soil degradation due to compaction and pollution. However, the supporting and cultural role of soils can become more important within an urban environment, potentially providing a variety of habitats and amenity areas such as playing fields, parks, gardens and roadside verges.
- Loss of soil to development occurs through land take (building on land that was formally open soil, EC, 2013) or by soil sealing. Soil sealing can be defined as the destruction or covering of soils by buildings, constructions and layers of completely or partly impermeable artificial material (asphalt, concrete, etc.) (Siebielec *et al.*, 2015). Although less than 5% of the land area of Wales is developed, there is an increasing need to build more houses and associated infrastructure. Development, whether it be due to housing, or commercial/industrial (including mineral extraction), inevitably leads to the permanent loss of soil and associated functions.
- Impacts on soil functions will include the loss of organic matter, compaction and loss of soil biodiversity. An increase in impermeable areas will reduce the regulation of water flows by reducing infiltration rates and increasing peak discharge rates and surface water runoff volumes (EC, 2012),which in turn increases the pressure on un-sealed soils to receive water causing greater risk of flooding (Defra project SP0541; National Soils Resources Institute, 2006).
- Population and economic pressure may lead to agricultural and rural land being used for building. However, since there are no specific requirements for development land (in terms of soil functions) soils which are less able to provide more exclusive functions should be used for

this purpose. For example, the use of Grade 1 agricultural land (the best and most versatile for agriculture) for urban development is not the most appropriate land use.

- The Best and Most Versatile (BMV) land is protected under current Planning Policy in Wales (Welsh Government, 2018c). This ensures development on good grade agricultural land (ALC grades 1, 2 and 3a) is a key consideration in the planning process. This is particularly relevant in Wales because BMV land is very scarce and thus development in these areas should be carefully controlled. There is significant divergence in the BMV policy wording, application and supporting evidence between England and Wales. The wording of Planning Policy Wales sets a high sequential test to justify the use of BMV land for other purposes. The provision of the Predictive Agricultural Land Classification Map (Wales 2017) provides a view of expected land quality on a 50m grid and allows for informed land use choices. This map is not available in England for planning authorities.
- All soils types are equally vulnerable to sealing or land take as the main driver of site selection is location rather than any soil related factor.
- A Welsh Government report, into the historic loss of agricultural land to urbanisation estimates the loss of:
    1. 29,000 ha of BMV agricultural land
    2. 35,000 ha of grade 3b moderate agricultural land
    3. 21,000 ha of grade 4 and 5 poor and very poor agricultural land

2.7 Soil contamination

- Soil can be contaminated from point or diffuse sources or from industrial, urban or agricultural sources and by organic, inorganic or particulate pollutants (Anaya-Romero *et al*., 2016).
- Livestock manures, inorganic fertilisers, biosolids and organic materials applied to agricultural land are sources of heavy metal to land. However, for materials other than livestock manures legislative or regulatory limit values exist to control the amounts of metals that can be applied (e.g. Sludge Use in Agriculture Regulations (SI, 1989) or the Safe Sludge Matrix (ADAS, 2001). For many heavy metals, atmospheric deposition is the biggest source of metal additions to soils (Nicholson *et al.,* 2010).
- Contamination mainly affects soil biological and chemical properties, although some contaminants (e.g. salts) may destabilize soil structure and affect soil physical properties (Gregory *et al*., 2015).
- Land that was previously industrial (metal works, coal or lead mines, gas works etc.) or used as landfill may be contaminated by metals, organic compound contaminants (e.g. polycyclic aromatic hydrocarbons-PAHs), hydrocarbons or pesticides. In Wales, the most common contaminants were Benzo(a)pyrene, lead and arsenic, all of which were identified at over 60% of contaminated land sites (Natural Resources Wales, 2016a).
- Across Wales, since 2001, a total of 175 sites were reported by 11 local authorities as contaminated land under Part 2A of the Environmental Protection Act (1990); this was later reduced to 111 after publication of updated guidelines and site specific risk assessment (Natural Resources Wales, 2016a). Remediation has been completed at 97 of the 111 Contaminated Land sites identified in Wales, but around 9,330 potentially contaminated sites have yet to be investigated.
- Contaminants may decrease pH which can affect nutrient availability and biomass production; pH is also an important determinant of soil biodiversity.

2.8 Media messages

- Headlines such as '100 harvests left'[7], 'We can only ignore the soil crisis for so long'[8], 'We're treating soil like dirt'[9], '£10m a year to ensure England's soil is fit for farming[10] and 'Soil cartel could control food supply'[11] have bought the issues surrounding soil protection (and in particular topsoil, organic matter loss and reducing rock phosphorus supplies) to a wider audience. However, despite these headline and undoubted need to protect vulnerable and poorly managed soils many soils remain in good condition.
- In Wales, specific areas of the country are at most risk of soil degradation as a result of agricultural management (either historic or current). The processes that drive these degradation processes have been described in detail in the preceding sections (e.g. land use change from grassland to arable and associated cultivations).
- As noted above, wind erosion, is particularly a problem on sandy and light soils which are uncommon in Wales. Average soil loss in Wales by wind erosion is 0.12 t/ha per year compared to the UK where it is 1.03 t/ha per year. Most of the headline stories are focussed on topsoil loss through wind erosion in the East Anglian fens (2.61 t/ha per year), where agricultural and land use policy has impacted on soil condition. Many parts of the fens were drained to grow crops and farming practices have resulted in substantial losses of soil organic matter, making the remaining peaty soil susceptible to wind erosion.

