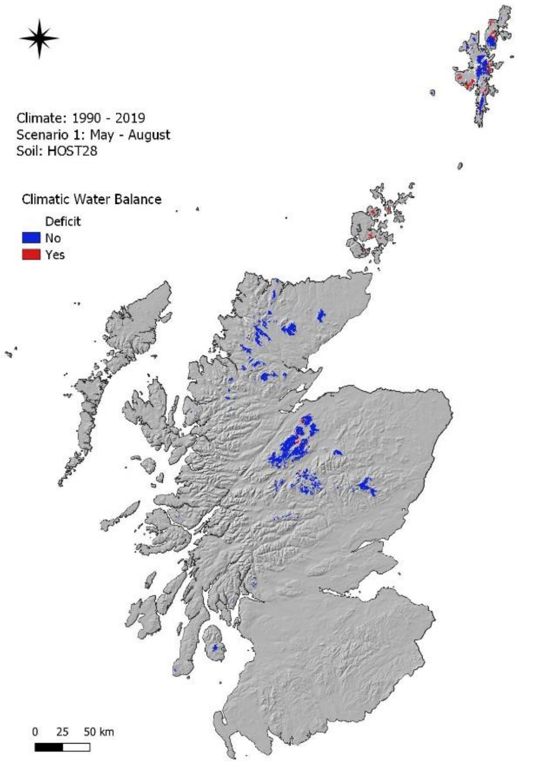
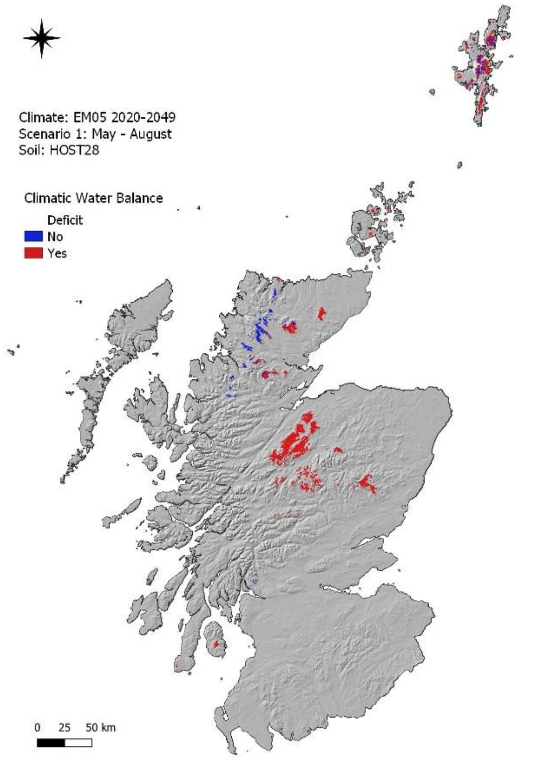
Climate change effects on soil properties and functions: the case of soil water balance

Deliverable 2.2a for the

Project D5-2 Climate Change Impacts on Natural Capital

April 2024





Summary

This report is a product of the Scottish Government Strategic Research Programme project JHI-D5-2 'Climate Change Impacts on Natural Capital'. It is produced in the context of Deliverable 2.2a: "Climate change effects on soil properties and functions" and builds on findings from the internal (James Hutton Institute) workshop on linkages between climate, soil water and soil function held on February 16th, 2024, in Aberdeen. The purpose of this report is to assess exposure levels of different soils to the threat of meteorological drought expressed by the Climatic Water Balance (CWB), defined as the difference between precipitation and reference evapotranspiration), as calculated in Deliverable 2.1a (Rivington and Jabloun, 2022). We also aim to provide an assessment of soils vulnerability to changes in CWB in relation to soil water balance and soil hydrological functioning.

This work builds towards the development of the Risk and Opportunities Assessment Framework (ROAF) being developed within the D5-2 project, in relation to the assessment of meteorological drought risk as part of the Risk as a function of Vulnerability, Exposure and Threat (R=VET) approach (see Deliverable D1.5). We provide this assessment for a national and regional case study using national soil maps and soil hydrological classifications in relation to the observed (1990-2019) and future (2020-20490 changes in climatic water deficits and surpluses.

Key Messages:

- More areas of peat are projected to be exposed to water stress and meteorological drought in the near future (to 2049), with c. 75% to 80% of upland blanket peat and eroded peat in Scotland (c. 7,900 km^2 and 1,450 and km^2, respectively, based on the soil map used) projected to be exposed to continuous climatic water deficits from May to August, while around 4,000 km^2 of upland blanket peat and 790 km^2 of eroded peat are projected to be continuously under water stress between April to September as well.
- Prolonged climatic water deficits could lead to lowering of local water tables that may favour the release of GHGs from the surface soil layer, highlighting the importance of keeping bogs in good condition (i.e., fully saturated) to improve the resilience of peat soils to climatic water deficits and improve the provision of their climate regulation services.
- Montane habitats in the Cairngorms are projected to experience dramatic reductions in climatic water availability in the near future, with continuous and strong water surpluses being replaced by prolonged periods of water stress for most of the spring to autumn period. Extensive areas of montane habitats on shallow and exposed soils of low water storage capacity are considered to be greatly vulnerable to future meteorological drought, which may have adverse effects on habitat biodiversity.

Advances in Technical Capabilities

This report has been developed through technical advances made in the JHI-D5-2 Project related to advanced geospatial processing for the joint analysis of digital soil maps and climatic data layers, and to visualisation techniques for improved presentation and dissemination of the results of this complex analysis.

Contents

Citation:

This report should be cited as:

Gagkas Z., Jabloun M., Rivington M., Aitkenhead, M. (2024). Deliverable 2.2a Climate change effects on soil properties and functions: the case of soil water balance. The James Hutton Institute, Aberdeen. Scotland. DOI 10.5281/zenodo.11210904

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Acknowledgements

This report has been produced by the D5-2 Climate Change Impacts on Natural Capital Project funded by the Scottish Government Rural and Environment Science and Analytical Services Strategic Research Programme (2022-2027).

Introduction

This report builds on findings from an internal (James Hutton Institute) workshop on linkages between climate, soil water and soil function (February 16th, 2024, Aberdeen) and its purpose is to conduct a mapping assessment of exposure levels of selected soils to the threat of meteorological drought for the observed (1990 – 2019) and projected future period (2020 – 2049), whilst also assessing the potential impacts of meteorological drought on soil water balance. We focused on soil water because changes in precipitation and temperature patterns, both spatially and temporally, will have a direct impact on soil water balance and affect soil hydrological functioning and the associated delivery of (supporting) soil ecosystem services. Soil water balance metrics considered include water table depth, surface runoff, soil moisture content and saturation levels.

Based on standard terminology (Chuvieco et al., 2023), exposure represents the areal extent of selected soil types at risk of potential loss or that may suffer damage from the impact of meteorological drought. Exposure forms a link between a given climatic-related threat or danger and the Natural Capital asset's vulnerability. Hence, the exposure assessment presented in this report contributes to the evolving approach that "Risk as a function of Vulnerability, Exposure and Threat (R=VET)" that forms the basis of the Risk and Opportunities Assessment Framework (ROAF) being developed in the D5-2 project.

This work builds on results from Deliverable D2.1a: "Climate Trends and Future Projections in Scotland" (Rivington and Jabloun, 2022) and in particular on the calculation of Climatic Water Balance (CWB), where CWB is defined as the difference between Precipitation and Reference Evapotranspiration. In this work, we use CWB Ratios, defined as ratios of Precipitation to Reference Evapotranspiration, an approach we recently used to provide a more quantifiable assessment of meteorological drought (Gagkas et al., 2023a). Findings of potential linkages between climate change metrics and soil water and soil function are presented in the internal workshop report (*in prep*.). Here, we present results from the mapping assessment of potential effects of CWB on soil water balance and associated soils functioning for two case studies, one of national and one of regional importance:

- Exposure of peat soil to meteorological drought and potential effects on water table levels in relation to regulation of greenhouse gas (GHG) emissions.
- Exposure of upland soils in the Cairngorms National Park to meteorological drought and potential effects on soil moisture contents in relation to supporting montane vegetation communities.

These case studies were selected as representative of the potential effects of climate change on soil water balance and respective soil functions for important soils and habitats in Scotland. This analysis was based on spatially overlaying the generated monthly data layers of CWB ratios at a spatial resolution of 1km grid cell (shown in the Appendix) with a digital soil map of Scotland, calculating the proportions of the selected soil area extents falling within classes of climatic water deficits or surpluses, and using expert knowledge to identify the vulnerability of these soils to meteorological drought and the effects on respective soil supporting ecosystem services.

Note: It is important to emphasise that the example shown (EM05) is one projection and hence one visualisation of a plausible future. We need to highlight that the results presented are the period means which are useful to illustrate overall potential changes over a c.30-year period, but masks annual variability. Individual years with extreme events (i.e. prolonged drought) may have substantial impacts on the vegetation microbiome and hence ecological function of peatlands. There is an increasing likelihood of extreme individual years, hence the illustrations provided are likely to be more accentuated in those extreme years. This report has not considered extreme years, but this will be a focus in further work within the D5-2 project. Details about future climate extremes are available here: Report: Climate extremes in Scotland

In this report we have focussed on the risks of spring and summer period water deficits, in relation to potential impacts on GHG emissions. However, the results also indicate levels of high water surplus in the winter months as well. Whilst not assessed here, these results also provide indications of higher risks of winter runoff, erosion and flooding.

Advancing analytical capability

Work presented here has advanced our technical analytical capability by:

- Developing scripts in R for combined geospatial processing of soil and climatic data layers.
- Developing a national database of soils info, such as series code and soil hydrological class, and CWB Ratio classes combinations.

Technical Developments

Main datasets

Climatic water balance

Climatic Water Balance (CWB) is defined as the difference between precipitation input (P) and reference evapotranspiration (ET_o) output. Evapotranspiration is the total amount of moisture returned to the atmosphere from evaporation from surfaces and water transpired from plants. Here it was calculated using the Priestly-Taylor method using precipitation, maximum and minimum temperature, and solar radiation (Rivington and Jabloun, 2022). Hence, CWB provides a metric of the combined impacts of changes in temperature and precipitation on water availability and its limitation that can lead to the occurrence of meteorological drought.

CWB was calculated for the whole of Scotland on a monthly basis by Rivington and Jabloun (2022) using 1 km interpolated gridded observed climatic data and UKCP18 climate projection daily climatic data (for x 12 Ensemble Members (EMs) – referred to here as 'projections' from a Regional Climate Model for the 'high emissions' scenario (RCP8.5)) for each year of the observed (1990 – 2019) and projected future periods (2020 – 2049).

Since it is not practically feasible for this analysis to present results for all 12 projections, in this study we used EM05, which represents a drier climatic scenario compared to the baseline period (1960-1989) in terms of mean annual precipitation. This represents a single plausible future climate scenario rather than the broad range of possibilities. Further visualisations of the observed changes in the climate and the 12 projections (as anomaly plots) are available here: The James Hutton Institute Climate Data Visualisation

Averages of CWB ratios (of P to ET_o) were calculated for each period to define CWB ratios, where values:

- <0.5 indicate Strong CWB Deficits; where precipitation covers only 50% or less of the evapotranspiration demand.
- <1 indicate a Moderate CWB Deficit; where precipitation covers 50 to 100% of the evapotranspiration demand.
- >1 indicate a Moderate CWB Surplus; where precipitation is 0 to 100% greater than the evapotranspiration demand.
- >2 indicate a Strong CWB Surplus; where precipitation is 100% or more greater than the evapotranspiration demand.

National monthly maps of these CWB ratio classes for the observed (1990 – 2019) and future period (2020 – 2049) based on EM05 are given in the Appendix. Overall, EM05 makes projections of wetter conditions in March compared to the observed period but overall drier conditions in April and May, although the area under strong climatic water deficits in May is greater in the observed period compared to EM05 climate. However, the main difference is that EM05 estimates a more prolonged period of continuous water deficits (moderate or strong) compared to the observed period, with water stress being dominant from April to September compared to the May to August period for the observed period. These maps also show the presence of a clear west to east distinction, with eastern Scotland being under water deficits more frequently than most areas in the West.

Digital soil map

Soils information was derived from an available digital map of soil class (series) at a 50m grid cell resolution, which had been previously generated by disaggregating the National Soil Map units (Soil Survey of Scotland Staff, 1981) using predictive soil modelling techniques (Gagkas and Lilly, 2019; Gagkas and Lilly, 2024). The National Soil Map units may contain a mixture of different types of soils, whose exact location within the polygon is often unknown; hence the digital soil map was produced to overcome this limitation by providing a continuous mapping of soil series in Scotland that can be used to identify the location of individual soil types within these complex map units.

The digital soil map has also been developed specifically to support national land and soil assessments by linking the soil series mapping with soils information held in the Scottish Soils Database, for example, it has recently been used to map areas likely to be wetlands in Scotland (Hare *et al.*, 2022).

Because the focus of this study is on soil water balance, we used information from the Hydrology of Soil Types (HOST) from the Scottish Soil Database for each soil series of the disaggregated map. HOST is a soil hydrological classification devised to predict river flows at ungauged catchments in the UK based on the rate and pathways of water movement through the soil (Boorman et al., 1998). HOST conceptual models of water movement and respective HOST classes (Figure 1) provide an integrated assessment of soil hydrological pathways by considering soil hydrological properties (soil infiltration and percolation) based on soil morphological characteristics (presence of a gleyed layer, a slowly permeable layer or a peaty topsoil) and the presence of an aquifer or groundwater.

Hence HOST is an appropriate soil property for the purpose of this work because it integrates soil water balance metrics such as the potential for surface runoff, water table presence and soil moisture and water content. Characteristics of individual HOST classes present in Scotland are given in Table 1.

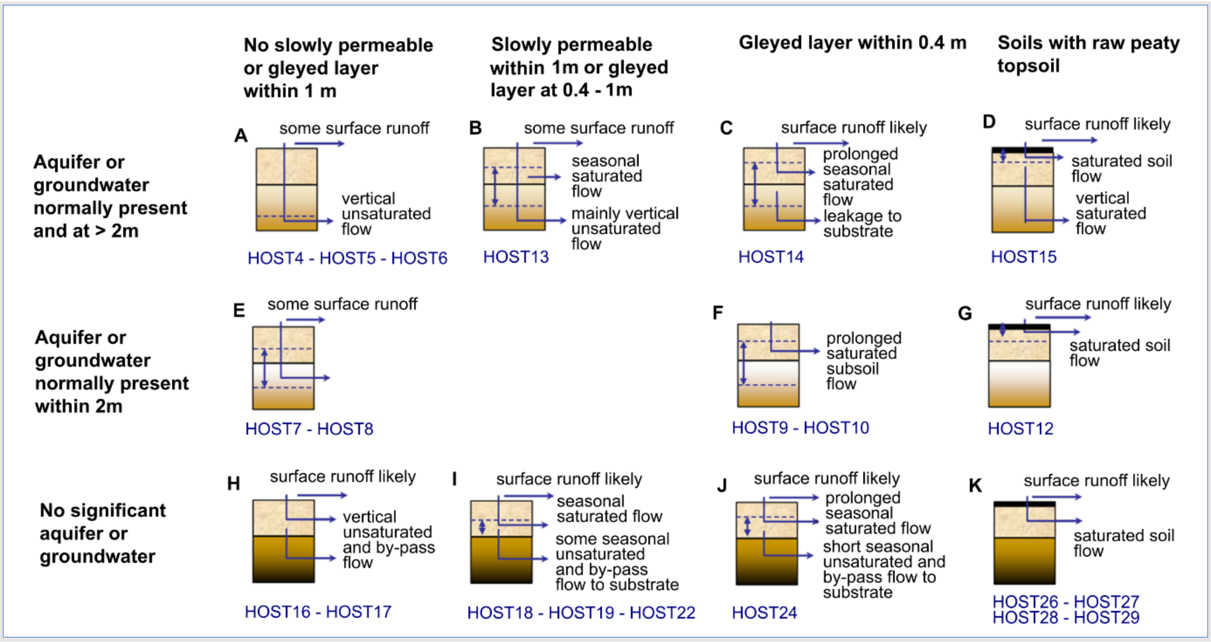

Figure 1. HOST conceptual models of water movement and respective HOST classes in Scotland.

The monthly CWB ratio data layers for the observed (1990 – 2019) and future (2020 – 2049) periods (Appendix) and the HOST class map derived from the disaggregated soil series map (Figure 2) were spatially overlaid to provide unique combinations of the four CWB ratio class (i.e., Strong Deficit; Moderate Deficit; Moderate Surplus; and Strong Surplus) and HOST class values. Then, for the two case studies, we selected the relevant HOST classes and calculated the areal extents and proportions of each HOST class that fell within the respective CWB ratio classes. This analysis was used to quantitatively assess the exposure of the selected soils to levels of climatic water deficits or surpluses by month, while soil properties based on the HOST class characteristics (Figure 1) were used to provide a semi-quantitative assessment of the vulnerability of certain soils to climatic water stress, in relation to their functioning and provision of the supporting ecosystem services selected in the two case studies.

Table 1 Description of HOST classes (See Figure 2 for mapped areas per HOST class).

HOST class	Description
4	Free draining permeable soils on hard but fissured rocks with high permeability but low to moderate storage capacity
5	Free draining permeable soils in unconsolidated sands or gravels with relatively high permeability and high storage capacity
6	Free draining permeable soils in unconsolidated loamy drifts
7	Free draining permeable soils in unconsolidated sandy or gravely alluvium with groundwater at < 2m from the surface
8	Free draining permeable soils in unconsolidated loamy alluvium with groundwater at < 2m from the surface
9	Soils seasonally waterlogged by fluctuating groundwater and with relatively slow lateral saturated conductivity
10	Soils seasonally waterlogged by fluctuating groundwater and with relatively rapid lateral saturated conductivity
12	Undrained lowland peaty soils waterlogged by groundwater
13	Soils with slight seasonal waterlogging from transient fluctuating water tables
14	Soils seasonally waterlogged by fluctuating water tables
15	Permanently wet, peaty topped upland soils
16	Relatively free draining soils with a moderate storage capacity over slowly permeable substrates with negligible storage capacity
17	Relatively free draining soils with a large storage capacity over hard impermeable rocks with no storage capacity
18	Slowly permeable soils with slight seasonal waterlogging and moderate storage capacity over slowly permeable substrates with negligible storage
19	Relatively free draining soils with a moderate storage capacity over hard impermeable rocks with no storage capacity
22	Relatively free draining soils with low storage capacity over hard impermeable rocks with no storage capacity
24	Seasonally waterlogged soils over slowly permeable substrates with limited storage capacity
26	Permanently wet, peaty topped upland soils over slowly permeable substrates with negligible storage capacity
27	Permanently wet, peaty topped upland soils over hard impermeable rocks with no storage capacity
28	Permanently wet eroded upland blanket peat
29	Permanently wet upland blanket peat

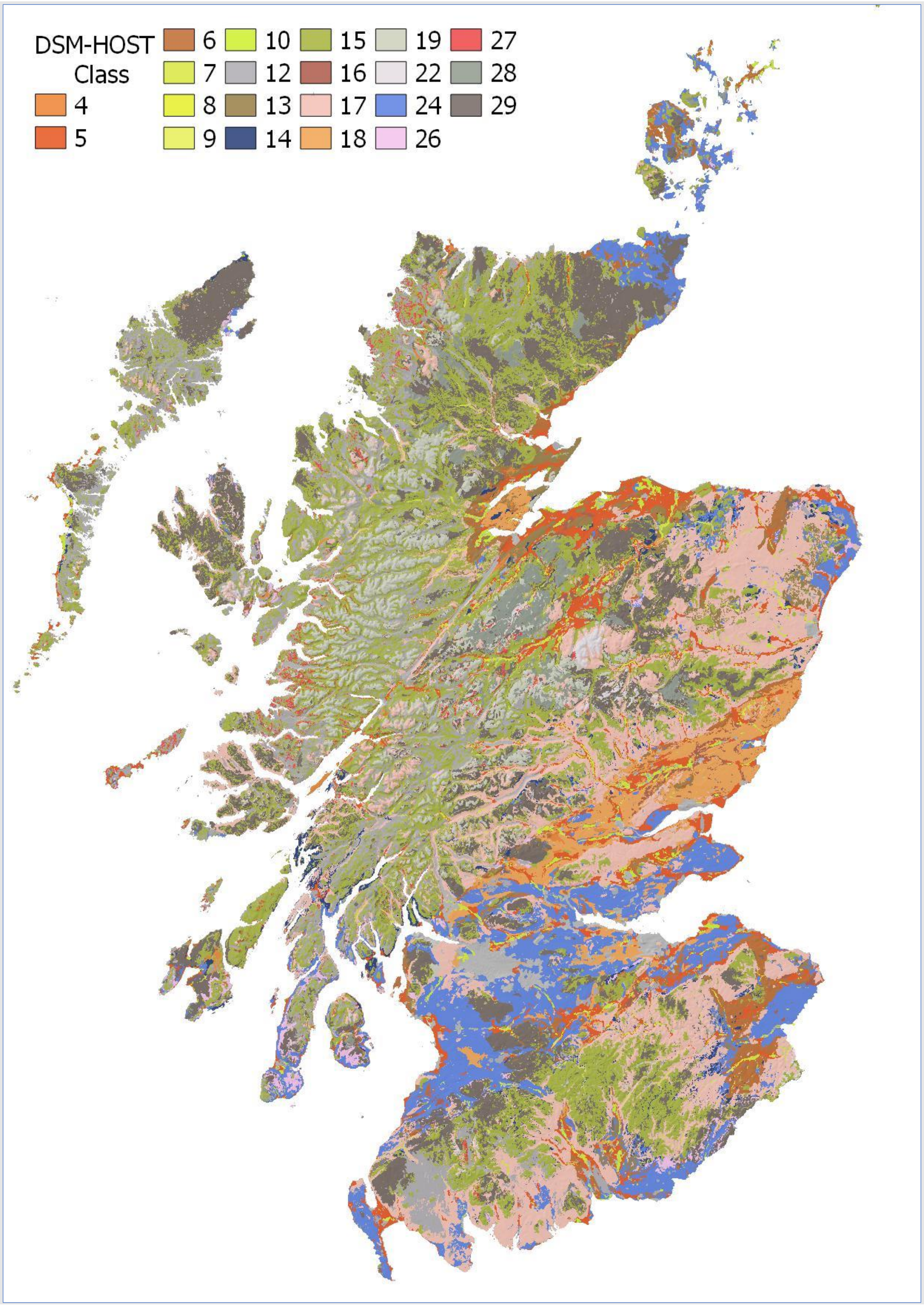

Figure 2. Map of HOST classes based on the disaggregated map of soil series at 50m grid cell (see Table 1 for class type descriptions).

