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Measuring the vulnerability of Scottish soils to a changing climate

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1 Executive summary

The second Scottish Climate Change Adaptation Programme (SCCAP) identifies soil health as a priority research area to support sustainable soil management and ecosystem services. This follows concerns over a perceived lack of data or gaps in understanding that have been raised in both independent assessments of the first SCCAP by the Committee on Climate Change. The aim of this study is to summarise previous work on Scottish soils, explore existing datasets, and identify those metrics which could support the monitoring of Scotland's soil health and measure the vulnerability of Scottish soils to climate change in future.

1.1 Key findings

- Scotland has a significant, world-leading soil knowledge base and a broad data resource portfolio (Table 2). However, the existing evidence base on soils does not contain tools identified as appropriate for monitoring change in Scottish soils (Table 2).

- Thirteen indicators with potential to measure soil vulnerability to climate change in all soil types were identified (Table 1).

- A total of 41 existing datasets that contain baseline and/or resurvey data for Scottish soils have been identified. Resampling of some of these long-term national datasets has potential to support further development of the 13 identified indicators (Table A10).

- A critical knowledge gap exists regarding the dependencies of the 13 identified indicators (i.e. factors they are reliant on), their interactions and hence whether a reduced core set of indicators could be identified at a future stage. This is compounded with critical gaps in our understanding of the interactions between soil properties. This knowledge gap has a major impact on soil biological diversity and therefore functioning of the soil system.

- No single indicator measures the full range of relevant properties encompassing all soils or climatic conditions.

Table 1: Potential indicators of Scottish soil vulnerability to climate change

Soil health indicators most likely to show impacts	Utility of indicator to indicate risk to climate change	Strengths	Weaknesses
DOC (Dissolved Organic Carbon) concentration	Indicates loss of soil carbon into streams/rivers High levels of DOC indicate higher carbon turnover High levels cause issues with provision of clean water Levels indicate impacts from climate change, soil erosion and land management	Easily detected and measured, with strong linkage between DOC and catchment soil carbon content	Levels can be influenced by recent weather patterns
Moisture content	Low levels indicate risk of erosion and soil carbon loss High levels indicate risk of runoff and flooding 'Healthy' range for different soil types and land uses is well understood High impact on peat and agricultural soils	Easy to measure with existing protocols; strongly influences multiple soil processes and functions	Varies rapidly with weather conditions, requiring frequent measurement
Soil Organic Matter (SOM) content	Vital for supporting multiple soil functions Contains approx. 50% carbon so provides a significant carbon store in organomineral & organic soils 'Healthy' range for different soil types and land uses is well understood Strong base of existing measurements & modelling	Present in all soils and an indicator of multiple soil health/soil function attributes; measurement is low-cost with good protocols	Direct measurement of rate of change in SOM is difficult; varying chemistry and particle sizes mean that SOM is not 'all the same'
Nutrient flux	Strongly linked to soil biological activity and soil food web Strongly linked to agricultural productivity pH is a major factor in nutrient transport and could act as a proxy indicator	Has great significance for all land uses; relatively slow variation under most conditions; good measurement protocols exist	Requires measurement of multiple soil properties; Different extraction methods can give different concentrations of 'total' or 'plant available' nutrients

Soil health indicators most likely to show impacts	Utility of indicator to indicate risk to climate change	Strengths	Weaknesses
Topsoil Depth (or total depth for peat)	Indicator of change in topsoil depth Topsoil thickness is an indication of soil loss through erosion or an indication of compaction which limits rainfall infiltration leading to poor roots growth and increased flood risk. Loss of peat thickness is indicative of increased oxidation of organic carbon	Applicable to all soils; easily measured (depthing rods may be needed in some peats)	Increases in topsoil thickness in cultivated soils could be due to cultivation; changes may be due to in-field redistribution of soil rather than degradation
Visual Evaluation of Soil Structure - VESS (topsoil/subsoil)	Indicative of soil structure and hence the ability of roots to grow; the ability of soil to retain water and infiltration capacity	Scale 1-5 means it is simple to apply in the field by non-specialists with minimal training (pictorial guidelines available); tested against range of physical properties and reproducible	Applicable mainly to cultivated soils; some subsoils are naturally poorly structured and these need to be recognised as they cannot be remediated
Erosion features	Accelerated erosion by wind or water indicates poor soil structure or loss of organic matter	Applicable to all soils; easily recognised with little training	Can be readily remedied making it difficult to record all instances; temporally variable
Bulk density	Indicates soil porosity and hence, infiltration capacity (affecting runoff), compaction, conditions for root growth and resilience to drought and water-logging Can indicate drying and shrinkage of peat soils	Applicable to all soils and easily measured	Limitations in some subsoils and e.g. high sand content soils, different optimal bulk density values required for different soil textures; interaction with land management and climate; some skill required for sampling
Bacteria and archaeal diversity (DNA methods)	A diverse community is indicative of a healthy functioning soil Soils dominated by bacterial communities are generally considered nutrient replete	Present in all soils; easily extracted from soils; well defined protocols available	As most bacteria are unculturable, diversity of bacterial/archaeal communities is inevitably

Soil health indicators most likely to show impacts	Utility of indicator to indicate risk to climate change	Strengths	Weaknesses
	Data can reflect impact of land management practices and perturbations on soil A highly productive agricultural soil is considered to have a 1:1 bacteria to fungal ratio		underestimated; not possible to characterise into functional groups
Fungal diversity (DNA methods)	A diverse community is indicative of a healthy functioning soil Soils dominated by fungal communities are generally considered nutrient depleted Data can reflect impact of land management practices and perturbations on soil A highly productive agricultural soil is considered to have a 1:1 bacteria to fungal ratio	Present in all soils; easily extracted from soils; well-defined protocols available	Fungal identification is complex; not possible to characterise into functional groups
Nematode diversity (DNA methods)	A diverse community of all functional nematode groups is indicative of a healthy functioning soil Due to position in soil food webs, recognised as an integrated indicator of medium to long-term impacts on soil Data can reflect impact of land management practices and perturbations on soil	Present in all soils; easily extracted from soils; well-defined protocols available; globally accepted as an indicator of soil function; well characterised into functional groups	Perceived link that all nematodes are pathogens
Earthworm diversity (morphology)	A diverse community of all functional earthworm types is indicative of a healthy functioning soil Data can reflect impact of land management practices and perturbations on soil	Readily recognised; well characterised into functional groups	Few experts available to identify species; not applicable to soils with low pH; not abundant in all soils
Functional genes	Provides information on the activity of soil nutrient cycles, especially the bacterial and fungal component. Data can reflect impact of land management practices and perturbations on soil	Applicable to all soils; well-defined protocols available	Potential results difficult to interpret

Contents

2 Background

In its final assessment of the first SCCAP [1], the Committee on Climate Change (CCC) rated 'soils and agriculture' as an area of high concern noting "*conclusions cannot be made about vulnerability in some areas where there is a lack of data or gaps in understanding of the risks. For example, there is a lack of research or appropriate metrics to assess the vulnerability of Scottish soils to climate impacts" (2019).* One example can be drawn from recent research by ClimateXChange, which concluded that the full extent of erosion or compaction is not currently known [2]. There is also currently no metric for soil vulnerability in the UK Climate Change Risk Assessment [3].

In September 2019 the Scottish Government published the second Scottish Climate Change Adaptation Programme (SCCAP2). It says:

> "*Soils are severely impacted by climate change but there is currently insufficient data and metrics to assess their vulnerability to climate change This has been raised in both Independent Assessments of the first SCCAP carried out by the Committee on Climate Change. Building on a recent report by CXC for the Scottish Government on the institutional governance for soil in Scotland, a new research project will look across the metrics and policy issues to establish a framework for soil health*."[4]

2.1 Existing Scottish soil resources

Scotland has a considerable amount of good quality soil data due, in part, to a long history of soil mapping, characterisation and quantification of soil properties supported primarily from the public purse. Various soil maps are available in both digital and hard copy that show the distribution of the different soil types found in Scotland and which are a product of around 10,000 years of soil development. For most purposes, these soil maps can be considered as representing a near-steady state as soils develop slowly over a long time. However, such maps are useful in quantifying stocks, providing a general inventory of the soil resource and facilitating the spatial extrapolation of research findings. Allied to the soil maps, is a national soil database (Appendix A10, Representative Soil Profiles of Scotland). These soil profiles (vertical exposure around 1m deep) were described and sampled to characterise the soils shown on the maps and provide the key attribute dataset that allows stocks to be calculated. These attributes can also be used to develop derived maps of, for example, vulnerability to soil erosion, when combined with terrain data (Table 2).

Many of these soil attributes (e.g. soil pH) are more dynamic than others (e.g. soil texture) and change over shorter timescales than the individual soil types. They are therefore more suited to providing baseline data to measure change over time or assess soil health e.g. where soil profiles at the same locations have been sampled at different points in time. The soil maps can be used to identify the scale and extent of the likely impact of these changes, and which soil types are most likely to be affected (see Appendix Table A2).

As well as the various soil, land capability, stock and risk maps (Table 2), there are a number of existing local, regional and national datasets. These comprise measurements of individual soil properties that are sensitive to land use and climate change that could be a basis of future monitoring networks (Appendix Table A10). Most of these surveys were documented in the Emmett et al. (2007) report on the review and assessment of a national soil monitoring network

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[1] https://www.theccc.org.uk/publication/final-assessment-of-scotlands-first-climate-change-adaptation-programme/ , page 7
[2] https://www.climatexchange.org.uk/research/projects/soil-erosion-and-compaction-in-scottish-soils-adapting-to-a-changing-climate/
[3] https://www.theccc.org.uk/uk-climate-change-risk-assessment-2017/
[4] Scottish Government 2019, page 166

and have been successively updated (see Appendix Table A10). Many of the surveys listed include many of the indicators deemed most relevant to measuring the vulnerability of Scottish soils to climate change.

