Climate change, soil water balance and risks to soil microbiological function.

Deliverable D2.2b for the

Project D5-2 Climate Change Impacts on Natural Capital

20th March 2024

Summary

This report details the findings of a workshop to discuss the impacts of climate change on soil water balance and consequences on soil microbiological functions. There were 21 participants in the workshop consisting of research staff from the James Hutton Institute.

Findings from the workshop are presented as two types of impact narratives. Firstly, the focus was on identifying the key drivers (e.g. precipitation, temperature) and the factors and properties within soils then producing qualitative narratives whilst also identifying other influencing factors (e.g. vegetation and soil properties). Secondly, each individual soil property or factor (e.g. soil organic carbon, pH etc.) were considered in terms of the key drivers and a second set of narratives produced. A third step in the process then considered the spatial and temporal distribution of future change direction agreement maps of Climatic Water Balance (Precipitation – Evapotranspiration, generated using daily data at a 1km resolution produced using x12 UPCP18 climate projections) and consequences on soil properties. Positive and negative feedbacks are identified in the narratives.

Key Messages:

- This report provides a broad range of narratives relating climate change drivers on soil properties.
- There is likely to be a mix of positive and negative impacts on soil properties and microbiological functions arising from changes in precipitation and temperature affecting multiple soil factors.
- Compaction and erosion risk is likely to increase.
- Water deficits in spring and summer are more likely to have negative impacts on soil organic matter content and GHG emissions.
- Impacts are variable and dependent on proportionality of soil organic matter, with peatlands being the most affected.
- There are multiple impact pathways but a key manifestation of these is via consequences on soil water and biota, particularly microbial biomass and role in organic matter turnover.
- Soil health indicators are important for helping to understand feedbacks between drivers and impacts and help identify which soils may be more or less vulnerable to climate change.

Contents

Citation:

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Introduction

The purpose of this report is to present the findings from a workshop focussed on climate change impacts on soil water and microbiological function. Participants were researchers with expertise in soils, soil microbiology, water and greenhouse gas emissions from the James Hutton Institute.

The broad context is to build an understanding of what projected climatic changes may mean for Natural Capital in Scotland. This report is a Deliverable for the Strategic Research Programme project 'Climate Change Impacts on Natural Capital' (JHI-D5-2).

The aim is to help develop our understanding of how climate change will likely impact Scottish soils in terms of relationships between the key climatic drivers of precipitation and temperature and their effect on soil properties, particularly the microbiota and consequences on soil functions.

This serves as an underpinning ability to provide risk and opportunity assessments of climate change impacts on Natural Capital assets at both a high spatial and temporal resolution. Please note: a follow-on Deliverable (D2.1b) assesses issues of changes in extremes.

The objective is to improve our understanding of the risks to Natural Capital and the opportunities for climate change mitigation and adaptation through ensuring the supply of ecosystem services. This report's findings help envisage the relationship between multiple drivers and properties of soils to help understand the complex relationships and feedbacks between them.

Hence this report demonstrates the increasing capabilities within the D5-2 project (and others within the Strategic Research Programmes) to assess climate change impacts on Scotland's Natural Capital.

As a broader objective, subsequent research and Deliverables produced by the Climate Change Impacts on Natural Capital project will help address the question 'what are the consequences on Natural Capital assets and their ability to both provide ecosystem services and serve as the basis for Nature Based Solutions?'.

Details and outputs from the project are available here:

Climate Change Impacts on Natural Capital | The James Hutton Institute

This report has utilised the Climatic Water Balance (CWB) approach of estimating the difference between precipitation and evapotranspiration as an indicator of potential meteorological water availability for plants and soils (thus including soil microbiota). Details of the CWB method and results are available here:

The James Hutton Institute Climate Data Visualisation and

Report: Assessment of Natural Capital exposure to current and future meteorological drought

Climate Extreme Indicators were also used, details available on the Hutton Climate Data Viewer (above) and Report: Climate extremes in Scotland

Advancing analytical capability

To facilitate further climate change impacts analysis on Natural Capital assets, analytical developments in the project have advanced the analytical capability by:

- Developing a two-dimensional approach to enable generation of impact narratives considering both climate drivers and soil properties.

- Collaboration with researchers outside of the D5-2 project, drawing on a range on knowledge and expertise.
- The qualitative approach to identify relationships between climate change drivers and feedbacks within soils helps inform quantitative modelling approaches.

