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The Land Capability for Agriculture: building a tool to enable climate change assessments

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March 2022

DOI: http://dx.doi.org/10.7488/era/2224

Executive summary

Aims

The Land Capability for Agriculture (LCA) classification for Scotland has been used since the 1980s to inform decision-making on land use management, planning and valuation.

The risks and opportunities posed by climate change mean we need to be able to understand how land capability may change in the future, and what this means in terms of developing adaptation responses and policies that mitigate negative impacts and support opportunities.

This report explores the potential for a new research tool to estimate land capability under future climatic conditions - the Land Capability of Scotland research platform. Development in this project has been based on the original LCA guidelines. The platform is a set of computing tools (not PC based) for data integration, calculation, analysis, mapping and visualisation, allowing models to be run to estimate land capability constraints and generate digital maps.

The Land Capability research platform is designed to be a 'risk and opportunities assessment' tool operated by researchers; the Land Capability of Scotland research platform does not replace the existing published LCA classifications.

The platform has initially been developed to produce estimates of Land Capability for Agriculture under different climate change projections and has further potential to support research on a broad range of land uses and benefits, such as forestry and ecosystem services.

Findings

- The original LCA guide has been successfully coded and computing structures implemented, integrating multiple spatial data sets and modelling tools to

estimate the individual constraints that determine the LCA and its overall classification.

- A key challenge is the ability to model soil water balance appropriately. A soil water balance model was implemented within the platform, but further work is required to better calibrate the model and validate the estimates. For example, errors have been identified for some locations which are due to the difficulty in accurately simulating soil water balance.
- Initial analysis between two baseline periods indicates that climate change has already altered land capability and is likely to further impact it in both positive and negative ways in the future. These changes have been and will continue to be spatially and temporally variable. Two primary climatic factors are used in the LCA:
    1. Temperature – that is the amount of energy from the sun as input to land (represented by the accumulation of temperature).
    2. How dry a soil might become (the Potential Soil Moisture Deficit, PSMD).

  Application of the platform shows that both factors will be affected by climate change, meaning some soils are likely to become drier due to reduced rainfall and increased evapotranspiration (water returned to the atmosphere from plants and surfaces, e.g. soil), whilst others could potentially get wetter.
- Reduced water availability is likely to be a key determining factor. Initial analysis suggests that soils, especially those with a low water holding capacity, are likely to become drier and with greater frequency. This means there is a risk of increased amounts of soil moisture deficit, meaning less water available for plants and more rain is needed to fill the soil profile up again.
- This implies an increased risk of crops, grassland and vegetation experiencing difficulties in accessing water. The LCA and constraint maps indicate where this may occur.
- There is a substantial risk that land currently classed as prime agricultural land (classes 1 – 3.1) may experience reduced production capability due to dry soils in an increasing number of years with drought conditions.
- Conversely, potentially areas such as the north-west Highlands may experience increased precipitation totals in some years, meaning soils there becoming wetter.
    - The climate is projected to become more variable, hence a likelihood of fluctuations in a particular location experiencing dry and wet periods during the growing season.
    - Warmer temperatures will mean a more rapid accumulation of temperature. The rate of accumulation determines when plants and insects progress through their development stages (phenology), meaning crops may take less time to mature, but also not have as much time to accumulate biomass.
- There is likely to be increased annual variability in land capability associated with increasing climatic variability and extreme events, such as wet seasons or years followed by dry ones.
- The platform development has been a ‘learning by doing’ iterative process, and further improvements are possible to increase the efficiency of calculations and generation of analysis outputs. The research platform will continue to be used and developed in the Scottish Government’s 2022-2027 Strategic Research Programme.

Contents

Abbreviations

ATo	Accumulated temperature
FC	Field Capacity (amount of water a soil can hold against gravity)
FCD	Field Capacity Days (number of days per year when soil water is at or above field capacity).
GIS	Geographical Information System
HPC	High Performance Computer
LCA	Land Capability for Agriculture classification system
LCF	Land Capability for Forestry classification system
MORECS	Meteorological Office Rainfall and Evaporation Calculation System
PSMD	Potential Soil Moisture Deficit
SSKIB	Scottish Soils Knowledge Information Base
SP	Saturation Point (maximum amount of water a soil can hold)
SWB	Soil Water Balance
UKCP18	UK climate projections 2018

Glossary

Term	Definition
Droughtiness	The vulnerability of soils to drought, assessed for a range of crops by calculating the available water reserve. Refer to page 34 and Figure 4 in Bibby et al (1991).
Evapotranspiration	Water evaporated to the atmosphere from plants (transpiration) and from surfaces such as soils.
Field Capacity	The maximum water amount (in mm) a soil can hold against gravity.
Gleyed/ gleying	A feature of soils that are developed under conditions of intermittent or permanent waterlogging. See: Gleys | Soils | Exploring Scotland | The James Hutton Institute
LCA constraints	The extent to which the interactions of biophysical factors such as Climate, soil, vegetation, Erosion risk, flood risk is unfavourable to crop growth and land management.
Permanent Wilting Point (PWP)	The degree of soil dryness that means plants cannot access water, become wilted and are unable to recover from.
Poaching risk	Damage risk to soils due to livestock trampling
Potential Soil Moisture Deficit	This is the accumulated deficit of the balance between rainfall and evapotranspiration.
Remote sensed	Use of satellite or other remote means to collect spatial data.
Trafficability	The assessment of the risk of moving field machines and animals across the land without causing any long-term structural damage to the soil.
Wetness	How wet a soil is, affecting workability, trafficability and poaching risk, as well as effects on plants from waterlogging and flood risk.
Workability	Refers to the ability to undertake soil management, being a function of soil physical properties, wetness, water retention and climate.

1 Introduction

Climate change is altering the physical and biological processes that determine land capability for many different purposes, including agriculture. Climate model simulations for Scotland indicate that there are likely to be changes in the amount of precipitation and its spatial and temporal distribution, with longer and more frequent dry periods and intense rainfall events expected. Temperature is projected to increase, implying increased loss of surface and soil water to the atmosphere through evapotranspiration (water transpired by crops and evaporated from surfaces). Thus energy input to land and the amount and timing of water available are likely to change.

The fundamental links between energy and water are the basis for determining the capability of land to support agriculture and other land uses. There is therefore a need to develop research tools that assess risks and opportunities arising from changes in biophysical conditions and how this determines land capability. Such tools will help provide evidence for policy support and adaptation within agriculture, the food system and management of ecosystems for wider environmental benefits.

This report presents the results of a research project to develop new capabilities and explore possible future land capability under climate change projections. The research builds on the long-standing Land Capability for Agriculture classification system (LCA). The purpose of the project was not to replace the original LCA, rather to use the classification guidelines and methods to produce a research platform to enable initial assessments of climate change impacts on land capability for agriculture. This new computer-based platform means that new research questions can be applied (i.e. how will land capability change under different climate projections; where in Scotland may be more or less impacted; what climatic factors drive the changes and how?) and enable further developments in research and analytical capabilities to be made.

1.1 Project aim

The aim of this project has been to transfer the existing Land Capability for Agriculture classification system for Scotland (MISR 1982, Bibby et al 1991) to a computing platform. This computer-based platform allows the integration of new data, modelling tools and computing resources alongside climate projections to inform our understanding of the impact of a changing climate on land capability in Scotland. The LCA classification system is summarised in Section 2 and detailed in Appendix A.

There have been several significant changes since the LCA was developed in the 1980s:

- Observed changes in climate;
- Improvements in data availability and increased computing capability; and
- Corresponding opportunities to integrate data to enable modelling and high-resolution spatial simulations.

Land use objectives have also changed over time, with an increasing interest in the multiple benefits from land beyond just agriculture, particularly for carbon sequestration purposes (i.e. woodland creation) to help achieve net zero emissions targets whilst benefitting other ecosystem services.

The project was designed to assess the future LCA conditions, following these key steps:

- Develop a computer-based research platform to integrate new spatial data to enable repeatable estimation of the classification criteria.
    - Generate new data sets of LCA constraints for detailed analytical purposes.
    - Design the platform to enable land capability for other objectives such as forestry and ecosystem services.
- Producing digital maps and an underpinning database of estimated criteria values to enable detailed research at a high spatial resolution.
- Estimating the LCA classes using historical climate data to detect trends in changes of classifications.
    - Understand how changes in individual constraints have changed.
- Using future climate projections to estimate changes in land capability classification.
    - Improve understanding of how land capability constraints may change in the future.
- Informing policy and land management stakeholders of early results on how land capability may change.

It is important to note that it was not the aim of the project to replace the original LCA system or maps.

2 Land capability mapping and land use policy

2.1 The origins of Land Capability for Agriculture

The Land Capability for Agriculture system was first developed and used in Scotland in the early 1980s. It was developed primarily for agricultural productivity, to help identify where land management had the potential to improve land capability for agriculture. The system was less concerned with other environmental considerations (i.e. what we now refer to as ecosystem services). The new overall research platform has been developed to recognise broader aspects of land capability.

2.1.1. The classification system

The LCA classifies land according to the limitations imposed on it by six physical and biological factors which affect agriculture:

- Climate
- Gradient
- Soil
- Wetness
- Erosion
- Vegetation

Land is ranked based on its potential productivity, cropping flexibility and ease of management. The climate controls energy and moisture supply for plant growth and so provides the biophysical conditions within which other factors interact. Flexibility of cropping determines the extent to which farmers and growers can respond to market and policy conditions.

Table 1 sets out the original descriptions for the LCA classes, which were determined in the field through surveyors' application of a set of guidelines (MISR 1982, Bibby et al

1991) to produce hand-drawn maps. Appendix A Table 4 provides a full description of the classes.

Table 1. Land Capability for Agriculture classes (note: a full description is provided in Appendix A Table 4)

Class	Description
Land suited to arable cropping	
1	*Land capable of producing a very wide range of crops.*
2	*Land capable of producing a wide range of crops*.
3.	*Land capable of producing a moderate range of crops*.
3.1	Division 1 land is capable of producing consistently high yields of a narrow range of crops and /or moderate yields of a wider range.
3.2	Division 2 land is capable of average production but high yields of some crops grass, barley and oats are often attained.
4	*Land capable of producing a narrow range of crops*.
4.1	Land in this division is suited to rotations
4.2	Land is primarily grassland with some limited potential for other crops.
Land suited only to improved grassland and rough grazing	
5	*Land capable of us as improved grassland*.
5.1	*Land well suited to reclamation and to use as improved grassland.*
5.2	*Land moderately suited to reclamation and use as improved grassland.*
5.3	*Land marginally suited to reclamation and use as improved grassland.*
6	*Land capable of use only as rough grazing*.
6.1	*High grazing value.*
6.2	*Moderate grazing value*
6.3	*Low grazing value.*
7	*Land of very limited agricultural value*.

The original LCA classification is based on climatic datasets for periods between 1958 – 1978 (1965 -1973 for wind) which is termed the climate reference period for the LCA. This data thus has implications from a climate change perspective, as the LCA classification is sensitive to the climate reference period applied to estimate capability classes (Hudson and Bernie 2000, Brown and Castellazzi 2015).

2.1.2 Practical application of LCA

Though not part of the design considerations, the original land capability mapping was found to be beneficial for environmental and amenity planning (e.g. by local authorities), and to assess the financial value of agricultural land (e.g. by land agents). As such, there is anecdotal evidence to suggest land capability classification has supported broader planning and land use decision making. Consequently, the original LCA remains a valuable tool to policymakers, and agricultural, forestry, economic and environmental stakeholders. Because of this use, we re-emphasis here that the Land Capability platform is not a replacement of the original LCA.

2.1.3 Climate change policy and the LCA

Understanding where and how the climate is changing, and the potential influences on land use, can help to inform the development and implementation of agricultural and environment policies. The Climate Change (Scotland) Act (2009) and subsequent Climate Change (Emissions Reduction Targets) (Scotland) Act 2019[1] commits Scotland to reduce GHG emissions by 75% by 2030 and reach net zero by 2045 (from 1990 levels). The land use sector has a key role to play in reducing emissions and understanding land capability in a changing climate will be particularly useful.

Spatial analysis and planning tools have been identified as a key need for emissions reduction by the UK Government (HMG 2021)[2]. Understanding land capability change may help inform a number of land related policies, including the implementation of the second Scottish Climate Change Adaptation Programme (SCCAP 2021) and the Scottish Forestry Strategy (SFS 2019) under the Forestry and Land Management (Scotland) Act 2018.

3 Differences between the original LCA and the platform

It is important to note that there are significant differences between the original LCA classifications and those produced by the computer-based platform developed in this project. There are several key reasons for these differences, including:

- The original LCA is a set of written guidelines that enabled field surveyors to make objective assessments based on set criteria and their expertise to determine the limiting factors to land capability for agriculture, using climate and soils data available at the time.
- This project has implemented the guidelines as computer code, hence the objective process has been captured, but not the location-specific expert assessment.
- The platform uses current digital input data to determine constraints and class values. These are new, more recent and detailed data, representing higher resolution spatial and temporal scales (e.g. daily, 1km climate data).