2.2 Previous commissioned reports

In 2006 the Climate Change and Air Division of the Scottish Executive commissioned a report on the current state of Scottish soils and the threats to the resource (Towers et al. 2006). Some of the key findings of that report, particularly around the threat of climate change, formed part of the landmark Scottish Soil Framework [5] designed to protect the Scottish soil resource. This Framework set out a range of activities that contributed to 13 soil outcomes to improve soil and environmental health and included a chapter on the impact of climate change on soil. Two of the actions contained within the Soil Framework report were to undertake a review of the state of Scottish soils and to establish a soil monitoring network. An implementation plan has been developed for the latter [6] and a report of the state of Scotland's soils was published in 2011 (Dobbie et al., 2011). The report highlighted climate change as one of the key pressures on Scottish soils and identified the need for policy integration to protect the Scottish soil resource, understanding the role of soil management in protecting soils, and assess what information was already available, identify knowledge gaps and make recommendations for future soil monitoring.

3 Monitoring soil health and vulnerability to climate change – key issues

Definitions and quantifications of soil health are notoriously difficult to resolve, but some initiatives have explored its potential as a holistic entity [7] [8]. Rinot et al. (2019) noted that in order to attempt an assessment of soil health with the multiple functions and demands made on soil, flexible integration of multiple properties according to varying criteria is required. However, there are three critical overarching categories of properties that determine whether or not a soil can be judged as healthy – the chemical, biological and physical properties of soil. The indicators discussed here are broken down into these categories, although further work would be required to understand the impact of climate change on the interaction of these properties.

Risks to soil health (i.e. the functioning of soil to deliver ecosystem services) through climate change can be assessed by examining the level of the direct or indirect threat. This includes the threat of climate change in combination with the vulnerability of one or more of the ecological functions, or underlying properties of these functions, of a given soil type/location to be affected by such threats.

We assessed the most likely changes in climatic factors influencing vulnerability/ resilience of Scottish soils and summarise these as a series of likely threats (Appendix Table A1).

We then assessed the likely impact of the climate change threats in Appendix Table A1 on a pool of potential indicators of vulnerability. Given that certain soil types occur more readily in a specific geographical area, we considered differential impacts across different soil types (Appendix A2, Tables A3-A5). Furthermore, we assessed the likely impacts of climate change

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[5] https://www.gov.scot/publications/scottish-soil-framework/

[6] https://soils.environment.gov.scot/media/1063/soil-monitoring-action-plan-implementation-march-2013.pdf

[7] The concept of *soil health* has not been formally defined. It is sometimes termed *soil quality*, defined in Bunemann et al 2018, 105 as "the capacity of a soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality and promote plant and animal health".

[8] The European Commission Mission Board for Soil Health and Food has defined soil health for its purpose as "the continued capacity of soils to provide ecological functions for all forms of life, in line with the Sustainable Development Goals and the Green Deal" (Veerman et al 2020, 5).

threats on Scottish soils (Appendix A3) focusing on soil chemistry (Appendix Table A6), physics (Appendix Table A7) and biology (Appendix Table A8).

The author team used expert judgement to assess these chosen indicators to represent those with greatest confidence in their robustness (defined as repeatability of results) and integrity (defined as returning unequivocal data). Finally, we assessed whether baseline and/or resampling data were already available for such indicators (Appendix Table A10). We deemed indicators where baseline and/or resampling data were available as the most imminently useful. This final assessment, however, while not exhaustive due to the time constraints, is a comprehensive collation of expert knowledge of datasets that are known to contain information on potential indicators of vulnerability of soil health to climate change.

We identified a pool of 13 indicators associated with soil chemical health (Appendix Table A3), 17 indicators associated with soil physical health (Appendix Table A4) and 23 potential indicators of biological soil health (Appendix Table A5). This list was further condensed to a total of 13 indicators of soil health that would be responsive to climate change (four chemical, four physical and five biological) that represented, in the opinion of the experts, as those of most utility and, where noted, imminently available indicators (Tables 2 and 3). However, a critical knowledge gap exists regarding the dependencies of the 13 identified indicators, their interactions and whether a core set of indicators could be further identified. An associated assessment of the level of currently available underpinning or baseline data for each of the identified candidate indicators was also considered (Table 3). The detail of how these indicators were chosen can be found in the Appendix.

Indicator types for these different parts of overall soil health may represent soil health at different spatial scales or temporal dimensions. For example, soil chemistry indicators may be better able to detect impacts on soil health than some biological indicators, which might only be sensitive at certain times of the year, or vice versa.

Table 2. Soil survey and derived data products that characterise the Scottish soil resource.

	Name of dataset	Date created	Extent	Description	Purpose	Capable of measuring change	Availability
	National Soil Map of Scotland	1947-1981	National	National coverage of the main soil types within landform units across Scotland mapped originally at 1:250 000 scale.	To provide a general inventory of the soils of the country to assist strategic and regional planning.	No	Scotland's soil website
	Soil map of Scotland (partial cover)	1947-1987	Cultivated agricultural soils and some of the adjacent uplands	Individual soil types within the main cultivated land area of Scotland originally mapped at 1:25 000 scale	To provide a general inventory of the soils of the country and information on the basic soil types used for crop and livestock production.	No	Scotland's soil website
	World Reference Base soil map	2012	National	The map was based on a reclassification of the 580 soil map units of the National Soil Map of Scotland.	To show the soil types in Scotland in relation to a world-wide soil classification system.	No	Scotland's soil website
	National scale land capability for agriculture map (LCA)	1978-83	National	National scale land capability for agriculture ranks land on its potential productivity and cropping flexibility determined by the extent to which its physical characteristics (soil, climate and relief) impose long term restrictions on its agricultural use. in 7 classes at 1:250 000 scale.	Initially designed to provide an inventory of agricultural potential and to protect high quality agricultural land.	No (though efforts to update and forward project LCA classes under future climates have been undertaken).	Scotland's soil website
	Land capability for agriculture (partial cover) map	1984-86	Almost all of Scotland's cultivated agricultural land and adjacent uplands.	The land capability for agriculture (partial cover) map ranks land on the basis of its potential productivity and cropping flexibility determined by the extent to which its physical characteristics (soil, climate and relief) impose long term restrictions on its	To present detailed information on soil, climate and relief in a form which will be of value to land use planners, agricultural advisers, farmers and others involved	No (though efforts to update and forward project LCA classes under future climates have been undertaken).	Scotland's soil website

	Name of dataset	Date created	Extent	Description	Purpose	Capable of measuring change	Availability
				agricultural use in 7 classes (and 10 divisions) at a scale of 1:50 000.	in optimising the use of land resources.		
	National scale land capability for forestry map (LCF)	1989	National	National scale land capability for forestry ranks on its potential to grow trees and flexibility for growth and management based on a number of factors including soil, climate and topography.	To provide an inventory of the potential for commercial forestry, as a broad-scale planning and as a guide for land managers.	No (though efforts to update and forward project LCF under future climates are being considered)	Scotland's soil website
	Topsoil Organic Carbon Content map	2012	National	The concentration of organic carbon in the surface layer of soil in 6 classes based on summary data from the Representative Soil Profile database.	Map prepared for EU project GS-SOIL - Assessment and strategic development of INSPIRE compliant Geodata-Services for European Soil Data. ECP-2008-GEO-31800	No as based on summary of data collected from 1947-2004. Other measures of change in national scale soil C stocks are available through the National Soil Inventory of Scotland (see Appendix A10)	Scotland's soil website
	Topsoil pH map	2014	National	The map shows the average pH of the uppermost major horizon of the most extensive soil in each 1:250 000 soil map unit.	To show the extent of low pH soils in Scotland	No as based on summary of data collected from 1947-2004. Other measures of change in national scale soil pH are available through the National Soil Inventory of Scotland (see Appendix A10)	Hutton website/UKSO website
	Available Water Capacity map	2018	National	The available water capacity gives information on the water available for plant growth in 7 classes. It is calculated from other soil properties and is the amount of water found in the top 1 m of	To estimate the amount of water that can be stored in Scottish soils as	Not readily as based on regression equations to predict water storage capacity of the soil	Scotland's soil website

	Name of dataset	Date created	Extent	Description	Purpose	Capable of measuring change	Availability
				soil after any excess has drained and before the permanent wilting.	input into agronomic models	though can be used to estimate effect of changing carbon concentration on water availability.	
	NVZ Soil Texture map	2016	Land area of Scotland designated as vulnerable to Nitrate pollution of ground and surface waters	Soil texture grouped into broad categories as designated by NVZ legislation.	Developed to show the distribution of land within NVZ with soil texture classes that restrict certain management practices at specific times of the year.	No	Scotland's soil website
	Map of topsoil compaction risk (partial cover)	2018	Most of Scotland's cultivated agricultural land area.	The vulnerability of topsoils to compaction from agricultural machinery or other traffic in 4 classes.	To help land managers identify land susceptible to structural damage through the use of heavy machinery	No as based primarily on soil texture and inherent soil drainage morphological characteristics	Scotland's soil website
	Map of subsoil compaction risk (partial cover)	2018	Most of Scotland's cultivated agricultural land area.	The vulnerability of subsoils to compaction from agricultural machinery or other traffic in 5 classes.	To help land managers identify land susceptible to structural damage through the use of heavy machinery	Partially as a component of the assessment is long term climate	Scotland's soil website
	Map of runoff risk (partial cover)	2018	Most of Scotland's cultivated agricultural land area.	The map shows the risk of the soil becoming saturated, causing water (or any liquid applied to the soil) to flow over land (runoff) and carry potential pollutants into water courses, or to collect (pond) on the surface.	To aid land managers and agencies to identify land that could be a source of pollution to water courses	No as there is no climate or weather component	Scotland's soil website
	Map of soil leaching potential (partial cover)	2018	Most of Scotland's cultivated agricultural land area.	The map shows the risk of potential pollutants and nutrients leaching through the soil to ground and surface waters.	To identify the likelihood of a potential pollutant that is applied to the soil surface filtering through the soil and	No as there is no climate or weather component and the underlying model is insensitive to	Scotland's soil website