The benefits of this technical development are aimed at helping to improve support to policy in developing appropriate steps to maintain and enhance Scotland's soil health, as this has been recognised as a key sustainability priority.

Introduction

The findings given here are derived from notes taken during a workshop to assess the impacts of climate on soil function, through the lens of soil water balance. The two-stage workshop focused first on how climate change could affect soil water characteristics, and then on how changes to these soil water characteristics could affect soil properties commonly thought of as soil health indicators. The impact pathway focus was on how these changes would affect soil microbial function (referred here simplistically as soil biota).

The workshop was held online with breakout groups; each breakout group was facilitated by one of the workshop organisers and was given the role of answering specific questions relating to elements of the impact pipeline from climate to soil functionality. Comments from participants were recorded within the structure of the workshop's goals and then translated into a series of text responses. Additionally, a spreadsheet was developed to characterise the strength of relationships between various elements under consideration, using a scoring system from 1 (low) to 3 (high) strength of relationship. This scoring allowed us to focus on the most important elements within the impact pathways within the climate-soil-water system.

The findings have been structured into two types of impact narratives. Firstly we focused on drivers and their impacts described qualitatively, with each single driver and multiple associated factors that could/would be impacted by changes to that driving factor. Secondly, we identified each single factor that could be affected and qualitatively described how multiple driving factors could affect it.

The Drivers used were:

- Precipitation
- Temperature
- Evapotranspiration
- Climatic Water Balance (P-ET)
- Number of Dry Days
- Number of Very Wet Days

The key soil properties used that are affected by multiple drivers were:

- Soil Organic Carbon (SOC)
- pH
- Depth to bedrock
- Bulk density
- Water holding capacity
- Porosity and air permeability
- Hydraulic conductivity & infiltration
- Soil Biota
- Structure & aggregation
- Soil temperature
- Subsoil pans

Impact narratives: Drivers

The following tables set out the key climate drivers and soil properties affected from which narratives are described. Influencing factors are identified that affect the feedback between climate and soils.

Driver	**Rainfall**
Impacts	SOC, pH, Depth to bedrock, Bulk density, Water holding capacity, Porosity & air permeability, Hydraulic conductivity & infiltration, Biota, Structure & aggregation, Temperature, Subsoil pans
Narrative	Changes to rainfall (total and distribution) will directly affect water table depth, surface water & runoff, soil moisture content, frequency/total days of saturation and frequency/total days of wilting point. The rate of SOC decomposition is directly affected by water-filled porosity, and responds relatively rapidly to this factor as the decomposition is largely microbial driven. Accumulation of organic matter in response to reduced decomposition would lead to thicker/deeper soil and lower bulk density, increased water holding capacity and porosity. Increased decomposition would have an opposite effect on these factors. Changes to pH are driven by multiple processes but in general, microbial and plant changes under more consistently wet conditions will drive pH lower (as the soil habitat will drive changes in biota). Increased leaching will also likely reduce pH values. Water holding capacity and porosity can be negatively affected if soils are driven on by machinery when wet, as the structure can collapse. This will also affect bulk density, structure, hydraulic conductivity and may result in more subsoil pans. Wetter soils have a greater heat capacity and so tend to provide a greater temperature buffering effect; this will mean soils will stay cooler on hot days.
Influencing factors	Vegetation deposition of organic material, soil drainage properties, soil depth and organic matter content.

Driver	**Temperature**
Impacts	SOC, Porosity & air permeability, Biota, Temperature
Narrative	Changes to temperature (mean and distribution) will indirectly affect water table depth, soil moisture and total days/frequency of saturation through changes to evapotranspiration. Interactions between temperature and rainfall (through increased evaporation leading to more local rainfall for example) can also influence these factors. Temperature will also have a direct effect on the frequency and total number of days at wilting point.

	The indirect effects of temperature on a number of soil moisture factors will drive effects on soil organic carbon, with higher moisture content implying lower rates of microbial decomposition of SOC (and with the opposite being true). A positive feedback loop linking temperature, soil moisture and soil thermal capacity exists, with hotter air temperatures increasing evapotranspiration, lowering soil moisture content and reducing the heat capacity of the soil so that it is less effective as a temperature buffer for the local area.
Influencing factors	Vegetation type (linked to water uptake and water stress characteristics), soil organic matter content, porosity, texture and water holding capacity.