[7] https://www.fwi.co.uk/news/only-100-harvests-left-in-uk-farm-soils-scientists-warn
[8] https://www.telegraph.co.uk/news/earth/agriculture/farming/11838959/We-can-only-ignore-the-soil-crisis-for-so-long.html
[9] https://www.theguardian.com/commentisfree/2015/mar/25/treating-soil-like-dirt-fatal-mistake-human-life
[10] https://www.theguardian.com/environment/2018/apr/24/10m-a-year-needed-to-ensure-englands-soil-is-fit-for-farming-report-warns
[11] https://www.thetimes.co.uk/article/soil-cartel-could-control-food-supply-f7sc8vrzbq7

3 Practicality and cost/benefits of measures to prevent and remediate soil degradation in Wales.

- Measures to prevent and remediate soil degradation in Wales are discussed below for each factor in turn. However, it should be noted that many measures, both to prevent and remediate, may influence more than one soil factor. Also, that many of the methods are targeted at the small area of soil in arable systems, rather than at grassland soils that make up the majority of soils in Wales. Cost/benefit assessment is sometimes complicated by the multiple services provided by soils.
- In all cases it is acknowledged that best practice should aim to prevent degradation rather than remediate it.

3.1 Soil compaction

- Cultivating compacted tillage soils can be feasible at any point between crops within an arable or horticultural rotation when conditions allow. However, cultivation in wet field conditions, including disrupting tramlines when 'wet', is likely to exacerbate soil structure, surface runoff and erosion (Martin *et al*., 1999; Chambers *et al*., 2000). To minimise soil compaction from machinery both load size and contact area of wheels with the soil should be reduced as loads greater than 3.5 tonnes can cause serious and permanent compaction (AHDB, 2015) (Figure 23).

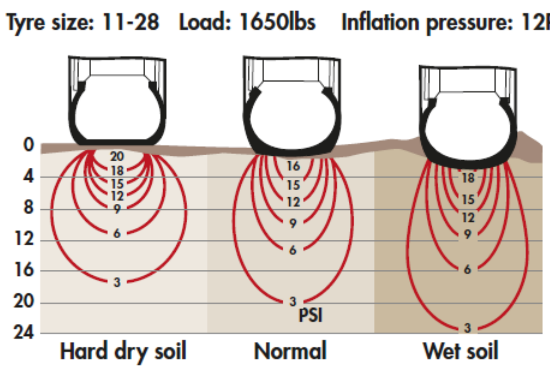


Figure 23. The effect of tyre pressure on soil compaction by farm machinery (Source: AHDB, 2015).

- Controlled traffic (the practice of running farm machinery over the same paths in the field, from event to event and year to year) can prevent soil compaction at the field scale in arable systems; compaction will be confined to the areas that are regularly trafficked. This is only likely to be practical where controlled traffic fits easily with field operations.
- To prevent soil structural damage late harvested arable crops (e.g. sugar beet or maize) should only be planted where soil conditions will allow field operations to take place without damage to soil structure, i.e. in areas where fields are dry in spring.
- Where compaction occurs only in the topsoil, routine tillage is usually effective at remediating soil structural damage to establish good growing conditions in the seed bed. However for deeper compaction, subsoil loosening will be required. This can be costly and requires careful timing with regard to soil conditions to ensure that the practice will be successful.
- Soil compaction in grasslands can be remediated without the need for ploughing. There are three main types of mechanical grassland soil 'loosening' devices, i.e. aerators (spikes or slitters working at a depth of 10 cm), sward lifters (working at depths of 20-35 cm) and sub-soilers (working at depths of 35-50 cm) (Bhogal *et al*., 2011). All are effective at reducing soil compaction, although the improvements in soil physical properties can be short-lived. However, remediation must be carried out when the soil is not too wet to prevent soil smearing which

may create a sealed layer which restricts water, air and roots. Recently loosened soil is also sensitive to re-compaction and is best cut and conserved rather than grazed immediately post loosening. However, mechanical loosening should only be used where soil compaction has been positively identified, i.e. it is not a preventative measure. Reduction in grass yield due to sward and root damage has been noted where loosening was carried out in soils that were not compacted (e.g. Frost, 1988).

- Grassland soil compaction can also potentially be mediated through the inclusion of plant species that are have extensive and deep root systems, although the benefit is likely to occur over the longer-term. For example, red clover, lucerne and chicory have deep tap roots that can potentially improve structure and drainage (AHDB, 2015).
- Grazing or over-grazing by livestock is a major cause of grassland compaction. Measures to prevent compaction by livestock include: keeping livestock off wet field, increasing grazing rotations, carrying out strip grazing with a back fence, providing multiple gateways and feeders/drinkers, regular moving of temporary feeders/grazers and limiting stocking rates (AHDB, 2015).
- Soil compaction mitigation strategies incur cost due to the direct costs of, for example, subsoiling, investment in new equipment, decreasing or altering the timing of traffic of equipment or livestock turnout, changes in cropping/grazing system and a range of other possible practices (Chamen *et al*., 2015).
- Soil compaction mitigation strategies incur cost due to the fuel, machinery and labour costs required. In livestock systems it may be necessary to invest in livestock housing in order to reduce the need to stock fields when soils are wet (Chamen *et al*., 2015).
- In their review of options for mitigating arable soil compaction Chamen *et al*., 2015, noted that for mitigation options, only targeted subsoiling resulted in a positive change to gross margin, between <£5/ha for sandy soil and £22/ha for clay soil. In contrast, all soil compaction avoidance technologies increased gross margins significantly, ranging from £26/ha for tracked tractors on sandy soil to £118/ha for CTF on clay soil. The findings demonstrated that soil management practices that avoided soil compaction were more cost effective than remediation strategies.