	Name of dataset	Date created	Extent	Description	Purpose	Capable of measuring change	Availability
					reaching a water course or ground water based on fundamental soil characteristics	changes in soil carbon concentration	
	Map of soil erosion risk (partial cover)	2014 (revised 2018)	Cultivated agricultural soils and some of the adjacent uplands	Provides information on the likelihood of a bare soil being eroded under intense or prolonged rainfall (NB, rainfall is not explicitly considered)	To help land managers and agencies identify land most likely to erode	No as there is no climate or weather component	Scotland's soil website
	Hydrology of Soil types (HOST)	1995	National	Map showing the distribution of soils classified according to their hydrological response.	Designed to predict annual river flows (low flow and flood flow)	Although based on regression between soil types and river flow indices there is some scope for using HOST to identify rivers susceptible to changing climate.	Available under licence
	Soil carbon Stocks	2012	National	Estimation of the soil carbon stocks to 1m depth based on summary data from the Representative Soil Profile dataset and the 1:250 000 scale National Soil Map of Scotland	To provide a general inventory of the national carbon stock held within Scottish soils	No as based on average data from 1947 to 2004	Available on request. Current research is improving on these estimates and incorporating C stored in peat at depths greater than 1m
	Carbon and peatland 2016 map	2016	National	Map showing the likely presence of carbon-rich soils, deep peat and priority peatland habitat in 7 classes and based on an amalgamation of the National Soil Map and the Soil map of Scotland (partial cover).	Designed as a high-level planning tool created to promote consistency and clarity in the preparation of spatial	No, reworking of National Soil Map and the Soil map of Scotland (partial cover).	Scotland's soil website

	Name of dataset	Date created	Extent	Description	Purpose	Capable of measuring change	Availability
					frameworks by planning authorities.		
	Topsoil organic carbon	2017	National	This soil organic carbon dataset is based on the digital (vector) version of the soils of Scotland 1:250 000 maps and the land cover of Scotland 1988. The topsoil carbon percentage in this dataset has been computed using data from the Scottish soils knowledge and information base (SSKIB).	To provide a general inventory of the national carbon stock held within Scottish topsoils	No, reworking of National Soil Map and Scottish Soil Database	Scotland's Natural Asset Register
	Topsoil median pH	2020	National	The topsoil pH in this data set has been computed using data from the Scottish Soils Knowledge and Information Base (SSKIB).	To provide a general inventory of the pH values of Scottish topsoils	No, reworking of National Soil Map and Scottish Soil Database	Scotland's Natural Asset Register
	Peat depth	2019	National	Map showing depth of peat and depth of organic layer for non-peat, using Scottish Soil Database, satellite imagery and Peatland Restoration survey data with Digital Soil Mapping.	Carried out as part of RESAS-funded work in SRP 2016-2020. Intended to provide improved spatial resolution mapping of organic soil (peat).	No, based on legacy and recent survey data. Incorporates remote sensing imagery so could be used for future detection of peat condition/depth change if combined with new survey data and updated remote sensing data.	Scotland's Natural Asset Register
	Soil profile depth	2019	National	Map showing depth of soil profiles at 100m resolution, using Scottish Soil Database, satellite imagery and Peatland Restoration survey data with Digital Soil Mapping.	Carried out as part of RESAS-funded work in SRP 2016-2020. Intended to provide improved spatial resolution mapping of organic soil (peat). Extended to all soils.	No, based on legacy and recent survey data.	Scotland's Natural Asset Register
	Total soil carbon (all soils)	2019	National	Map showing total soil carbon estimate at 100m resolution, using Scottish Soil Database, satellite imagery and Peatland Restoration survey data with	Carried out as part of RESAS-funded work in SRP 2016-2020. Intended to	No, based on legacy and recent survey data. Incorporates remote sensing	Scotland's Natural Asset Register

	Name of dataset	Date created	Extent	Description	Purpose	Capable of measuring change	Availability
				Digital Soil Mapping. Shows estimates of total soil carbon stock in full profile.	provide improved spatial resolution mapping of organic soil (peat). Extended to all soils.	imagery so could be used for future detection of change if combined with new survey data and updated remote sensing data.	
	Total peat carbon	2019	National	Map showing total organic soil carbon estimate at 100m resolution, using Scottish Soil Database, satellite imagery and Peatland Restoration survey data with Digital Soil Mapping. Shows estimates of total organic soil carbon stock in full profile.	Carried out as part of RESAS-funded work in SRP 2016-2020. Intended to provide improved spatial resolution mapping of organic soil (peat).	No, based on legacy and recent survey data. Incorporates remote sensing imagery so could be used for future detection of peat condition/depth change if combined with new survey data and updated remote sensing data.	Scotland's Natural Asset Register
	Total soil carbon (all soils) to 1 metre depth	2019	National	Map showing total soil carbon estimate at 100m resolution, using Scottish Soil Database, satellite imagery and Peatland Restoration survey data with Digital Soil Mapping. Shows estimates of total soil carbon stock to 1 metre depth.	Carried out as part of RESAS-funded work in SRP 2016-2020. Intended to provide improved spatial resolution mapping of organic soil (peat). Extended to all soils.	No, based on legacy and recent survey data. Incorporates remote sensing imagery so could be used for future detection of change if combined with new survey data and updated remote sensing data.	Scotland's Natural Asset Register

Table 3. Baseline and/or trajectory data for potential indicators of soil vulnerability to climate change.

Soil health indicators most likely to show impacts	Baseline availability		
	National	**Regional**	**Land use specific**
	Soil chemical Indicators		
DOC concentration	Weak potential: few data	Weak potential: few data	Weak potential: few data
Moisture content	Not yet possible: insufficient data	Weak potential: few data	Weak potential: few data
Soil Organic Matter	Strong potential: considerable data	Strong potential: considerable data	Strong potential: considerable data
Nutrient flux	Not yet possible: insufficient data [9]	Not yet possible: insufficient data [6]	Not yet possible: insufficient data [6]
	Soil physical Indicators		
Topsoil Depth (or total depth for peat)	Strong potential: considerable data	Strong potential: considerable data	Strong potential: considerable data
Visual Evaluation of Soil Structure -VESS (topsoil/subsoil)	Medium potential: some available data	Medium potential: some available data	Medium potential: some available data
Erosion features	Weak potential: few data	Strong potential: considerable data	Medium potential: some available data
Bulk density	Medium potential: some available data	Medium potential: some available data	Medium potential: some available data
	Soil biological indicators		
Bacteria and archaea diversity (DNA methods)	Medium potential: some available data	Medium potential: some available data	Medium potential: some available data
Fungal diversity (DNA methods)	Weak potential: few data	Weak potential: few data	Medium potential: some available data
Nematode diversity (DNA methods)	Strong potential: considerable data	Strong potential: considerable data	Strong potential: considerable data
Earthworm diversity (morphology)	Strong potential: considerable data	Strong potential: considerable data	Strong potential: considerable data
Functional genes	Medium potential: some available data	Weak potential: few data	Medium potential: some available data

[9] Nutrient flux is highly variable over time, so monitoring would require continuous/frequent observations at locations of interest

4 Conclusions and recommendations

This study demonstrates that Scotland is replete with resources that characterise Scottish soils. These support an acknowledged world-leading knowledge base and expertise on soils (Tables 2 and Appendix A10) and have potential to be applied to Scottish soils in the context of a changing climate (Table 1 and Table 3).

Overall, climate change is expected to have a negative impact on all soil properties (Appendix Tables A6-A8), individually and in combination with wider risks to the ecosystem services they deliver. However, localised soil/climate interactions may be such that the land capability of some soils may improve. The negative impacts include risks of increased emissions of nitrous oxide (an important GHG), increased soil erosion, increased nitrate leaching, increased flood risk, increased soil borne pest and pathogen pressure resulting, in an agricultural context, of decrease in crop yield, increased incidence of crop disease, increased requirement for irrigation, and a requirement for novel (chemical free where possible) agronomic interventions to manage crop disease (see Appendix A.3. for further detail).

Based on a combination of expert knowledge, published and experimental data, a suite of potential candidate indicators for soil biology, chemistry and physics has been identified that have potential to provide timely and sensitive measures of soil vulnerability to climate change.

Seasonal influences would likely impact aspects of soil chemistry and physics, but are less likely to impact soil biology. Interactions between soil biology, chemistry and physics are key and have a major impact on soil biological diversity and, therefore, the functioning of the soil system. The generic climate scenarios under consideration would have a substantial economic impact, both on farm and in the wider rural environment, through impacts on soil health (see Appendix for further detail). Potentially, this may have a cascade effect along the full supply chain. While some of these interactions have been identified, there is a recognised knowledge gap in the full understanding of the intimate interactions that underpin soils and the economic consequences of changes in soil function.