As such, there are substantial differences in the input data used (Table 2). These differences mean that it is not meaningful to undertake direct comparisons between the

[1] Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 (legislation.gov.uk)

[2] "Develop the tools and capabilities to inform land-use decisions and policy interventions at national and local scales, including research on green financing, economic values of protected landscapes and monitoring and evaluation of landscape policies" HMG (2021) Figure 23, p113.

original LCA maps and platform outputs. However, the original LCA maps do provide an important 'sense check' baseline against which to check the platform outputs.

Table 2. Differences in data use and implementation between original LCA and computing platform versions.

Inputs	**Original LCA**	**Computing platform**
Climate data	Limited number of meteorological stations with 20-year records for precipitation, temperature (1958-78) and wind (1965-73), whilst wetness classes based on 1941-71.	1km resolution daily spatially interpolated observed precipitation, maximum and minimum temperature (1960-2018), solar radiation (derived from satellite observations for 1994-2020, and estimated using Machine Learning from 1960-1994), wind (MORECS[3] covering 1960-2017). There have been detectable changes in the climate since the 1958-78 original period.
Estimation of climatic constraints	Accumulated temperature (*ATo*) and maximum potential soil moisture based on limited climatic data. Soil wetness class was generally based on field observations.	*ATo* and maximum PSMD estimated using a daily time step soil water balance model and 1km resolution daily time-step climate data. Soil wetness classes estimated from soil water balance model run using soil database details.
Potential soil moisture deficit (PSMD)	This was a climatic constraint only and used an 'ideal' soil (loamy, free draining, no limitation to water) and had simplistic 'bucket' approach to calculate evaporation.	Evapotranspiration and soil water balance estimated on a daily basis, to determine PSMD.
Soils data	1:25,000 soil series maps	National Soils Inventory / SSKIB database, based on original 1:250,000 soil series, update through resampling.
Topography	Ordnance Survey relief maps (50m contours)	Digital Elevation Model (10m contours). Note: currently no areas above any specified elevation have been excluded e.g. mountain tops.
Guideline application	Based on surveyors skilfully applying the guidelines in an objective way (hence standardisation between surveyors).*	Guidelines implemented within computer code, but it has not been possible to factor in the human 'on-site checking' element. Some text descriptions and structures of the assessment of the physical factors cannot be directly converted to computer code.

* The LCA guide (Bibby et al 1991) often states 'the guidelines should be used with care and understanding, and where possible, individual effects [of a constraint] should be checked'. This means that the original classifications were based on application of the guidelines and the expert assessment of the physical factors 'in the field'.

[3] Meteorological Office Rainfall and Evaporation Calculation System (MORECS version 2.0) - Catchment Management Modelling Platform (ceh.ac.uk)

The original LCA was limited in its ability to consider climatic variability over time, as it used a median class value from a 20 year time period (1958-78), rather than the variation in an individual year's LCA class (Hudson and Birnie 2000, Brown and Castellazzi 2015). Hence, the land capability class when mapped, does not reflect the annual variability in climate. This is important as climate projections indicate that variability is likely to increase in the future (e.g. a location may be wetter in some years, but drier in others), however changes in the median may not reflect this. The platform has been developed to enable assessment of individual years, as well as the median over time periods.

4 Building the platform

The Land Capability of Scotland research platform is primarily a computer-based data integration, calculation, mapping and visualisation tool. The platform was built by converting the written descriptions of the LCA guidelines (Bibby et al 1991) into code and developing the computing structures to enable the integration of the data and calculation of the constraints determining the LCA classes. Details of the process are set out in Appendix B.

5 Spatial and temporal evaluation of climate change impacts on land capabilities

The detailed process of the spatial and temporal evaluation of climate change impact on land capabilities are set out in Appendix C. The platform has been developed to enable multiple climate projections to be used and the outputs to be spatially analysed. This is to enable the assessment of uncertainty and presentation of a range of plausible futures.

Hence, before presenting examples of the platform outputs, it is important to explain that the platform currently uses a range of twelve climate projections to produce unique LCA maps (and associated datasets of constraints), representing a range of plausible possible futures. This helps cover a range of how the climate may change and what the LCA responses may be. To illustrate a plausible range of future climate conditions, Figure 1 shows how the temperature and precipitation is different for each projection (referred to as an 'ensemble member') for the 2040s and 2070s from a baseline observed period (1994-2015).

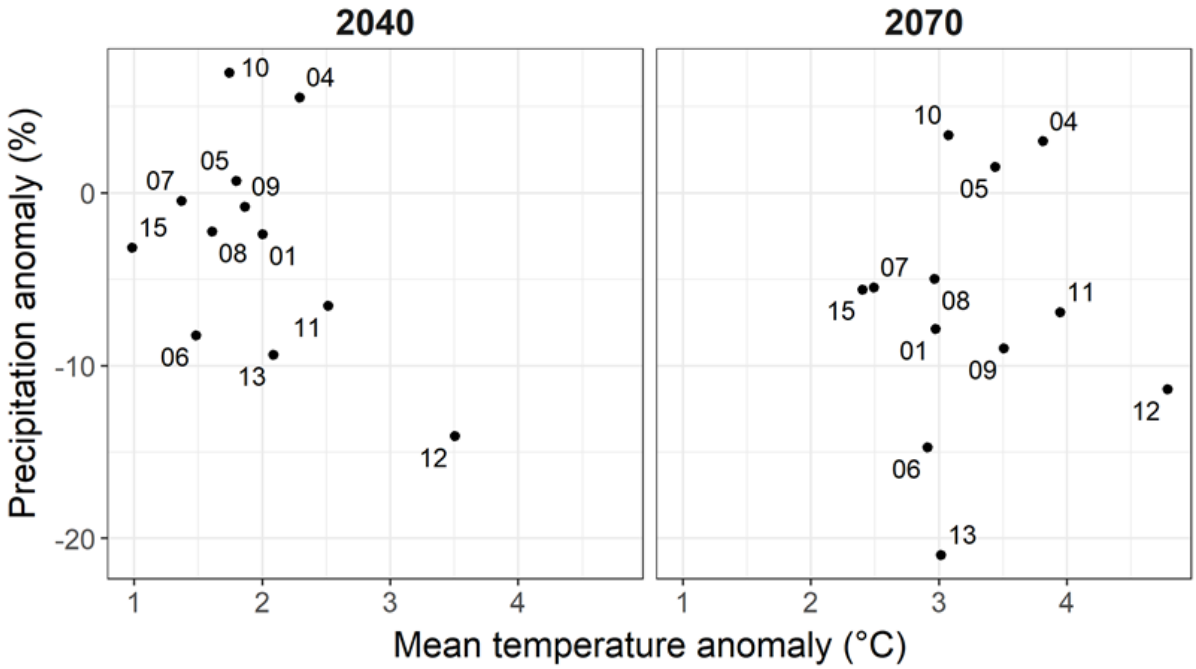

Figure 1. Example of variation between climate model projections (ensemble members): comparison of Scotland's' arable area (LCA classes 1 – 3.1) mean climate change signal in seasonal (March to September) precipitation and temperature under RCP8.5 for 2030-2049 and 2060-2079 with respect to a baseline period of 1994-2015 for the twelve different climate ensemble members.

Figure 1 shows how all projections used have a temperature increase, but some (e.g. 04, 10) may have an increase in precipitation, whereas others are similar to the present or may have as much as a 20% reduction. Knowing the differences between projections helps us to understand the variation in time and space of the LCA estimates.

6 Platform outputs – an illustration of potential

The results presented below are provisional and provided as illustrations of the outputs from the platform. To complete the implementation of the original LCA guidelines further work is required, such as:

- Incorporation of flood risk constraints on the LCA.
- Improving the erosion risk maps.
- Improving representation of vegetation cover for grazing value.

These limitations means these outputs should only be used for exploring how the results could be used in the future. The limitations associated with the current state of platform development are explored in 6.6. Suggestions for increasing the utility of the platform are provided in section 7 – Future Technical Developments.

6.1 Historical changes in Land Capability

The following three maps represent estimates of land capability using observed climate data for two periods: 1960 – 1990 (baseline) and 1987 – 2017, and a difference map showing gains and losses in LCA class between these two time periods.

In the maps of the two observed periods of 1960 – 1990 (Figure 2) and 1987 – 2017 (Figure 3), the outputs indicate a change in the distribution of LCA classes. On the basis that other constraint aspects (such as soil, topography etc.) have remained constant, the changes are due to differences in climate. Class 6.1 land is dependent on what types of

plants are present at a site, hence changes in species composition due to climate impacts will also need to be considered in more detail.

The difference map (Figure 4) indicates that historically there have been changes in land capability with gains being predominantly in the west and losses in the east. Whilst the causes need to be investigated further, this pattern generally corresponds with the distribution of warmer conditions in the west and drier in the east.

Assessments of the input climate data, outputs from the soil water balance model (e.g. Figures 7 and 8) and the individual LCA constraints for specific locations will help identify the causes of class changes.

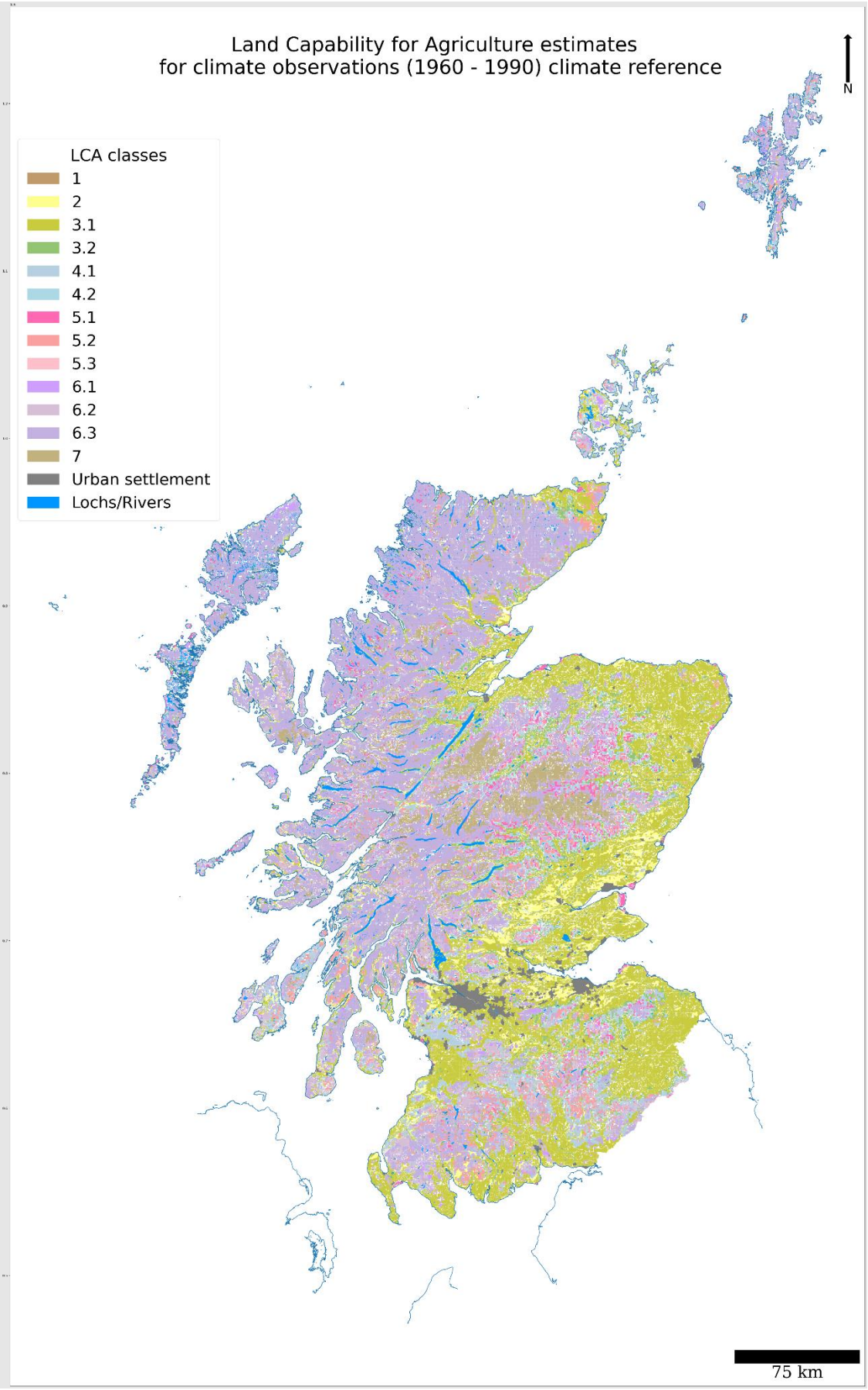

Figure 2. Land Capability for Agriculture estimates for the 1960 – 1990 baseline period.