3.2 Water erosion

- The key to controlling soil erosion by water is to maximise rainfall infiltration into soils and minimise damage to soil structure.
- Planting vegetation is a relatively inexpensive erosion control measure that protects soil from the impacts of rainfall; the rooting system will also help to hold the soil together. Grass which is short and dense is often more effective than taller more sparse vegetation (Bai *et al*., 2015).
- Permanent soil cover will minimise erosion and hence grassland soils are often at low risk of water erosion. For arable/horticultural crops grown in rotation crop cover can be maintained by using cover or green manure crops (Bai *et al*., 2015). Winter cover crops can reduce sediment losses and surface runoff by 20-80% compared with leaving soil bare overwinter (Balshaw *et al*., 2013). This is particularly relevant for late sown crops such as maize, which are also slow to develop after sowing and can leave the soil surface at risk of erosion until mid-summer. The inclusion of cover crops in a rotation has cost and time implications and may reduce soil moisture and can potentially increase the pest population or risk of diseases.
- Soil cover can also be provided from crop residues that remain in the field after harvesting; this can be as effective as, and significantly less costly than establishing cover crops (Balshaw *et al*., 2013).
- Vegetative strips (e.g. hedges, trees or grassed areas) can also be used to control erosion in arable systems as they provide areas of permanent crop cover around or within a field. These are often located at field edges, and as well as preventing erosion, may also reduce nitrate

leaching. The main disadvantage is the loss of productive land, although potentially trees can provide an additional income in a well-managed silvo-arable agroforestry system.

- Another simple method for erosion control for arable systems is to crop across the slope to reduce infiltration, surface runoff and erosion (Newell Price *et al*., 2011). However, this is not suitable for steep slopes where machinery can overturn. Consequently, this method is only likely to be practical for crops grown on gently sloping fields with simple slope patterns, which restricts the scope of this practice. Some additional costs will be incurred as field operation time will be increased.
- Reduced, minimum or zero tillage helps to control erosion as the soil is undisturbed and is positive for soil structure (reducing soil compaction), biodiversity, organic matter and soil moisture (Newell Price *et al*., 2011). Production costs are reduced whilst yield is maintained but can be more variable. However, it may be necessary to purchase new machinery, which may restrict uptake to larger farms. Not suitable for soils with poor drainage and structure (Bolton, undated).
- To prevent erosion in grazed grassland, field drainage should be maintained and reviewed (to confirm it is fit for purpose) and stock should be managed to avoid poaching (i.e. no grazing on wet land, particularly in winter) or overgrazing (which will expose bare soil). Both should be simple to put into practice but have associated costs (e.g. reduced stock numbers = reduced farm income).

3.3 Wind erosion

- There are two factors that are essential for the control of soil erosion by wind: protecting the soil surface and reducing wind velocity.
- As for water erosion, vegetative cover will protect the soil from erosion; cover >10% reduces wind erosion (Bai *et al*., 2015). The risk of wind erosion in grassland systems is negligible. For arable systems, planting shelterbelts or windbreaks including hedges will physically separate and protect fields from wind erosion (Newell Price *et al*., 2011). However, the installation of shelterbelts is quite expensive and may only become effective after a number of years. Therefore, it is more practical to use shelterbelts in combination with in-field measures that are more quickly established.
- Tillage that creates surface roughness by leaving a cloddy seedbed or by ploughing (perpendicular to the prevailing wind direction is the most effective) can also minimise erosion by wind (Balshaw *et al*., 2013) in arable systems. Because no special equipment is needed these measures are simple and cost effective to achieve. However, this practice is best suited to those crops that are able to establish effectively in a rough seedbed. As a result, it is not well suited to crops such as oilseed rape, sugar beet and reseeded grasslands that require fine, clod-free seedbeds. In addition, rough seedbeds can reduce the effectiveness of agro-chemicals (Bhogal *et al*., 2009). The cost is low unless additional agro-chemicals are required.

3.4 Soil organic matter

- Management practices for arable systems can either protect, maintain or enhance SOM for soil quality/fertility or enhance SOM/SOC levels for soil carbon storage and climate change mitigation. If the rate of accumulation of SOC is greater than the rate of decomposition, then the amount of carbon in the soil increases, i.e. it will be sequestered. Practices that enhance soil organic matter levels are likely to benefit other soil properties such as improving soil structural stability, water holding capacity and the availability of crop nutrients. Enhancing and maintaining soil organic matter levels will also reduce the risk of water and wind erosion.
- Most arable soils are depleted in SOC relative to the native ecosystems from which they were derived, due to soil disturbance and export of harvested biomass (Paustian *et al*., 2019). It has

been reported that many mineral arable soils have lost 30-50% of the C stocks in the top 0-30 cm following conversion to agriculture (Davidson and Ackerman, 1993). Consequently, to avoid negative effects on SOC stocks then conversion of native ecosystems to tillage land should be avoided (i.e. maintain carbon stocks at current levels), albeit this will have concomitant consequences for food production/security.