National case study: Peat soils

Peat soils forms where high rainfall or impeded drainage causes waterlogging, restricting oxygen supply and suppressing decomposition. Water table depth has been identified as the main control of greenhouse gas (GHG) emissions from peat, with healthy, saturated bogs emitting less than degraded ones (Evans et al., 2021). Precipitation is the main water source for upland blanket bogs, the most expansive type of peat in Scotland, which are also hydrologically connected to surface waters, making them less resilient to climatic water deficits than other types of bogs, such as lowland basin peat areas that have groundwater as their main water source and are confined (e.g., not hydrologically connected surface water bodies) or semi-confined. At the same time, eroded peat (semi-confined or upland peat) has a diminished water holding capacity and potential of water storage compared to bogs in good condition.

Therefore, for this analysis, we used the HOST classification scheme (Figure 1) to select areas of peat soils belonging to Eroded Peat (HOST class 28) and Upland Blanket Peat (HOST class 29), which based on the digital soil map cover around 3% (1,790 km^2) and 14% (10,624 km^2) of Scotland, respectively (excluding water features and urban areas). The intersected areas of CWB ratio data layers for the observed (1990 – 2019) and future (2020 – 2049) periods, and the areas of HOST classes 28 and 29 were then used to calculate proportions of areas falling within each CWB ratio class by month, shown in the bar plots of Figures 3 and 6 for HOST class 28 and 29, respectively. This analysis was complemented by a mapping assessment for both HOST classes based on two scenarios of climatic water stress for the observed (1990 – 2019) and future (2020 – 2049) periods:

- Scenario 1 (S1): Areas under continuous climatic water deficit for the May to August period.
- Scenario 2 (S2): Areas under continuous climatic water deficit for the April to September period.

The purpose of this mapping assessment was to identify the most vulnerable peat soils to prolonged dry periods (S1: shorter vs S2: longer dry period) and produce respective maps for both HOST classes and scenarios (Figures 4, 5 and 7, 8). It should be noted that areas shown in blue in these maps are not in continuous climatic water surplus for the whole duration of the two scenario periods assessed, meaning that they can be in deficit as well in one or more months, but areas in red are in continuous climatic water deficits for all months considered.

Results: National scale assessment

Based on Figure 3, all areas mapped as HOST class 28 were in climatic water surpluses for the October to March period, for both the observed (1990 – 2019) and future periods (2020 – 2049); this was a strong surplus for all months for the observed climate, while around 45% of HOST class 28 area is projected to be in moderate as opposed to strong surplus in March. However, differences emerge between observed and future climate for the April to September period. Around 78% and 81% of the HOST class 28 area is projected to be in water deficit in April and August, respectively, compared to just 14% and 10% based on the observed climate. Approximately 45% of the HOST class 28 area is projected to be still in water stress in September, compared to none based on the observed climate. Most HOST class 28 area is under climatic water deficit for May, June and July and areal proportions are broadly similar for both the observed and future climate (Figure 3), with a greater areal proportion projected to be under strong water deficit in June for the 2020 – 2049 period (24%) compared to the observed one (3%).

Based on the mapping assessment for Scenario 1 (areas under continuous climatic water deficit for the May to August period), around 10% of all the HOST class 28 area (170 km^2) was found to be in continuous deficit in late spring and summer (May to August) for the observed period (1990 – 2019), mainly located in the Cairngorms area (Figure 4), while no HOST class 28 area was in continuous water deficit for the April to September period (Scenario 2, Figure 5). However, when the EM05-based future climate (2020 – 2049) was considered, the area under continuous water deficit from May to August and from April to September greatly increased to 1,447 km^2 and 787 km^2, respectively, representing 81% and 44% of all HOST class 28 area, respectively. This means that almost all but the areas of Eroded

Peat in northwestern Scotland (Figure 4) are projected to be in continuous water stress based on future climate for Scenario 1, while most of Eroded Peat in the Cairngorms and some in the North is projected to be in water stress from spring to early autumn (Scenario 2, Figure 5).

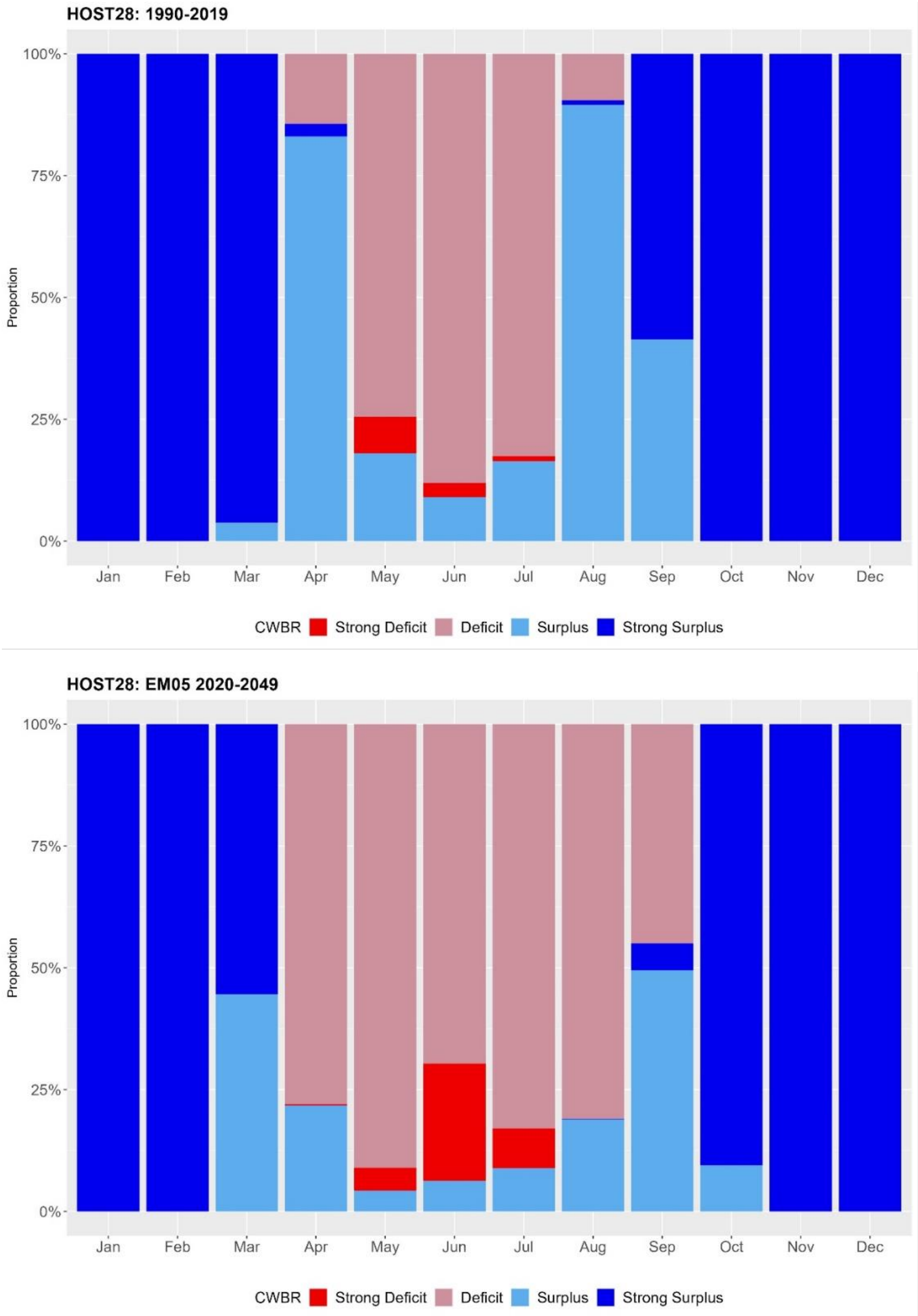

Figure 3. Area proportions for the monthly Climatic Water Balance Ratio classes for HOST class 28 for the observed (1990 – 2020) period and future (2020 – 2049) period for Ensemble Member (EM) 05.

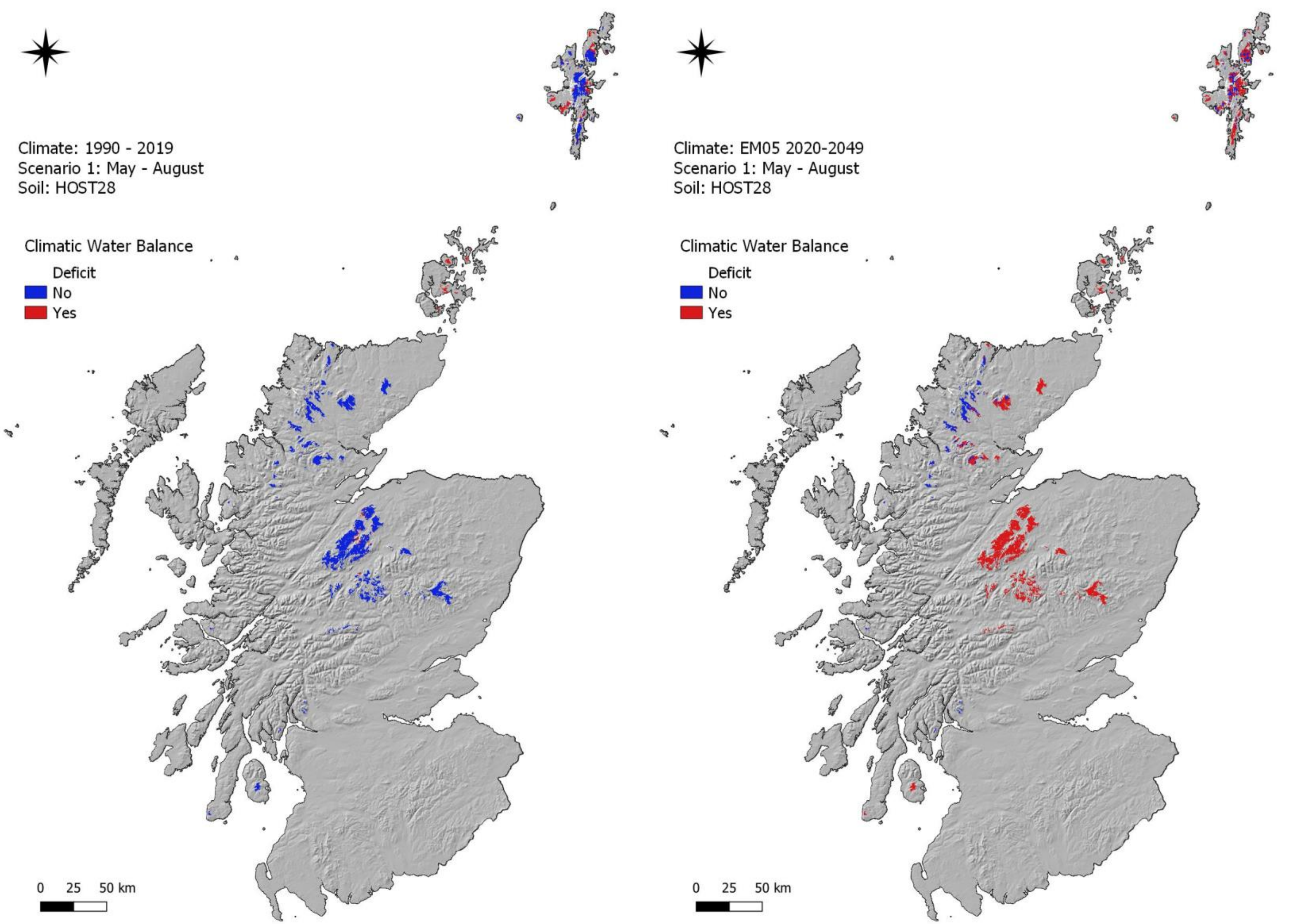

Figure 4. Maps of HOST class 28 based on Scenario 1: Continuous climatic water deficit from May to August, for the observed (1990 – 2020) period and future (2020 – 2049) period for Ensemble Member (EM) 05.

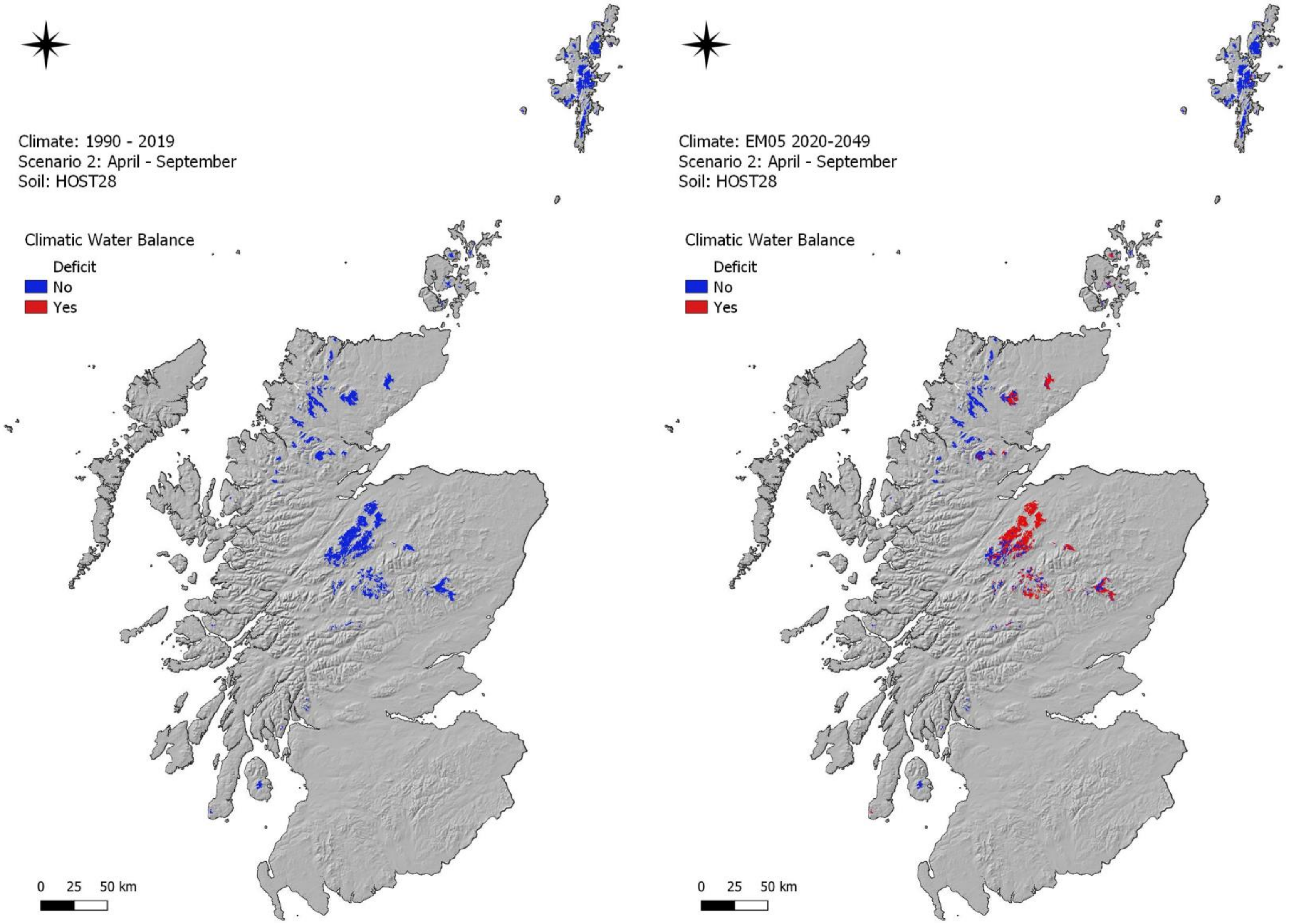

Figure 5. Maps of HOST class 28 based on Scenario 2: Continuous climatic water deficit from April to September, for the observed (1990 – 2020) period and future (2020 – 2049) period for Ensemble Member (EM) 05.

Similarly to HOST class 28, areas mapped as HOST class 29 were found to be in continuous climatic water surpluses as well for the October to March period for both the observed (1990 – 2019) and future periods (2020 – 2049), with all areas being in strong climatic water surplus until February and 21% and 39% of the area being in moderate water surplus in March for the observed and future climate, respectively (Figure 6). As before, differences emerge between observed and future climate for the April to September period. Around 71% and 73% of the HOST class 29 area is projected to be in water deficit in April and August, respectively, compared to 23% for both months based on the observed climate, while 38% of the HOST class 29 area is projected to be still in water stress in September, compared to none based on the observed climate. Around 96%, 95% and 86% of the HOST class 29 area is projected to be under climatic water deficit in May, June, and July, respectively, compared to 88%, 88% and 79% for the same months based on observed climate (Figure 6).

The mapping assessment shows that for Scenario 1, around 23% of all the HOST class 29 area (2,460 km^2) was found to be in continuous deficit in late spring and summer (May to August) for the observed period (1990 – 2019); these areas were mainly located in the north of Scotland (eastern area of the Flow Country), on the Isle of Lewis and in the Cairngorms area (Figure 7), while only a small area of HOST class 29 area (13 km^2) was in continuous water deficit for the April to September period (Scenario 2, Figure 8). However, when the EM05-based future climate (2020 – 2049) was considered, the area under continuous water deficit from May to August and from April to September greatly increased to 7,851 km^2 and 4,027 km^2, respectively, representing 74% and 38% of all HOST class 29 area, respectively. This resulted in extensive areas of Upland Blanket Peat in the Flow County, the Isle of Lewis, the Cairngorms, and the Southern Uplands to be projected to be in continuous water stress based on one plausible future climate for Scenario 1, with the exception of peat areas in northwestern Highlands, the Isle of Skye, and the Isle of Mull (Figure 7). Moreover, the HOST class 29 areas under continuous climatic water stress from April to September are mainly found in the eastern part of Scotland (Figure 8).

The area proportion change for HOST28 (Figure 3) in June for a Strong Deficit appears to be more than for HOST class 29 (Figure 6) but it is important to note that HOST29 is much more extensive and occurs both in the western and eastern side of Scotland, while HOST28 mainly occurs in the Cairngorms area that is projected to be drier than western part of the country. This is also evident in the maps shown in Figures 7 and 8.

Overall, the results of this analysis for the selected climatic future (EM05 for 2020 – 2049) show a greater increase of peat areas being exposed to water stress and meteorological drought compared to the observed period (1990 – 2019), with up to 80% of the areas of either Eroded or Upland Blanket Peat (according to the HOST classification) in Scotland projected to be exposed to continuous climatic water deficits from May to August. Considering a longer period, around 40% of this area is projected to be under water stress between April to September as well. In periods of climatic water surpluses and if there is potential for storage in the peat's saturation zone, the distance from the surface of the soil to the water table can potentially be reduced, with potential positive effects related to the reduction of GHGs emissions. However, prolonged climatic water deficits could lead to further depletion of water in the water table that may favour the release of GHGs from the surface soil layer.

Eroded and degraded peat is more vulnerable to climatic water deficits. Prevention of methane emissions by *Sphagnum* covering ponds may become reduced if they dry out. Therefore, these results highlight the importance of restoring and/or maintaining bogs in good condition (i.e., fully saturated) because this can maintain and/or improve the resilience of peat soils to climatic water deficits and improve the provision of their climate regulation services.