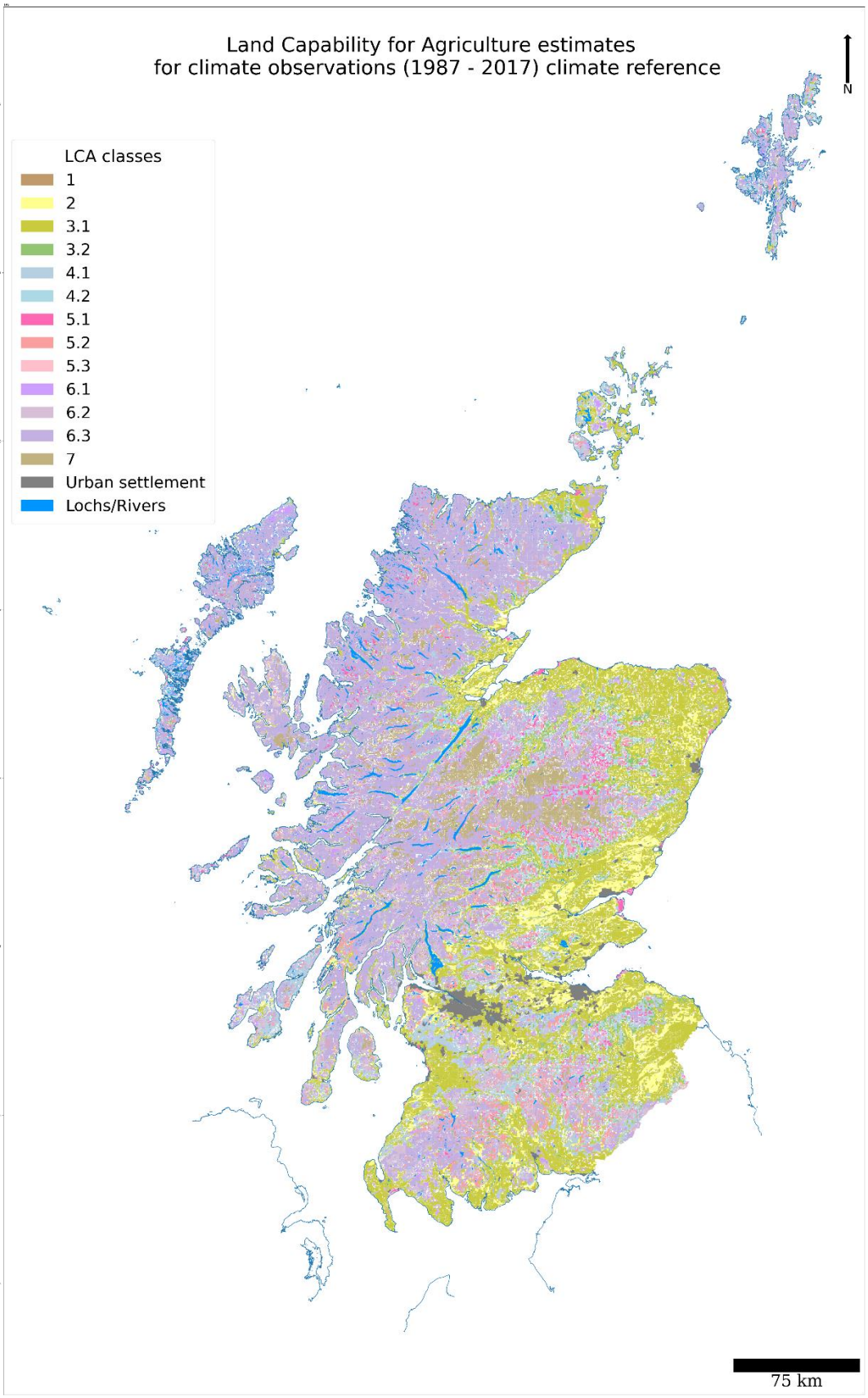

Figure 3. Land Capability for Agriculture estimates for the 1987 - 2017 baseline period.

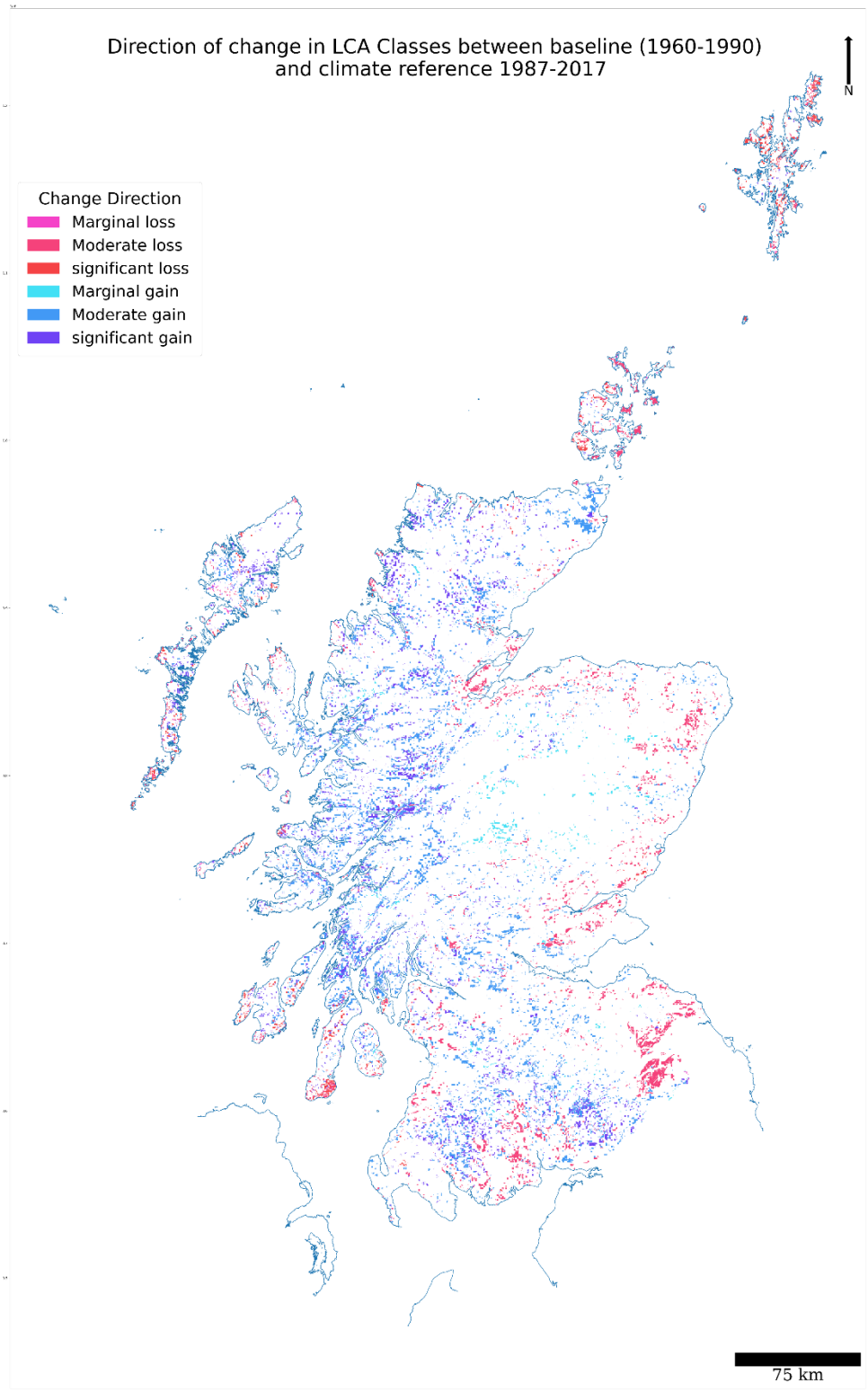

Figure 4. Gains and losses in LCA class between the observed baseline of 1960 – 1990 and 1987 – 2017 indicating possible observed climate change impacts. No change (white) = no impact from changes in climate and influence on soil factors; Marginal gain/loss = change in Divisions only (e.g. 3.2 to 3.1); Moderate gain/loss = change in class (e.g. 3.1 to 2); Significant gain/loss = change by more than 1 class (e.g. 3.1 to 1).

6.2 Projected future changes in Land Capability

The following maps in Figures 5a-d illustrate the potential future LCA classes for the period 2020 – 2050 produced by the platform using the climate model ensemble members summarised in Table 3.

Table 3. Summary of climate projections used to generate future LCA maps.

Ensemble member	2040s	2070s*
01	about 3% wetter and 2°C warmer	about 8% drier and 3.0°C warmer
04	about 5% wetter and 2.3°C warmer	about 3% wetter and 3.8°C warmer
05	little change in precipitation from the historical baseline but 1.8°C warmer	about 2% wetter and 3.4°C warmer
06	about 8% drier and 1.5°C warmer.	about 15% drier and 2.9°C warmer
07	no change in precipitation from the historical baseline but 1.3°C warmer	about 6% drier and 2.5°C warmer
08	about 3% drier and 1.6°C warmer	about 5% drier and 3.0°C warmer
13	about 9% drier and 2.1°C warmer	about 22% drier and 3.0°C warmer

Note: these values are derived from Figure 1 which are for the crop growing season (March – September) in the arable areas of Scotland only.

* Maps for the 2070s have not yet been generated.

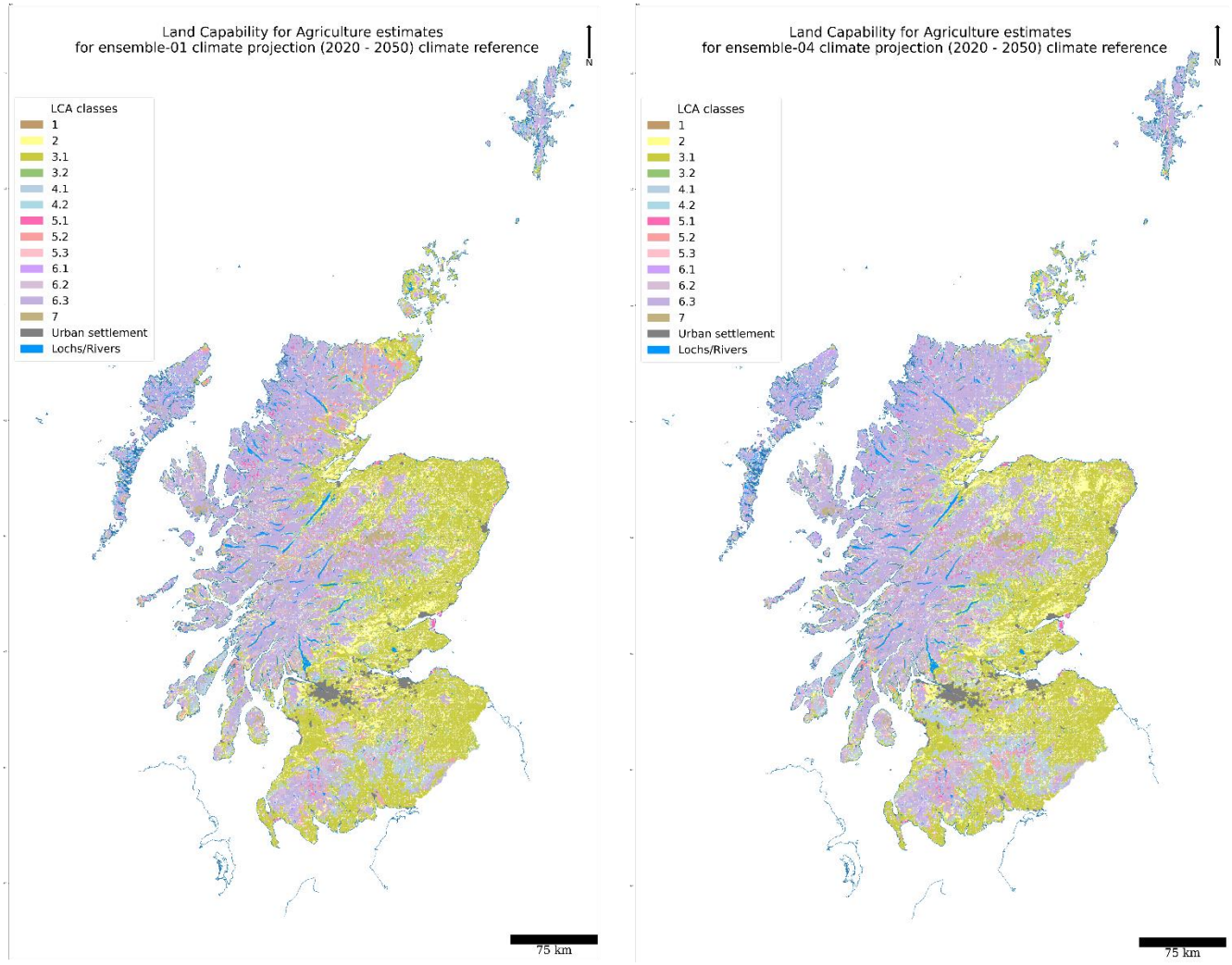

Figure 5a. Land Capability for Agriculture estimated using future climate projections (ensemble members 01, left, and 04, right) representing potentially wetter and warmer scenarios.