For many of the chosen indicators, there are existing baseline and/or resurvey data. While not an exhaustive list (due to time constraints for this project), nevertheless, the assessment is comprehensive, representing 41 datasets that are known to contain information on potential indicators of vulnerability of soil health to climate change. However, it was not possible in the short timeframe of this project to assess fully the likely sensitivity of the individual indicators against the list of climate change threats. It was therefore not possible to assess the level of effort required to develop a soil health risk assessment framework along the lines of existing models, such as the climate change risk-based assessment for nationally and internationally important geoheritage sites in Scotland as developed by SNH. It would be prudent to start such assessments by focusing on the soils most likely under immediate threat from climate change.

Further work is required to understand the specific potential of the identified indicators for the different types of Scottish soils and different habitats. Many of these indicators have yet to be assessed as metrics of risk within the context of an overarching framework at national scale and therefore the sensitivity and accuracy of these indicators as risk metrics requires further assessment.

4.1 Recommendations

- Using indicators identified in this report, scope out a national soil monitoring framework for Scotland primarily aimed at soils under most immediate threat of climate change, e.g. agricultural and peatland soils;
- Further work is required to determine which combination of biological, chemical and physical indicators will be optimal for Scottish conditions and specific habitats;

- Initiate a soil health risk assessment framework along the lines of existing models (e.g. the climate change risk-based assessment for nationally and internationally important geoheritage sites in Scotland [10]);
- Explore how existing soil indicator capability might be enhanced through integration of novel remote and proximal sensing techniques from the expanding global satellite infrastructure and for in-field applications, placing Scotland in the forefront of climate change mitigation and adaptation (as per bullet point 1 above);
- A key knowledge gap in soil science is the detailed understanding of interactions between soil biological diversity and function. Explore how such innovative data might be generated to better inform current climate models and more accurately predict impacts of climate change on Scottish soils; and
- Acknowledging that remote sensing data cannot satisfy all our requirements for monitoring Scottish soils, explore also how novel ground-based sensing technology might be used to provide large-scale long-term soil monitoring.

5 References

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6 Appendix

We approached this research by considering the following two questions, using methodology as set out in this Appendix.

> *What are the likely impacts on components of the soil system and the wider environment?*
>
> *How might the vulnerability of Scottish soils to climate change be measured in future, to provide a robust baseline against which change can be monitored?*

6.1 Assessment of the UKCP18 Climate Change Scenarios

The most recent climate projections for the UK (UKCP18) [11] are presented as probabilistic projections, providing local low, central and high estimates of changes across the UK for different emissions scenarios.

The UKCP18 present an overall message of an increased chance of warmer, wetter winters and hotter, drier summers, along with an increase in the frequency and intensity of extreme events (Figures A1 to A4). Within these overall messages are more specific changes (at different levels of probability and over a range of spatial extent and time scales) that may impact soil health.

In Box A1 we present a summary of the climate change conditions for the high emissions scenario, as this is the trajectory we are currently on and may experience in the future given risks of missing global reduction targets and positive feedback loops within natural systems (e.g. Arctic permafrost melt leading to CO_2 and methane emission increases) adding more CO_2. However, less damaging emissions pathways are possible, hence the scale of climate change and severity of features may be less.

Based on these general scenario descriptions, the following (Table A1) are example challenges to Scottish soils that a changing climate may present, for several specific conditions of the

Box A1. The General scenario description used in this assessment - an overview of future factors influencing vulnerability/ resilience of Scottish soils to general changes in condition (2040-2060):

- Summer: Likely to see a steady increase in probability of future summers being hotter and drier than the past (e.g. years like 2018 occurring once in every four years). Precipitation range 30 – 40% drier (Figure A1), temperature 2 - 4°C warmer (Figure A2).
    - Heavy rain events likely to be higher in intensity but possibly less frequent.
    - Higher rates of evapotranspiration likely.
- Winter: Steady increase in probability of future winters being warmer (by 1.5 to 2.5°C) and wetter (by 5 to 10%).
    - Storm events likely to have heavier rain and associated increase in risks of flooding.
    - Likely decrease in winter snow cover.
- Seasonality: Shift in precipitation seasonality, variable spatially with the driest 3-month period occurring earlier (east) or later (west) (Figures A3 and A4)
- Other:
    - Increase in average night-time (minimum) temperature of 2 to 3°C.
    - Fewer frost days, first frosts occurring later in autumn and earlier in spring.

[11] https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/index

weather that are likely to occur within the general changes predicted. These were derived from the expert knowledge of the author team.

Please note many other climate change features also exist and there will be spatial variability in the distribution of the estimated future specific conditions. It is also important to note that there will likely be increased year-to-year variability, with some years being similar to the past, but with other years (or even between seasons) experiencing conditions at the upper and lower ranges of variability, i.e. new levels of extremes.

Table A1. Generic future challenges, caused by climate change, based on the UKCP18 (version 2) local high emissions scenario projections, to Scottish soils [12].

Challenge caused by climate change. Climate change specific conditions (high emissions scenario)
Increased drought duration and higher levels of soil moisture deficit
Increased highest maximum temperature on hot dry summer days (Scotland range 30 to 34°C)
Increased frequency and duration of hot spells (max $T_{daytime}$ >30°C, for between 2 to 5 days) from once per 4 years to about four times per year.
Reduced number of ground frost days, with first autumn frost occurring later and last spring frost occurring earlier.
Extreme hourly rainfall intensity, associated with an event that typically occurs once every two years, increases by 25%
More of the winter rain events will come from frontal rain events of higher intensity
More of the summer rain events will come from short lived high intensity showers.

Using expert knowledge, published data and experimental data generated through the Strategic Research Programme we have assessed the potential impact on soil biology, chemistry and physics and consider the wider environmental impact of the generic climate scenarios. This has been assessed for the main soil types in Scotland (Table A2). Also, an overview of the potential economic impacts of climate scenarios on soils are presented. Consideration is also given to potential indicators that could be used for monitoring the status of soils.

[12] https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/ukcp-infographic-headline-findings.pdf; further links here: https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/index

Table A2. Areal extent of the main soil types in Scotland.

Rank	Amalgamated soil type	Component major soil subgroup	Areal extent (ha)	Percentage area
1	Peat	Blanket peat, Basin peat, Semi-confined peat	1 726 320	22
2	Mineral gleys	Brown earths with gleying, Calcareous, Humic, Magnesian and Noncalcareous gleys	1 263 040	16
3	Peaty gleys	Peaty gleys, Peaty alluvial soils	1 080 990	14
4	Brown soils	Brown calcareous, Brown magnesian, Brown rendzinas and Brown earths	997 970	13
5	Mineral podzols	Humus iron podzols	928 430	12
6	Peaty podzols	Peaty and subalpine podzols	908 360	12
	Total		**6 905 110**	**89**

Note: the remaining percentage area comprises oroarctic, alluvial and shallow soils.

The author team filtered the UKCP18 climate projections for specific projected changes (Table A1) that may impact soil health, using the high emissions scenario projections (as this is the current trajectory). In turn, expert knowledge among the author team was then used to populate a series of tables of indicators of soil health relevant to soil chemistry, soil physics and soil biology (Tables A3-A5) for the most likely impacts of future climate change as defined above (Table A1). We then assessed the potential impact of these projected changes on aspects of soil health, as well as the potential economic impacts for the main soil types in Scotland (Tables A6-A9). Further expert scrutiny and assessment yielded a candidate suite of indicators (Table 1) that would have the potential to be currently most effective and reliable for monitoring the climate vulnerability of soils at this moment in time. The authors further considered the candidate suite of indicators in terms of whether baseline and/or trajectory data were already available (Table 2).

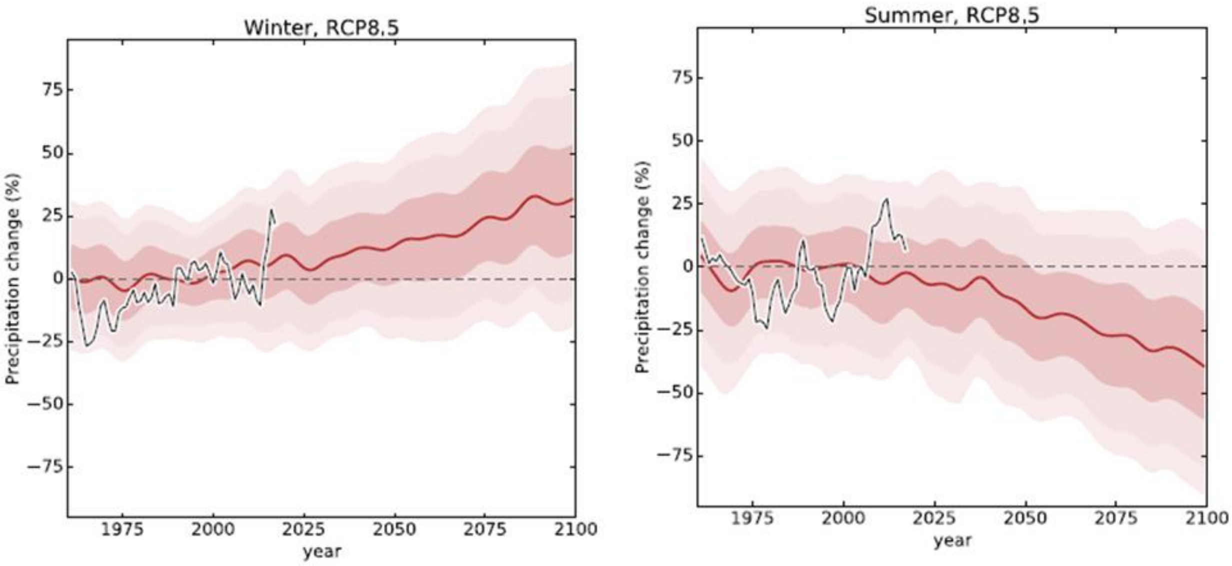

Figure A1. UK precipitation change (%)(past data with future projections) for the high emissions scenario in winter and summer. Shaded bands represent 5th to 95th probability levels.