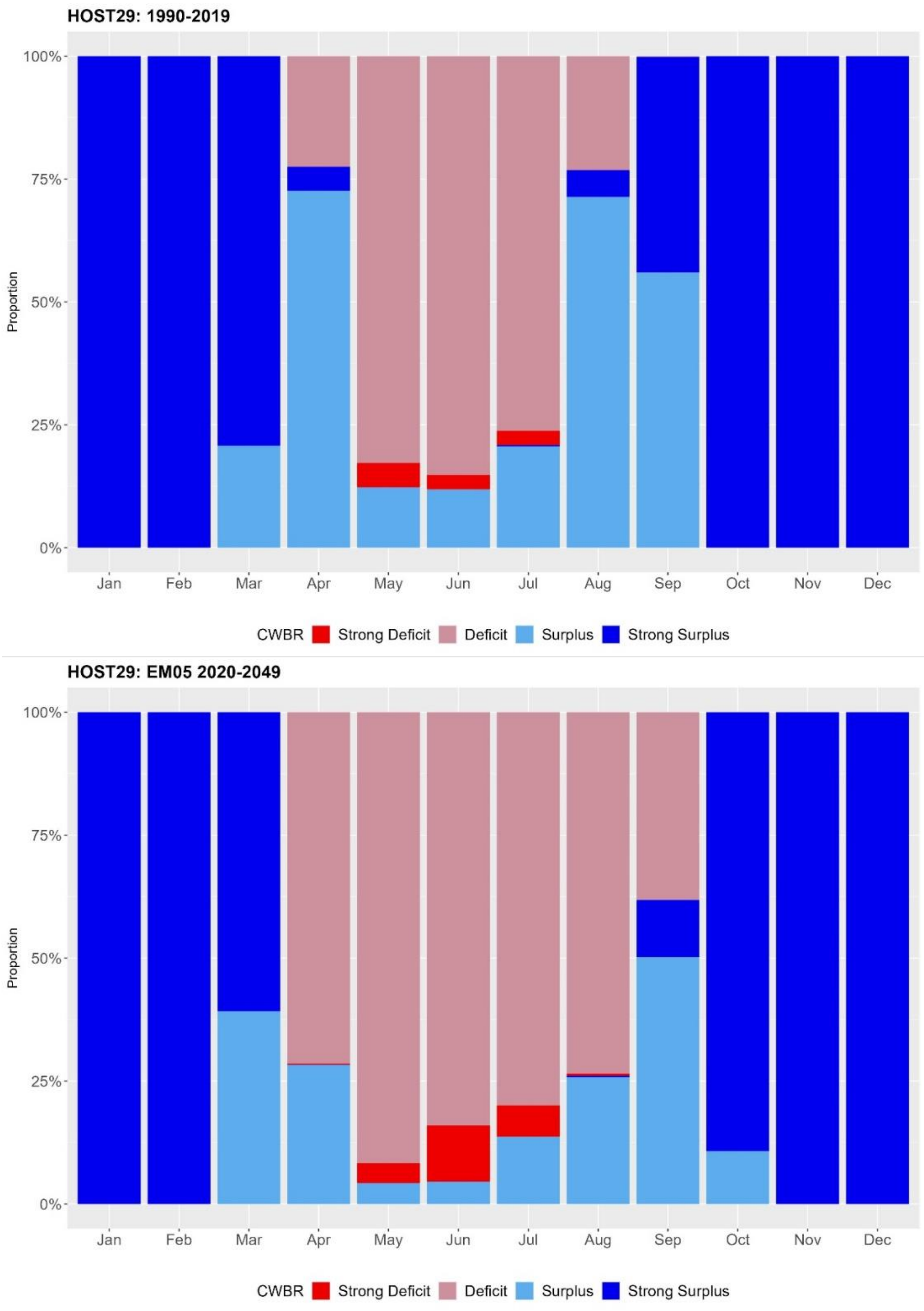

Figure 6. Area proportions for the monthly Climatic Water Balance Ratio classes for HOST class 29 for the observed (1990 – 2020) period and future (2020 – 2049) period for Ensemble Member (EM) 05.

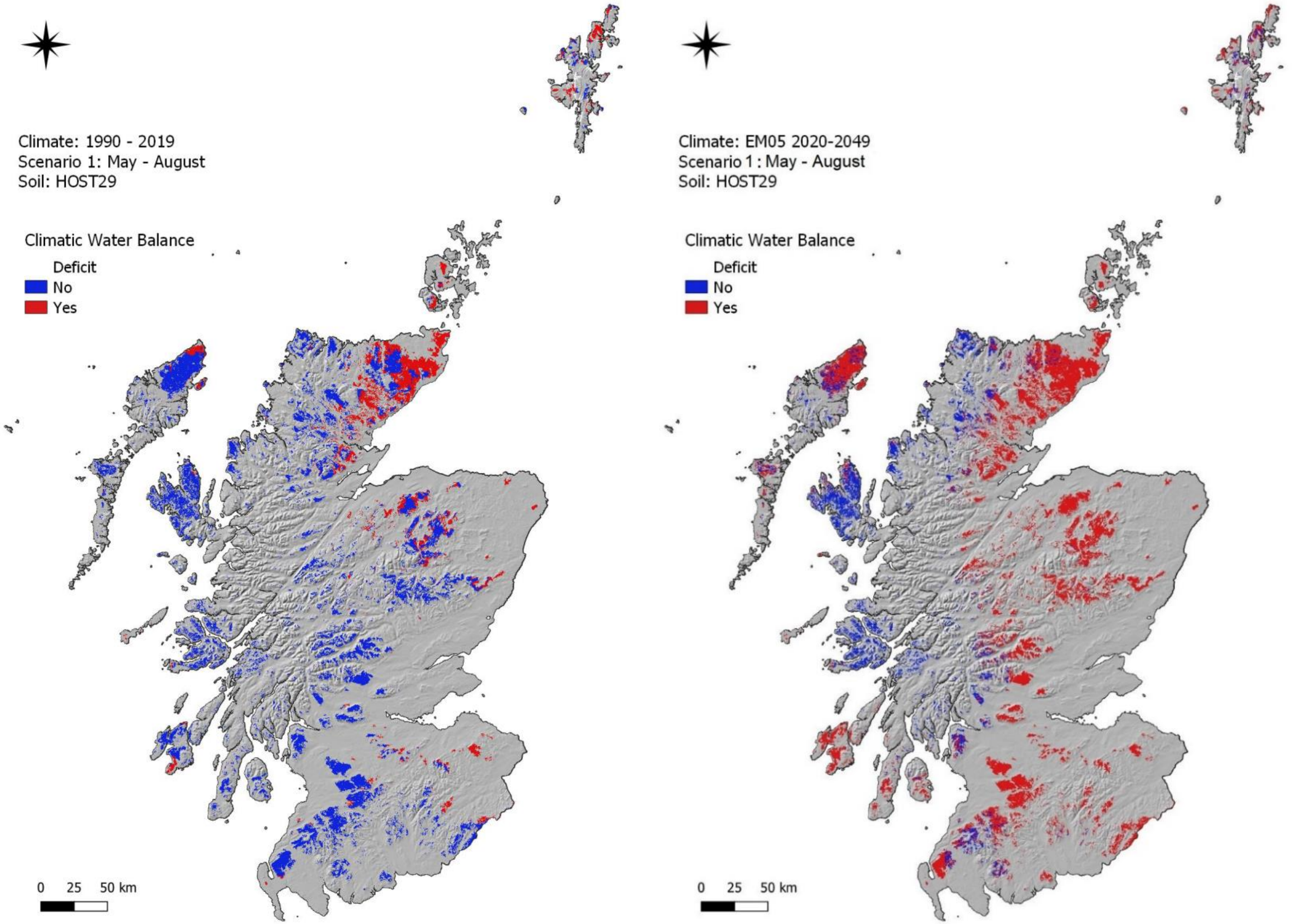

Figure 7. Maps of HOST class 29 based on Scenario 1: Continuous climatic water deficit from May to August, for the observed (1990 – 2020) period and future (2020 – 2049) period for Ensemble Member (EM) 05.

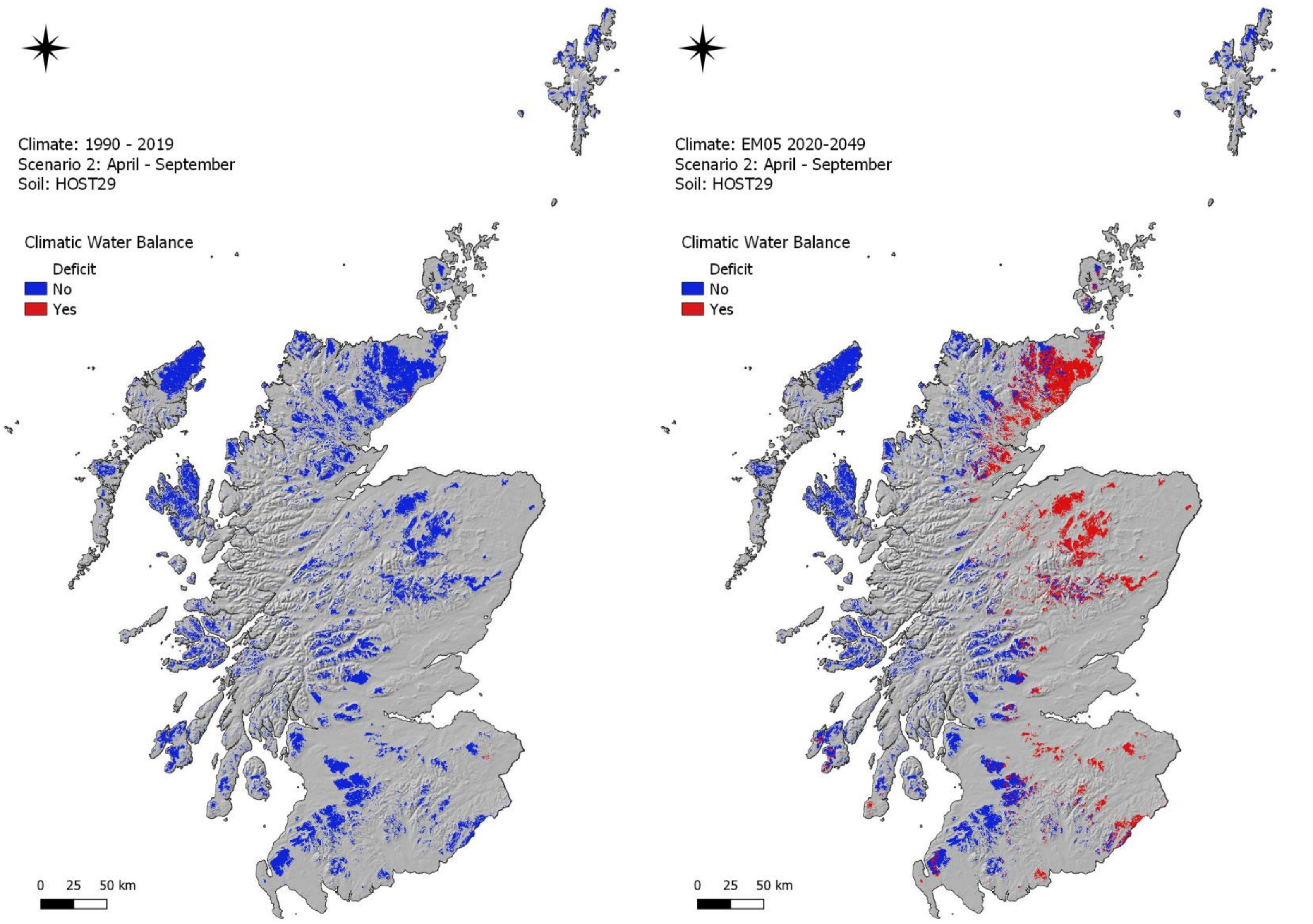

Figure 8. Maps of HOST class 29 based on Scenario 2: Continuous climatic water deficit from April to September, for the observed (1990 – 2020) period and future (2020 – 2049) period for Ensemble Member (EM) 05

Results: Regional case study - upland soils in the Cairngorms

A key finding from Rivington and Jabloun (2022) is that some upland areas of central Scotland are projected to shift from water surplus to deficit, most notably in May for the central Highlands, while large parts of eastern Scotland in September are projected to see a shift to CWB deficit. Such changes may have substantial impacts on the ecological functions and condition of montane habitats, i.e., low arctic-alpine flora found on exposed summits and mountain slopes above the treeline that support a range of rare and threatened plants and invertebrates and are important foraging areas for birds and mammals. The resilience of these habitats to drought conditions would depend to a great extent on the moisture contents and water storage of montane soils. CWB deficits are expected to reduce soil moisture contents, especially for topsoils, but this would depend on the soil's ability for water storage and on the depth of soil horizons to underlying rock.

For this reason, we looked at the exposure of montane habitats to meteorological drought within the boundaries of the Cairngorms National Park and assessed their resilience to climatic water deficits by considering moisture content levels of the respective upland soil types using the HOST classification. The Cairngorms National Park was selected for this regional case study because it contains extensive areas covered with montane vegetation and is also one of the areas where shifts from climatic water surpluses to deficits are projected to occur in the future. We used the Scotland Habitat and Land cover map (SLAM-MAP) for 2020 at 20m pixel resolution, produced by Space Intelligence in partnership with NatureScot[1], to identify the areas of montane habitats in the study area. SLAM-MAP was preferred to CEH Land Cover Map because it maps land cover at EUNIS Level 2, and this gives the granularity needed for selecting the appropriate habitats for this particular case study. An evaluation of the SLAM-MAP and CEH Land Cover Map products is given in Gagkas et al. (2023b). We selected areas mapped by SLAM-MAP as:

- E4: Alpine and subalpine grasslands.
- F2: Arctic, alpine, and subalpine scrub.
- H2: Screes.
- H3: Cliffs and rock pavements.

These areas are shown in Figure 9. Screes and montane scrubs in the Cairngorms National Park are found in median altitudes of around 820 m above sea level, while alpine and subalpine grasslands are found close to 960 m above sea level. The montane habitats map was then spatially overlaid with the HOST class digital soil map to identify the main soil types and produce the combined areas of Table 2. Around 10% of alpine and subalpine grasslands and screes and 23% of montane scrub is found on peat soil (HOST class 29) (Table 2); for this case study we removed these areas because peat was the focus of the national assessment and because these areas are expected to be less vulnerable to climatic water deficits due to the high water storage of peat. HOST class 17 soils cover around 26% – 30% of the selected area of montane habitats, HOST class 19 soils cover around 22% and 28% of montane grasslands and scrubs, respectively, while HOST class 22 soils cover most of the habitats found on screes (39%) and cliffs (63%) (Table 2 and Figure 10). Therefore, the study area was defined by selecting areas of montane habitats on HOST class 17, 19 and 22 soils, which covered a total area of 312 km^2 (Figures 9 and 10).

[1] https://www.space-intelligence.com/scotland-landcover

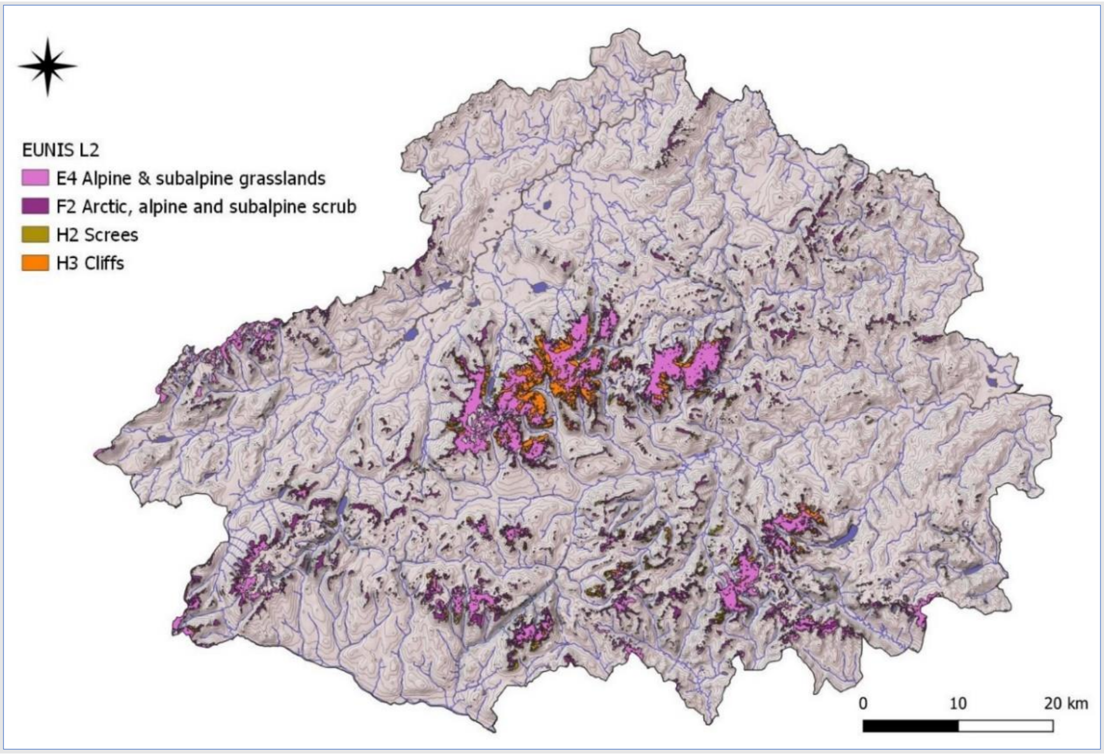

Figure 9. Map of montane habitats based on SLAM-MAP in the study area in the Cairngorms National Park © Crown copyright and database right (2024). All rights reserved. The James Hutton Institute, Ordnance Survey Licence Number AC0000812928

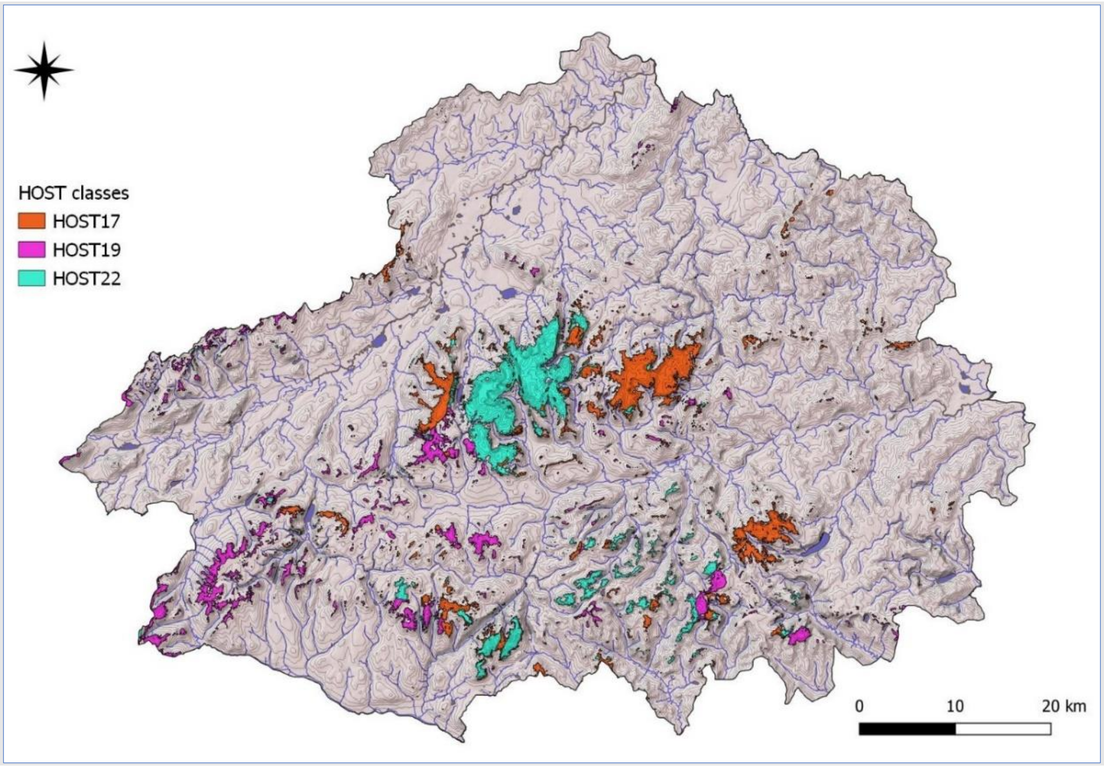

Figure 10. Map of HOST class 17, 19 and 22 in the study area in the Cairngorms National Park © Crown copyright and database right (2024). All rights reserved. The James Hutton Institute, Ordnance Survey Licence Number AC0000812928

Soils belonging to HOST classes 17, 19 and 22 in the study area are mineral montane soils of variable water storage capacity over hard impermeable rock with no groundwater influence (Table 3 and Figure 1). Areas of HOST class 17 and 19 in the study area are mapped as Alpine (Oroarctic) podzols based on the Scottish Soils Classification 2013[2] and are found on moderate to strong mountain slopes that can be non-rocky to rocky. Based on soil property summary statistics (Soil Survey of Scotland Staff, 2018), HOST class 17 soils in the study area have a surface organic horizon (H) with median carbon contents around 26%, while HOST class 19 soils in the study area have an organic-rich mineral Ah horizon with median carbon contents of 7% - 9%. These soils experience annual freeze-thaw process so that the upper soil horizons have a relatively loose and porous fabric, and may be relatively deep, up to 1 metre before bedrock is reached. Soils belonging to HOST class 22 in the study area are Lithosols and Rankers that are restricted to depth with coherent rock present usually less than 10 and 20 cm from the surface, respectively, and are found in very rocky mountain summits with strong to very steep slopes. Where these soils are developed, generally only mineral A, organic (O or H) horizons are found although some intermediate organic-rich humose horizons may also occur. Based on the above, HOST class 17 soils are expected to have the greater water storage capacity and higher soil moisture contents of the selected montane soils, while the weakly-developed shallow HOST class soils are considered to have much lower storage capacity and soil moisture contents (Table 3).