Driver	**Evapotranspiration**
Impacts	SOC, Porosity & air permeability, Biota, Temperature
Narrative	Evapotranspiration is driven directly by temperature as described above, and so strong links exist between this factor, temperature and soil moisture characteristics. However, evapotranspiration can also be affected by humidity and wind speed, as well as by the amount of water remaining in the soil. Increased evapotranspiration will also negatively affect the soil's ability to buffer temperature extremes. These impacts on soil moisture can affect organic matter turnover (wetter soils = lower decomposition) and also drive changes to the soil biota functional types. If these changes combine to produce higher soil moisture at times of year when agricultural machinery normally drives over the soil, then soil structure, porosity and permeability can be negatively affected as the soil is more vulnerable to compaction.
Influencing factors	Vegetation, soil organic matter content, texture and structure.

Driver	**Climate Water Balance**
Impacts	SOC, Porosity & air permeability, Hydraulic conductivity & infiltration, Structure & aggregation, Biota, Temperature
Narrative	Higher climate water balance will raise water tables, and lower CWB will lower water tables. CWB is also a direct positive driver of surface water runoff, moisture content and days of saturation, and a negative driver of days of wilting point. CWB's impact on soil moisture directly links to SOC turnover rates through microbial activity. Higher moisture content and runoff can increase erosion rates and compaction risk, driving changes to porosity, hydraulic conductivity, infiltration and structure. Long-term

	changes to soil moisture will drive changes in soil biota structure and function. Higher CWB values will cause direct increases in temperature buffering within the soil, and negative changes through erosion risk.
Influencing factors	Soil texture, structure, organic matter content and depth.

Driver	**Number of Dry Days**
Impacts	SOC, Porosity & air permeability, Hydraulic conductivity & infiltration, Structure & aggregation, Biota, Temperature
Narrative	More dry days will result in lower water table, reduced runoff and erosion, and increase the number of days that the soil is accessible for agricultural machinery (the converse is also true). Changes to water table depth will affect soil moisture, particularly in the topsoil, with impacts on SOC turnover and hydraulic conductivity. Lower water tables will mean less effective temperature buffering, and increase risk of vegetation wilting and organic soils becoming hydrophobic (resulting in greater runoff risk when rainfall does occur).
Influencing factors	Soil permeability and underlying rock permeability, also soil structure, texture and organic matter content.

Driver	**Very wet days**
Impacts	SOC, Porosity & air permeability, Hydraulic conductivity & infiltration, Structure & aggregation, Biota, Temperature, Subsoil pans
Narrative	Increases to very wet days will have largely the opposite impacts of dry day increases listed above, but will also increase the risk of soil structure collapse from animal movement and other factors, leading to an increase in the presence of subsoil pans. A change in distribution and severity of dry and wet days will exacerbate the above impacts.
Influencing factors	Soil texture, structure, organic matter content and topography.

Soil factors being influenced

The following tables set out the key individual soil properties and relationships with multiple drivers to enable further narrative development. The key influencing factors affecting this relationship are identified.

Affected	**Soil Organic Carbon (SOC)**
Drivers	Rainfall, Temperature, Evapotranspiration, Climate water balance, Dry days, Very wet days
Narrative	Soil organic matter decomposition is lower at the extremes of drying and wetting, but the drying extreme is rarely seen in Scotland and is considered unlikely to be seen under future climate. The wetter extreme will become less common in areas where total rainfall decreases, dry days increase in frequency and very wet days decrease in frequency, or where evapotranspiration and temperature increase. All of these are predicted under future climate, with the opposite being less commonly occurring see section on spatial distribution of impacts, below). More extreme rainfall events also increase the risk of SOC loss through erosion and compaction.
Influencing factors	Existing soil organic matter content, soil texture and soil depth.

Affected	**pH**
Drivers	Rainfall
Narrative	Changes to pH are driven by multiple processes but in general, microbial and plant changes under more consistently wet conditions will drive pH lower (as the soil habitat will drive changes in biota). Increased leaching will also likely reduce pH values. Under conditions of less average rainfall, the opposite trends will occur.
Influencing factors	Current soil moisture regime, organic matter content and drainage properties.

Affected	**Depth to bedrock**
Drivers	Rainfall
Narrative	If saturated when machinery is driven over them, soil structure can collapse, making it shallower with increased bulk density. In places where peat formation is affected by rainfall pattern changes, soils will become deeper or shallower depending on whether organic matter is accumulating or being lost.
Influencing factors	Land use, existing soil moisture regime, soil organic matter content.