- Best practice methods for SOM can be broadly grouped into the following categories: land use change (e.g. convert tillage land to permanent grassland), reduction in soil erosion (e.g. leave autumn seedbed rough), changes to tillage/cultivation practices (e.g. reduced or zero tillage) and increased organic matter additions/returns.
- Alison *et al*. (2019b) grouped management practices for increasing SOM into three categories: 1) well tested and proven, with no dis-benefits, 2) Limited evidence and some trade-offs and 3) Limited practical potential, small benefits of significant trade-offs. The best management practices (i.e. those classified the first category) were for improved grassland: organic fertilisers and retention of grassland management (i.e. no land use change) for cropland: cover cropping and conversion to grassland and for upland habitats: prevent drainage and restore peatland.
- The conversion of tillage land to permanent grassland and woodland is most effective at increasing soil organic matter content as it avoids the frequent cultivations that under arable cropping stimulate the mineralisation of organic matter. However, taking arable land out of agricultural production is likely to reduce farm productivity and consequently farm income. Newell Price *et al.* (2011) estimated that converting around 10% of tillage land to low intensity grassland would reduce farm income by around £200/year on a typical dairy farm and £35,000 on a farm dominated by roots and combinable cropping. The authors also predicted that conversion of arable land to unfertilised grassland would reduce nitrate and ammonium losses to water by 90% with similar reductions in ammonia and nitrous oxide emissions. Arable reversion was also predicted to reduce particulate P and associated sediment losses in surface runoff were predicted to be reduced by around 50%.
- Practices that protect and maintain organic matter in tillage soils include: growing green manure crops, perennial forage crops and cover crops; applying animal manure or compost and incorporating straw and other crop residues into the soil (Bhogal *et al*., 2009).
- The application of organic materials is practical where supply is plentiful and the cost is likely to be minimal; some cost savings are possible due to the reduced use of manufactured fertilisers. However, repeated applications of organic materials (especially solid manures) are likely to lead to increased soil phosphorus levels as the quantities supplied by the manures are likely to exceed crop offtakes. For manures that have a high readily available N content (i.e. poultry manures, livestock slurries and digestate) applications should be managed to minimise the risks of nitrate leaching. It is important that manure applications are included in soil management plans to ensure that the nutrients supplied are accounted for when planning manufactured fertiliser applications and to minimise nutrient loadings which will limit the risks of diffuse air and water pollution. (Bhogal *et al*., 2009).
- Cover crops are used in tillage systems between harvest and the establishment of the following cash crop. They are usually used in spring cropping rotations and can be effective at reducing nitrate leaching losses and reducing the risk of soil damage from rainfall impact by providing a cover for the soil over winter.
- Studies have shown that cover crops can increase soil organic matter content but the magnitude of the increase will depend on the amount of biomass that is produced and incorporated into the soil. Sainju *et al*. (2002) observed a 25% decrease in SOC following six years of conventional tillage without cover crops, whereas with a hairy vetch cover crop (returning c.0.7 t C/ha/year) SOC levels only declined by 1% and with a rye cover crop (returning c.3.7 t C/ha/year) SOC levels increased by 3-4%. Soil and weather conditions at the time of cover crop establishment are important factors controlling the effectiveness of cover crops. A meta-analysis of 30 studies (37 sites), including sampling depths which ranged from 2.5 cm to

120 cm found that the use of cover crops as a green manure led to a significant increase in SOC stocks (Poeplau and Don 2013). The time since cover crop introduction also influences the SOC stock exchange, with a mean accumulation rate of 0.32 ± 0.08 t C/ha/year to an average maximum increase of 16.7 t/ha (Poeplau and Don 2013).

- Reduced tillage or minimum tillage has been widely promoted as a potential means of increasing SOM levels and storing carbon within arable soils, due to less soil disturbance (and hence SOM decomposition) and reduced soil erosion rates. The greatest challenge for implementing this method is the likely need for new machinery which is not achievable for some smaller farms. It is most commonly implemented on medium/heavy soils, but is less likely to be used in wetter parts of the country, potentially limiting the uptake of this practice in Wales.

3.5 Soil biodiversity

- There is a close link between soil biodiversity and SOM so that land management that increases or maintains SOM levels will also be beneficial for soil biodiversity.
- Practices that increase organic matter in arable systems include: growing green manure crops, perennial forage crops and cover crops; applying animal manure or compost; leaving crop residues in the field; using reduced/minimum/no tillage to prevent soil compaction and enhance soil biodiversity and include crops within the rotation that will lead to high residue (leaf and root material) incorporation. These practices are typically cost effective but may not be practical in some crop rotations or at some sites.
- Major changes in land use will also affect soil biodiversity. Land take or soil sealing will cut off water and nutrient inputs and will have a negative impact on soil biodiversity. In contrast, a change from intensive agriculture to, for example, woodland will benefit biodiversity (due to increased OM inputs and lack of soil disturbance).
- Measures that prevent soil structural degradation caused by compaction or erosion will also benefit soil biodiversity. Some remediation measures may be expensive so where possible it will be more cost effective to mitigate rather than remediate.
- The appropriate use of manures and fertiliser in arable systems may have indirect (increased above ground biomass may increase OM inputs) and direct benefits for soil biodiversity.
- Changes in climate leading to flooding (oxygen depletion and structural damage) and/or periods of drought are likely to have negative impacts on soil biodiversity.

3.6 Loss of soil to development

- Soil sealing can only be mitigated by de-sealing which is likely to be costly and impractical. However, the use of permeable sealed surfaces can help to conserve soil functions and mitigate the effects of soil sealing to a certain extent.
- Future soil degradation by land take can be minimised by focusing, as far as practically possible, on using brownfield land and reuse of already developed land. Also, through the promotion of development that maintains some soil functions through the maintenance of soil permeability.
- In some cases, the economic benefits of development may outweigh the damage caused to soil, in particular where this is of low productive or natural value.
- The use of the ‘best’ agricultural soils for development should be avoided. This can be prevented by a legislative approach or via charging or trade-off schemes. For example, in the Czech Republic and Slovakia, the use of the ‘best’ agricultural soils for development requires a fee per square metre of soil lost (Prokop *et al*., 2011). In both countries the income from the fee is used for soil research and monitoring. Whereas, in Germany, the Eco Account System, which is based on trading eco-points requires developers to undertake compensation projects to earn

points. The developer receives a certificate stating that compensation was done according to law and thus is able to proceed with the project concerned (Prokop *et al*., 2011).

- Planning Policy for Wales (Welsh Government, 2018c) offers some protection for the best and most versatile land agricultural land (ALC grades 1-3a), which should be 'conserved as a finite resource for the future'. However, the policy further states that the land 'should only be developed if there is an overriding need for the development and either previously developed land or land in lower agricultural grades is unavailable, or available lower grade land has an environmental value recognised by a landscape, wildlife, historic or archaeological designation which outweighs the agricultural considerations'.