Table 2. Area (in km) of montane habitats in the Cairngorms National Park based on SLAM-MAP and proportions of coverage (in %) by the more extensive HOST classes.

EUNIS L2 Classes	Area (km^2)	HOST17 (%)	HOST19 (%)	HOST22 (%)	HOST29 (%)
E4 Alpine and subalpine grasslands	201.0	29.3	22.2	30.6	12.3
F2 Arctic, alpine, and subalpine scrub	119.9	30.0	28.5	13.0	23.0
H2 Screes	23.8	26.2	10.7	39.3	10.5
H3 Cliffs and rock pavements	45.1	27.3	5.6	63.0	2.2

Table 3. Description of selected HOST classes 17, 19 and 22.

HOST class	Description
HOST17	Relatively free-draining mineral soils with moderate to high storage capacity over hard impermeable rock
HOST19	Relatively free-draining mineral soils with moderate storage capacity over hard impermeable rock
HOST22	Relatively free-draining mineral soils with low storage capacity over hard impermeable rock

Based on the spatial intersections between the digital soil map and CWB data layers, most of the area of montane habitats on HOST class 17 soils for the observed period (1990 – 2019) was found to be in continuous strong climatic water surpluses from September to March and in moderate water surplus in April and August as well (Figure 11). May was the only month when most of this area (60%) was found to be in moderate water deficit, while 40%-45% of this area was in water deficit in June and July as well. However, when looking at future climate (2020 – 2049) based on EM05, most of this area is projected to be in continuous climatic water deficit from April to September: around

[2] https://www.hutton.ac.uk/learning/soilshutton/soil-classification

71% of the area in April and September and >90% of the area in May and the summer months. All of this area is projected to be in continuous strong water surpluses between October and February, while around 70% of this area is projected to be in strong water surplus in March, with the remaining 30% being in moderate deficit (Figure 11).

Similarly for montane habitats on HOST class 19 soils and for the observed period (1990 – 2019), their area was found to be in continuous climatic water surpluses from August to April, with almost all of the area being in strong surplus between March and September. Around half of this area was found to be in moderate water deficit in May and June, and around 40% in August, while no strong water deficits were observed (Figure 12). However, when looking at future climate (2020 – 2049) based on EM05, a continuous climatic water deficit is projected for the April to September period for most of this area: from 85% to 97% of the area for the April to August period, and 60% of the area in September. Continuous strong water surpluses are projected for all of this area between October and February, with around 55% of this area projected to be in strong water surplus in March, with the remaining 45% being in moderate deficit (Figure 12).

Wetter conditions were found for the montane habitats on HOST class 22 soils for the observed period compared to the areas of HOST classes 17 and 19 (Figure 13). Around 30% of the HOST class 22 area was found to be in climatic water deficit in May, which decreased to 18% and 14% of this area for June and July, respectively. Strong climatic water surpluses were observed for 95% - 100% of this area for the September – March period, and moderate climatic water surpluses for 79% and 69% of this area for April and August, with the remaining areas for both months being in strong water surplus. However, based on future climate (2020 – 2049) from EM05, a continuous climatic water deficit is projected for the April to September period for most of this area: from 89% to 96% of the area for the May to August period, and 77% and 60% of the area in April and September, respectively. Continuous water surpluses are projected for all this area between October and March, with strong surpluses projected for all of this area for this period apart from around 30% in March that is projected to be in moderate deficit (Figure 13).

Overall, the results of this case study show that these upland habitats in the Cairngorms are projected to experience dramatic reductions in the future with regards to climatic water availability, with continuous and strong annual climatic water surpluses for most of their area being replaced by prolonged periods of water stress for most of the spring to autumn period. The resilience of these sensitive ecosystems to drought conditions will depend on their respective plant physiological traits, but also on the moisture content of underlying soils.

Although some HOST class 22 soils in the study area can have organic surface horizons, meaning that they can hold more water than mineral topsoils, these are shallow and exposed soils that are considered to provide the least resilience to montane plants. On the other hand, deeper HOST class 19 and 17 soils with their moderate to high storage capacity can offer a greater buffering capacity to the impacts of prolonged drought conditions. Therefore, this mapping assessment found that around 115 km^2 of montane habitats, mainly located at the mountain slopes and summits at the centre of the Cairngorms National Park, can be considered to be greatly vulnerable to future meteorological drought (Figure 10).

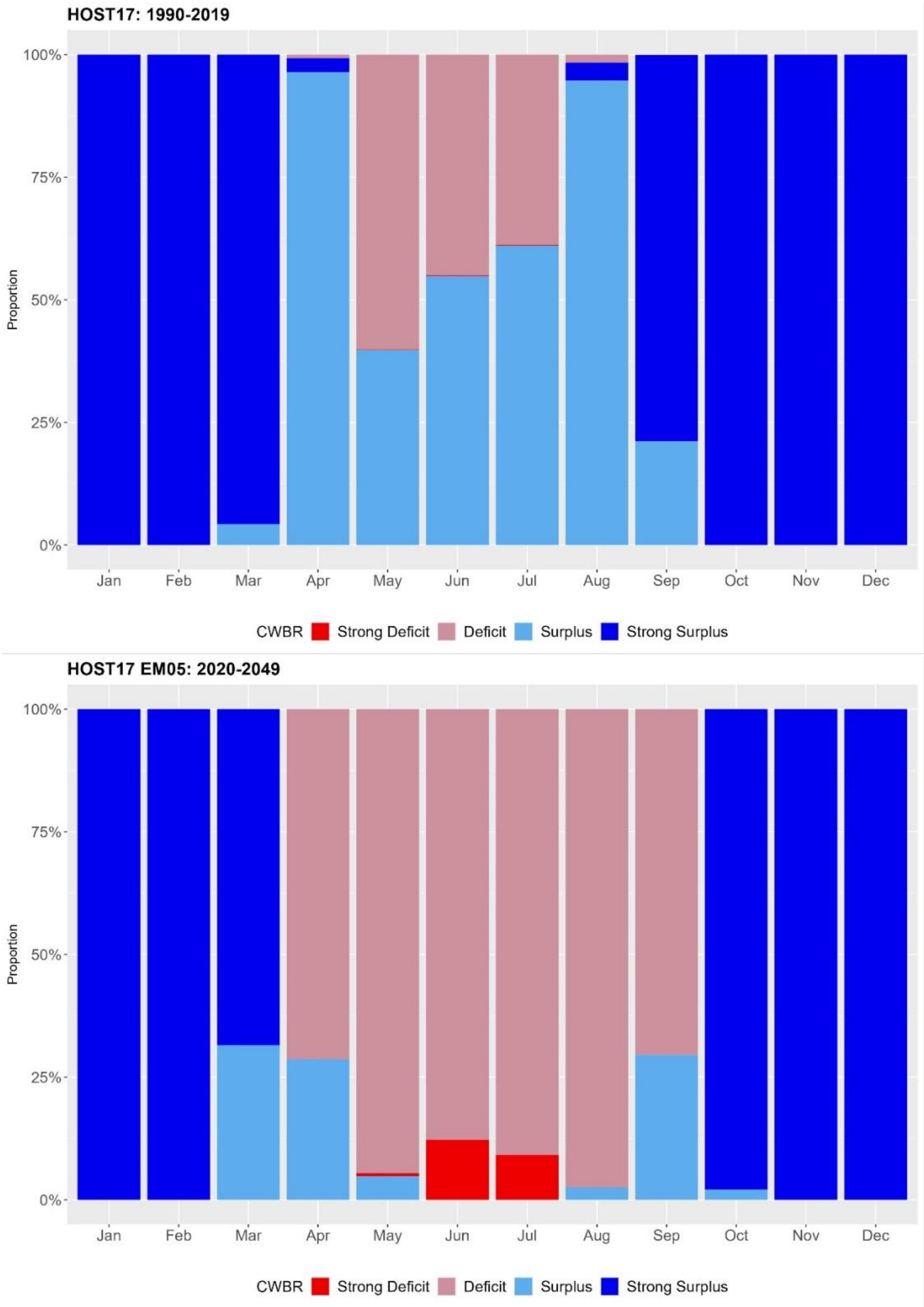

Figure 11. Area proportions for the monthly Climatic Water Balance Ratio classes for HOST class 17 for the observed (1990 – 2020) period and future (2020 – 2049) period for Ensemble Member (EM) 05.

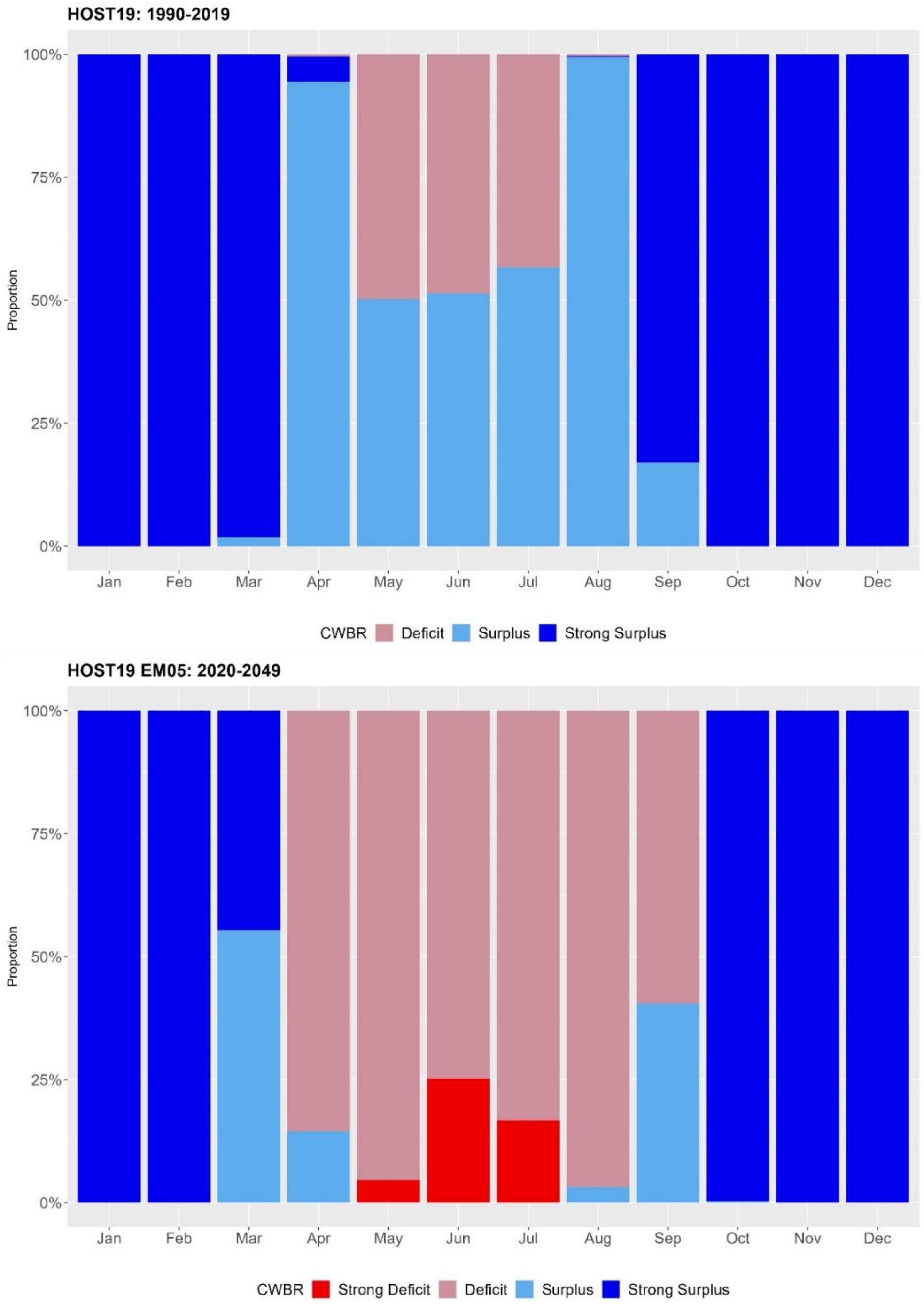

Figure 12. Area proportions for the monthly Climatic Water Balance Ratio classes for HOST class 19 for the observed (1990 – 2020) period and future (2020 – 2049) period for Ensemble Member (EM) 05.

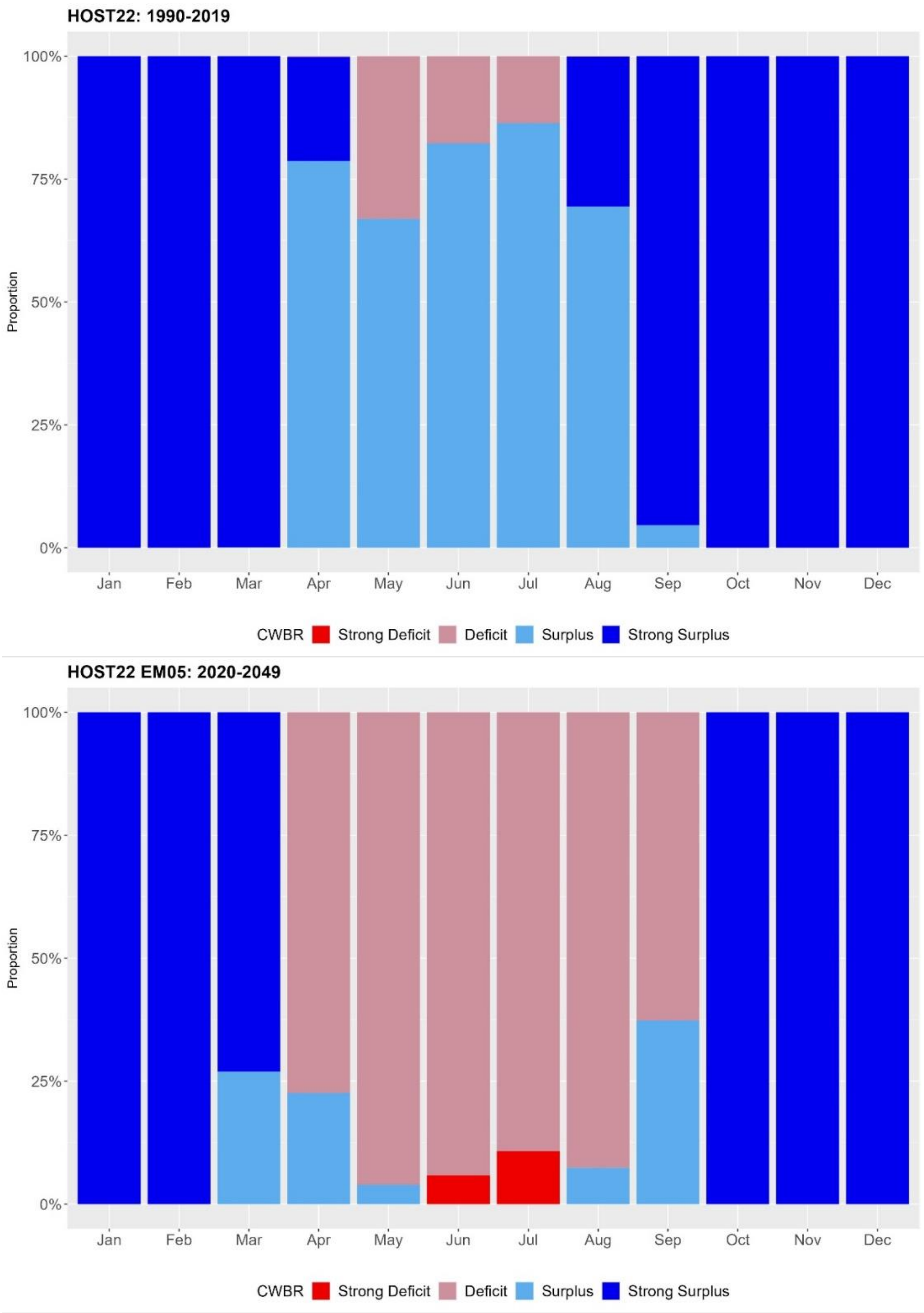

Figure 13. Area proportions for the monthly Climatic Water Balance Ratio classes for HOST class 22 for the observed (1990 – 2020) period and future (2020 – 2049) period for Ensemble Member (EM) 05.

Conclusions

- This analysis has found that, nationally, a great increase of peat areas being exposed to water stress and meteorological drought is expected to occur in the near future (2020 – 2049), with up to 80% of the areas of upland blanket peat in Scotland projected to be exposed to continuous climatic water deficits from May to August and around 40% of this area being under water stress between April to September as well.
- Prolonged climatic water deficits could lead to further depletion of water in the water table that may favour the release of GHGs from the surface soil layer. This highlights the importance of keeping bogs in good condition (i.e., fully saturated) to improve the resilience of peat soils to climatic water deficits and improve the provision of their climate regulation services.
- The regional case study showed that montane habitats in the Cairngorms are projected to experience dramatic reductions in climatic water availability in the near future, with continuous and strong water surpluses being replaced by prolonged periods of water stress for most of the spring to autumn period.
- Deeper upland soils with moderate to high water storage capacities can improve the buffering capacity and resilience of these sensitive ecosystems to the impacts of prolonged dry conditions. However, our mapping assessment identified extensive areas of montane habitats on shallow and exposed soils that are greatly vulnerable to future meteorological drought.
- This analysis was based on the climatic projections of a single Ensemble Member (EM05), considered to represent more prolonged dry conditions, but not necessarily the most intense dry ones. The results presented are the means for the period, hence do not represent the extreme individual years. Using a different climate projection would alter the magnitude of climatic water balance shifts presented here, and hence the levels of exposure; however, there is strong agreement between different projections with regards to the direction of change in climatic water balance in Scotland. This provides confidence in the assumption that can be made based on the findings of this analysis.

Next Steps

This assessment of soils exposure to climatic water deficits can be further extended to include more soil types and associated ecosystem services by using additional soils datasets, such as data layers of peat extent or peatland condition. The assessment presented in this report was based on combining habitat and soil maps and then using our conceptual understanding of relevant soil hydrological processes and how these can be influenced by changes in climatic water availability. A more quantifiable approach could be to use process-based modelling, such as soil water balance modelling, crop modelling or peatland hydrological modelling that can be used to provide a quantitative assessment of changes in precipitation and temperature patterns on soil hydrological functioning and associated supporting ecosystem services. Further work would also benefit by collating information on Natural Capital asset (both soils and habitats) condition that can be used to provide a more quantifiable assessment of their resilience to meteorological drought and respective vulnerability levels. This will be considered within the Deliverable D2.2c - Development of soil health indictors (and linked to work in Topic C3 on peatland condition mapping). Assessments of extreme years and their frequency, i.e. sequential dry years, will help inform understanding the impacts on surface vegetation and risks of non-recovery to droughts and subsequent cascading consequences on soil water exposure to runoff and erosion and subsequent impacts on soil ecosystem services. The further development of visualisation of extremes will be undertaken within Deliverables D1.7 (identifying communication of risks and opportunities) and D1.8 - Development of web-based risk media.