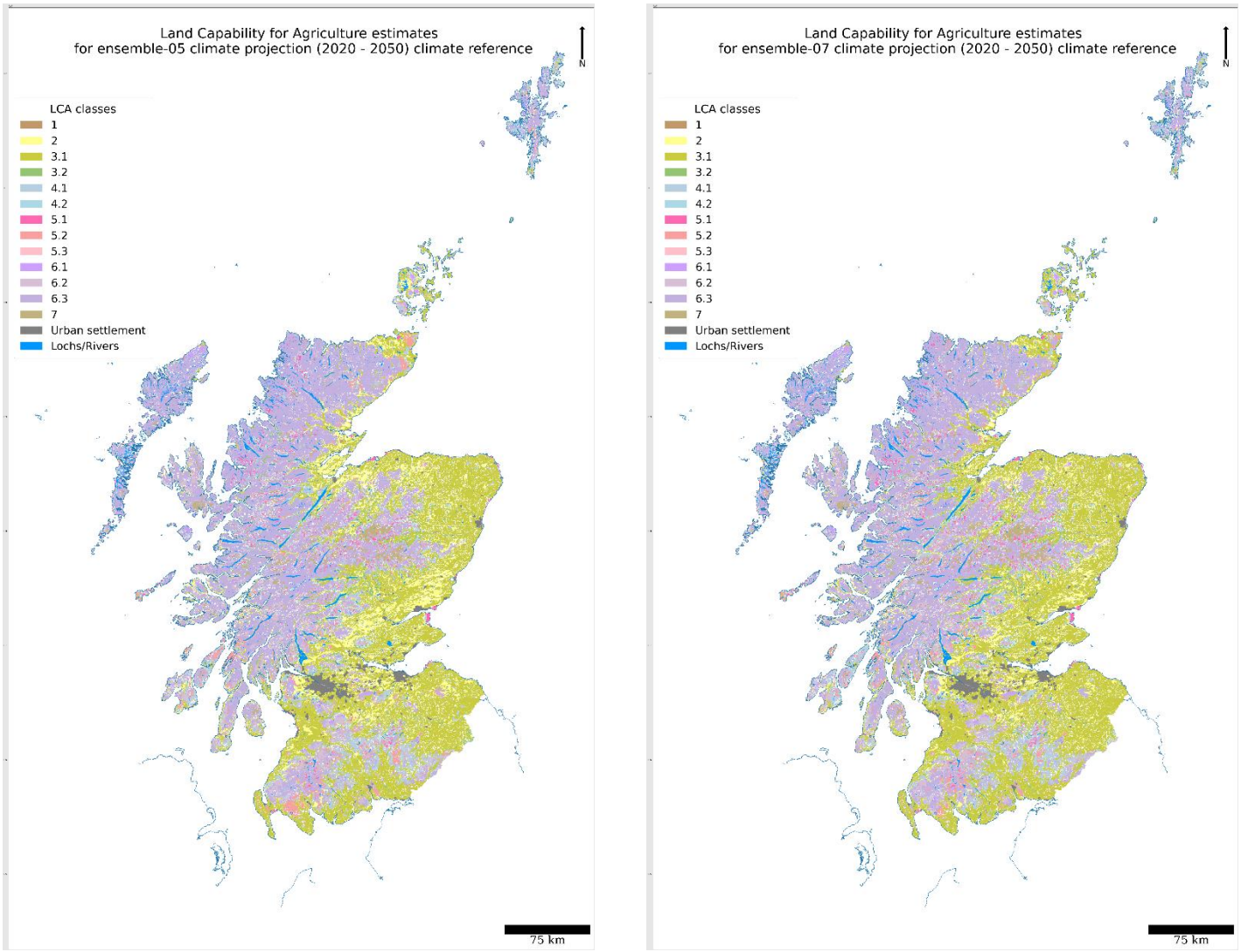

Figure 5b. Land Capability for Agriculture estimated using future climate projections (ensemble members 05, left, and 07, right) representing warmer scenarios but with little change in precipitation.

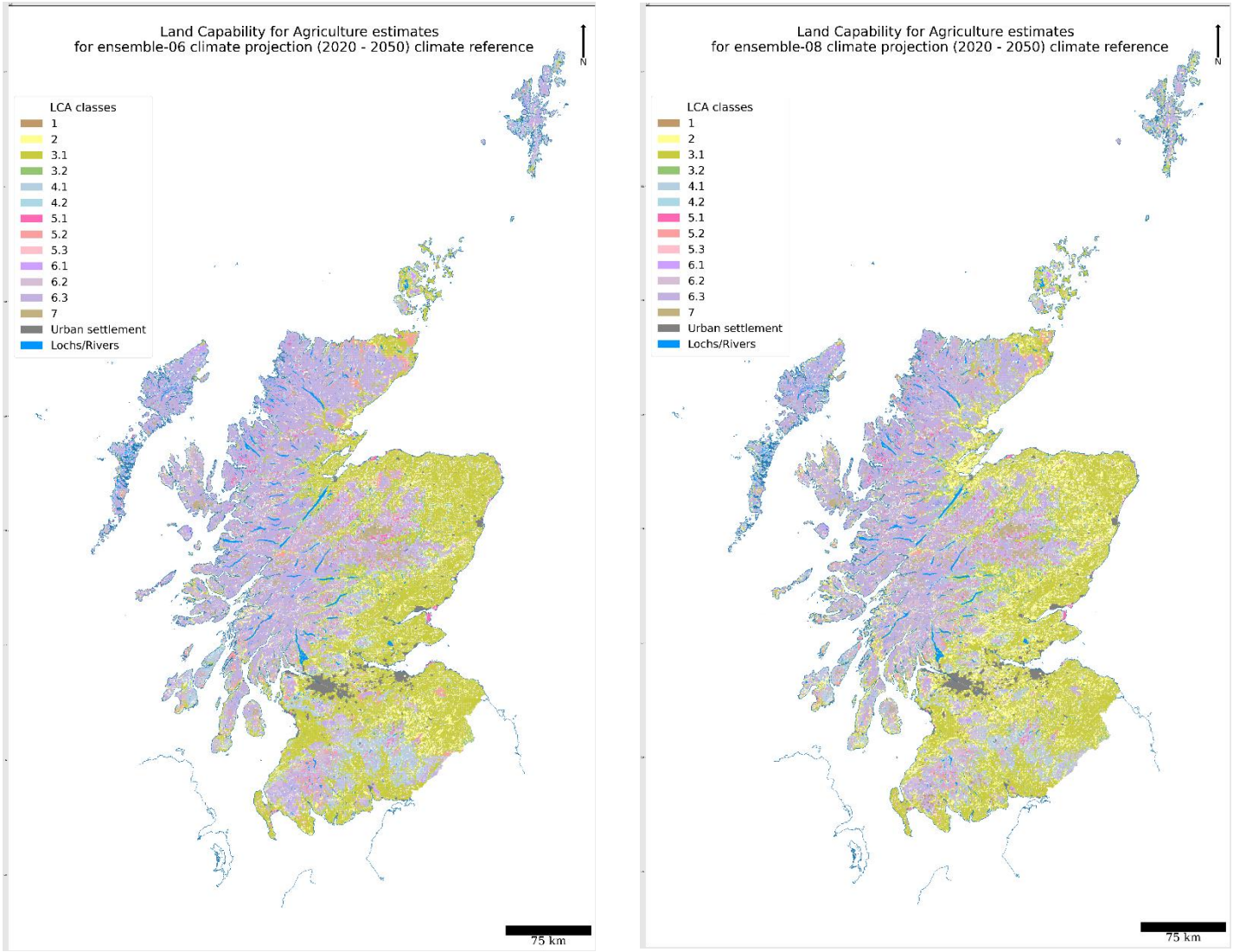

Figure 5c. Land Capability for Agriculture estimated using future climate projections (ensemble members 06, left, and 08, right) representing warmer and drier scenarios

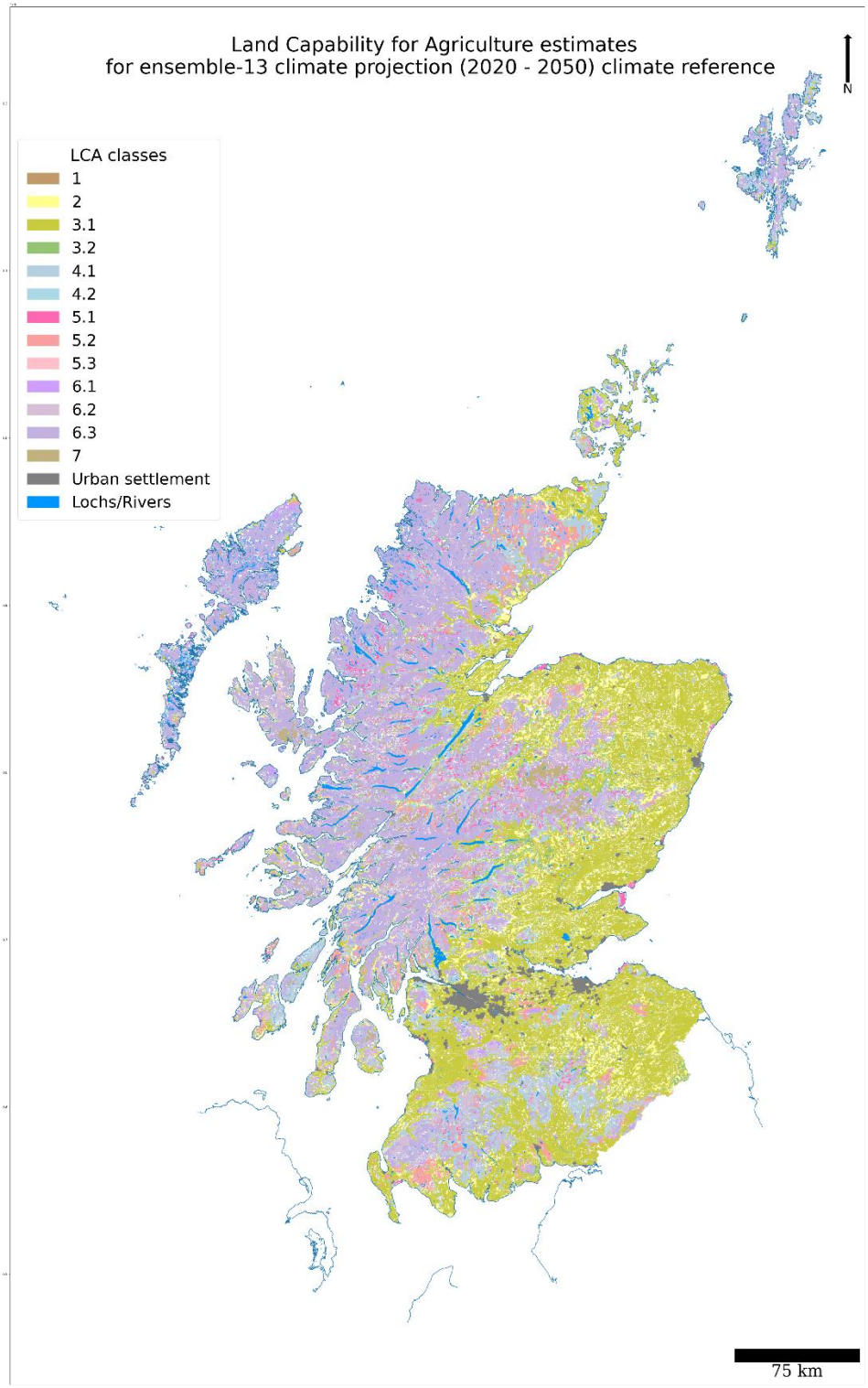

Figure 5d. Land Capability for Agriculture estimated using future climate projections (ensemble member 13) representing the most changed scenario.

The maps presented in Figures 5a-d and corresponding land area (hectares) change in Table 4 show changes to land capability between the computed baseline (1960 – 1990) and LCA estimates for climate projections for 2020 – 2050 using seven ensemble members.

From Figure 1 we know that some ensemble member projections are similar to the past in respect of amount of precipitation (04 is about 5% wetter, 05 is about the same as the baseline) but are both about 2°C warmer. From this we can interpret the changes in LCA

class seen in Figure 5a as being more likely due to the effects of temperature increasing the amount of evapotranspiration, and so reducing soil wetness constraints in some soils, or conversely making others wetter, rather than because of reduced precipitation. Figure 5b, representing little change in precipitation but warmer temperatures, and Figure 5c representing drier and warmer futures, on the other hand show a different LCA distributions.

The effect of the range of input precipitation and temperature influencing evapotranspiration can be investigated further for a specific location using the outputs from the soil water balance model (e.g. Figures 7 and 8). Figure 5d represents the largest change in temperature and precipitation, where there is a noticeable increase in class 3 into more upland areas.

Table 4. Change in land area per LCA class between the 1987-2017 observed climate period and 2020 – 2050 for two ensemble members. No change = no impact from changes in climate and influence on soil factors; Marginal gain/loss = change in Divisions only (e.g. 3.2 to 3.1); Moderate gain/loss = change in class (e.g. 3.1 to 2); Significant gain/loss = change by more than 1 class (e.g. 3.1 to 1).

	Total Changes in LCA (thousand hectares)							
	Baseline*	2020 - 2050						
Direction of Change	1987-2017	EM 01	EM 04	EM 05	EM 06	EM 07	EM 08	EM 13
No change	7,921.6	6,577.9	6,836.1	6,714.4	6,844.4	6,910.8	5,4767.0	6,359.5
Marginal gain	49.6	5.1	32.9	29.7	8.6	7.2	6.9	8.3
Marginal loss	8.0	259.6	249.0	245.7	276.2	277.6	239.0	267.2
Moderate gain	671.4	474.1	831.3	672.9	718.0	596.4	503.3	653.9
Moderate loss	285.3	1,638.1	1,205.6	1,455.4	1,371.4	1,437.1	1,838.9	1,562.3
Significant gain	671.7	515.9	794.4	711.2	604.2	592.8	347.4	564.1
Significant loss	73.1	1,398.6	920.2	1,040.1	1,047.0	1,047.9	2,459.7	1,454.7

* From the 1960-1990 baseline period.