3.7 Soil contamination

- Policy and regulation are the main factors that prevent soil contamination.
- Large-scale contamination may require the contaminated soil to be excavated and removed (often to landfill); this is expensive and is not practical for large areas, however, it remains common in Europe (Cundy *et al*., 2008).
- Other options for mitigation include phytoremediation which uses green plants to break down pollutants in soils through hyper-accumulation, complexation, volatilisation and degradation. However, this will only work for some chemicals at some sites (Bai *et al*., 2015).
- More low level soil contamination will be minimised by well-managed applications of manure, biosolids, organic materials, manufactured fertilisers and agro-chemicals. This is largely achieved by applications in accordance with legislative or 'good practice' guidelines.

4 The challenges involved with regulating soils in Wales.

- There is no single piece of regulation for soil protection in Wales (or in the rest of the UK). The UK Government's 25 Year Environment Plan (HM Government, 2018) aims to improve soil health and restore and protect peatlands. However, this is a visionary rather than regulatory plan.
- Similarly, there is no specific EU legislation on soils. Some EU Directives have indirectly addressed aspects of soil management (e.g. the Nitrates Directive and the Environmental Impact Assessment Directive) and there are also indirect effects from agri-environment schemes and statutory designations such as SSSIs. However, in order to receive Basic Payment Scheme payments under CAP, UK farmers must maintain minimum soil cover (with vegetation, crop, cover crop, stubble or crop residue), minimise soil erosion and compaction (by livestock and vehicle management and minimising machinery use on wet soil) and maintain good levels of organic matter (by not burning straw, stubble or crop residues). Compliance with regulations must be enforced by inspection of at least 1% of farms per year.
- There are a number of challenges to regulating which mainly relate to: the establishment of baseline and/or target values for soil properties, the mismatch between the policy cycle and measurable changes in soil and the need to balance the ability of soils to provide a full range of ecosystem services at the local, regional and national scale. This involves managing soil resources in ways that take account of their multiple functions.
- To regulate soil effectively there is a need to establish both baseline and target values for soil that can be included in legislation. Soil quality indicators (SQIs) are often proposed to assess the delivery of soil ecosystem service and recent studies have reduced 'useful' physical, chemical and biological indicators to around 10-20 in each case (ADAS & Reading University, 2015). For example, Merrington *et al*. (2006) proposed a minimum dataset of soil quality indicators for England and Wales of: soil organic carbon, total nitrogen, Olsen phosphorus, available and total copper, nickel and zinc, bulk density and pH. More recently, Bünemann *et al*. (2018) reviewed 62 publications (65 datasets) relating to soil quality indicators; the data showed a wide range of proposed potential indicators (Figure 24). In addition, Bünemann *et al*. (2018) noted that non-soil factors such as climate and site conditions, plant performance or socio-economic factors could be also be important soil quality indicators.
- For some indicators there is sufficient data and model development to link values to the delivery of specific ecosystem services across a number of land uses, soil types and management conditions (e.g. relating saturated hydraulic conductivity to surface runoff generation and flooding risk). However, despite significant progress with interpreting indicator values, major scientific and practical issues remain to be addressed (ADAS & Reading University, 2015). These include the development of indicator reference values for different combinations of land use, soil type and climate; and obtaining a better predictive understanding of the relationships between soil degradation, soil biodiversity and ES delivery (Pulleman *et al*., 2012). As a result, SQI are difficult to include in regulation.
- Soil properties are influenced by many factors and it is not usually possible to link particular changes in SQI values to particular policy activities, not least because physical changes in soil quality usually occur more slowly than any developments in soil protection policy. However, soil monitoring can be used to determine the overall effectiveness of soils policies in reducing soil degradation, even if it cannot be used to evaluate the effectiveness of individual measures (Rickson *et al*., 2012).