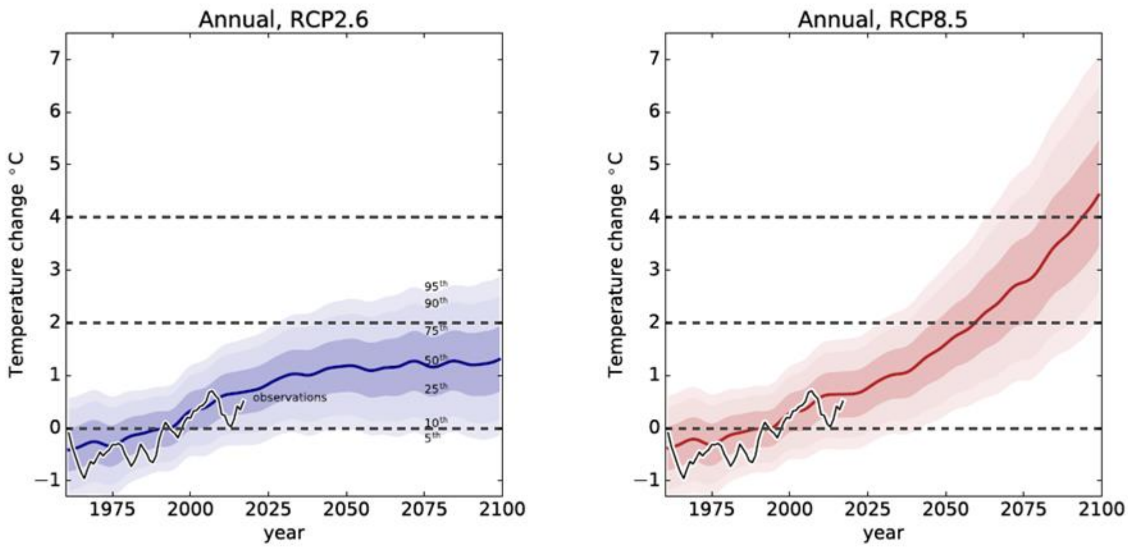

Figure A2. Observed annual temperature change (against pre-industrial period) and projected rise for low (RCP2.6) and high (RCP8.5) emissions scenarios. Shaded bands represent 5th to 95th probability levels.

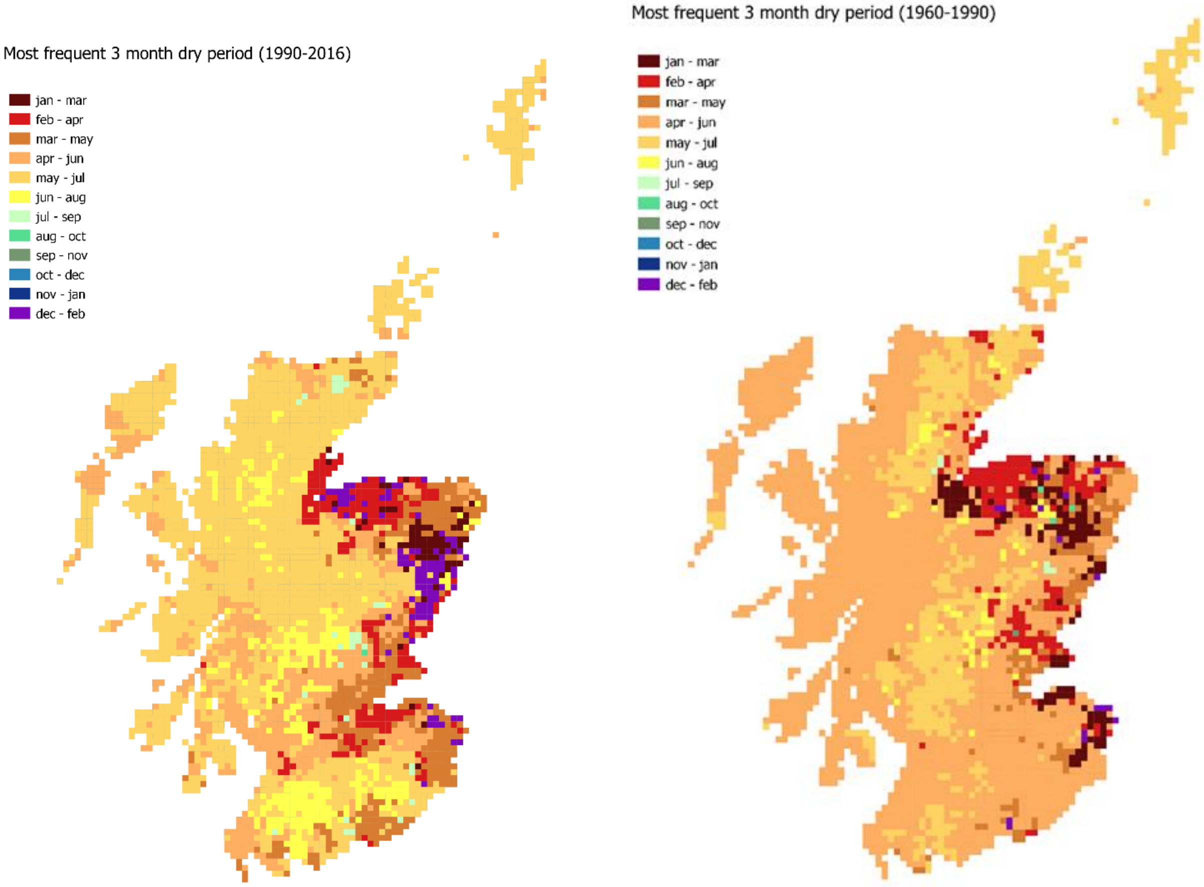

Figure A3. 5km cells that most frequently have the driest three months for the two observed baseline periods (1960-1990 and 1990-2016).

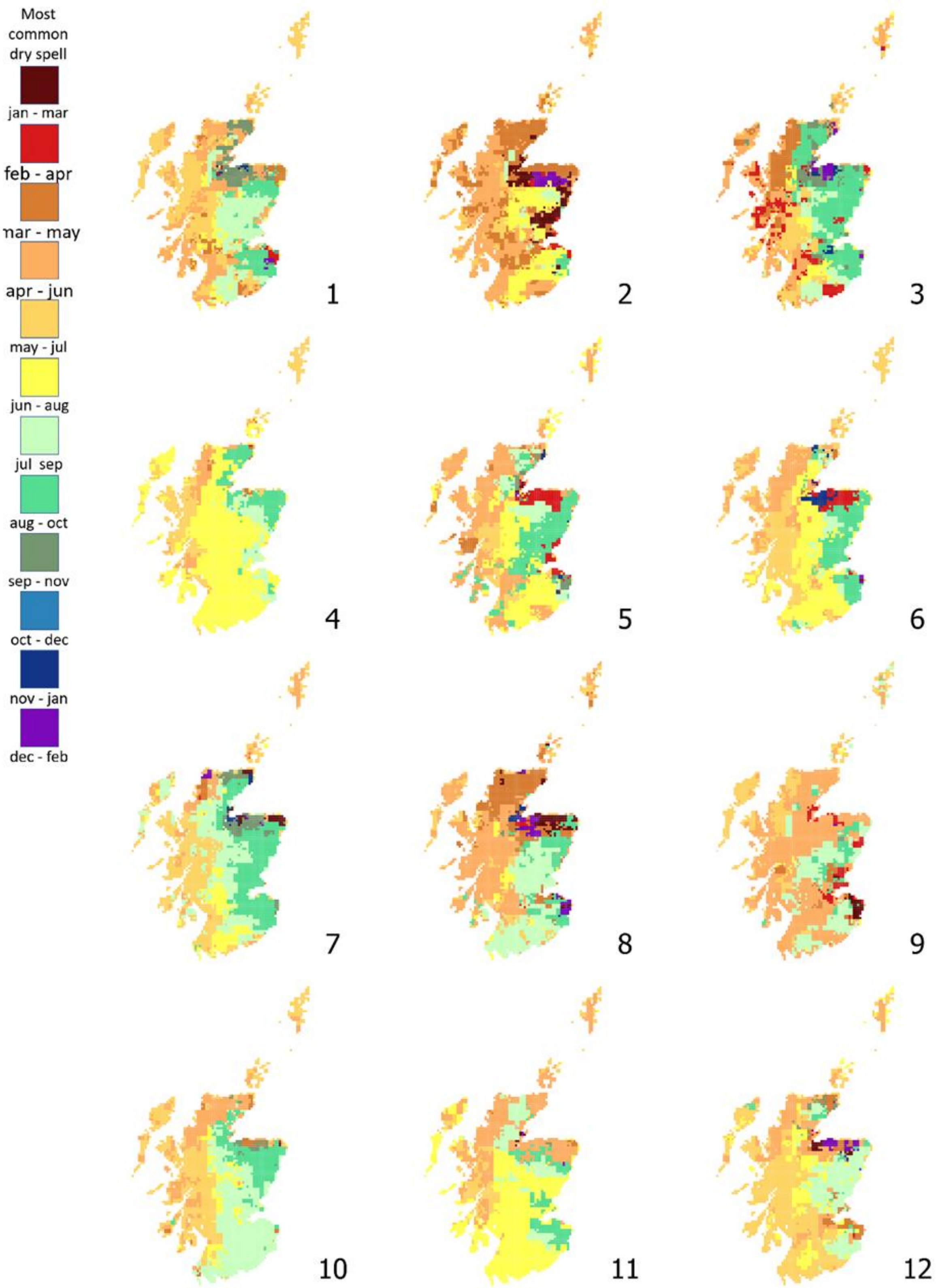

Figure A4. Projected future driest consecutive three month period for 2020-2050, estimated using UKCP18 climate projection data. Each map represents one projection from the Hadley Centre Regional Climate Model (HadRM3) for the 'High' emissions pathway (RCP8.5).