The impacts on the LCA spatial distribution arising from the different climate projections seen in Figures 5a-d result in different amounts of land area having gains or losses in capability (Table 4). Across the seven projections illustrated, there is a similar quantity of

land area that is estimated to have no change in capability, the exception being ensemble member 08, as it has higher values for moderate and significant loss.

The land area having a marginal gain in capability is substantially less (mean across 7 examples of 14,087 ha) than that having a marginal loss (mean of 259,178 ha). Similar differences in balance are seen between moderate loss of capability (mean of 1,501,263 ha) and gain (mean of 635,700 ha) and significant loss (mean of 1,338,311 ha) and gain (mean of 589,995 ha).

6.2.1 Changes in LCA class

For the future projections, there is a varied response between ensemble members. The results for each ensemble member in Figure 6 indicate there are projected to be a range of gains and losses in land capability, and that these vary depending on the combinations of precipitation and temperature change for any one location. Production of difference maps (e.g. Figure 4) for each combination of projection against baseline will enable the spatial identification of where changes in LCA class occur.

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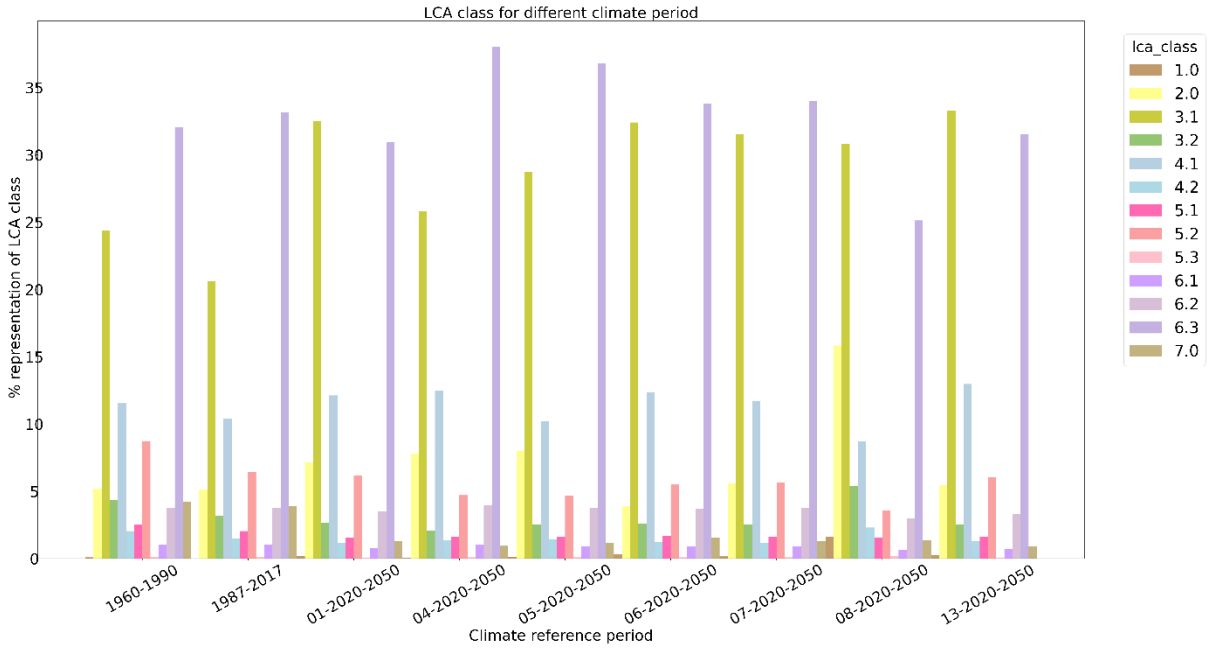

Figure 6: Changes in the percentage representation of LCA classes for two observed periods (1960 – 1990 and 1987 – 2017) and a future (2020 – 2050) using seven climate projections (ensemble members 01, 04, 05, 06, 07, 08 and 13).

A common response for all the projections illustrated in Figure 6 is that class 2 and class 3.1 land area increases from the baseline periods in all cases. This may be due to reduced climate constraints leading to class 3.2 becoming class 3.1. Further development of the platform capabilities is required to enable more rapid and detailed analysis of these changes and why they have occurred (e.g. assessment on input climate data, changes in determining constraint, soil water balance etc.).

6.3 Soil water balance estimates

Figures 7 and 8 provide the time-series outputs from the soil water balance model for two soil types with the changes in soil water content for the layers (detailed in Figure 13). This illustrates the level of detail now possible through the platform. The first example is for an uncultivated peaty alluvial soil that is gleyed within 70cm, with a depth to a semi-permeable layer greater than 80cm for a site near Stranraer. The soil has a Saturation Point of 633 mm of water and Field Capacity of 427 mm. As it is an alluvial soil, is likely to be strongly affected by the groundwater table, hence the results presented in Figure 9 should be interpreted considering water table movements as well. The second example is for a brown earth near Biggar, it is not gleyed within 70cm and there are no semi-permeable layers within 80cm and has a Saturation Point of 380mm and Field Capacity is at 259mm.

The layers shown reflect the amount of water in a soil and hence whether it is wet or dry at any time in a year. This is important as it indicates the range between water being easily available to plants (no limitation to growth) to below permanent wilting point (PWP) and an air-dried soil (plants are unable to access water).

The examples below are produced using ensemble member 12, the projection with the highest temperature rise (3.5°C) and most reduced precipitation (14%).

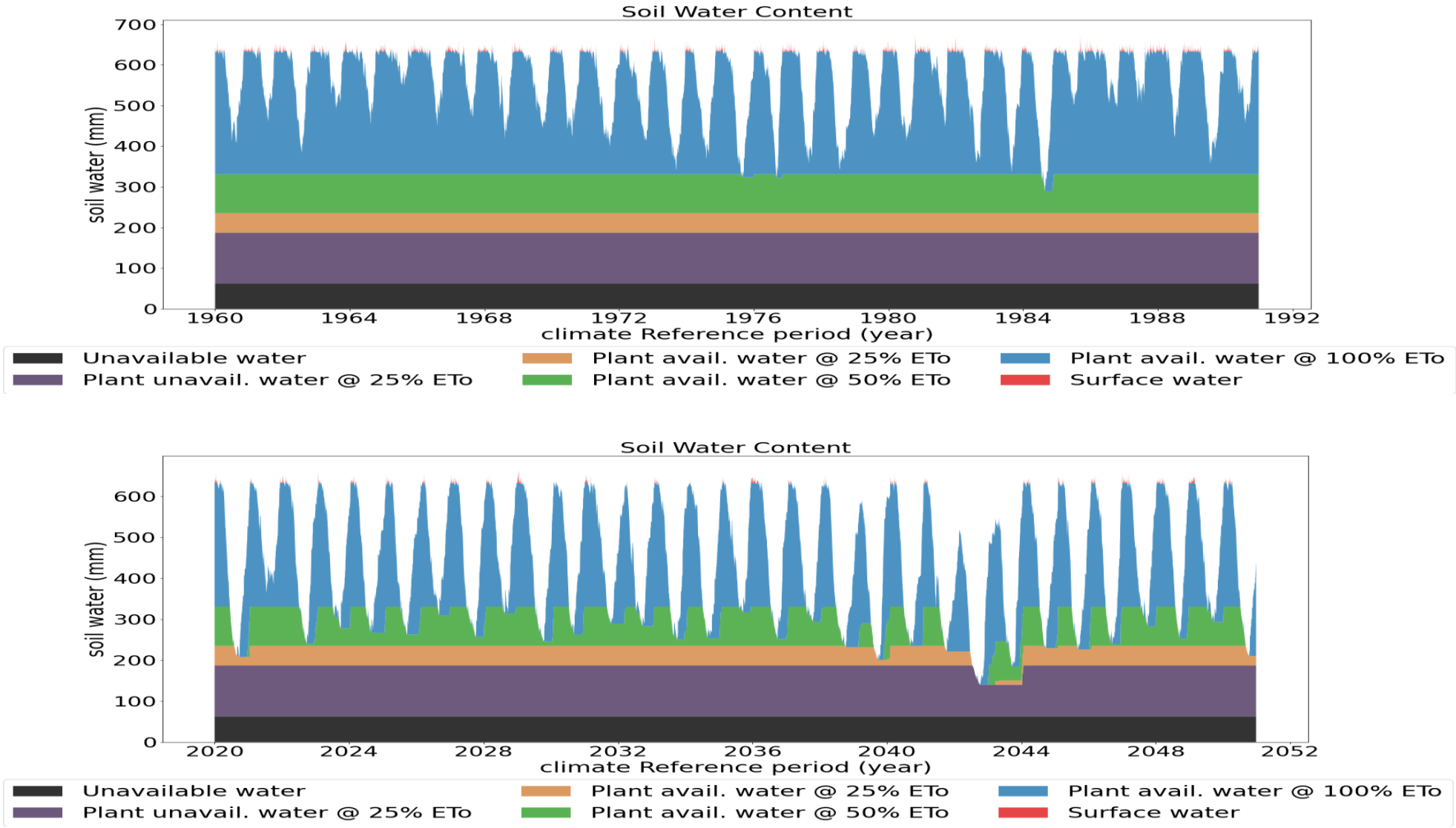

Figure 7: Time series of soil water balance for a Peaty Alluvial Soil (unique ID 104). Top: 1987-2017, Bottom: 2020-2050 for ensemble member 12. Y axis is soil water (mm), X axis is Year.

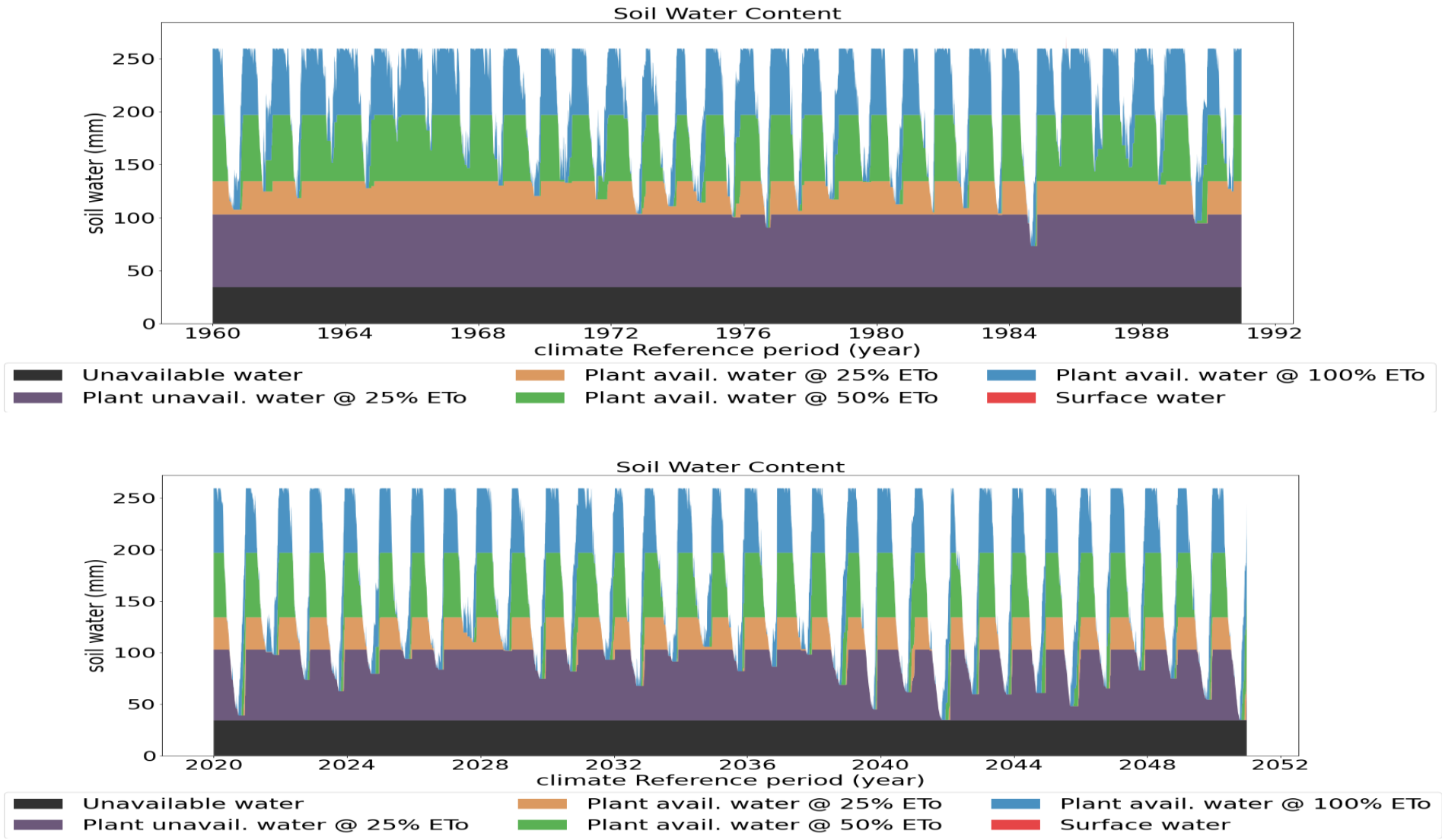

Figure 8. Time series of soil water balance for a Brown Earth Soil (unique ID 355179). Top: 1960 - 1990, Bottom: 2020-2050 for ensemble member 12. Y axis is soil water (mm), X axis is Year.