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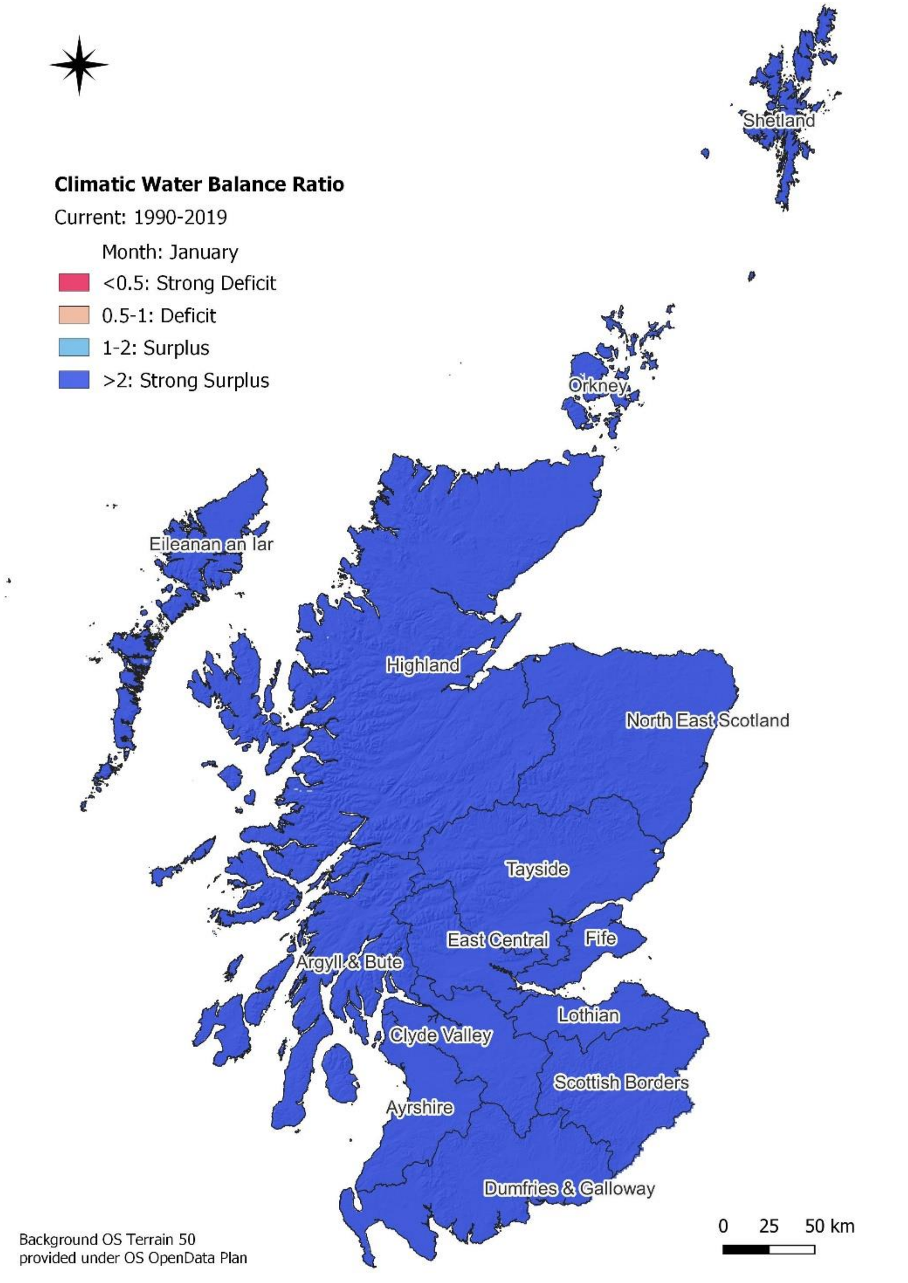
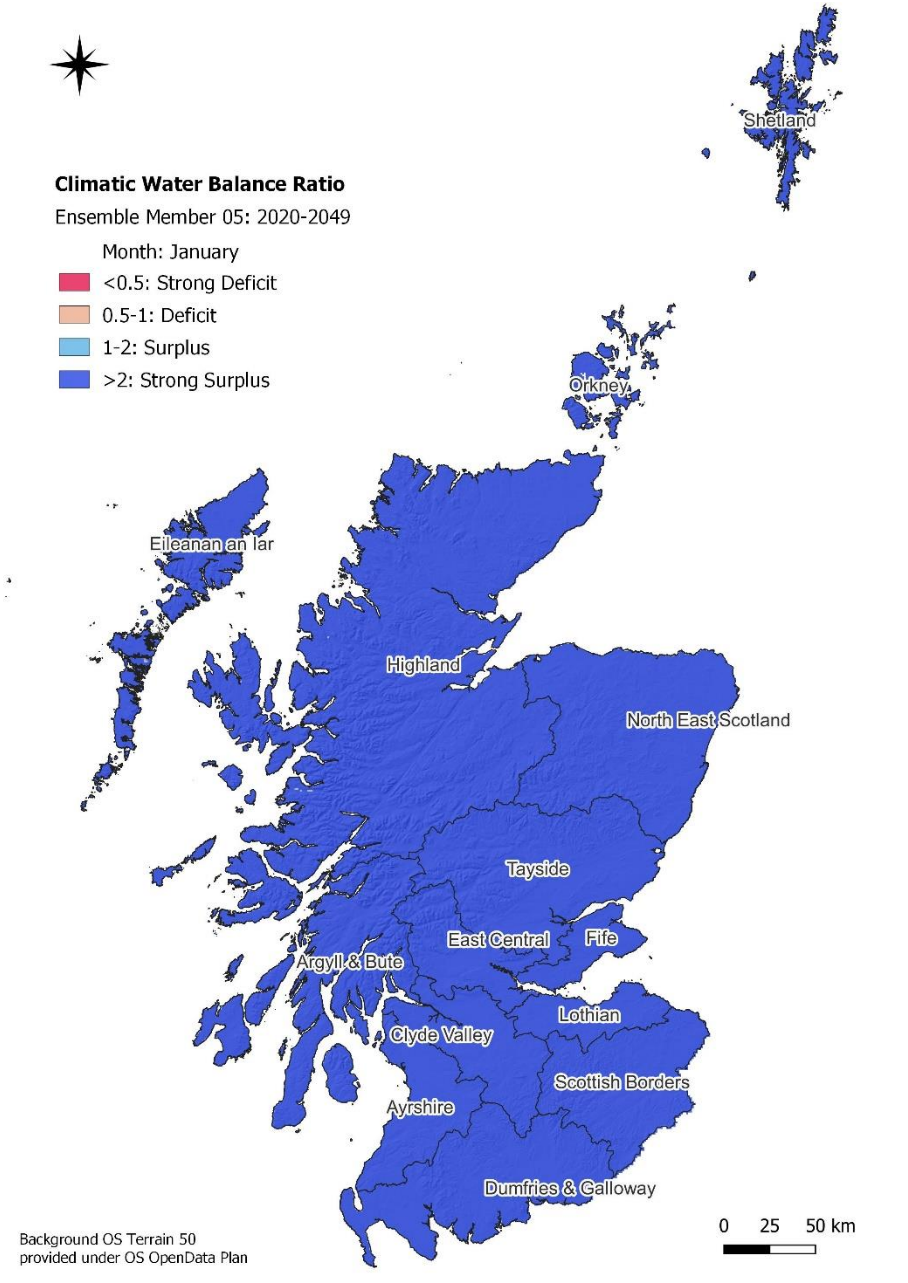
Appendix

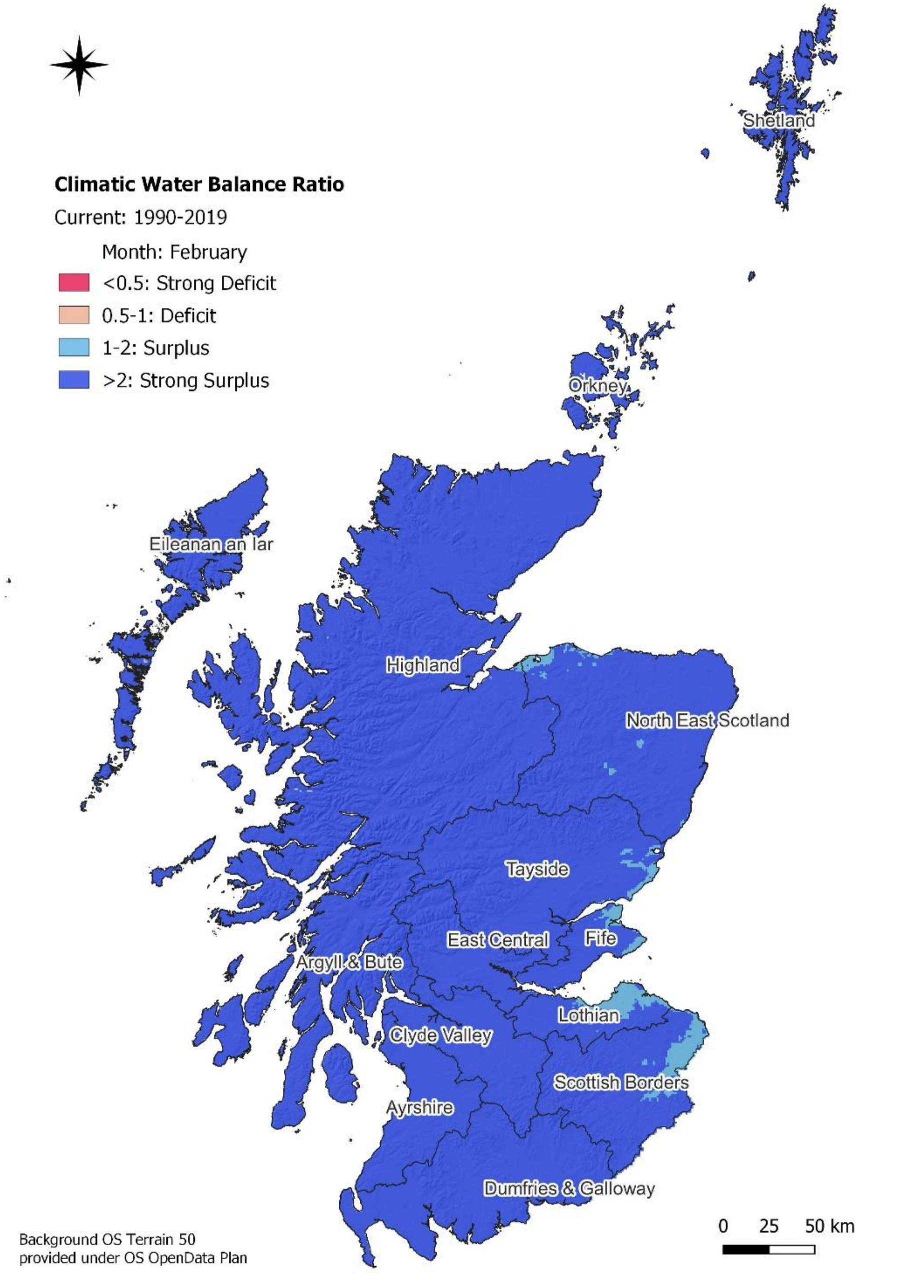
This section shows the national maps of Climatic Water Balance Ratio classes by month based on observed climate for the recent 1990 – 2019 period and projected future climate based on EM05 (Dry scenario). These are superimposed by the boundaries of Scotland’s Agricultural Regions to provide a geographical context for map interpretation.

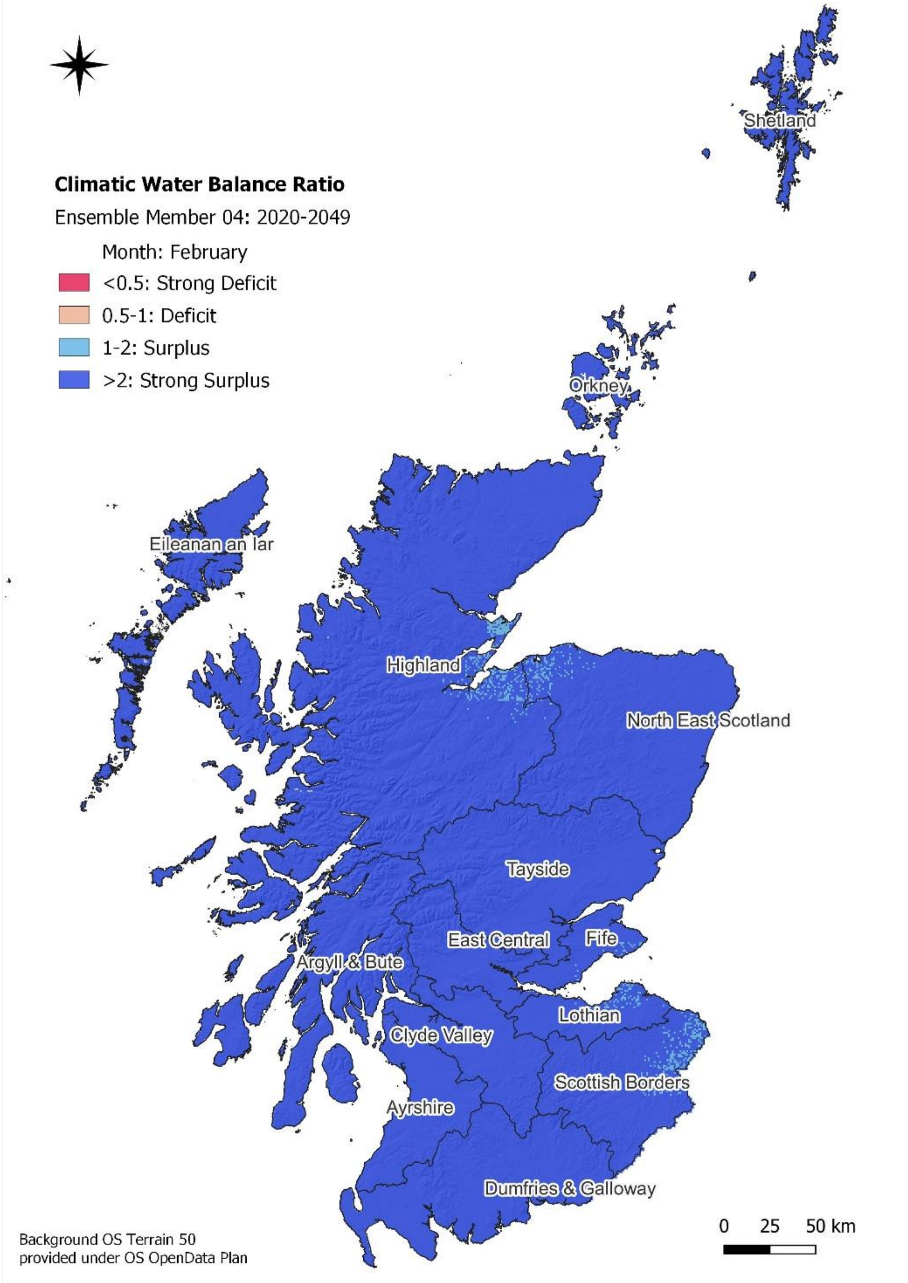


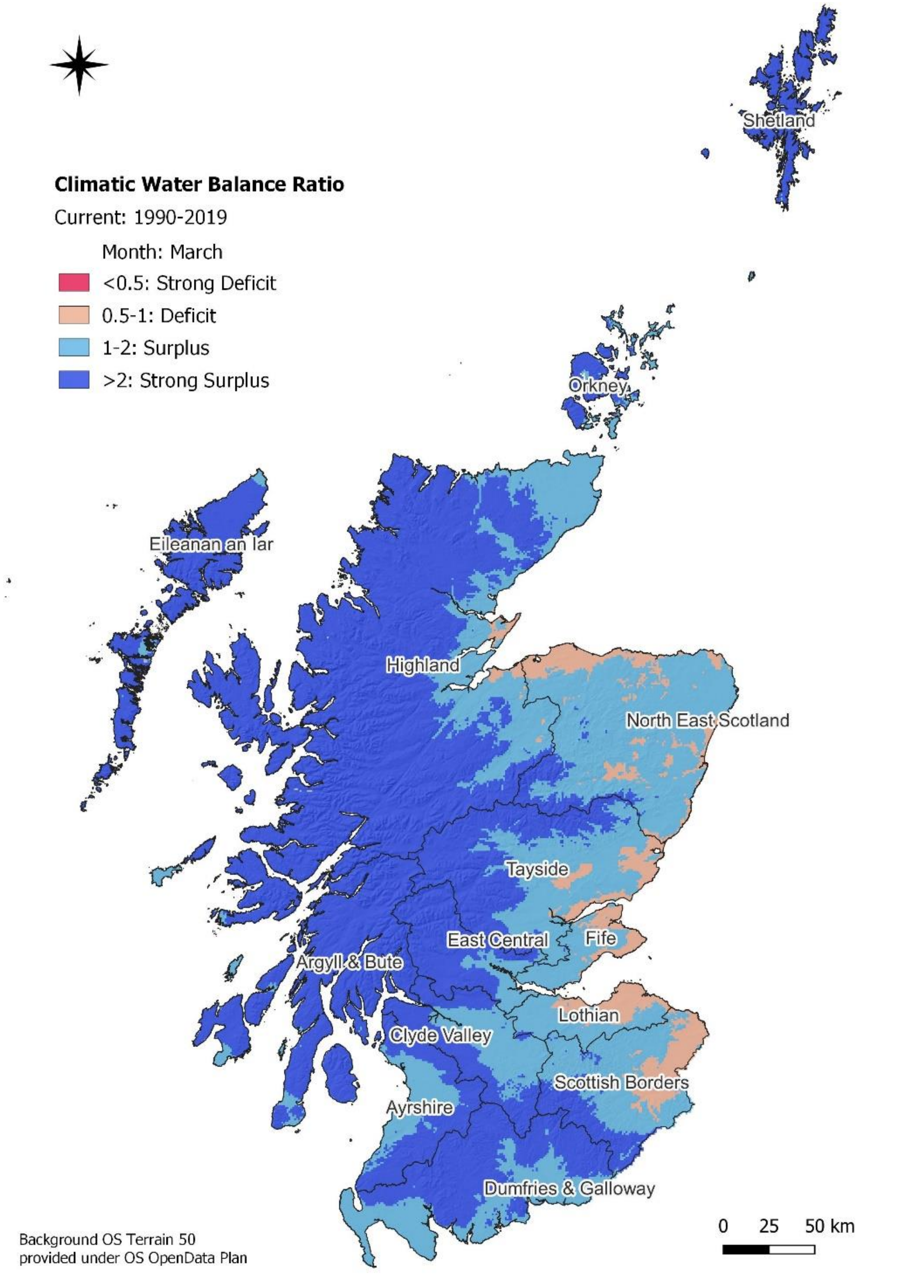
Climatic Water Balance Ratio
Current: 1990-2019
Month: January
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Shetland
Orkney
Eileanan an Iar
Highland
North East Scotland
Tayside
East Central
Fife
Argyll & Bute
Lothian
Clyde Valley
Scottish Borders
Ayrshire
Dumfries & Galloway
0 25 50 km
Background OS Terrain 50
provided under OS OpenData Plan