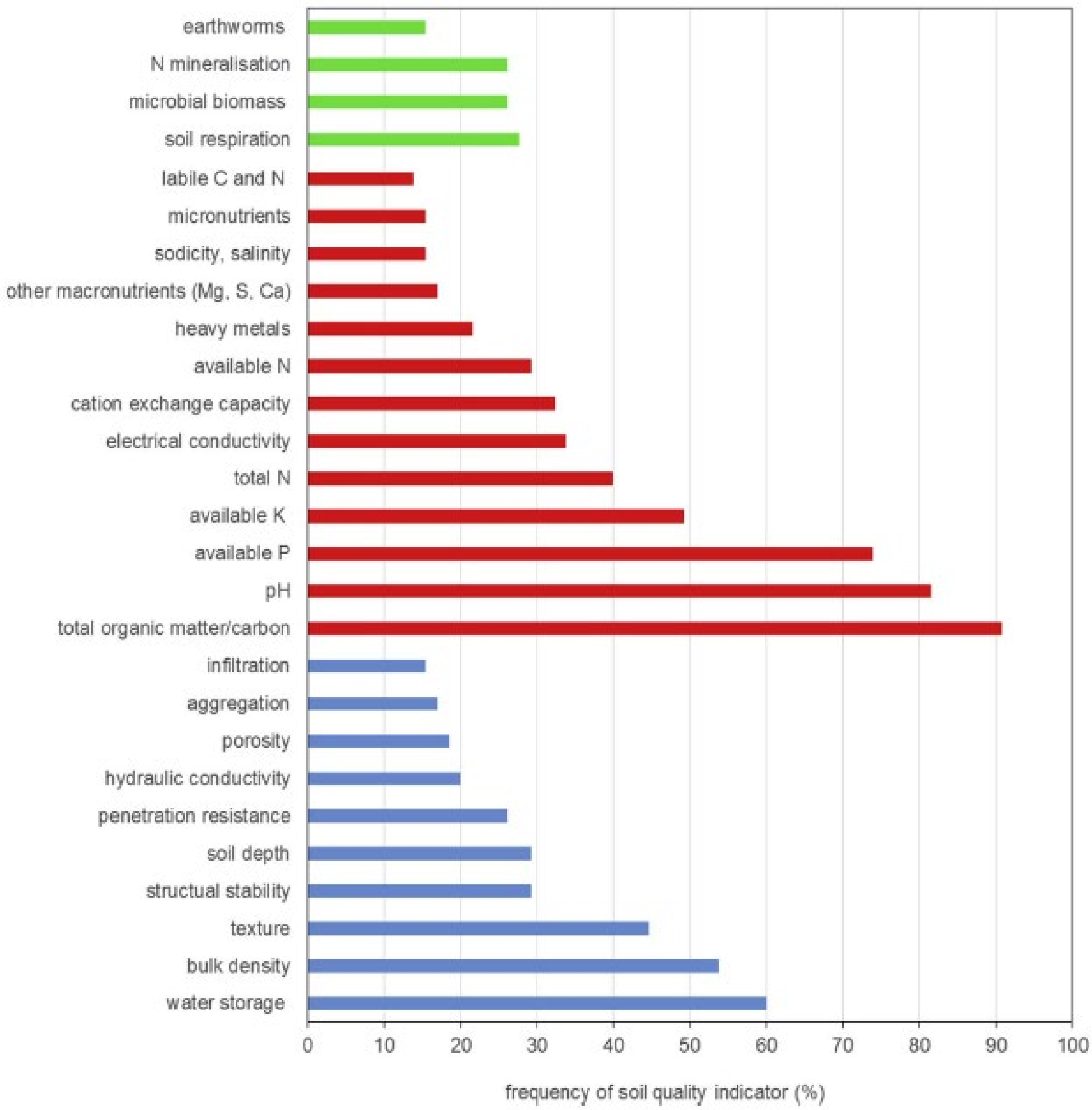


Figure 24. Frequency of different indicators (min. 10%) in all reviewed soil quality assessment approaches (n=65). Soil biological, chemical and physical indicators shown in green, red and blue, respectively (Source: Bünemann *et al.*, 2018).

- Typically soil quality indicators are unable to respond to management changes within a policy cycle of five years. This presents challenges in detecting trends that can feed into short-term policy development or to gauge the effectiveness of soil protection policies (Rickson *et al.*, 2012).
- Regulation can also be complicated by issues of land ownership as well as the mismatch between farm boundaries and ecological processes. For the first, there is anecdotal and some research evidence to indicate that short-term land tenancies can result in poor soil management practices and a deterioration in soil quality (e.g. Fraser, 2004). The benefits of good soil management might not be immediate and those farmers on contracts or short tenancies may have little incentive to invest financially in safeguarding long-term soil quality. Collaboration to deliver landscape scale benefits is required to deal with the mis-match between farm and soil which may be difficult to regulate effectively.

- A further challenge for soil regulation is to manage soil is the need to promote practices that provide a balance of goods and services, optimising land use for food production and environmental protection (Schulte *et al*., 2014). In general, management will enhance the provision of some ecosystem services and negatively influence the provision of others; for instance, ploughing a field contributes to food production, but it undermines other soil ecosystem services, such as carbon storage or microbial biodiversity. On the other hand, no-till management may reduce soil disturbance but may lead to other challenges (especially in terms of pest or weed control). Getting the optimum balance in policy requires well designed regulation.
- There is a clear need to define different criteria for soil sustainability depending on the ecosystem service in question and to define concepts such as 'soil health' (e.g. Kibblewhite *et al*., 2008), 'soil quality (e.g. Bünemann *et al*., 2018) and 'sustainable' in order to set goals and objectives that can be used in policy and management development.
- Payments for ecosystem services can be difficult to regulate due to the need to clearly define the link between soil management and the outcome that is to be rewarded by the payment.
- Unintended side-effects of 'other' policies can also impact on soil regulation. For example, government policy to support anaerobic digestion (AD) of organic materials for the production of biogas (for subsequent conversion to heat and power) has resulted in a rapid increase in AD plants. Although the feedstock for AD plants can include food waste and slurry, purpose-grown crops such as maize are also used. Currently there are around 25 AD plants in Wales of which about quarter use feedstocks containing a proportion of crop-based feedstock; another c.40 AD plants are located in the border counties of Herefordshire and Shropshire of which c.75% include crop-based feedstocks (including maize) (NNFCC, 2019[12]).

[12] http://www.biogas-info.co.uk/resources/biogas-map/attachment/ad-portal-map_site-list_external_may-_2019/

5 Identify policy options to maintain/improve soil quality in Wales.

- Policy drivers can have direct or indirect effects on soil quality by banning, discouraging or incentivising particular land management strategies.
- A comprehensive soils policy should not just focus on preserving/improving the (physical, biological, chemical) condition of soils, but rather on enhancing the services they support. In Wales, this may mean that rather than having an over-arching soils policy for the whole country it may be appropriate to have different options for different areas or different land use types (e.g. lowland or upland; extensive upland grazing or lowland arable).
- The Common Agricultural Policy (CAP) is key policy and funding source for land management in the EU. In order to qualify for the full single farm payment farmers must provide minimum soil cover, take measures to prevent erosion, and maintain soil organic matter levels. However, in practice the low levels of inspection make it difficult for these requirements to be enforced. Voluntary agri-environment schemes (Glastir in Wales) funded under Pillar II of the CAP are also important mechanisms for encouraging soil conservation; one of the aims of Glastir is to 'improve soil quality and management'.
- The inclusion of soil management plans as part of Glastir requirements would potentially improve soil quality in Wales by raising awareness of the importance of soil management practices on productivity and the environment. In addition, the Welsh Government proposal for sustainable land management (SLM) outlined in the recent consultation document 'Sustainable Farming and our Land' outlines the benefits of soil husbandry for SLM and SOM (Welsh Government, 2019).
- Simplification and support for farmers to apply for agri-environment schemes is required; feedback from farmers is that current stewardship schemes are not 'farmer friendly'[13].