Affected	**Bulk density**
Drivers	Rainfall
Narrative	As mentioned above, wetter soils are easier to compress when driven over, which can lead to compaction and subsoil pans.
Influencing factors	Land use, soil organic matter content, texture and structure.

Affected	**Water holding capacity**
Drivers	Rainfall
Narrative	If compacted by machinery when wet, soil structure will collapse. This will lead to reduced water holding capacity and infiltration, and increased erosion risk.
Influencing factors	Land use, organic matter content, texture, structure.

Affected	**Porosity & air permeability**
Drivers	Rainfall, Temperature, Evapotranspiration, Climate water balance, Dry days, Very wet days
Narrative	All of the above factors can and will affect soil porosity if soil moisture changes are sustained and long term; in the short-term, saturated soils are mechanically weak and can be compacted by machinery, reducing their porosity and air permeability.
Influencing factors	Soil organic matter content, texture, structure, land management.

Affected	**Hydraulic conductivity & infiltration**
Drivers	Rainfall, Climate water balance, Dry days, Very wet days
Narrative	In the same way as porosity and air permeability can be influenced when soil is saturated and driven over by machinery, hydraulic conductivity and infiltration will be negatively affected by soil compaction. Additionally, these factors will be reduced when soil is saturated, as less water can enter and move through the soil system.
Influencing factors	Soil organic matter content, texture, structure, land management.

Affected	**Soil Biota**
Drivers	Rainfall, Temperature, Evapotranspiration, Climate water balance, Dry days, Very wet days
Narrative	The relative proportions of air and water within the pore space will drive the functional response of soil biota, with an additional secondary impact through long-term changes in soil pH and temperature. Short-term changes in soil moisture will have short-term impacts on emissions and carbon turnover; long-term changes will drive functional changes in soil biota and how it responds to soil moisture patterns.
Influencing factors	Existing soil moisture and temperature regime, soil organic matter content.

Affected	**Structure & aggregation**
Drivers	Rainfall, Climate water balance, Dry days, Very wet days
Narrative	Soil trafficability and the risk of compaction and erosion are strongly linked to whether or not the soil is saturated or close to saturation. Changes in soil moisture regime during periods when land managers are driving machinery over the soil will therefore have an impact on soil structure.
Influencing factors	Land use, soil texture and structure, soil organic matter content, existing soil moisture regime.

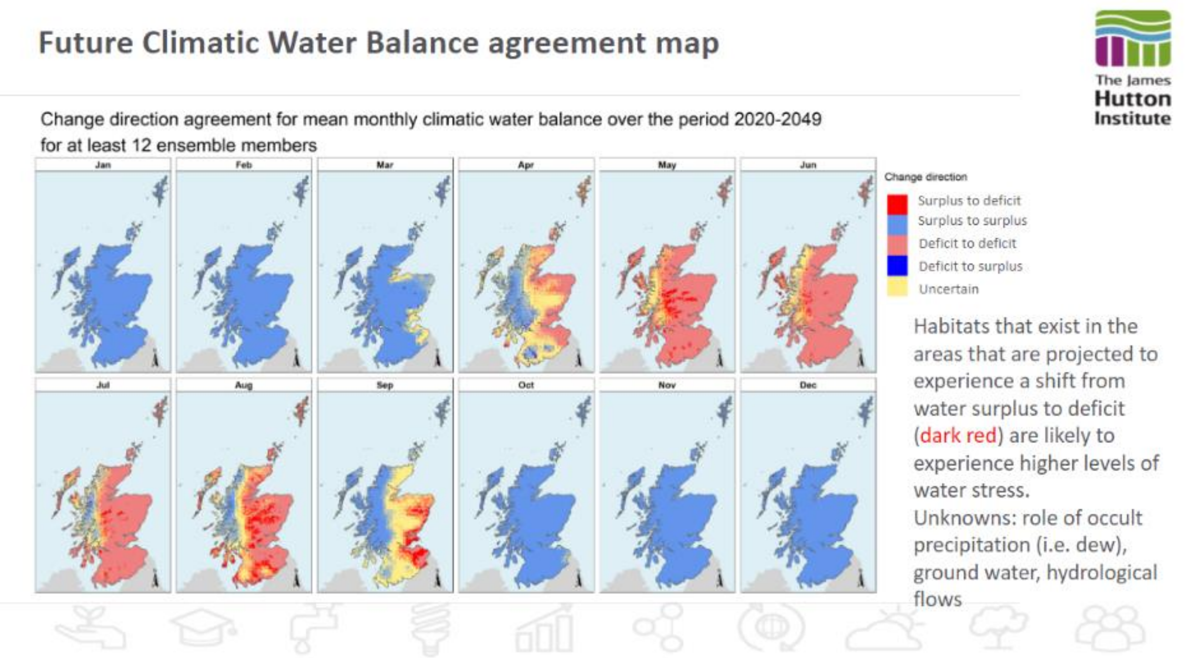
Affected	**Soil Temperature**
Drivers	Rainfall, Temperature, Evapotranspiration, Climate water balance, Dry days, Very wet days
Narrative	Drier soils have a lower thermal capacity and so will respond more rapidly to temperature changes above-ground. Soils with a higher organic matter content have lower bulk density and so this impact will be stronger on organic soils.
Influencing factors	Soil hydraulic conductivity, existing soil moisture regime.