How to interpret Figures 7 and 8: The data generated by the soil water balance model is used to estimate LCA constraints (wetness, maximum potential soil moisture deficit, field capacity days) and hence a key determinant of land capability. The balance is a function of the difference between input precipitation and loss due to temperature driven evapotranspiration.

The blue shade represents water that is easily available to plants and can be evapotranspired (by plant transpiration and evaporation from surfaces) at 100%. The green shade represents water that is easily available to plants and can be evapotranspired at 50%. The orange shade represents water that is easily available to plants and can be evapotranspired at 25%. A reduction in the percent of water that can be evapotranspired represents water in the soil that is harder to harder to extract. The purple shade represents water that is unavailable to plants (e.g. exists in the soil but is too tightly bound to soil particle surfaces) but can be evaporated at 25%. The black section represents air dried soil, meaning plants cannot access water and no water is available for evapotranspiration. Red, when present (e.g. Figure 7, above plant easily available water), represents surface water and therefore potential runoff.

The wider and deeper the white space in the 'troughs' of the annual cycle, then the drier the soil is. Comparison between the observed and future illustrates the overall reduction in water availability. Plant available water (blue and green) can be present even when a soil has become dry, due to daily input precipitation. However, as this can be evapotranspired at 100 or 50%, it may not be available for long (e.g. during the summer) unless subsequent precipitation falls in sufficient quantities to start to refill the soil profile.

The key issues to note from Figure 7 are:

- This is a peaty alluvial in a wet location (near Stranraer), with soil water reaching saturation point every winter (when it can no longer hold any more water and any excess will be runoff, shown in red).
- There is a greater probability that the soil in the future will become drier and this will happen more frequently. There is more white space in the future, meaning there is less water within the soil.
- During the baseline period the soil water balance does not decrease to a point where plant water availability is limited whereas in the future projection it does.
    - This may impact on vegetation in terms of changes in growth and competitiveness between species and functional ability of plant communities, e.g. function as a wetland habitat and provide ecosystem services (drought and flood buffering).
    - The peat component of the soil is more likely to become dry, impacting its ability for carbon sequestration, and potentially becoming a carbon dioxide source.
- Not every year in the future projection has excess surface water each winter. In some years there are projected to be years when the saturation point is not reached and hence there is a reduced probability of runoff.

The key issues to note from Figure 8 are:

- This is a relatively dry location (near Biggar), where soil water does not reach saturation point in the winter.
- The extent to which the soil dries varies considerably between the baseline period and the near future projection, with the future projection indicating increased probability of more frequent years when the soil may become drier (there is a lot more white space in the wider and deeper 'troughs').

- During the baseline period there are few years (possibly 1984) when crop or vegetation growth on this site may have been limited by water stress (e.g. 1 in 30 years). Under the climate projection, water stress may occur 22 years in 30.

By archiving soil water balance model simulations, this level of detail can be made available for all 477,209 unique soil-climate combinations and each ensemble member. Currently the data (daily time step) is not archived due to storage constraints.

6.4 Agrometeorological indicators

The number of days when a soil is at or above field capacity (maximum water amount (in mm) a soil can hold against gravity) is a key part of estimating the workability, trafficability and poaching risk constraints to agriculture. Periods when a soil is at or above field capacity indicate when it may not be appropriate to cultivate or place animals onto land. Figure 9 indicates the spatial variation in field capacity days and how this may have varied between the 1960 – 1990 and 1987 – 2017 periods. Figure 10 indicates potential changes in the future under two projections (ensemble members 04 and 05), with there being noticeable differences between them, e.g. 05 shows larger areas in the east of Scotland with field capacity days in the 0 to 125 category than 04.

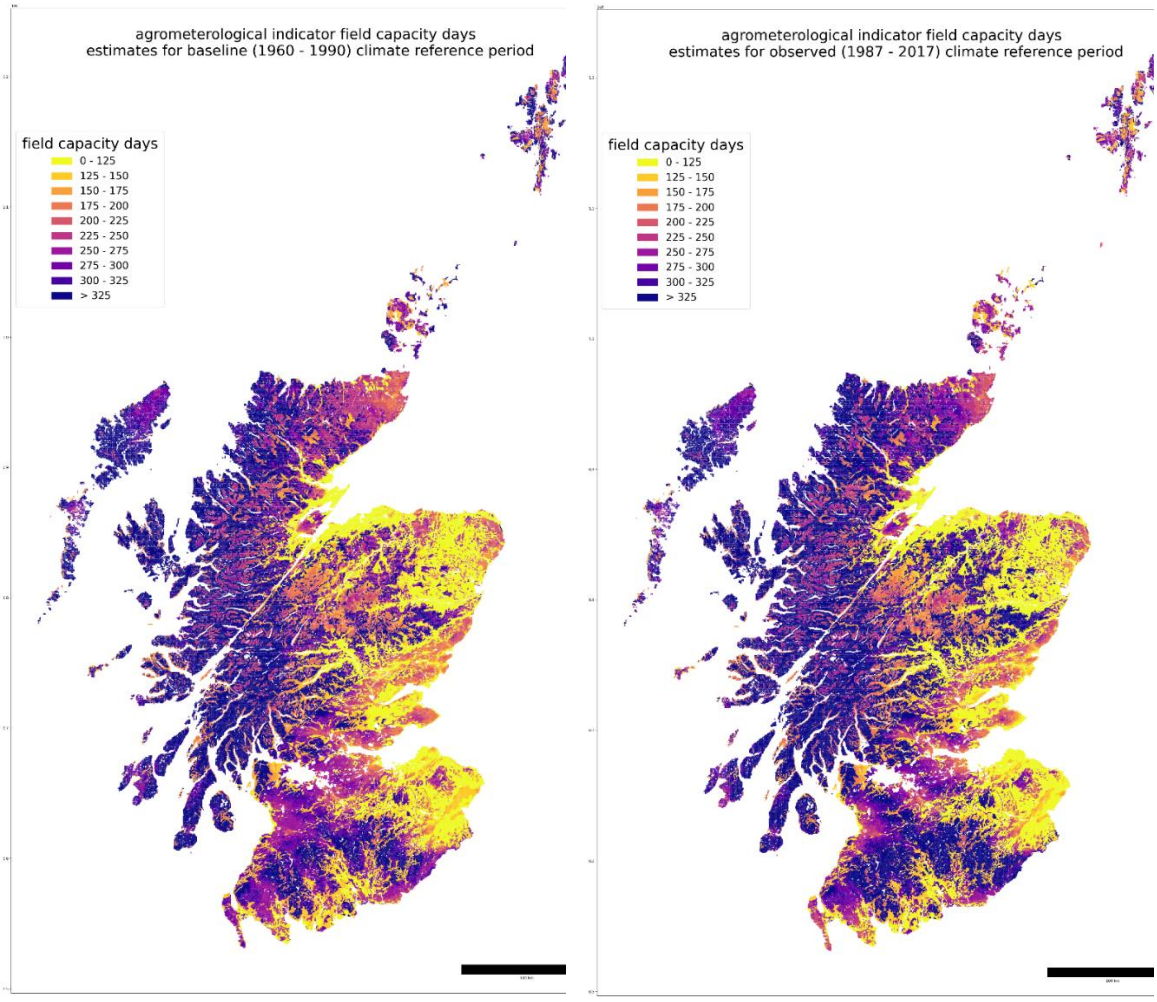

Figure 9. The number of days when a soil is at or above Field Capacity for the baseline period 1960 – 1990 (left) and 1987 – 2017 (right).

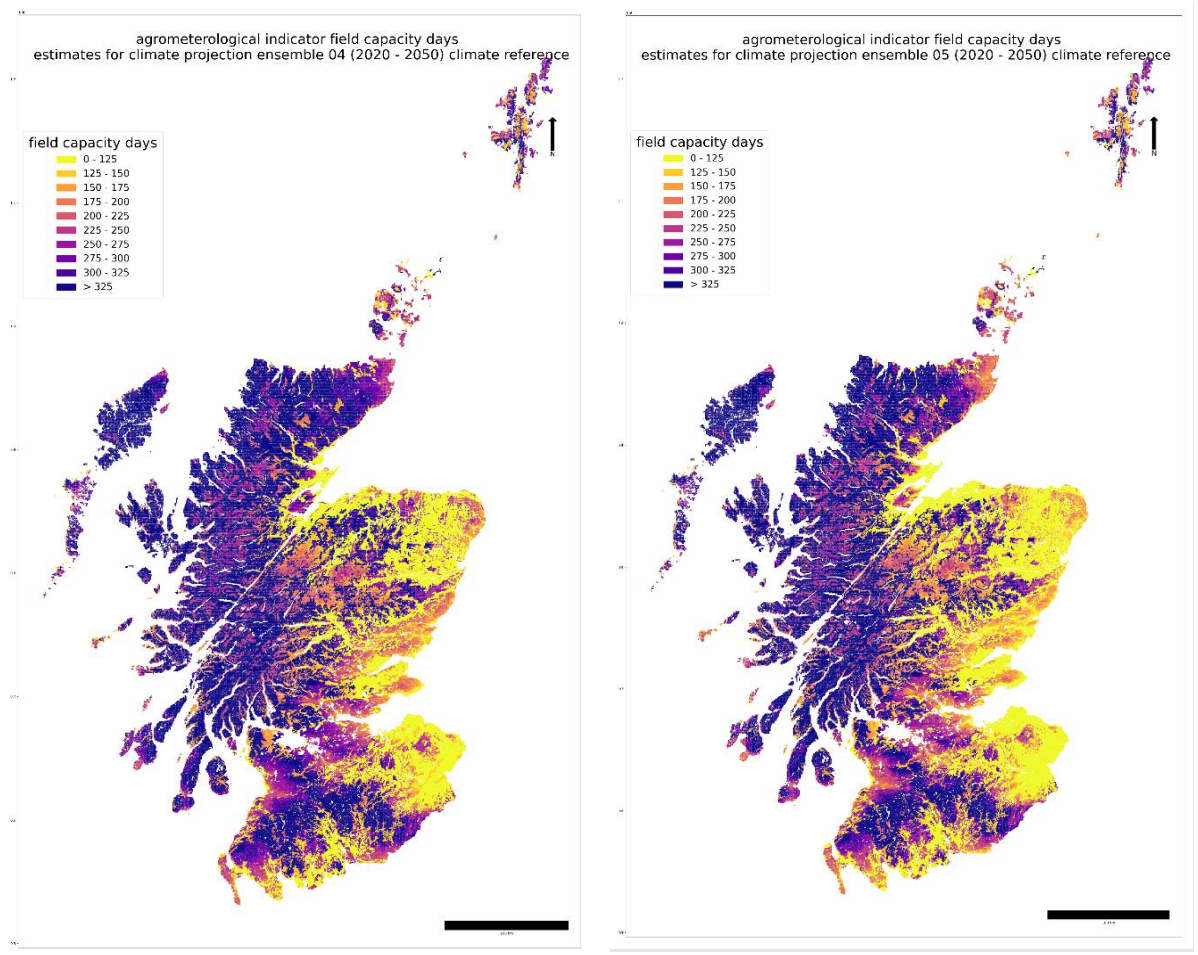

Figure 10. Estimated number of days in the future when soils are at or above Field Capacity for two ensemble members: 04 (left) and 05 (right).

6.5 Annual variability and differences between projections

An important aspect of making future projections of land capability is in understanding the variation in constraint values and LCA classes between years and climate projections. The Land Capability platform now enables the estimation of constraint and class values on an annual basis for any one of the 477,209 unique soil-climate combinations, meaning the variation between years can be assessed.

For example, a noncalcareous gley with no surface peat run with two ensemble members (01, 3% drier and 2°C warmer, and 13, 10% drier and 2.1°C warmer) for the period 2020 – 2050, varies between years and ensemble members by as much as a whole LCA class. The determining limiting factor type also varies between soil and wetness.

Alternatively, for a peaty alluvial soil with surface peat, whilst having some annual variability, does not change LCA class between the two ensemble members and wetness constantly remains as the determining limit factor.

Appendix D Tables 5 and 6 provide details for these two specific examples.

6.6 Limitations and learning from the output evaluation process

During the development of the platform, several key limitations on the use of the platform in its current state have been identified, along with some previously unforeseen benefits. These can be summarised as:

- With 477,209 unique soil-climate combinations used within the platform, validation of each individual LCA class and component constraints per combination becomes a challenge given details in Table 2 and inappropriateness of comparing platform outputs with the original LCA.
    - The results show there is need to disentangle what may be errors in the platform code from what may be appropriate estimates of LCA class due to use of the new input data.
    - It is important not to discard small map units that appear to be contrary to the surrounding LCA class. For example, one case was found on the north shore of Loch Arkaig of class 2 land surrounded by class 6. Investigation revealed the class 2 map unit to be a forest brown earth soil. Such cases require further assessments to check for plausibility of the estimated LCA class. Whilst potentially not significant from the perspective of agriculture due to its size, it did indicate the opportunity of the site for a non-agricultural purpose, e.g. targeted native woodland restoration.
- Capability units comprising groups of appropriate soil mapping units have similar potentials and limitations. With 477,209 unique soil-climate combinations, mapping a representative soil series to a map unit presents additional challenges. Similar soil series with different unique soil-climate identity may present different LCA class estimates.