5.1 Compaction

- A simple way to address one of the causes of soil compaction would be a policy to restrict the wheel load carrying capacity (Schjønning *et al*., 2015) for traffic on all agricultural soils. Differentiated limits could be applied, depending on soil vulnerability (texture), however, implementing such a scheme would be difficult in practice as it would be challenging to monitor and/or regulate.
- Another policy option to address soil compaction could be to incentivise controlled traffic approaches (perhaps through targeted grants or support programmes) for arable systems; this could be a management option within Glastir. However, significant investment in machinery and technology would be required to achieve the benefits associated with controlled traffic farming.
- Incentivising the maintenance of 'good' grassland management (i.e. prevent over-stocking and grazing in wet conditions) would reduce the risk of compaction in grassland systems. However, in practice this is complicated due to the difficulties of setting limits on grazing rates for varied systems and adequately defining 'wet' conditions. For example, soil type and grass cover will influence how susceptible a specific site is to compaction. Again, this would be challenging to monitor and/or regulate.

5.2 Erosion

- Policy to address soil erosion could include formal delimitation of erosion vulnerable zones (Berge *et al*., 2017). In these high risk areas the maintenance of permanent soil cover, prescribed tillage systems (e.g. no planting of maize, cultivation across the slope) or other erosion controls could be mandatory.

[13] https://www.fginsight.com/news/news/farmers-demand-changes-to-not-fit-for-purpose-country-stewardship-scheme-7079

- However, incentivising management practices that increase the natural capacity of soils and vegetation to store water or slow runoff rates can be challenging, as the recipients of the benefits tend to be located downstream (ASC, 2016).
- In some circumstances, substantial effort is required to reduce soil erosion rates to tolerable levels; particularly for tilled sandy and light silty soils on sloping land (Verheijen *et al.,* 2009). This has implications for policy in terms of the degree to which soil erosion needs to be controlled to maintain soil functions and the types of soil management practices that need to be encouraged in particular circumstances.

5.3 SOM

- It is important to reward farming systems that both maintain and build soil organic matter and improve long-term soil health. This could be included as an option within Glastir Advanced or developed as a separate policy. Note that GAEC 6 requires the maintenance of soil organic matter; additional policy should focus on increasing SOM.
- Although changes in SOM can occur within a 5-year agri-environment cycle (for example, through manure application or zero tillage) often change will occur over the longer-term making it difficult to reward increases within a policy framework. In addition, although, SOM is easy and relatively cheap to measure, multiple samples per field are needed to adequately represent the spatial variability within a field and accurately determine changes in SOM levels.
- Linking payments to changes to actual SOM levels is difficult and would require a policy that acknowledged differences in farming systems and soil types to set baseline levels and reward maintaining or increasing SOM.
- Increases in SOM as a result of a change in land management are finite and will stabilise as a new equilibrium is reached (Powlson *et al*, 2011). In addition, increases may be greatest where SOM levels are currently low.

5.4 Development

- The use of the 'best' agricultural or habitat soils for development should be avoided. This can be prevented by a legislative approach (strengthening existing regulation) or via charging or trade-off schemes. For example, this could be a fee per square metre of soil lost (as in the Czech Republic and Slovakia) or along the lines of the Eco Account System in Germany (see section 3.5). However, this kind of approach may have a limited impact on large corporations where this cost could be easily offset by potential profits from development.
- The BMV land protected under current Planning Policy in Wales (Welsh Government, 2018c) includes ALC land classified as grades 1, 2 and 3a. Given the finite amount of land in Wales, that this protects, there may be a case for extending protection to include land graded as 3b in some cases.

5.5 Contamination

- Metal limits are already in place for sewage sludge, compost and digestate that is applied to agricultural land, although adherence to these limits values is not required for livestock manures. In the future limits could also be applied to organic contaminant concentrations of the same materials, although these are often present at levels that make routine analysis difficult.
- Currently there is limited evidence on the metal concentrations of Welsh soils, baseline data would need to be collected in order to establish current levels.

5.6 Payment strategies

- One possible policy option is the payment for ecosystem services (PES), which pay land managers to deliver ecosystem services through good soil management. The Welsh Government's Sustainable Management Scheme under its Rural Development Programme for 2014-2020 has been designed to support PES schemes.
- Implementing effective policies requires organised systems for monitoring soil conditions and an understanding of the relationship between soils, local climatic regime and land management. Without this basic information, policy makers have no way of knowing whether regulations and incentive schemes are achieving the desired result.
- Before a PES scheme can be established a counterfactual baseline is needed to understand what would have happened in the absence of the PES policy. This establishes additionality (i.e. that the policy is having a benefit greater than would have occurred anyway) and help to determine the level of payment (Capodaglio and Callegari, 2018).
- A carefully designed comprehensive monitoring programme would be required to establish the baseline state of soils in Wales. The precise target of this monitoring would depend on the targeting of the PES programme.
- Some of these systems may have strong economic drivers because they are mandatory for market access (e.g. participation in supply chains to supermarkets).