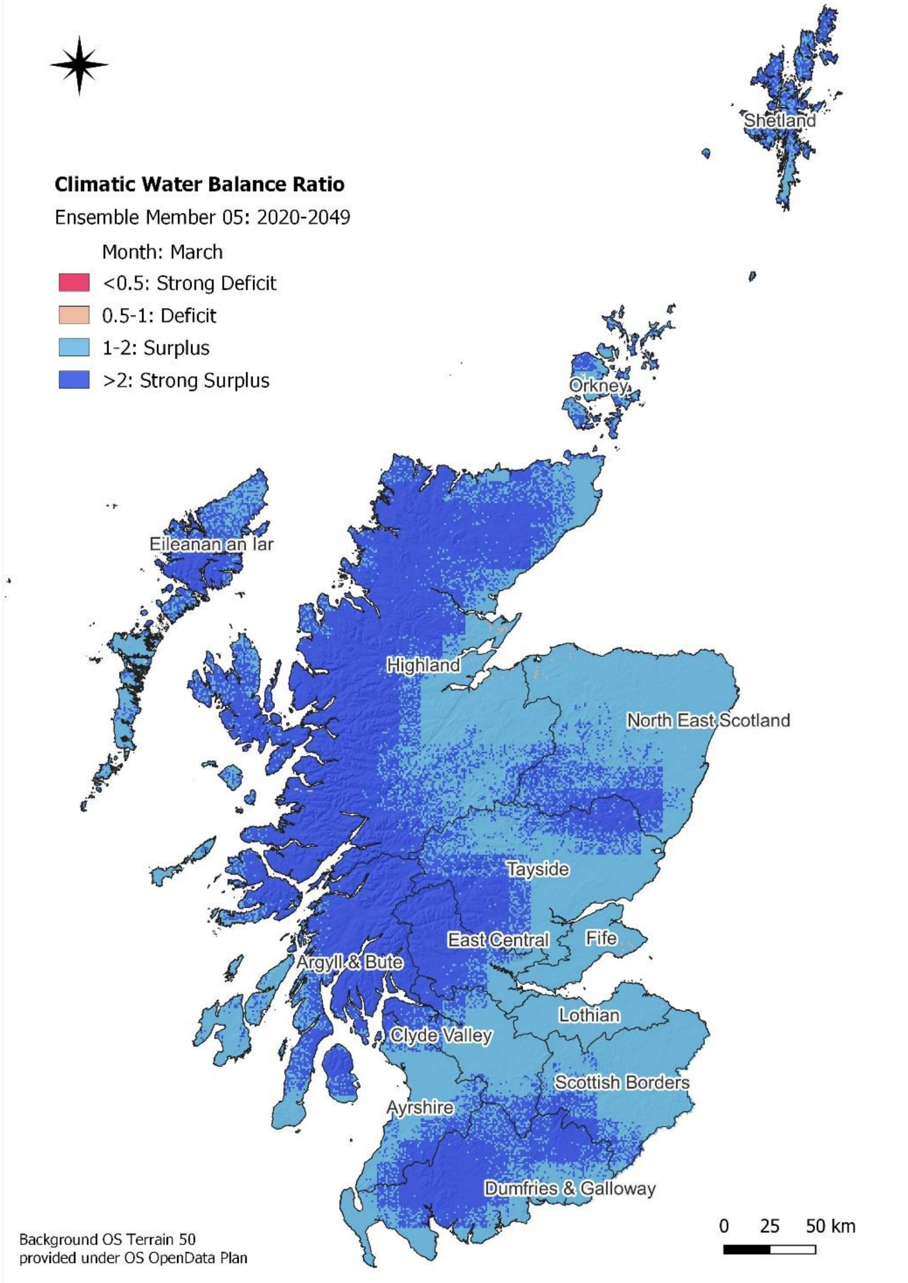


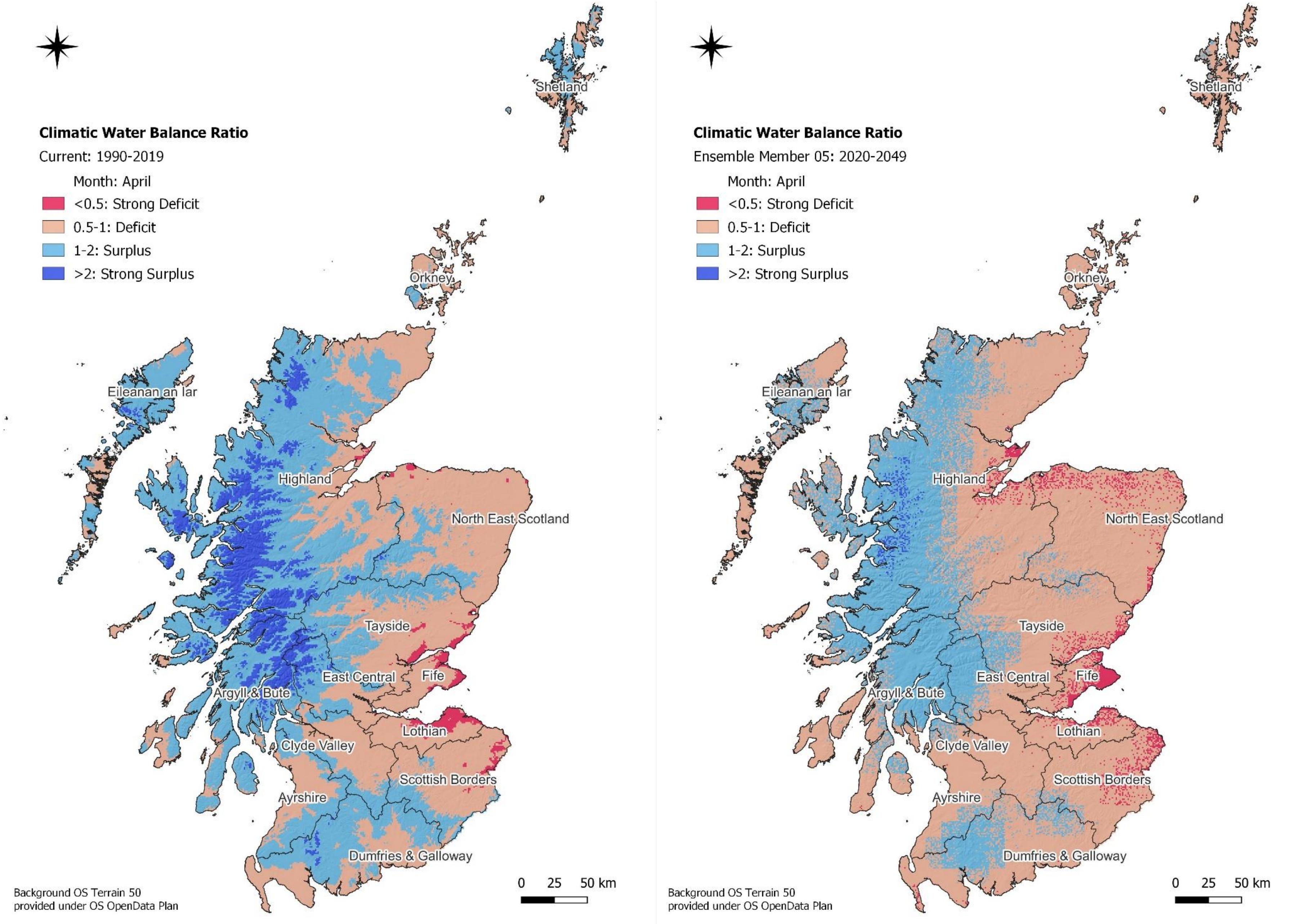
Climatic Water Balance Ratio
Ensemble Member 05: 2020-2049
Month: January
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Shetland
Orkney
Eileanan an Iar
Highland
North East Scotland
Tayside
East Central
Fife
Argyll & Bute
Lothian
Clyde Valley
Scottish Borders
Ayrshire
Dumfries & Galloway
0 25 50 km
Background OS Terrain 50
provided under OS OpenData Plan

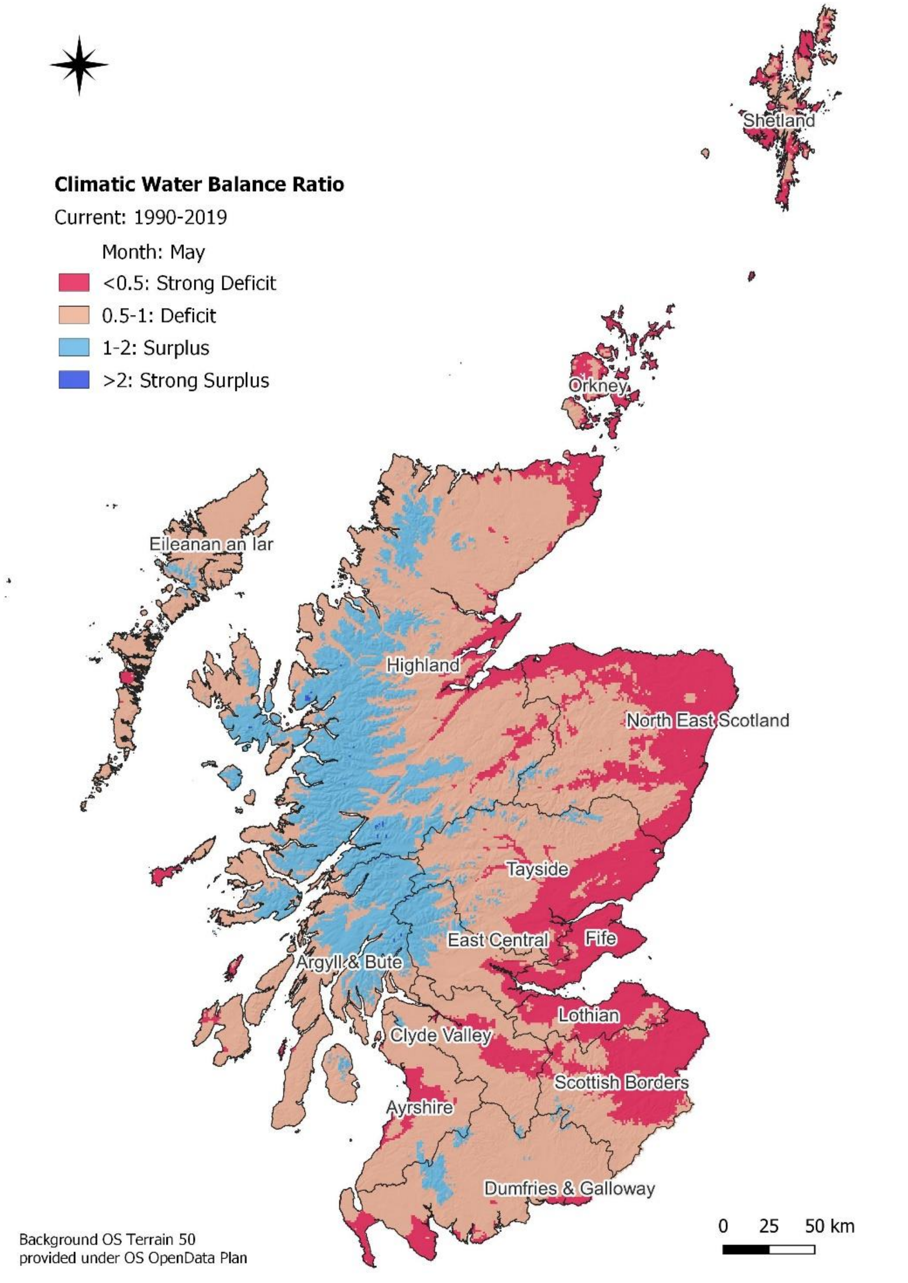

Shetland
Climatic Water Balance Ratio
Current: 1990-2019
Month: February
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Orkney
Eileanan an Iar
Highland
North East Scotland
Tayside
East Central
Fife
Argyll & Bute
Lothian
Clyde Valley
Scottish Borders
Ayrshire
Dumfries & Galloway
Background OS Terrain 50
provided under OS OpenData Plan
0 25 50 km


Shetland
Climatic Water Balance Ratio
Ensemble Member 04: 2020-2049
Month: February
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Orkney
Eileanan an Iar
Highland
North East Scotland
Tayside
East Central
Fife
Argyll & Bute
Lothian
Clyde Valley
Scottish Borders
Ayrshire
Dumfries & Galloway
Background OS Terrain 50
provided under OS OpenData Plan
0 25 50 km


Climatic Water Balance Ratio
Current: 1990-2019
Month: March
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Shetland
Orkney
Eileanan an Iar
Highland
North East Scotland
Tayside
East Central
Fife
Argyll & Bute
Lothian
Clyde Valley
Scottish Borders
Ayrshire
Dumfries & Galloway
0 25 50 km
Background OS Terrain 50
provided under OS OpenData Plan


Climatic Water Balance Ratio
Ensemble Member 05: 2020-2049
Month: March
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Shetland
Orkney
Eileanan an Iar
Highland
North East Scotland
Tayside
East Central
Fife
Argyll & Bute
Lothian
Clyde Valley
Scottish Borders
Ayrshire
Dumfries & Galloway
0 25 50 km
Background OS Terrain 50
provided under OS OpenData Plan


Climatic Water Balance Ratio
Current: 1990-2019
Month: April
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Shetland
Orkney
Eileanan an Iar
Highland
North East Scotland
Tayside
East Central
Fife
Argyll & Bute
Lothian
Clyde Valley
Scottish Borders
Ayrshire
Dumfries & Galloway
0 25 50 km
Background OS Terrain 50
provided under OS OpenData Plan
Climatic Water Balance Ratio
Ensemble Member 05: 2020-2049
Month: April
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Shetland
Orkney
Eileanan an Iar
Highland
North East Scotland
Tayside
East Central
Fife
Argyll & Bute
Lothian
Clyde Valley
Scottish Borders
Ayrshire
Dumfries & Galloway
0 25 50 km
Background OS Terrain 50
provided under OS OpenData Plan


Climatic Water Balance Ratio
Current: 1990-2019
Month: May
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Shetland
Orkney
Eileanan an Iar
Highland
North East Scotland
Tayside
East Central
Fife
Argyll & Bute
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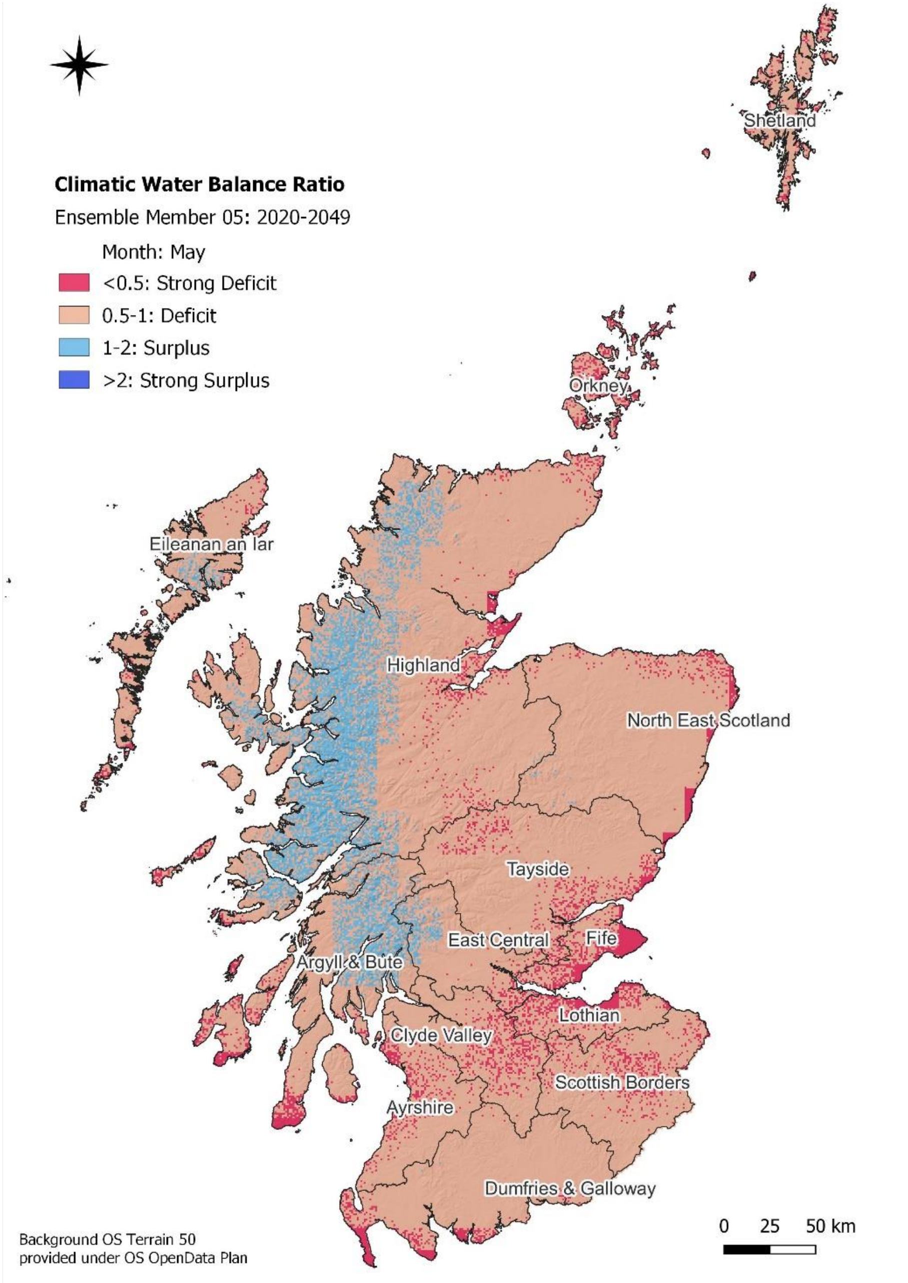
Clyde Valley
Scottish Borders
Ayrshire
Dumfries & Galloway
0 25 50 km
Background OS Terrain 50
provided under OS OpenData Plan


Climatic Water Balance Ratio
Ensemble Member 05: 2020-2049
Month: May
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Shetland
Orkney
Eileanan an Iar
Highland
North East Scotland
Tayside
East Central
Fife
Argyll & Bute
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Scottish Borders
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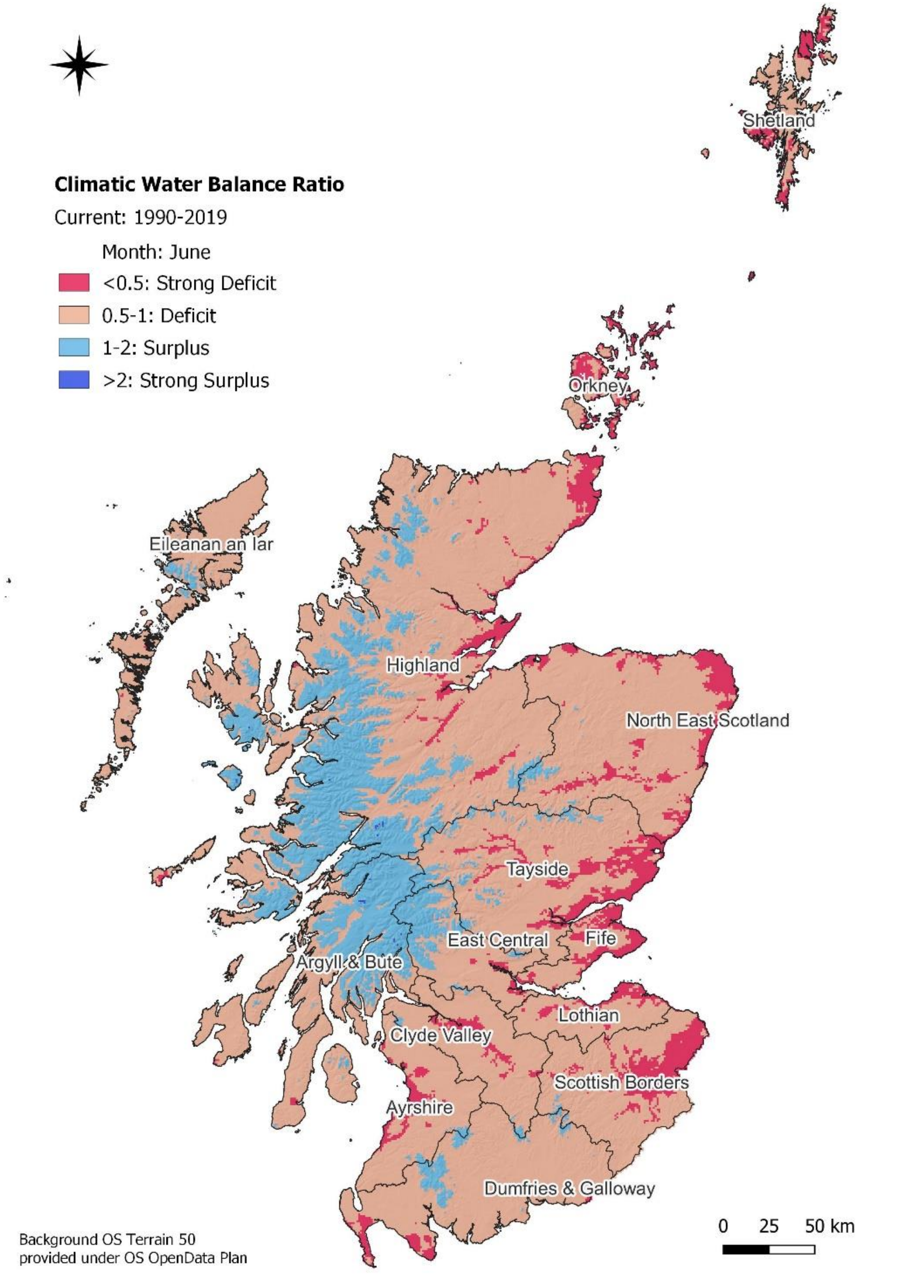
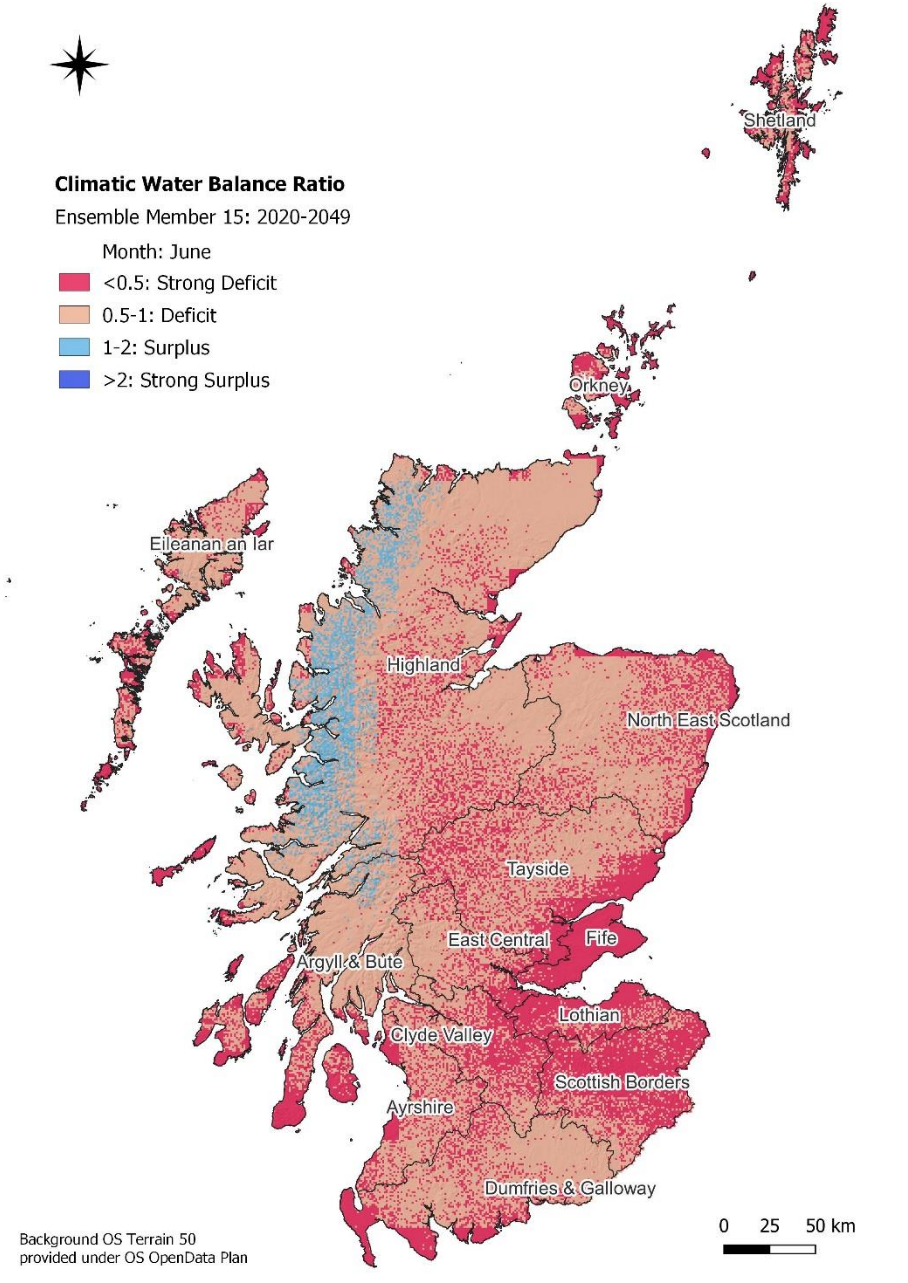
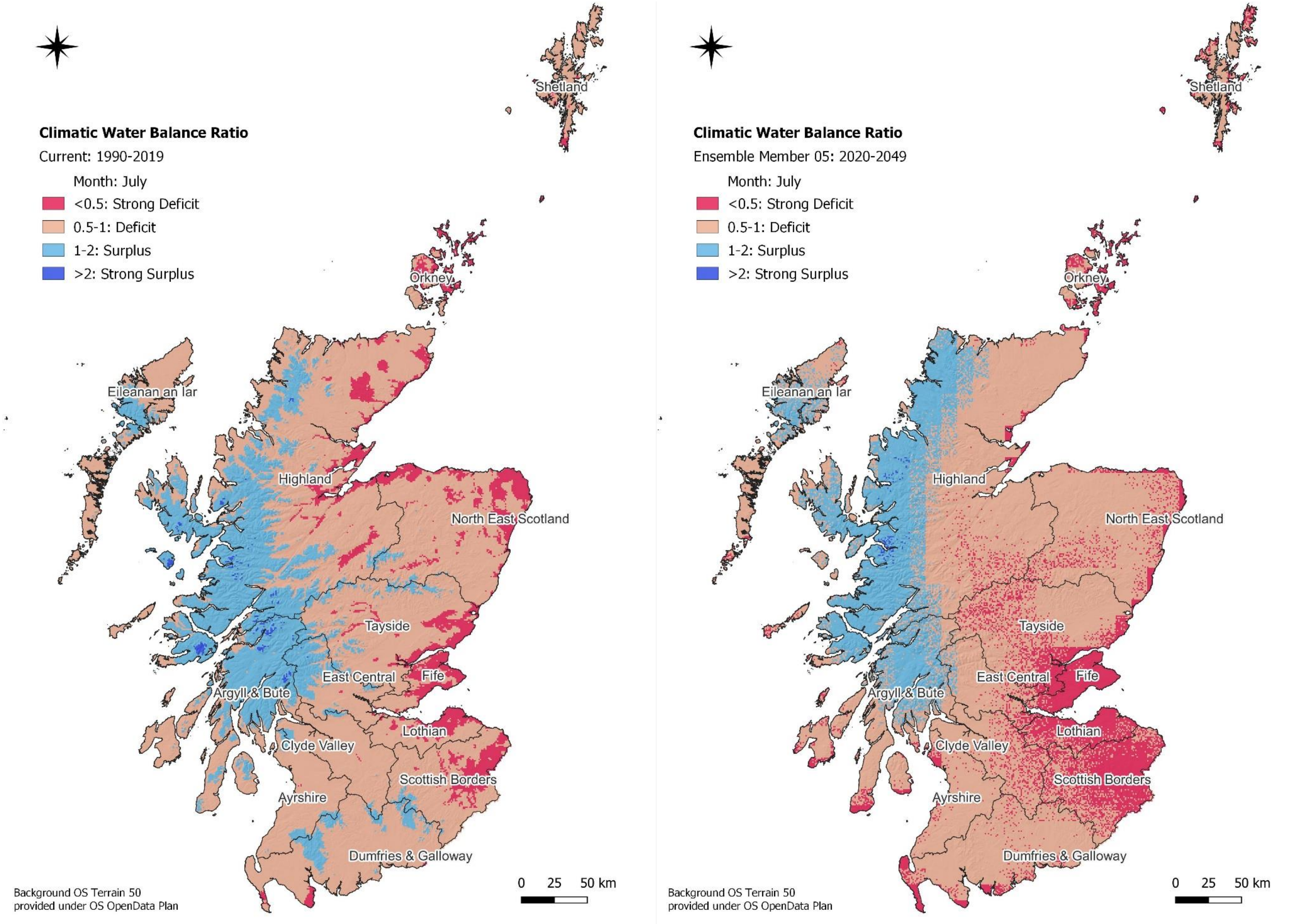
Dumfries & Galloway
0 25 50 km
Background OS Terrain 50
provided under OS OpenData Plan