6.2 Assessment of indicators of soil health

In total we identified 13 indicators associated with soil chemistry (Table A3). Of the soil chemistry indicators, DOC concentration, soil moisture content, soil organic matter, N mineralisation, nutrient flux, nitrification rate, base cation content and base saturation had broadest applicability across the amalgamated Scottish soil types (Table A3).

Table A3. List of soil health indicators (soil chemistry), examined against potential impacts of climate change, by soil type.

Soil health indicators most likely to show impacts of climate change	Soil types						
	Brown soils	**Mineral Podzols**	**Mineral gleys**	**Peaty Podzols**	**Peaty Gleys**	**Peat - organic soils**	**Montane - oroarctic soils**
DOC concentration	Limited impact	Limited impact	Limited impact	Most impact	Most impact	Most impact	Limited impact
Moisture content	Most impact	Limited impact	Most impact	Most impact	Most impact	Most impact	Limited impact
Base cation content	Most impact	Limited impact	Limited impact	Limited impact	Limited impact	Least impact	Least impact
Secondary metabolites	Limited impact	Least impact	Least impact	Least impact	Least impact	Not applicable	Not applicable
pH	Limited impact	Limited impact	Least impact	Limited impact	Least impact	Most impact	Least impact
Soil Organic Matter	Limited impact	Limited impact	Limited impact	Most impact	Most impact	Most impact	Limited impact
N mineralisation	Most impact	Least impact	Least impact	Limited impact	Limited impact	Limited impact	Least impact
Nutrient flux	Most impact	Least impact	Least impact	Limited impact	Limited impact	Most impact	Limited impact
Nitrification rate	Most impact	Least impact	Least impact	Limited impact	Limited impact	Limited impact	Limited impact
Base saturation	Most impact	Limited impact	Limited impact	Limited impact	Limited impact	Least impact	Least impact
Inorganic N	Limited impact	Least impact	Least impact	Least impact	Least impact	Not applicable	Not applicable
Clay weathering	Least impact	Limited impact	Least impact	Limited impact	Least impact	Not applicable	Not applicable

Nutrient export	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact	Least impact

We identified 18 soil physical indicators (Table A4) that can be grouped into five main categories; *soil loss* (Soil depth, Erosion rate, Erosion features); *measurements of soil porosity* (Bulk density, Total porosity, Soil water retention, Infiltration, Hydraulic conductivity, Air capacity, 'Dexters S' soil porosity', Least limiting water range); *visual assessments of soil structure and porosity* (Soil Structure, Visual Evaluation of Soil Structure - VESS (topsoil), Subsoil Visual Evaluation of Soil Structure - subVESS); *aggregate stability* (Structural stability indices, Aggregate stability) and *penetration resistance*. As most soil physical indicators of soil heath are primarily relevant to soils with mineral topsoils (particularly cultivated soils). *Hydrophobicity* (the ability to repel water on re-wetting) was added as a physical characteristic of peat and peaty soils. There is a paucity of physical indicators of soil health for organo-mineral (peaty) and peat soils apart from changes in depth, erosion (rate and features) and hydrophobicity.

Of those indicators identified, climate change was considered to have variable effects due to increased drought duration with associated greater levels of soil moisture deficit; reduced number of frost days; and those associated with summer and winter rainfall events (Table A4).

Table A4. Assessment of climate change impact on soil physical indicators (not ranked) by amalgamated Scottish soil type.

Soil health indicators most likely to show impacts	Soil types						
	Brown soils	**Mineral Podzols**	**Mineral gleys**	**Peaty Podzols**	**Peaty Gleys**	**Peat - organic soils**	**Montane - oroarctic soils**
Topsoil Depth (or total depth for peat)	Limited impact	Limited impact	Limited impact	Least impact	Least impact	Limited impact	Not applicable
Bulk density	Most impact	Most impact	Most impact	Not applicable	Not applicable	Not applicable	Not applicable
Total porosity	Most impact	Most impact	Most impact	Not applicable	Not applicable	Not applicable	Not applicable
Soil water retention characteristics	Most impact	Most impact	Most impact	Not applicable	Not applicable	Not applicable	Least impact
Infiltration	Most impact	Most impact	Most impact	Not applicable	Not applicable	Not applicable	Least impact
Hydraulic conductivity	Most impact	Most impact	Most impact	Not applicable	Not applicable	Not applicable	Least impact
Air capacity	Most impact	Most impact	Most impact	Not applicable	Not applicable	Not applicable	Least impact

'Dexters S' soil porosity	Most impact	Most impact	Most impact	Not applicable	Not applicable	Not applicable	Least impact
Least limiting water range	Most impact	Most impact	Most impact	Not applicable	Not applicable	Not applicable	Least impact
Erosion features	Most impact	Most impact	Most impact	Least impact	Least impact	Most impact	Least impact
Rate of erosion	Most impact	Most impact	Most impact	Least impact	Least impact	Most impact	Least impact
Soil Structure	Most impact	Most impact	Most impact	Not applicable	Not applicable	Not applicable	Limited impact
Visual Evaluation of Soil Structure - VESS (topsoil)	Most impact	Most impact	Most impact	Not applicable	Not applicable	Not applicable	Limited impact
Subsoil Visual Evaluation of Soil Structure - subVESS	Limited impact	Limited impact	Limited impact	Not applicable	Not applicable	Not applicable	Not applicable
Structural stability indices	Limited impact	Limited impact	Limited impact	Not applicable	Not applicable	Not applicable	Least impact
Aggregate stability	Limited impact	Limited impact	Limited impact	Not applicable	Not applicable	Not applicable	Least impact
Penetration resistance	Least impact	Least impact	Least impact	Not applicable	Not applicable	Not applicable	Least impact
Hydrophobicity	Least impact	Least impact	Least impact	Limited impact	Least impact	Limited impact	Least impact

In total, we identified 23 indicators associated with soil biology (Table A5). DNA-based methodologies associated with bacteria, archaea, fungi and nematodes were considered to be the ones to show the highest impact across all soil types. Similar methods associated with mites and collembola were scored lower as those two taxa are generally considered less informative (Table A5). While many morphology-related indicators scored highly, it should be noted that their utility is dependent upon those that have specialised taxonomic skills and whose numbers are decreasing. Going forward, DNA methods are likely to be those of choice. Earthworm numbers, currently a popular metric, are considered to have low impact as simply assessing numbers provides no indication of diversity and function (Table A5). In contrast, DNA or morphological assessment of earthworms would be of utility. Please note, however,that earthworms are limited by soil pH and thus, unlike other soil biological groups, would not be of utility across all soil types (Table A5). Of real potential is the use of functional genes that provide information primarily on microbial activity and soil processes.

Table A5. Assessment of climate change impact on soil biological indicators (not ranked) by amalgamated Scottish soil type.

Soil health indicators most likely to show impacts	Soil types						
	Brown soils	**Mineral Podzols**	**Mineral gleys**	**Peaty Podzols**	**Peaty Gleys**	**Peat - organic soils**	**Montane - oroarctic soils**
Bacteria and archaea diversity (DNA methods)	Most impact	Most impact	Most impact	Most impact	Most impact	Most impact	Most impact
Microbial biomass (DNA methods)	Most impact	Most impact	Most impact	Most impact	Most impact	Most impact	Most impact
Fungal diversity (DNA methods)	Most impact	Most impact	Most impact	Most impact	Most impact	Most impact	Most impact
Fungal diversity (morphology)	Most impact	Most impact	Most impact	Most impact	Most impact	Most impact	Most impact
Nematode diversity (DNA methods)	Most impact	Most impact	Most impact	Most impact	Most impact	Most impact	Most impact
Nematode diversity (morphology)	Most impact	Most impact	Most impact	Most impact	Most impact	Most impact	Most impact
Mite diversity (DNA methods)	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact
Mite diversity (morphology)	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact
Collembola diversity (DNA methods)	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact
Collembola diversity	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact

(morphology methods)							
Protozoa diversity (morphology)	Least impact	Least impact	Least impact	Least impact	Least impact	Least impact	Least impact
Protozoa diversity (DNA methods)	Least impact	Least impact	Least impact	Least impact	Least impact	Least impact	Least impact
Enchytraeid diversity (morphology)	Least impact	Least impact	Least impact	Least impact	Least impact	Least impact	Least impact
Enchytraeid diversity (DNA methods)	Least impact	Least impact	Least impact	Least impact	Least impact	Least impact	Least impact
Earthworm numbers	Least impact	Least impact	Least impact	Not applicable	Not applicable	Not applicable	Least impact
Earthworm biomass	Limited impact	Limited impact	Limited impact	Not applicable	Not applicable	Not applicable	Least impact
Earthworm diversity (morphology)	Most impact	Most impact	Most impact	Not applicable	Not applicable	Not applicable	Limited impact
Earthworm diversity (DNA methods)	Most impact	Most impact	Most impact	Not applicable	Not applicable	Not applicable	Limited impact
Functional genes	Most impact	Most impact	Most impact	Most impact	Most impact	Most impact	Most impact
Multiple enzyme assays	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact
Respiration (various methods)	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact
Litter bags	Most impact	Most impact	Most impact	Limited impact	Limited impact	Least impact	Limited impact
PLFA	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact	Limited impact

6.3 Detailed assessment of the likely impacts of climate change on soil health

6.3.1 Soil chemistry

Based on our assessment, soil chemistry (Table A6) will likely have a more rapid 'turnover' with the result that higher rates of export from the soil system occur. There will likely be periods of higher concentration caused by increased biological activity, but also periods of reduced concentration due to increased output in soil water export. Overall, soil water chemistry will be less stable and more variable. Year-round impacts will include decreased/altered secondary metabolites; increased DOC concentration; increased nutrient flux; increased nutrient concentrations; cation depletion; and reduced organic matter stock. Seasonal impacts will exist with summer impacts focused on reduced moisture content; variable pH impacts (mostly reduced); increased base saturation; reduced nitrate leaching; and increased organic N. During the winter period, impacts will likely be seen associated with larger cation and nutrient export in streams and runoff; decreased pH; increased weathering; and increased geological nutrient production.