6 Priorities to improve knowledge exchange and enable land managers to maintain/improve soil quality.

- It has been suggested that four key communities form the knowledge infrastructure for soil and water management (Kibblewhite *et al*., 2010): 1. Farmers/land managers, 2. Advisors, 3. Developers (translate knowledge into tools and systems) and 4. Researchers. There is a need to make sure that the communities work together to ensure effective knowledge exchange (KE). Also to understand the processes and mechanisms by which knowledge is transferred.
- For land managers, time is a primary constraint on knowledge transfer and so it is essential that KE is delivered efficiently and accessibly. KE should take multiple formats such as, one to one conversations, leaflets, workshops, the internet, courses, group discussions, demonstrations, meetings, conferences and research papers etc. Well targeted KE is essential to ensure that messages are specific and targeted rather than generalist and untargeted.
- Social media, such as Twitter (twitter.com), could be used for sharing soil management knowledge and for interactive communication. Twitter can capture the immediacy of field operations and visual impacts in the field. Furthermore, the brief messages channelled through Twitter appeal to time-constrained farmers (Mills *et al*., 2019). However, Twitter works best for those actively seeking information, rather than passive recipients of new knowledge. However, Twitter messages need to be carefully formulated to ensure important caveats or limitations to the headline message are also acknowledged.
- For literature to be effective e.g. pamphlets, leaflets, reports, guides etc., it must either be preceded by workshops, demonstrations or one-to-one visits by advisors or get its point across quickly, effectively and show value (Kibblewhite *et al*. 2010).
- Farm advisors are still one of the primary sources of information to farmers (Ingram, 2008) and it is essential that they are able to provide up to date information on soil management.
- Engagement between policy makers, researchers and farmers is important to ensure understanding of agricultural issues (e.g. practical and economic challenges) and to aid the effective implementation of new knowledge and technologies. To be effective this collaboration should be structured in ways that the farmers see it as useful and relevant with appropriate use of non-technical language.
- Formal or informal networks of land managers enable best practice to be shared between practitioners; farmers seem more willing to adopt new methods where other farmers are advocating their use (Kibblewhite *et al*., 2010).
- Initiatives for farmers and researchers to work together to improve soil management practices and provide information about their effectiveness in enhancing soil quality for production and environmental protection on-farm.

7 Conclusions

- The extensively, grazed grassland soils (e.g. where the total amount of nitrogen in organic manure applied, either directly by livestock or as a result of spreading is ≤100 kg N/ha) that predominate in Wales are generally at low risk of soil degradation and typically will have low rates of soil erosion and compaction, coupled with high organic matter contents. The main threat to intensively managed grassland soil is damage by heavy machinery (e.g. harvesters and manure spreaders) intensively/poorly managed grazing livestock and land use change, i.e. cultivation for arable and fodder production. In comparison, arable soils are much more vulnerable to a range of threats caused by cultivation practices that may compact soils, influence soil erosion rates and lead to reductions in organic matter. The intensity of any threat to soils will be directly linked to a range of soil, site and climatic factors.
- ***Climate Change:*** It is not yet clear how soils are responding to a changing climate, with much debate over whether measured declines in UK soil carbon concentrations over the last few decades are a result of climate change or other factors such as changes in land management. However, given the predicted increases in temperature and changes in the seasonality and magnitude of rainfall events, changes to soils and the services they provide are highly likely, particularly if land-use patterns also change.
- ***Compaction**:* Based on modelling assessments of soil wetness classes, it has been suggested that 25% of the total grassland area is liable to compaction from machinery damage or livestock. Compaction by livestock is strongly linked to livestock density and is much higher with wet soil and low plant density (i.e. in early spring and later autumn or early winter). In comparison, the same modelling studies estimated that only <5% of arable soil was at risk of compaction, mainly from cultivation and harvest operations.
- ***Erosion:*** Large areas of Wales are assumed to have low erosion rates due to grassland land use, although this has not been quantified by measurements or observations. However, land use change is an important factor in soil erosion risk and significant decreases in erosion risk have been noted when fields changed from winter cereals to permanent grass. This is because grassland soils have year round crop cover and so soil is not exposed to the erosive forces of water or wind although the erosion risk will be higher during the reseeding phase.
- ***Soil organic matter (SOM):*** SOM maintenance and accumulation is favoured by management systems which add high amounts of biomass to soil, cause minimal soil disturbance, improve soil structure, enhance activities and species diversity and strengthen mechanisms of element cycling. Such low disturbance, high carbon input (e.g. litter and roots) and SOM content are typified by the grassland soils that predominate in Wales. Thus most soils in Wales will be at low risk of SOM loss although SOM loss may occur when grasslands are reseeded. For the minority of soils in Wales that are in arable systems, the risk of SOM loss is significantly greater, as SOM loss is triggered by soil disturbance, which increases oxidation and by reduced accumulation or removal of OM (crop residues may not be returned to the soil so levels become depleted).

Remediation of soil degradation

- Grazing or over-grazing by livestock is a major cause of grassland compaction. Measures to prevent compaction by livestock include: keeping livestock off wet fields, increase increasing grazing rotations, carrying out strip grazing with a back fence, providing multiple gateways and feeders/drinkers, regular moving of temporary feeders/grazers and limiting stocking rates.
- The key to controlling soil erosion by water is to maximise rainfall infiltration into soils and minimise damage to soil structure. Permanent soil cover will minimise erosion and hence grassland soils are often at low risk of water erosion.
- Best practice methods for SOM can be broadly grouped into the following categories: land use change (e.g. convert tillage land to permanent grassland), reduction in soil erosion (e.g. leave autumn seedbed rough), changes to tillage/cultivation practices (e.g. reduced or zero tillage) and increased organic matter additions/returns. There is a close link between soil biodiversity

and SOM so that land management that increases or maintains SOM levels will also be beneficial for soil biodiversity.

Regulation and policy

- A comprehensive soils policy should not just focus on preserving/improving the (physical, biological, chemical) condition of soils, but rather on enhancing the services they support. In addition, there should be benefits for the farmer in terms of increased production, lowering costs or financial reward. However, there are a number of challenges to regulating soil which mainly relate to: the establishment of baseline and/or target values for soil properties, the mismatch between the policy cycle and measurable changes in soil and the need to balance the ability of soils to provide a full range of ecosystem services at the local, regional and national scale
- To regulate soil effectively there is a need to establish both baseline and target values for soil that can be included in legislation and that are practical, measurable and enforceable. Soil quality indicators (SQIs) are often proposed to assess the delivery of soil ecosystem service, however, despite significant progress with interpreting indicator values, major scientific and practical issues remain to be addressed and as a result, SQI are difficult to include in regulation. Nevertheless, it is clear that policies that maintain or enhance SOM contents should result in multiple benefits in terms of climate change mitigation and the sustainability of agricultural systems.

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