Climatic Water Balance Ratio
Current: 1990-2019
Month: June
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Shetland
Orkney
Eileanan an Iar
Highland
North East Scotland
Tayside
East Central
Fife
Argyll & Bute
Lothian
Clyde Valley
Scottish Borders
Ayrshire
Dumfries & Galloway
0 25 50 km
Background OS Terrain 50
provided under OS OpenData Plan


Climatic Water Balance Ratio
Ensemble Member 15: 2020-2049
Month: June
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Shetland
Orkney
Eileanan an Iar
Highland
North East Scotland
Tayside
East Central
Fife
Argyll & Bute
Lothian
Clyde Valley
Scottish Borders
Ayrshire
Dumfries & Galloway
0 25 50 km
Background OS Terrain 50
provided under OS OpenData Plan


Climatic Water Balance Ratio
Current: 1990-2019
Month: July
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Shetland
Orkney
Eileanan an Iar
Highland
North East Scotland
Tayside
East Central
Fife
Argyll & Bute
Lothian
Clyde Valley
Scottish Borders
Ayrshire
Dumfries & Galloway
0 25 50 km
Background OS Terrain 50
provided under OS OpenData Plan
Climatic Water Balance Ratio
Ensemble Member 05: 2020-2049
Month: July
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Shetland
Orkney
Eileanan an Iar
Highland
North East Scotland
Tayside
East Central
Fife
Argyll & Bute
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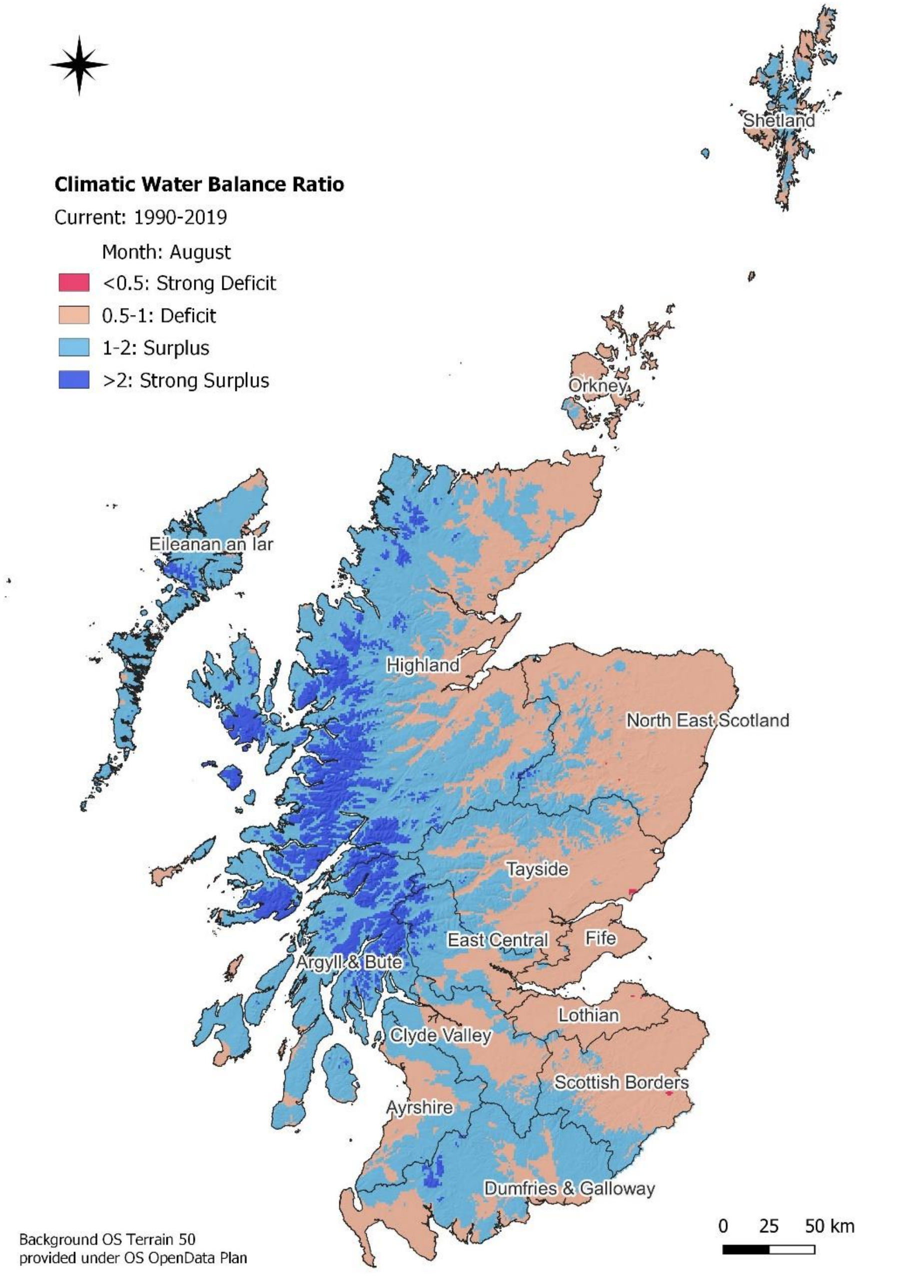
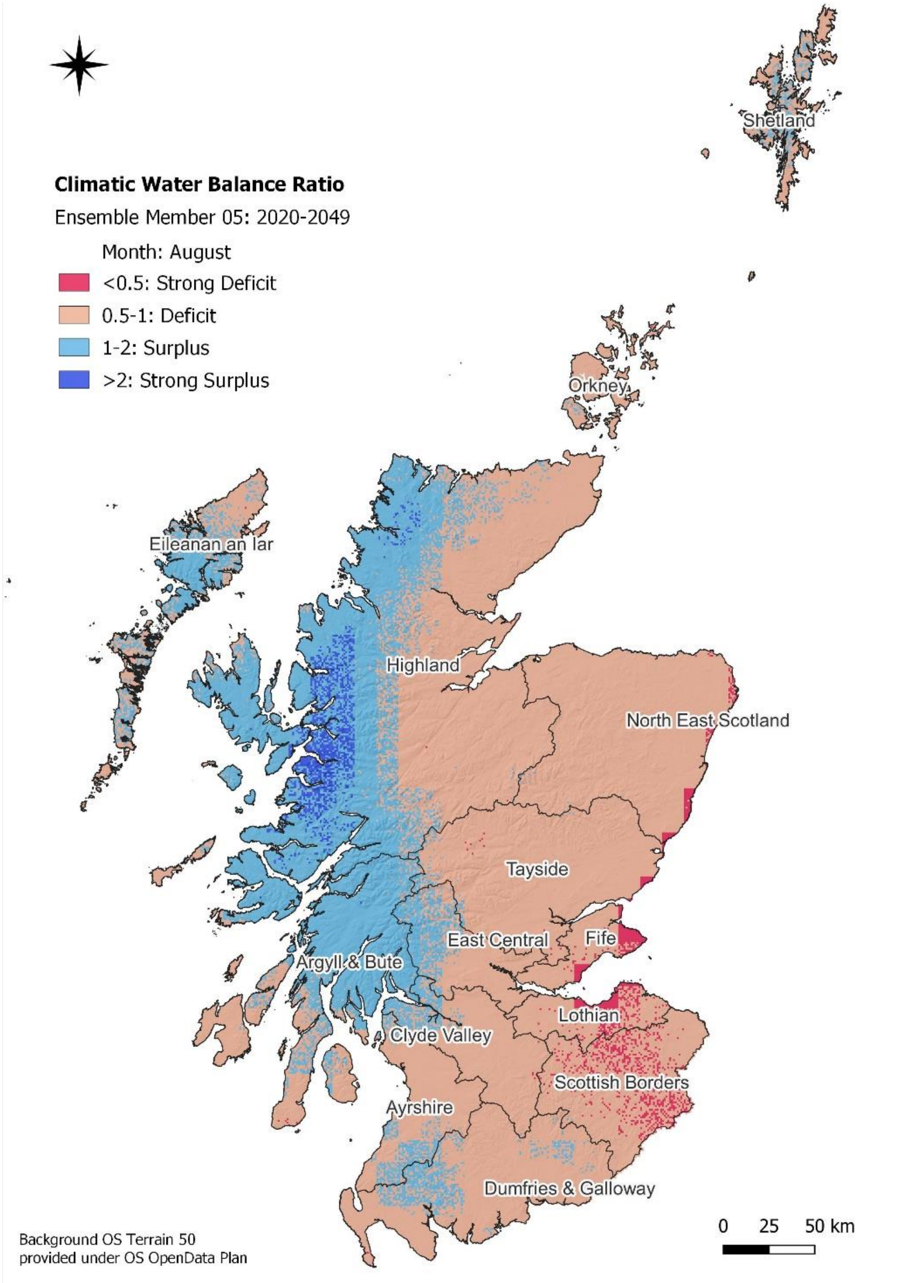
Background OS Terrain 50
provided under OS OpenData Plan


Climatic Water Balance Ratio
Current: 1990-2019
Month: August
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Shetland
Orkney
Eileanan an Iar
Highland
North East Scotland
Tayside
East Central
Fife
Argyll & Bute
Lothian
Clyde Valley
Scottish Borders
Ayrshire
Dumfries & Galloway
0 25 50 km
Background OS Terrain 50
provided under OS OpenData Plan


Climatic Water Balance Ratio
Ensemble Member 05: 2020-2049
Month: August
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Shetland
Orkney
Eileanan an Iar
Highland
North East Scotland
Tayside
East Central
Fife
Argyll & Bute
Lothian
Clyde Valley
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Ayrshire
Dumfries & Galloway
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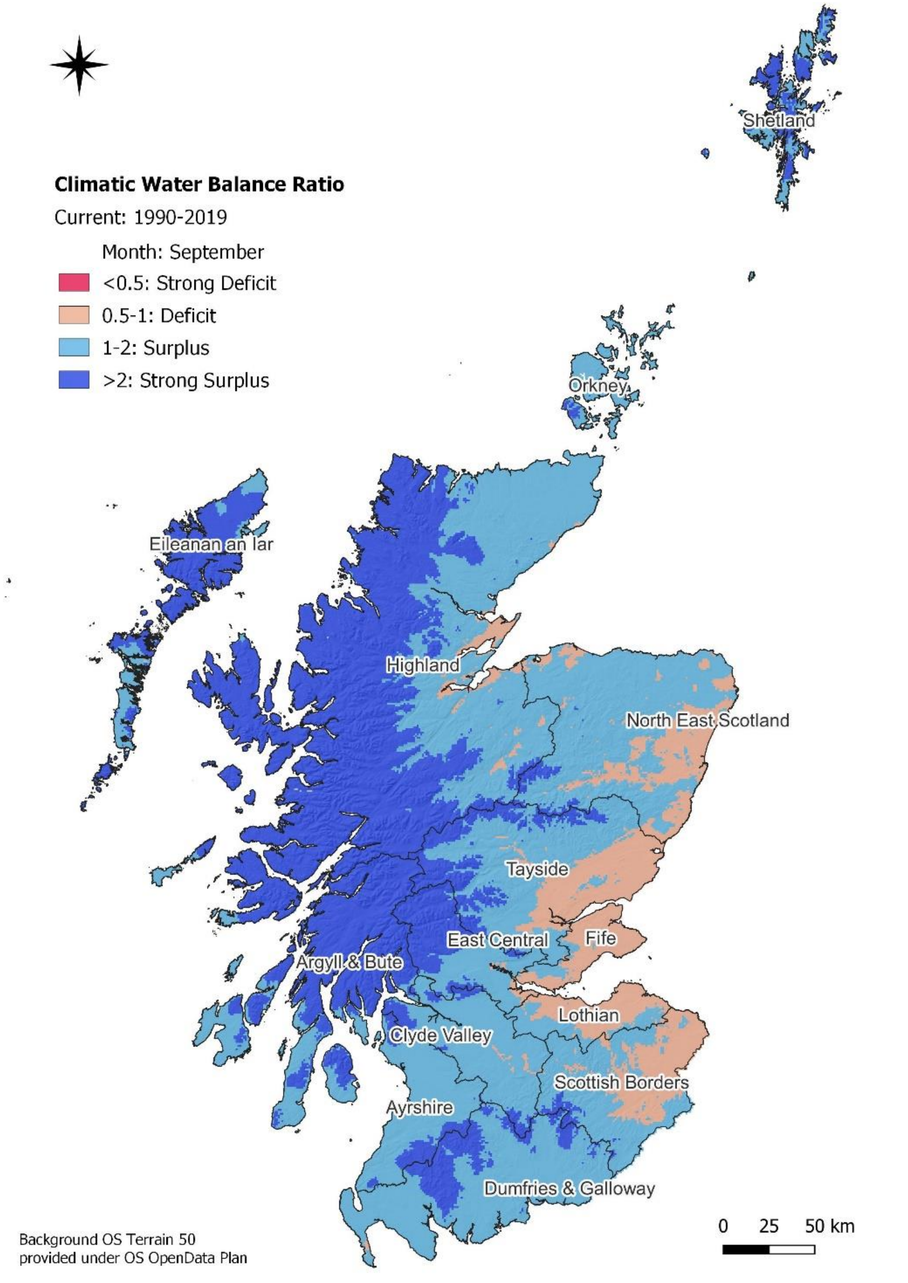
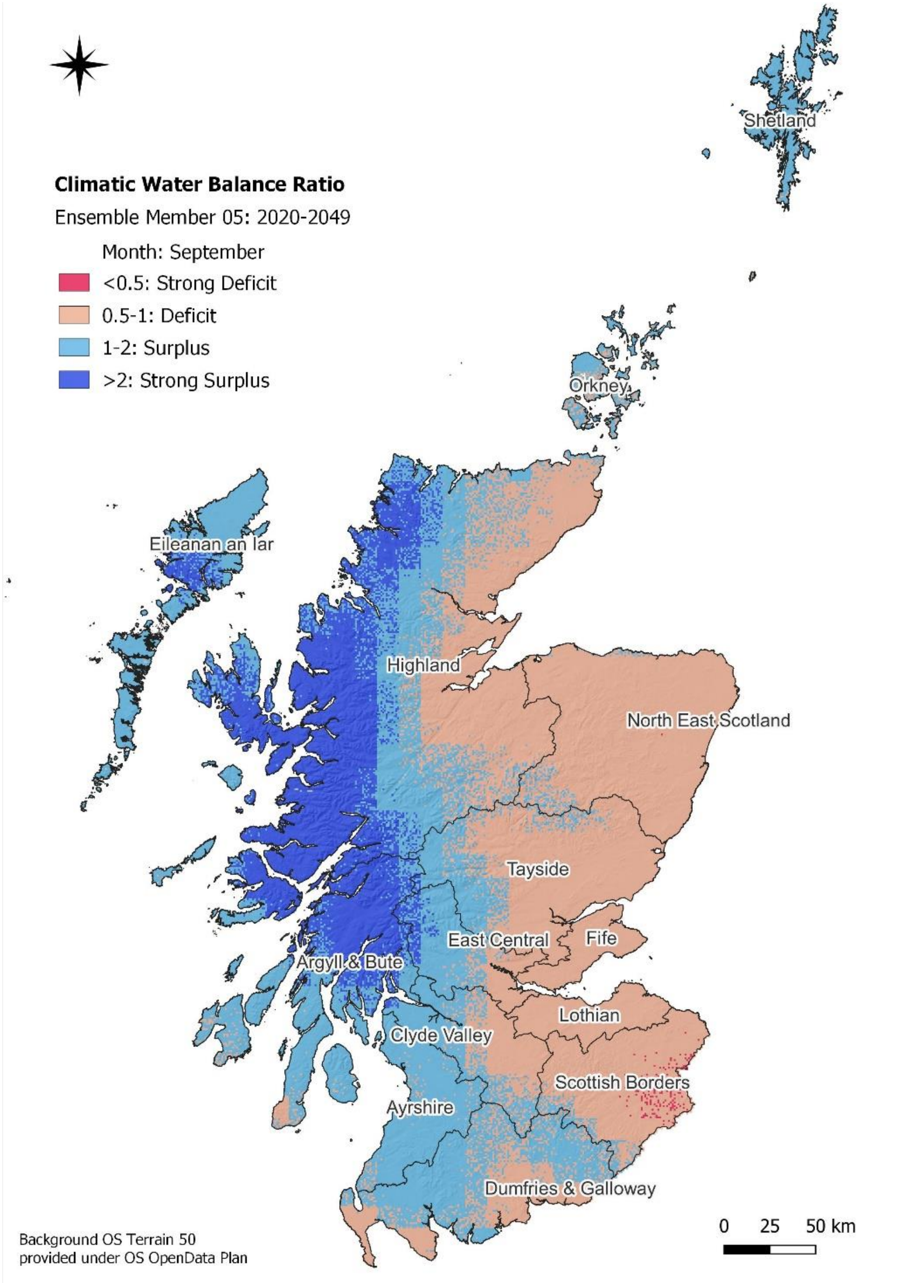
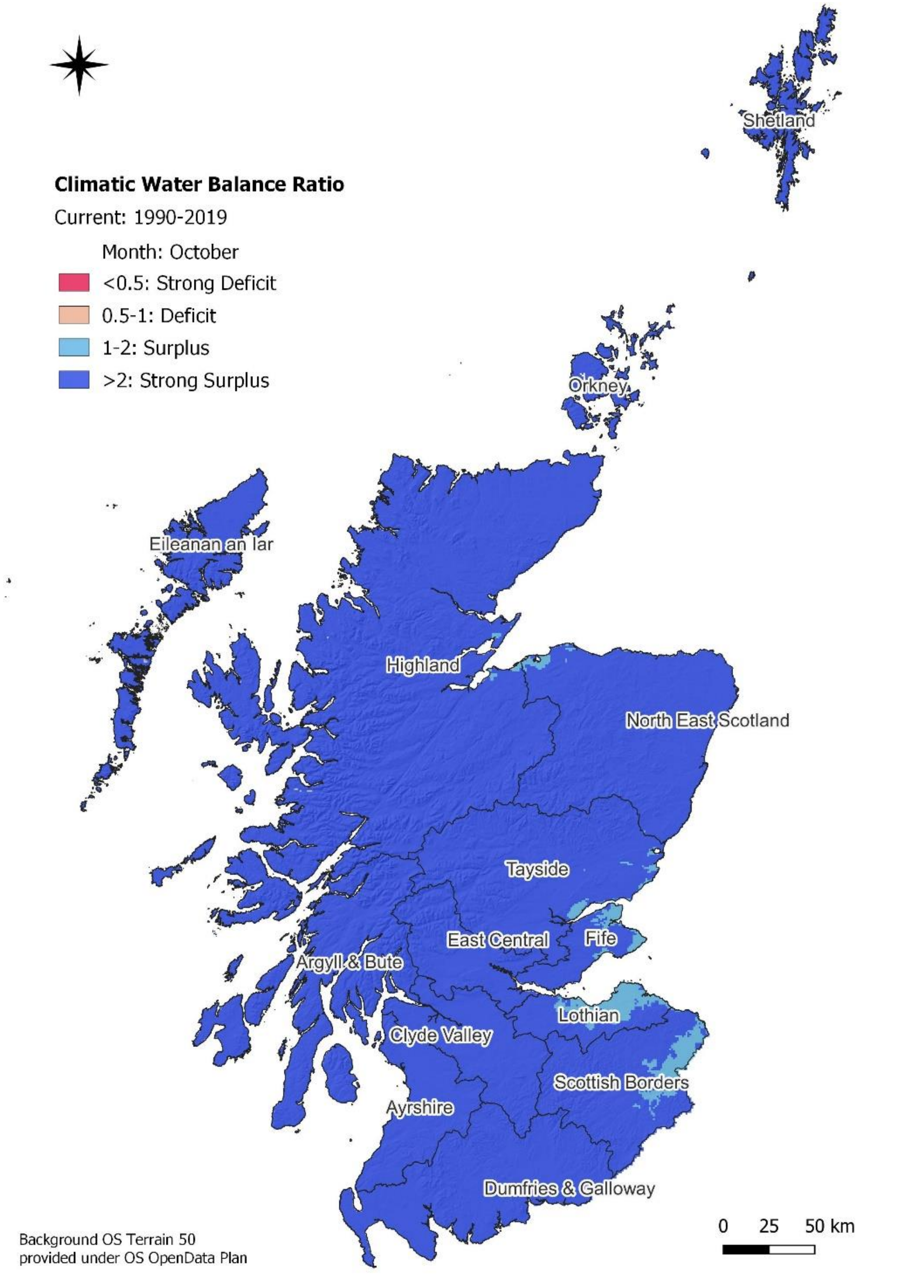
Background OS Terrain 50
provided under OS OpenData Plan