Affected	**Subsoil pans**
Drivers	Rainfall, Very wet days
Narrative	As above, the risk of soil compaction and the formation of subsoil pans is significantly greater when the soil is saturated or nearly so; if machinery moves over the soil at this time then compaction risk is higher.
Influencing factors	Existing soil moisture regime, soil organic matter, soil texture and structure.

Spatial distribution of impacts

The work by Mohamed Jabloun and Mike Rivington on future Climate Water Balance mapping (see below) shows a small proportion of Scotland's area (on the west coast) having an increase in CWB at the start or end of the growing season. These areas will see an increase in risk of soil compaction and the formation of subsoil pans, with the associated effects of increased runoff, erosion risk and impact on infiltration.

Larger areas in the middle, south and east of Scotland are shown to move from surplus to deficit CWB from May to September; these areas will likely see a negative impact on soil organic matter content as organic matter turnover by biota is increased. There will also be an increase in high-intensity rainfall events with associated short-term increase in risk of compaction and erosion immediately after these events.



Feedbacks & synergies

As identified in the tables above, there are multiple factors that will affect how strongly a change in rainfall and temperature patterns will drive changes to a range of soil properties. Some of these factors lead to positive or negative feedbacks within the soil system, and some soils will be more resilient to these driven changes than others. Current soil health indicators including organic matter content, texture and structure are important factors in this.

Conclusions

The approach taken for the workshop has enabled valuable discussion and multiple perspective identification of potential impacts and relationships between climate change and soil properties.

Compaction and erosion risk increases across Scotland will be linked to high-intensity rainfall events and so are impossible to predict, but the risk can be mitigated through appropriate communication with land managers about avoiding machinery movement over soils when they are near saturation. Dynamic compaction and erosion risk mapping in response to recent rainfall events may be possible, linking to work carried out by Zisis Gagkas and Nikki Baggaley.

Wider impacts of soil water deficits during summer months will have a more predictable negative impact on soil organic matter content and GHG emissions from soils; there will also be negative impacts on temperature buffering and erosion/runoff risks. These impacts will be proportionally dependent on the baseline organic matter content of the soil, with organic soils (peats) being most affected. There are multiple impact pathways for this, with the main ones going through soil biota, particularly microbial biomass responsible for organic matter turnover.

Next Steps

Whilst the use of a selection of the key climatic drivers is a sensible starting point to identify impacts relationships, there is need for inclusion of a broader range of climate indicators to capture the wider consequences on soil health. Further climate change indicators and soil health indicators will be developed to help advance and broaden this coverage.

Specific modelling of peatland soil microbial activity and consequences of climate change on GHG emissions is ongoing in both SRP (CentrePeat) and UKRI and EU Horizon funded projects. Outputs from these projects will be utilised within D5-2.

Appendix A:

Workshop attendees – all from James Hutton Institute:

1. Nikki Baggaley
2. Mike Rivington
3. Rebekka Artz
4. Gillian Donaldson Selby
5. Alessandro Gimona
6. Kenneth Loades
7. Mads Trolborg
8. Margaret McKeen
9. Mohamed Jabloun
10. Fraser McFarlane
11. David Boldrin
12. Allan Lilly
13. Roy Neilson
14. Happison Chikova
15. David Miller
16. Mhari Coyle
17. Tracy Valentine
18. Betsy Cowdery
19. Amin Sharififar
20. Bhaskar Mitra
21. Priscila Matos

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