Consequently, there will be several impacts to the agricultural sector including increased use of irrigation, increased nitrate leaching and soil erosion, and reduced soil water holding capacity (Table A6). While the assessment has considered generic scenarios across major soil types, it is recognised that site-specific impacts will occur. For example, hydrological connectivity has a major impact on the effects of climate change on soil hydrology. Also, climate change can increase the transport of ions into soil water and rock chemistry will lead to significant local variation.

Table A6. Impacts on soil chemistry and beyond of the generic future climate challenges.

Climate change scenario	Soil chemistry impacts	Risks posed by climate change
Increased drought duration and higher levels of soil moisture deficit	Increased DOC concentration Reduced moisture content Decreased secondary metabolites Reduced cation content Increased pH SOM loss Reduced N mineralization Reduced C flux Changes in nutrient flux	Risk of reduced crop growth Need to irrigate arable land Decreased crop nutrient content Risk of erosion Peat fire risk increase

Climate change scenario	Soil chemistry impacts	Risks posed by climate change
Increased highest maximum temperature on hot dry summer days (Scotland range 30 to 34°C)	Increased DOC concentration Reduced moisture content Variable effects on pH, mostly reduced Increased nutrient flux Increased N mineralization Increased nitrification Increased base saturation and C/N Variable effects on secondary metabolites Reduced nitrate leaching Increased nutrient concentration Increased availability of mineral N and P and some heavy metals Increased inorganic N Decreased soil minerals e.g. K Increased Al-humus complexes, Al minerals	Crop moisture deficit Irrigation requirements Nitrate leaching Greatly increased water requirements by crops Potential hyperaccumulation of toxic elements Soil erosion increase Peat fire risk increase Reduced soil water holding capacity
Increased frequency and duration of hot spells (max $T_{daytime}$ >30°C, for between 2 to 5 days) from once per 4 years to about four times per year	Increased DOC concentration Reduced moisture content Increased nutrient flux Variable effects on pH, mostly reduced Increased base saturation and C/N Variable effects on secondary metabolites Reduced nitrate leaching Increased nutrient concentration Increased inorganic N in soils	Crop moisture deficit Reduced soil water holding capacity Irrigation requirements Nitrate leaching Greatly increased water requirements by crops Potential hyperaccumulation of toxic elements Soil erosion increase Peat fire risk increase

Climate change scenario	Soil chemistry impacts	Risks posed by climate change
Reduced number of ground frost days, with first autumn frost occurring later and last spring frost occurring earlier	Decreased secondary metabolites Larger nutrient export from streams Increased DOC and nutrient levels Increased C losses (C mineralisation)	Carbon loss from soil Erosion risk Reduced soil water holding capacity Streamwater 'browning' requires more cost/effort to purify
Extreme hourly rainfall intensity, associated with an event that typically occurs once every two years, increases by 25%	Increased nutrient flux Decreased pH Depletion of S and base cations Reduced OM stock Clay weathering Increased N_2O emissions Variability in N mineralization	Soil erosion risk increase Reduced water holding capacity Nitrate flush increases
More of the winter rain events will come from frontal rain events of higher intensity	Decreased secondary metabolites Increased cation export Increased geological N, K production Reduced OM stock Larger nutrient export from streams Increased DOC and nutrient concentration in runoff Increased N mineralization Increased C flux	Increased soil erosion Periods when soil is unworkable, risk of compaction Reliability of water supply becomes reduced Streamwater contamination with DOC and soil nutrients
More of the summer rain events will come from short lived high intensity showers	Decreased secondary metabolites Reduced cation content Increased pH SOM loss Change in nutrient leaching	Crop damage/reduced growth Erosion events

6.3.2 Soil physics

Soil physics will be affected as much by land management as by climate change, although the interaction between climate and land management will also be a key factor in maintaining soil in good physical condition. Focusing on generic climate change scenarios, key impacts to highlight include an increase in soil erosion, shrinkage of organic layers in peat-based soils and increased structural degradation of soils (Table A7). In the wider environment, these impacts will likely result in rapid runoff during high intensity rainfall events leading to an increased flood risk.

As with soil chemistry, there will be seasonal impacts with summer focused on reduced moisture content; increased soil porosity and increased infiltration in mineral soils; increased hydrophobicity in peats and peaty soils; increased penetration resistance affecting root growth; and increased aggregate strength. During the winter period, impacts will focus on a decrease in soil porosity and hence, infiltration capacity; an increase in soil erosion; loss of nutrients and carbon; and increased potential for flooding and eutrophication of rivers.

In an agricultural context, this has potential to lead to crop loss or reduced crop yields and loss of nutrients and organic matter (Table A7). The latter will lead to increased inputs (e.g. fertiliser) to compensate for the nutrient loss leading to an increase of farm unit costs and greater environmental impact.

Table A7. Impacts on soil physics and beyond of the generic future climate challenges.

Climate change scenario	Soil physical impacts	Risks posed by climate change
Increased drought duration and higher levels of soil moisture deficit	Increased soil moisture deficit Shrinkage and cracking of soils with high clay contents Shrinkage of organic layers in peats and peaty soils Hydrophobicity in soils with organic surface layer Increased penetration resistance affecting root development Increased oxidation of soil carbon especially in organic layers	Loss of crop yield Possible effects on foundations of infrastructure Increased risk of flash flooding Reduction in crop yield of yield Potential ‘flush’ of Dissolved Organic Carbon (DOC) on rewetting
Increased highest maximum temperature on hot dry summer days (Scotland range 30 to 34°C)	Shrinkage of peaty layers and development of hydrophobicity	Increased risk of rapid runoff during rainfall events

Climate change scenario	Soil physical impacts	Risks posed by climate change
Increased frequency and duration of hot spells (max $T_{daytime}$ >30°C, for between 2 to 5 days) from once per 4 years to about four times per year	Shrinkage of peaty layers and development of hydrophobicity Increased soil moisture deficit	Increased risk of rapid runoff during rainfall events
Reduced number of ground frost days, with first autumn frost occurring later and last spring frost occurring earlier	Increased bulk density and decreased infiltration Decrease in extent of oroarctic (montane) soils due to lack of freeze/thaw cycles	Possible increase in flood risk Possible change in vegetation communities
Extreme hourly rainfall intensity, associated with an event that typically occurs once every two years, increases by 25%	Increase in soil erosion Increase in structural degradation in mineral soils	Potential increase in flooding due to low infiltration capacity caused structural degradation
More of the winter rain events will come from frontal rain events of higher intensity	Increase in soil erosion Increase in structural degradation in mineral soils	Potential increase in flooding due to low infiltration capacity caused structural degradation
More of the summer rain events will come from short lived high intensity showers	Increase in soil erosion Increase in structural degradation in mineral soils	Potential increase in flooding due to infiltration excess and pollution of river system

6.3.3 Soil biology

In addition to land management that has an impact on soil physics. crop, genotype and climate change will all have an impact on soil biology. These changes will include changes in levels of activity, function and diversity of various soil biological communities (Table A8). Changes will be variable depending upon the biological group studied and soil type, but. in an agricultural context, there is potential for increased soilborne pest and pathogen pressure on crops (Table A8). In a wider context, with exceptions (increased drought duration and higher soil moisture deficits) there will likely be a general increase in greenhouse gas emissions (CO_2 and N_2O) due to increased biological activity. Due to an increase in soil borne pest and pathogen pressure, crop disease incidence is likely to increase with a requirement for deployment of diverse agronomic solutions, based on integrated pest management interventions. Unlike aspects of soil chemistry and physics, most biology-related impacts are unlikely to exhibit seasonality.

Table A8. Impacts on soil biology and beyond of the generic future climate challenges.