Climatic Water Balance Ratio
Current: 1990-2019
Month: September
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Shetland
Orkney
Eileanan an Iar
Highland
North East Scotland
Tayside
East Central
Fife
Argyll & Bute
Lothian
Clyde Valley
Scottish Borders
Ayrshire
Dumfries & Galloway
0 25 50 km
Background OS Terrain 50
provided under OS OpenData Plan


Climatic Water Balance Ratio
Ensemble Member 05: 2020-2049
Month: September
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Shetland
Orkney
Eileanan an Iar
Highland
North East Scotland
Tayside
East Central
Fife
Argyll & Bute
Lothian
Clyde Valley
Scottish Borders
Ayrshire
Dumfries & Galloway
0 25 50 km
Background OS Terrain 50
provided under OS OpenData Plan


Shetland
Climatic Water Balance Ratio
Current: 1990-2019
Month: October
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Orkney
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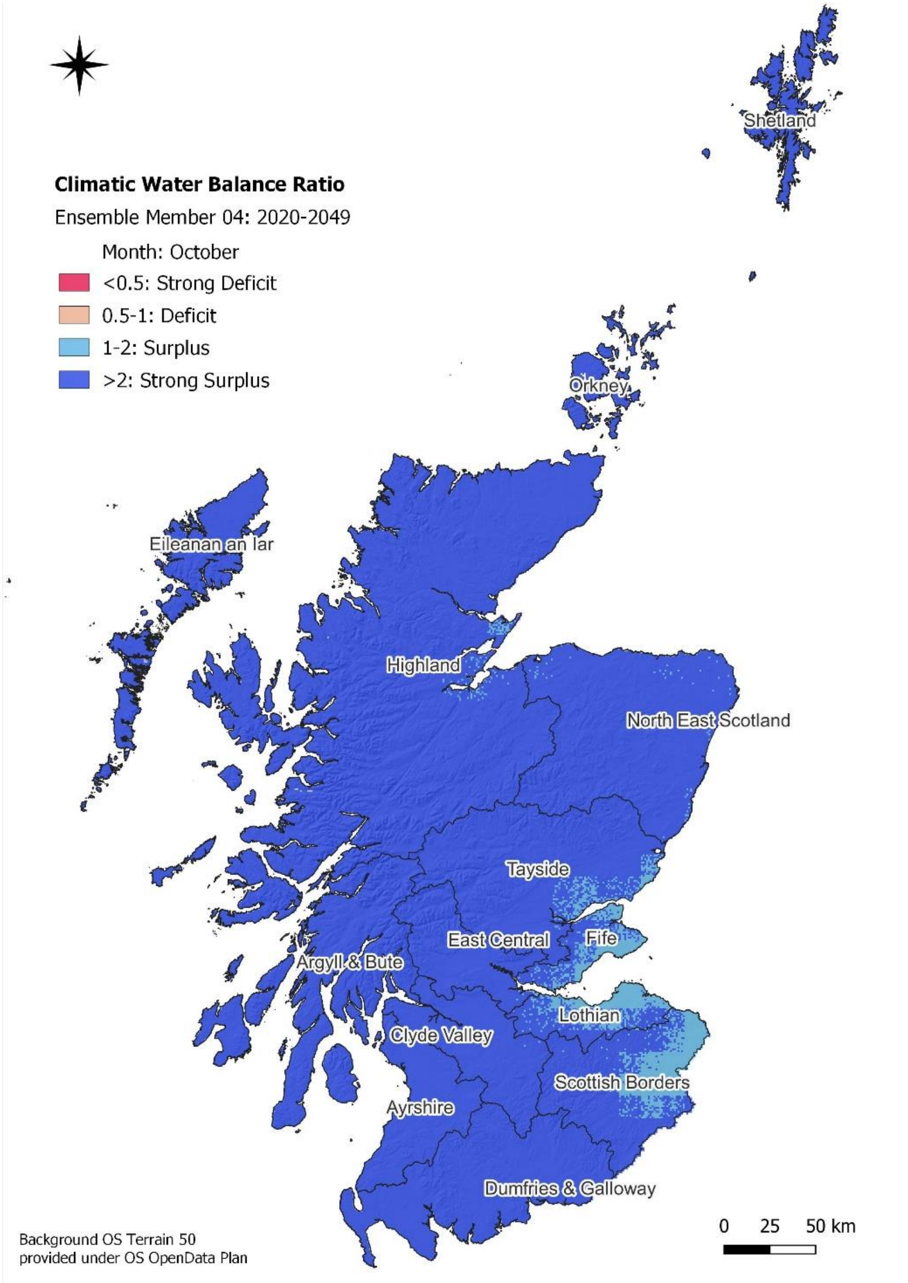
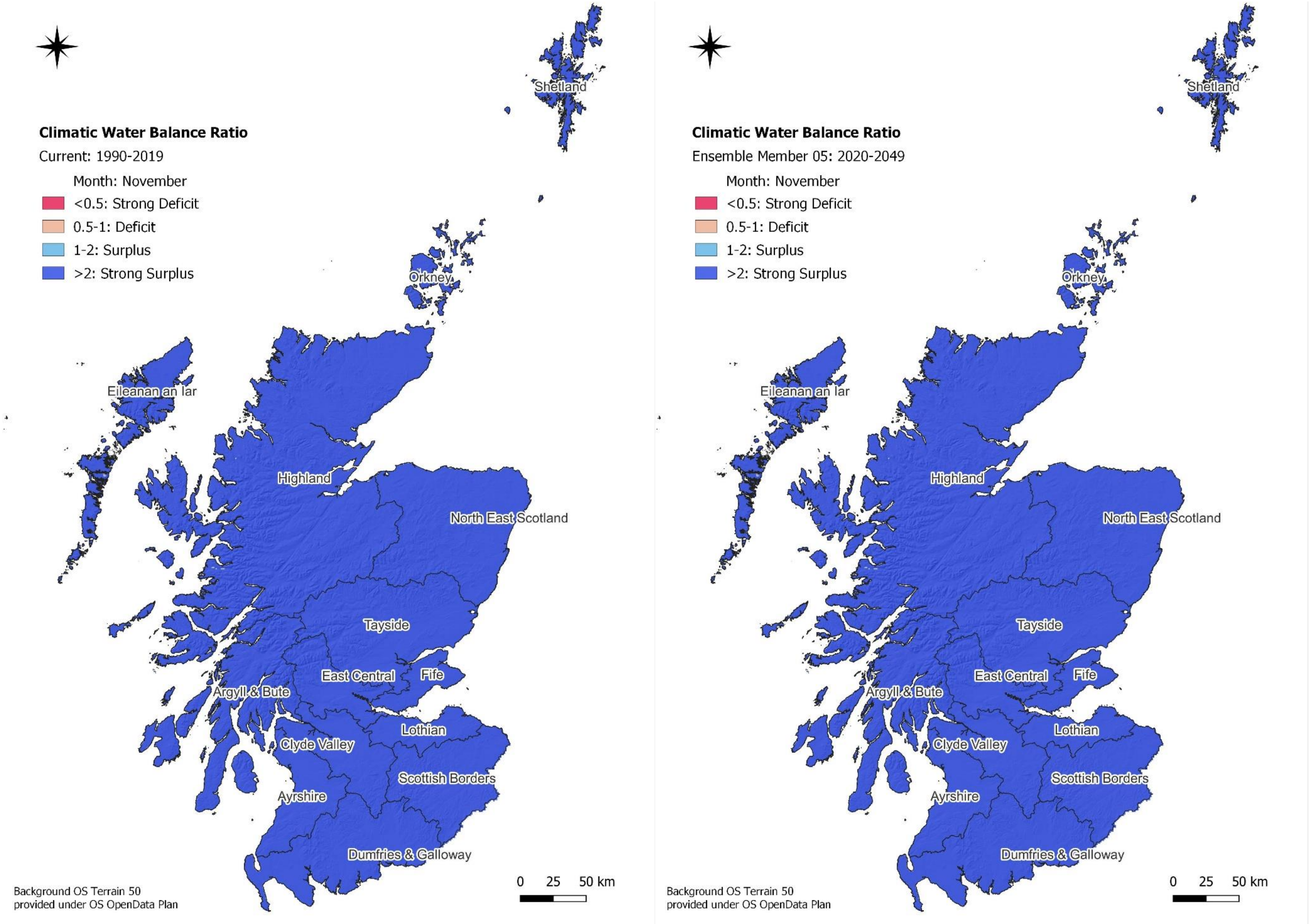
Argyll & Bute
Lothian
Clyde Valley
Scottish Borders
Ayrshire
Dumfries & Galloway
0 25 50 km
Background OS Terrain 50
provided under OS OpenData Plan


Shetland
Climatic Water Balance Ratio
Ensemble Member 04: 2020-2049
Month: October
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Orkney
Eileanan an Iar
Highland
North East Scotland
Tayside
East Central
Fife
Argyll & Bute
Lothian
Clyde Valley
Scottish Borders
Ayrshire
Dumfries & Galloway
0 25 50 km
Background OS Terrain 50
provided under OS OpenData Plan


Climatic Water Balance Ratio
Current: 1990-2019
Month: November
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Shetland
Orkney
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Argyll & Bute
Lothian
Clyde Valley
Scottish Borders
Ayrshire
Dumfries & Galloway
0 25 50 km
Background OS Terrain 50
provided under OS OpenData Plan
Climatic Water Balance Ratio
Ensemble Member 05: 2020-2049
Month: November
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Shetland
Orkney
Eileanan an Iar
Highland
North East Scotland
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Argyll & Bute
Lothian
Clyde Valley
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Background OS Terrain 50
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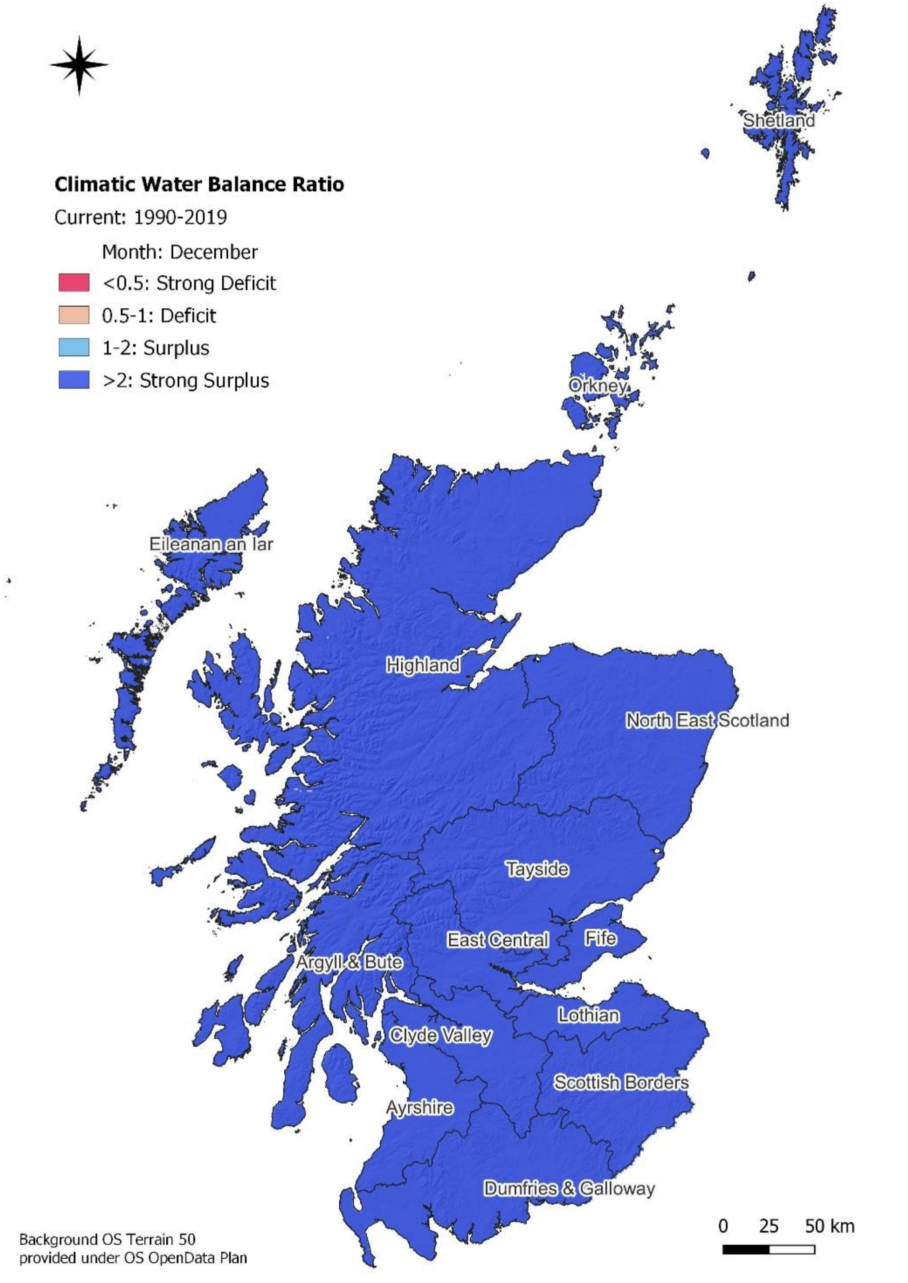
Climatic Water Balance Ratio
Current: 1990-2019
Month: December
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
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Shetland
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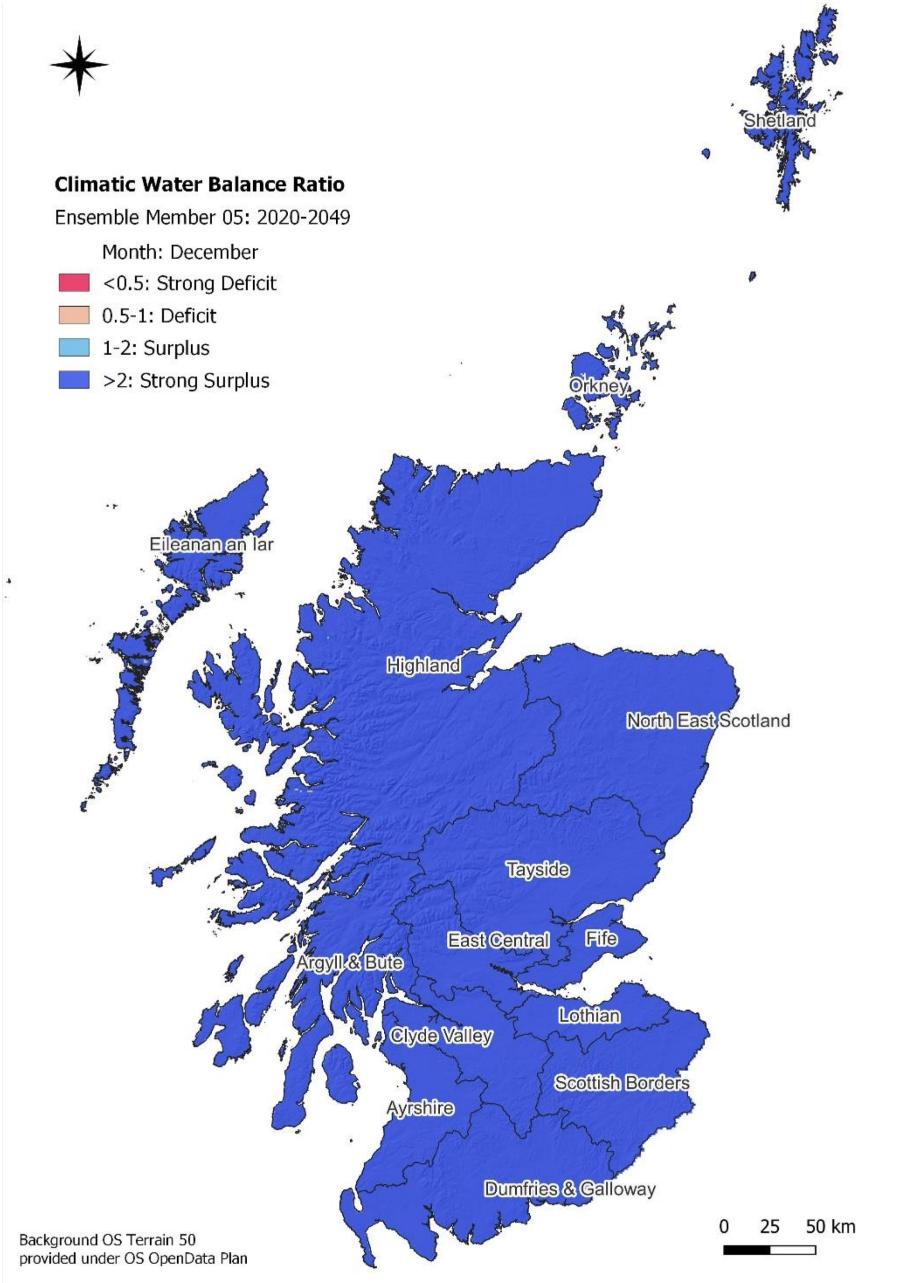
Climatic Water Balance Ratio
Ensemble Member 05: 2020-2049
Month: December
<0.5: Strong Deficit
0.5-1: Deficit
1-2: Surplus
>2: Strong Surplus
Shetland
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The James Hutton Institute