Vegetation cover: The LCA considers the composition of existing vegetation as a requirement to determine the quality of the land, especially where improvement is not possible by mechanical means. This forms the basis for the divisions in LCA Class 6, and there is scope for improvement in the current LCA class estimates if the grazing values of the plant communities in hill lands can be retrieved. Currently vegetation cover included in the range of input data to the platform is very coarse on a scale of 10km National Geographic Reference (NGR) gridding. Options to use habitat maps and remote sensed data have been investigated.

Soil erosion: Erosion risk, particularly evidence on wind erosion resulting in crop damage necessitating redrilling, crop yield penalties or the restriction in the range of cropping, in addition to site evidence of loss or accumulation of soil material still presents some degree of limitation in accurately estimating the LCA classes. Currently erosion risk included in the range of input data to the platform have only sparsely been modelled on the susceptibility of the soil type to erosion with giving account to evidence of loss / accumulation of soil material or crop damage or yield penalties. Flood risk: Currently flood risk is not included in the LCA class estimation. Advice from the original LCA surveys has been that the overall area of flood risk (according to the guidelines) is relatively small, but may be significant given some flood risk area's soils having production favourable properties. Options to include flood risk have been investigated, e.g. SEPA Flood Risk Maps[4] and flood inundation modelling[5].

[4] Flood maps | Scottish Environment Protection Agency (SEPA)

[5] Flood inundation modelling | Environmental and Biochemical Sciences | The James Hutton Institute

7 Future technical development

The project has focused on building a Land Capability for Scotland research platform. In the process we have identified potential for improvements in utility and accuracy.

7.1.1 Modelling:

- The ability to model soil water balance is increasingly important for understanding how soils, crops and ecosystems will respond to climate change. There is a need to improve soil water modelling, which has been incorporated in plans for the Scottish Government's 2022-2027 Strategic Research Programme.
- There is a need for improved measurement of soil water balance in a diverse range of locations and compilation into a database to enable monitoring of change and use for calibration and validation purposes.
    - There is potential to use Sentinel-2 satellite data[6] to provide real-time soil surface moisture data to support calibration and validation of the soil water balance model.
- There is scope for improving the ability to utilise the soils data to separate mineral soils on the bases of their water retention capability between cultivated and semi natural soil.
    - It may be possible to utilise COSMOS[7], Sentinel-2 and other remote sensed as well as site-specific soil moisture monitoring data for soil water balance model calibration and validation.
- Where vegetation types determine land capability (particularly Class 6), there is a need to better incorporate climate change impacts on species composition and ecosystem functionality.
- The original LCA guidelines did not include constraints arising from crop or livestock diseases, but potential exists to utilise disease epidemiological modelling tools that assess climate change risk[8].
- Developing the capabilities to spatially model grass responses to climate change in Scotland and align with land capability will improve our understanding of the impacts on grazing quality and hence alternative feed requirements and livestock production.
- Use of the agrometeorological indicators (Appendix E3) can provide evidence to assess impacts on livestock welfare, e.g. heat stress and additional water requirements.
- Increased access to data storage is required to enable more archiving of modelled data, e.g., daily soil water balance model estimates for each unique-soil weather combination, to facilitate location specific analysis.

7.1.2 Analysis and addressing uncertainty:

- Separating where variable climatic constraints rather than non-variable ones (e.g., slope or soil depth) determine the LCA class, to identify where, regardless of climate change, land capability for agriculture is physically constrained.
- Improve the difference mapping to include changes in LCA class.
- Apply ensemble member 'agreement maps' (see Appendix E Figure 16 for an example used for crop model outputs) showing where there is agreement on the

[6] Sentinel-2 - Data Products - Sentinel Handbook - Sentinel Online (esa.int)
[7] COSMOS cosmic ray soil moisture measurement: COSMOS-UK | (ceh.ac.uk)
[8] 4C model: Crop Connectivity under Climate Change | The James Hutton Institute

LCA classes and constraints across any given number of ensemble member. This will provide spatial indications of projection certainty, e.g., the same LCA class for one location is produced by 10 of the 12 ensemble members.

- Utilise other climate projection sources (e.g., UKCP18 'Local' 2.2km resolution, Euro-CORDEX[9]) and for different emissions scenarios.

7.1.3 Platform structure, code and use of High-Performance Computing (HPC):

- Running the land capability calculations places a large demand on computing resources, especially memory within the HPC. Data generated in the calculation of the constraints can be retained, but this produces vast quantities of data (billions of rows in a database) that if stored would require large storage capacity.
    - Streamlining the process is possible by reducing the amount of data retained during platform runs.
    - The platform has been structured to enable land capability calculations to be rapidly re-run with new data, e.g., climate projections, on the Hutton Institute's HPC, without archiving all estimates, such as daily values of the soil water balance model.
- Separating the calculations of soil moisture computation, climate-soil interaction and guideline implementation into individual processes that can be run independently will give flexibility in running estimates to recalculate the constraints and LCA classes, i.e. when a model within the platform has been re-calibrated or refined.
- Planned work within the Scottish Government's 2022-2027 Strategic Research Programme includes developing a risk and opportunity assessment framework to investigate climate change impacts on Natural Capital. Potentially this research can link to the land capability platform capabilities for estimating soil water balance.
- It is possible to develop more scripts for automating analysis and result visualisation to increase the range of outputs generated and analysed and facilitate results presentation.
- There is potential for the results from the platform to be made available on a website to enable communication or risks and opportunities to land management stakeholders. However, additional validation is required of platform estimates and there are issues concerning how the platform outputs relate to the use of the existing LCA maps.

7.1.4 Integration with other research and data:

- It will be possible to integrate with other spatial data sets such as land cover and land use, Hydrology Of Soil Types classification (HOST), the RESAS Crop Map of cereals being grown, hydrological modelling, historical land use, habitat maps, protected status designation etc.
    - Given current interest in ecosystem restoration, for example woodlands and wetlands, there is scope for integration with historical records and archaeological data sets to identify former habitats are areas of land use, settlements, runrigs etc.
- Links can be made to other research outputs, such as spatial crop simulation modelling and agrometeorological indicators estimated using the same climate

[9] EURO-CORDEX

projections, to add value to the platform's outputs. This enables researchers to assess things like the crop responses and soil conditions to changes in the climate and the types of agrometeorological conditions (e.g., length of the growing season) land managers or planners will need to consider when making strategic decisions.

- Mapping crop responses to the same soil-weather unique combinations used to produce the LCA classes means we can compare crop productivity with land capability. This adds a substantial refinement to the LCA system.

7.1.5 Expansion to other land capabilities:

- The computing aspect of the research platform has been designed to enable wider data integration and development of code to allow for a range of other land capability assessments to made, helping to research multi-functional landscapes, for example for ecosystem services and forestry.
  - Discussions are ongoing with Forest Research to link the Ecological Site Classification – Decision Support System[10] for tree species matching to site characteristics with a revised version of the Land Capability for Forestry (LCF). This would enable a better scale representation from site-specific (ESC-DSS) to national (LCF).

8 Conclusions

This research has successfully developed a Land Capability research platform on which a range of newly available soils, hydrology and climate data can be integrated to estimate historical and future land capability. The platform will serve as the basis on which further technical developments can be made and research questions applied. Such a research platform has important potential for informing a broad range of issues concerned with land use and management, land use planning and climate change impacts. The mapped outputs and associated data from the platform can serve as a powerful medium for engagement with a wide range of stakeholders to explore adaptation and mitigation options and help understand their consequences.

A key function of the platform is to serve as a risk and opportunities assessment tool. The ability to simulate key constraints to land capability, particularly soil water, means that it is now possible to identify where in Scotland land capability may change due to climate impacts on the constraints.

The increasing annual variability and emerging trends in the climate, such as changes in rainfall distribution (e.g., wetter winters, drier summers, shifting west to east rainfall gradients, more intense rainfall events etc.), coupled with the spatial distribution of widely variable soil types, means that a specific location may experience both reductions and increases in climatic constraints to land capability.

The platform is not a complete implementation of the original LCA guide, in that the flood and erosion risk elements require refining. There are also challenges remaining to be addressed in validating the soil water balance model and subsequent use in estimating constraints. As such, the results presented here whilst provisional, provide a useful insight into how the LCA classes vary between climate projections and where there are potential gains and losses in land capability for agriculture.

[10] Ecological Site Classification (ESC) - Forest Research

- Implications for land uses:
    - The provisional results indicate that shifts are likely in land capability due to climate change, with some locations experiencing positive benefits whilst others will be negatively impacted. The research helps highlight the spatial differences in potential impacts and so can be used to help localise adaptation strategies. Soil water balance, as influenced by its water holding capacity, appears to be a key factor in determining whether arable agricultural locations (Class 1 – 3.2) change in capability.
    - Arable-based land uses may experience increased inter-annual variation, with crops produced on prime land potentially being at increased risk of dry soil conditions, reducing yields.
- Informing policy and strategic planning:
    - The platform's provisional results provide a valuable insight into how land capability may change. This indicates the potential to provide spatial land capability information that may be useful where there is need to take changes into account in the development of land-related policies.
    - The spatial resolution of the LCA mapping and underpinning database has the potential, alongside the use of other spatial data, to inform strategic planning of land uses, e.g. to identify areas that might be for targeted land use change, e.g. opportunities for conversion to forestry, or establishment of habitat restoration.

The capacity to use integrated data has potential to better identify areas at risk or where there are beneficial opportunities, to aid 'future proofing' spatial planning against climate risks, e.g., protection of prime agricultural land (Scottish Government 2017). The platform has the potential to contribute to the Scottish Government digital transformation in planning and aims in the Scottish Planning Policy (Scottish Government 2020) and development of the 4th National Planning Framework[11]. At the UK level, the LCA platform outputs (alongside research outputs covering mapped Agrometeorological Indicators and spatial crop modelling undertaken within the Scottish Government Strategic Research programme (2016-2022)), could also contribute to future Climate Change Risk Assessments.

The value of the Land Capability platform can be increased by aligning it with other research assessments such as spatial crop modelling estimates of yields and yield gaps, and agrometeorological indicators, ecosystem and habitat mapping, catchment hydrology modelling and mapping. The Land Capability research platform will make integration with other spatial research assessments easier, enabling better access to information and analytical capabilities for researchers to support policymakers.

9 Potential opportunities

The computing platform development process has enabled the identification of a number of technical development opportunities, as detailed above, which might further develop the platform utility. Beyond these, additional research effort could focus on the validation of the methods and estimates made for individual land capability constraints. Of particular importance is the need to validate the soil water balance model, as this is the primary route through which future precipitation and temperature changes will manifest themselves in land capability. The appropriate level of validation will require additional

[11] Draft NPF4 | Transforming Planning

soil water data from a diverse range of locations and representing time series to capture annual variability.

Whilst it is not feasible to compare outputs from the computing platform directly with those from the original LCA, there is scope for meaningful sense checking to ensure the platform estimates are logical. This can be achieved through dialogue with the original LCA surveyors and those familiar with the use of the original LCA maps. Credibility for the platform can also be gained from engagement with land use practitioners and their knowledge of particular locations.

10 ClimateXChange fellowship

The CXC research fellow Dr Emmanuel Udugbezi has learnt many new scientific and technical skills and describes the fellowship position as having been extremely rewarding. It has allowed him to fill gaps in his technical knowledge and skills, and greatly expand his research capabilities. Through the fellowship, Dr Udugbezi has developed skills in new fields (e.g., soil, agriculture and land use), and developed his knowledge of the policy landscape relevant to Land Capability. The support provided by scientists and technical expert colleagues at the James Hutton Institute, and advice and guidance from CXC, have helped in achieving the aims and objectives of the project.

The fellowship provided opportunities to build a strong professional network with scientists, technical experts and policy staff within various research institutes and departments of the Scottish Government, as well as agencies including SEPA, Forestry Research and NatureScot. During the research, the fellow has had the opportunity present his research directly to stakeholders and attend CXC training workshops. These opportunities have enabled him to improve his communication and stakeholder engagement skills. In this respect, the project has been a success in respect of both developing the Land Capability platform and in advancing the career of the fellow. Dr Udugbezi is grateful to the support provided by the Scottish Government and ClimateXChange.

11 Acknowledgements

The authors would like to thank the Scottish Government for its funding support of this project and for ClimateXChange for facilitating it. Thanks are also given to the numerous stakeholder who have participated in meetings and provided guidance, feedback and suggestions on development. Dr Udugbezi acknowledges the UK Meteorological Office for use of the UKCP18 climate projections and gridded observed climate data. Thanks also go to James Hutton Institute colleagues Dr Zisis Gagkas for assistance with the soils and HOST data; Dr Mohamed Jabloun for developing a method to provide estimated historical solar radiation data and advice on platform operation on the HPC; and Dr Iain Milne for assistance and advice with the use of the HPC.