Climate change scenario	Soil biology impacts	Risks posed by climate change
Increased drought duration and higher levels of soil moisture deficit	Lower microbial turnover Reduced earthworm activity Lower nematode activity Reduced soil biological diversity Selection for tolerant biological communities	Reduced soil CO_2 and N_2O emissions Reduced crop growth Decreased crop nutrient content Reduced soil borne pathogen pressure Increased fertiliser inputs to compensate for lower soil faunal activity
Increased highest maximum temperature on hot dry summer days (Scotland range 30 to 34°C)	Assuming no nutritional limiting factor: Increased microbial, earthworm and nematode activity Reduced soil biological diversity Selection for tolerant communities Increased soil borne pest and pathogen activity	Increased CO_2 and N_2O emissions across all soil types (greatest impact likely to be arable soil due to synthetic fertiliser inputs) Reduced CH_4 emissions (peat soils) Increased soil borne pathogen pressure Increased agronomic interventions to manage pest and pathogens
Increased frequency and duration of hot spells (max $T_{daytime}$ >30°C, for between 2 to 5 days) from once per 4 years to about four times per year.	Assuming no nutritional limiting factor: Increased microbial, earthworm and nematode activity Reduced soil biological diversity Selection for tolerant communities Increased soil borne pest and pathogen activity	Increased CO_2 and N_2O emissions across all soil types (greatest impact likely to be arable soil due to synthetic fertiliser inputs) Reduced CH_4 emissions (peat soils) Increased soil borne pathogen pressure Increased crop disease incidence Increased agronomic interventions to manage pest and pathogens

Climate change scenario	Soil biology impacts	Risks posed by climate change
Reduced number of ground frost days, with first autumn frost occurring later and last spring frost occurring earlier.	Reduced freeze/thaw cycling thus fewer episodic events that saturate soils which lead to an increase in microbial activity Slight increase in earthworm and nematode activity Increased soil borne pest and pathogen activity	Likely slight reduction in N_2O emissions across all soils Increased soil borne pathogen pressure Increased crop disease incidence Increased agronomic interventions to manage pest and pathogens
Extreme hourly rainfall intensity, associated with an event that typically occurs once every two years, increases by 25%	Increased microbial denitrification (assuming increased saturation due to infiltration) Minimal effect on earthworm activity Loss of microbial and nematode diversity due to increased run-off Redistribution of soil borne pest and pathogens	Increased N_2O emissions Increased CO_2 emissions (not applicable to peat soil) Increased fertiliser inputs to compensate for diversity loss Infection of previously pest and pathogen free soils Change in spatial distribution of soil borne related crop disease
More of the winter rain events will come from frontal rain events of higher intensity	Potentially temperature limited but increased microbial denitrification (assuming increased saturation due to infiltration) Minimal effect on earthworm activity Loss of microbial and nematode diversity due to increased run-off Redistribution of soil borne pest and pathogens	Increased N_2O emissions Increased CO_2 emissions (not applicable to peat soil) Increased fertiliser inputs to compensate for diversity loss Infection of previously pest and pathogen free soils Change in spatial distribution of soil borne related crop disease

Climate change scenario	Soil biology impacts	Risks posed by climate change
More of the summer rain events will come from short lived high intensity showers.	Increased microbial denitrification (assuming increased saturation due to infiltration) Minimal effect on earthworm activity Loss of microbial and nematode diversity due to increased run-off Redistribution of soil borne pest and pathogens	Increased N_2O emissions Increased CO_2 emissions (not applicable to peat soil) Increased fertiliser inputs to compensate for diversity loss Infection of previously pest and pathogen free soils Change in spatial distribution of soil borne related crop disease

6.3.4 Socio-economic impacts

The socio-economic impacts of declining soil health due to climate change are likely to be widespread and currently underestimated due to the limited evidence available of the contribution of soil to ecosystems services outside of agriculture. Overall, we would expect costs of agricultural inputs to increase, due to the need to replace lost nutrients and soil organic matter, as well as potential irrigation in drought periods (Table A9). Agricultural yield is likely to decline, and changes in the composition of soils will mean that crop choices will change to match those which are able to grow in changed soil conditions. Increased erosion and dissolved organic matter will result in increased costs of water purification, although this will show temporal variation, with drought conditions being associated with reduced run-off (Table A9). Tourism and recreation are likely to be affected due to changing landscape characteristics, although this will be highly spatially specific.

Estimated costs are available for soil biodiversity and soil compaction. If earthworms were absent in topsoil, cost of their replacement is estimated at £8,600 per 30cm topsoil ha^{-1} (Robinson et al., 2014). Earthworms are used to suppress toxins and fungi in crops. If earthworm friendly conservation tillage practices are adopted, fungicide applications can be reduced while production is maintained. This has a resultant gain of €75-€132 ha^{-1} over conventional tillage practices (Plaas et al., 2019). While use of low ground pressure machinery to reduce compaction costs €4.5 ha^{-1} per annum across Europe, on-farm benefits of reduced compaction generate €1027 million per annum across Europe (Kuhlman et al., 2010). Recent assessment of the cost of soil compaction to agriculture in England and Wales is estimated at £472 million per annum, of which 50% of costs are associated with reduced yield, and 50% off-site costs associated with flood damage, flood risk management, and emissions from irrigation and fertilisation (Graves et al., 2015).

Table A9. Potential wider socioeconomic impacts of changing soil health by generic future climate challenges.

Risks posed by climate change
• Reductions in yield leading to declines in agricultural profit. • Decline in water quality leading to increased cost of purification and of prevention of public health problems • Changes to agricultural practices may favour those farms with more adaptability, likely those with higher profits already. • Changes to native flora and landscape will have varied impacts on tourism, scientific interest and recreation. • Increased risk of landslides, impacting housing, infrastructure and tourism.

6.4 Existing baseline or resurvey data

Indicators are only effective when data can be compared to optimally long-term, baseline data. The author team has identified 41 existing datasets that contain baseline and/or resurvey data for Scottish soils (Table A10). These datasets represent a range of scales (local to national), dataset size, and land use. An indication is also provided as to whether the sampling was a single occasion or whether resampling had occurred.

Table A10. Datasets containing baseline and/or resurvey data for soil health indicators.

	Names of sampling scheme	Number of sites	Extent	Specific land use	Resurvey data available?
1	National Soil Inventory of Scotland (1978-88) and Aqua Regia digest of National Soil Inventory Topsoil Samples.	721(787)	National	General	Yes
2	National Soil Inventory of Scotland 2007-9	183(195)	National	General	Yes
3	Representative Soil Profiles of Scotland	~15000	National	General	No
4	Scottish soil map unit transect study	6 transects (64-138 sites	Local	Cultivated soils	No
5	Trends in pollution of Scottish Soils	30	National	Moorland	Yes
6	Grid Surveys in Scotland	7 grid surveys (19-1214)	Local	General	No
7	Afforested soils	39	National	Yes	Yes
8	Birse and Robertson Survey soils	660	National	Woodland, grassland, montane	Yes
9	Scottish Coastal Survey Soils	1651	Local	General	No
10	Machair Soils	10	Local	Machair	No
11	East of Scotland Farm Survey	105	Regional	Arable land	Yes
12	Barley Soils	50	Local	Arable land	Unknown
13	Forsinard	40	Local	Peatland	Yes
14	Culardoch	1	Local	Montane	Time series
15	Balruddery	124	Local	Arable land	No
16	SNH woodland exclosures	12	Regional	Woodland	No
17	Countryside survey	256	National	General	Yes
18	Geochemical Baseline Survey of the Environment	~ 40,000	National	General	No
19	UK Soil and Herbage Survey	56	Regional	General	No
20	Environmental Change Network - soil solution chemistry	3	Regional	General	Time series
21	Environmental Change Network - soil	3	Regional	General	Yes
22	*Racomitrium* Heath Survey	17	Local	*Racomitrium* heath	No
23	ITE/NCC 'Bunce 1971' woodland survey	103	National	Woodland	Yes

	Names of sampling scheme	Number of sites	Extent	Specific land use	Resurvey data available?
24	Level I Forest Conditions survey	67	National (UK)	Woodland	No
25	Level II Intensive Monitoring of Forest Ecosystems	10	National (UK)	Woodland	Yes
26	Level II Intensive Monitoring of Forest Ecosystems- soil solution	10	National (UK)	Woodland	Yes
27	Effects of sewage sludge applications to agricultural soils on soil microbial activity and the implications for agricultural productivity and long-term soil fertility.	2	Local	Cultivated soils	Time series
28	Forum of European Geological Surveys European Geochemical Atlas	3200	National (GB)	General	No
29	BioSoil	69 in Scotland	National	Woodland	No
30	Alpine Mosaics	99 (35 soil profiles)	Local	Montane	No
31	Soil Wetness class monitoring scheme	32	Regional	Cultivated soils	Time series
32	Water stable aggregates	203	Catchment	Cultivated soils	Yes
33	Observations of erosion	~ 2500	Regional	Cultivated soils	No
34	CREW soil compaction	120 fields	Regional	Cultivated soils	No
35	Allt a'Mharcaidh soil water regime	4x 6 sites	Local	Montane	No
36	NE experimental Farm	37	Regional	Cultivated soils	Yes
37	LUCAS	189	Regional	Cultivated soils	Yes
38	Earthworm Survey	200	National	Cultivated soils	Yes
39	Nematode survey of various crops	~ 800	National	Arable land	No
40	NATO soil survey	5451 samples (~2000 in Scotland)	National	General	No
41	SoilBio	5152 samples (~2000 in Scotland)	National	Cultivated soils	No
42	Scottish Soil Fertility database	~180,000	Regional	Cultivated soils	Some fields will have been sampled more than once

Data for Table A10 is based on Emmett, B., Black, H.I.J., Bradley, R.I., Elston, D.A., Reynolds, B., Creamer, R., Frogbrook, Z.L., Hudson, G., Jordan, C., Lilly, A., Moffat, A., Potts, J., and Vanguelova, E. 2007; National Soil Monitoring Network: Review and assessment study. Final report., SNIFFER, Project LQ09; and Dobbie, K.E., Bruneau, P.M.C and Towers, W. (eds) 2011. The State of Scotland's Soil. Natural Scotland, www.sepa.org.uk/land/land_publications.aspx with subsequent modifications by Britton, 2017; Lilly and Baggaley 2020.

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