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Appendix A: The LCA classification system

The LCA classes are estimated through application of a set of criteria to assess physical and biological factors. The physical are factors are:

- Climate: this is a key determinant of land capability through its influence on soil water and nutrients. Two direct factors are used:
    - Accumulated temperature (ATo) above 0°C from 1st January to end of June, representing the availability of energy from direct solar radiation.
    - Maximum Potential Soil Moisture Deficit (PSMD). The deficit represents the balance between precipitation and evapotranspiration. It is the maximum value of the deficit, indicating how dry a soil may become.
    - The two factors are combined to produce a single classification (see Figure 1)
- Gradient: the slope angle and length of slope influences the ability of machinery to operate.
- Soil: there is a complex set of physical qualities and how these interact with the climate.
    - Soil structure: this assesses to the potential for structural instability to be reduced by acceptable levels of management.
    - Shallowness:
    - Stoniness: limitations are based on size, abundance, shape and lithology (general characteristics).
    - Droughtiness: this assesses the available water reserve (AP) within a depth likely to be exploited by a crop and subtracting the PSMD (which is also adjusted by crop type).
    - Wetness: like droughtiness, this is a complex soil property. Its principal effect is on soil workability, trafficability and poaching risk.
        - Workability, trafficability and poaching risk. This assesses the susceptibility of soil to structural damage by cultivation, traffic and or stock. This constraint assesses:
            - Soil wetness class and the depth to slowly permeable horizons.
            - Topsoil properties (water retention, plasticity and strength) determined by particle size and organic matter content.
            - Climatic environment indicated by the length of the field capacity period (the number of days when the soil is at field capacity).
    - Erosion: assess risk of wind and water erosion of soils.
    - Pattern: there is large variation in the patterns of good and bad physical conditions within an area of land being assessed. This criterion assesses the percent area of land with a lower quality than the overall class.

Biological factors are:

- Vegetation: this is primarily utilised for hill land for grazing purposes.
    - Rating of plant species.
    - Relative Grazing Value

The land capability classes are described below in their original text (Table 4). This is provided as it gives useful insights to the production focussed rationale for the original LCA, and basis for the classification rules as they were developed at the time.

Table 4. Land Capability for Agriculture classes and their descriptions.

Class	Description
Land suited to arable cropping	
1	*Land capable of producing a very wide range of crops.* Cropping is highly flexible and include the more exacting crops such as winter vegetables (e.g. cauliflowers, brussels sprouts, leeks). The level of yield is consistently high. Soils are usually well-drained deep loams, sandy loams, silty loams or their related humic variants with good reserves of moisture. Sites are level or gently sloping and the climate is favourable. There are no or only very minor physical limitations affecting agricultural use
2	*Land capable of producing a wide range of crops*. Cropping is very flexible and a wide range of crops can be grown, though some root and winter harvested crops may not be ideal choices because of difficulties in harvesting. The level of yield is high but less consistently obtained on Class 1 land due to the effects of minor limitations affecting cultivation, growth or harvesting. The limitations include, either singularly or in combination, slight workability or wetness problems, slightly unfavourable soil moisture or texture, moderate slopes and slightly unfavourable climate. The limitations are always minor in their effect however and land in Class 2 is highly productive.
3.	*Land capable of producing a moderate range of crops*. Land is capable of producing good yields of a narrow range of crops, principally cereals and grass, and /or moderate yields in a range of wider crops including potatoes, some vegetables (e.g. field beans, and summer harvested brassicae) and oil-seed rape. The degree of variability between years will be greater than Class 1 and 2, mainly due to interactions between climate, soil and management factors affecting the timing and type of cultivations, sowing and harvesting. The moderate limitations require careful management and includes wetness restrictions to rooting depth, unfavourable structure or texture, strongly sloping ground, slight erosion or a variable climate. The range of soil types within the class is greater than Class 1 and 2.
3.1	Division 1 land is capable of producing consistently high yields pf a narrow range of crops (principally cereals and grass) and /or moderate yields of a wider range (including potatoes, field beans and other vegetables and rooting crops). Short grass leys are common.
3.2	Division 2 land is capable of average production but high yields of gras, barley and oats are often attained. Other crops are limited to potato and forage crops. Grass leys are common and reflect the increasing growth limitations for arable crops and degree of risk involved in their production
4	*Land capable of producing a narrow range of crops*. The land is suitable for enterprises based primarily on grassland with short arable breaks (e.g. barley, oats, forage crops). Yields of arable crops are variable due to soil, wetness or climatic factors. Yields of grass are often high but difficulties of production or utilisation may be encountered. The moderately severe levels of limitation restrict the choice of crops and demand careful management. The

	limitations may include moderately sever wetness, occasional damaging floods, shallow or very stony soils, moderately steep gradients, moderate erosion, moderately sever climate or interactions of these which increase the levels of farming risk.
4.1	Land in this division is suited to rotations which, although primarily based on long-ley grassland, include forage crops and cereals for stock feed. Yields of grass are high but difficulties of utilisation or conservation may be encountered. Other crops yields are very variable and usually below the national average.
4.2	Land is primarily grassland with some limited potential for other crops. Grass yields can be high but the difficulties of conservation or utilisation may be severe, especially in areas of poor climate or on very wet soils. Some forage cropping is possible and, when extra risks involved can be accepted, and occasional cereal crop.
Land suited only to improved grassland and rough grazing	
5	*Land capable of us as improved grassland*. The agricultural use of land in Class 5 is restricted to grass production but such land frequently plays an important role in the economy of hill lands. Mechanised surface treatments to improve the grassland, ranging from ploughing through rotation to surface seeding and improvement by non-disruptive techniques are all possible. Although an occasional pioneer forage crop may be grown, one or more severe limitations render the land unsuitable to arable cropping. These include adverse climate, wetness, frequent damaging floods, steep slopes, soil defects or erosion risk. Grass yields within the class can be variable and difficulties in production and primarily utilisation, are common.
5.1	*Land well suited to reclamation and to use as improved grassland.* Establishment of a grass sward and its maintenance present few problems and potential yields are high with ample growth throughout the season. Patterns of soil, slope or wetness may be slightly restricting but the land has few poaching problems. High stocking rates are possible.
5.2	*Land moderately suited to reclamation and use as improved grassland.* Sward establishment presents no difficulties but moderate pr low trafficability, patterned land and/or strong slopes may cause maintenance problems. Growth rates are high and despite some problems of poaching satisfactory stocking rate are achievable.
5.3	*Land marginally suited to reclamation and use as improved grassland.* Land in this division has properties which lead to serious trafficability and poaching difficulties and although establishment may be easy, deterioration in quality is often rapid. Patterns of soil, slope or wetness may seriously interfere with establishment and maintenance. The land cannot support high stock densities without damage and this may be serious after heavy rain even in summer.
6	*Land capable of use only as rough grazing*. The land has very severe site, soil or wetness limitations which generally prevent the of tractor-operated machinery for improvement. Some reclamation of small

	patches to encourage stock to range is often possible. Climate is often a very significant limiting factor. A range of widely different qualities of grazing is included, from very steep land with significant grazing value in the lowland situation to moorland with a low but sustained production in the uplands. Grazing is usually insignificant in the full arctic zones of the mountain lands, but below this level of grazing which can be utilised for five months or longer in any year are included in the class. Land affected by severe industrial pollution or dereliction may be included if the effects are non-toxic.
6.1	*High grazing value.* The dominant plant communities contain high proportions of palatable herbage, principally the better grasses, e.g. ben-fescue, grassland or meadow grass-bent pasture.
6.2	*Moderate grazing value* Moderate quality herbage such as white and flying bent grasslands, rush pastures and herb-rich moorlands or a mosaic of high and low grazing values characterise land in this division.
6.3	*Low grazing value.* The vegetation is dominated by plant communities with low grazing values, particularly heather moor, bog heather moor and blanket bog communities.
7	*Land of very limited agricultural value*. Land with extremely severe limitations that cannot be rectified. The limitations may result from one or more of the following defects: extremely severe wetness, extremely stony, rocky land, bare soils, scree or beach sand and gravels, toxic waste tips and dereliction, very steep gradients, severe erosion including intensively hagged peat lands and extremely severe climates (exposed situations, protracted snow-cover and short growing season). Agricultural use is restricted to very poor rough grazing.

A.1.1 Climatic factors

Climate change impacts manifest themselves through the two primary climatic factors of potential soil moisture deficit (PSMD) and accumulated temperature (Figure 11). These are used to estimate other constraints (along with soil) such as soil wetness, workability and trafficability, and have a strong influence in determining the vegetation type. The project has paid particular attention to the estimation of PSMD, through the application of a soil water balance model, as water availability will be a key factor determining agricultural productivity and natural system resilience.

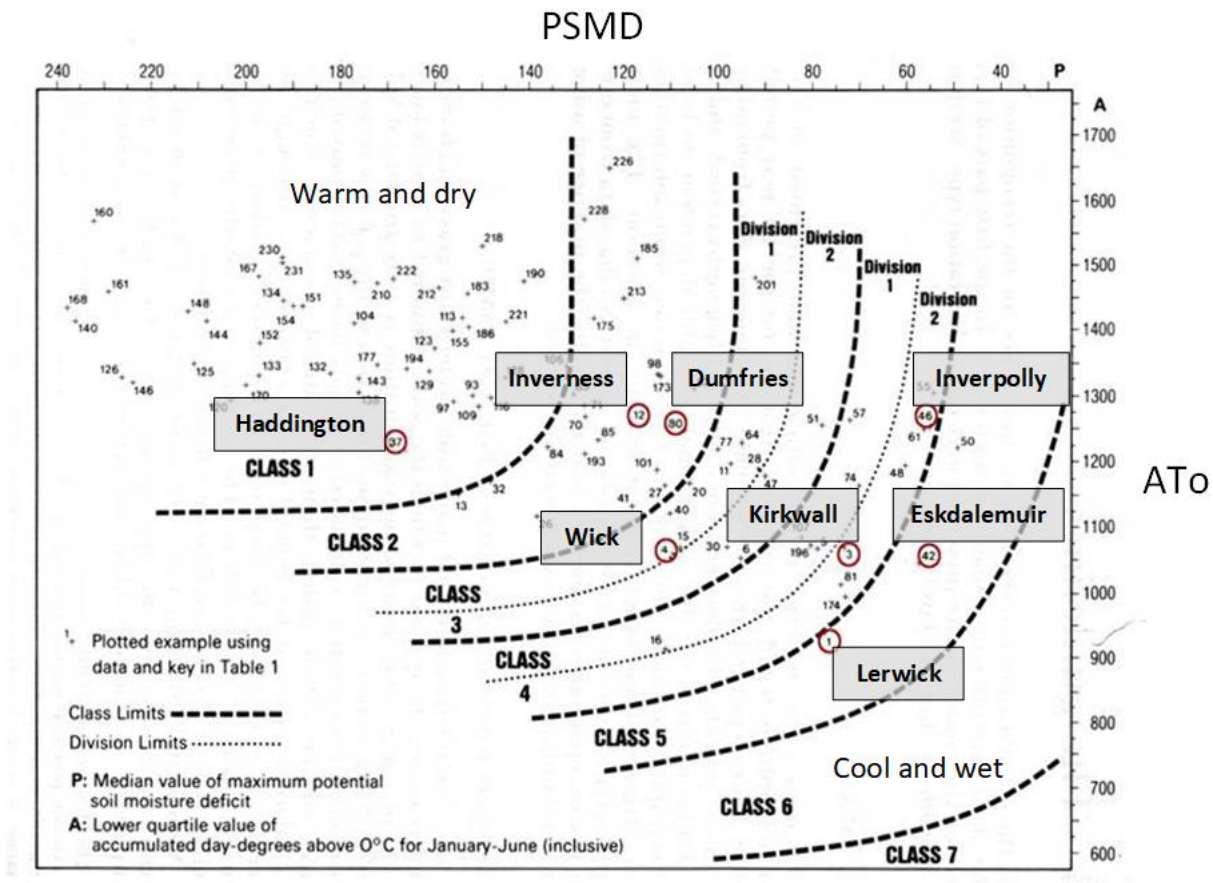


Figure 11 . Primary climatic parameters: potential soil moisture deficit (PSMD) representing how dry or wet a site may be; and accumulated temperature (1st Jan to 30th June) representing the solar energy input (ATo).

A2 Scale

LCA maps are currently published at a scale of 1:50,000 for the agriculturally productive lowlands of Scotland, and maps at 1:250,000 covering all of Scotland. Digital data are available online or download from Scotland's Environment Web[12], and map products from James Hutton Institute[13]. Currently, limitations to using them include the scope on how between-year climate variability affects the classification (though for soil wetness, it is assumed the wetness class occur in more than 10 years in 20, so there is a tacit accounting for variation), and how the classification has changed over time due to observed climate changes.

The new platform enables the production of maps at multiple scales, down to a single map unit (soil series within a 1km grid cell)

[12] National scale land capability for agriculture | Scotland's soils (environment.gov.scot)

[13] Land Capability for Agriculture in Scotland | Exploring Scotland | The James Hutton Institute

Test Box: Original guideline implementation – experiences of a field surveyor

Allan Lilly and Andrew Nolan.

The 1:250 000 scale reconnaissance LCA maps were largely desk-based but built on the recent (1978-80) 1:250 000 scale soil mapping. The climate class lines were drawn on to an overlay at 1:50,000 scale to match the underlying base maps which had topographic information and also the soil map unit lines and codes. There then followed an assessment of the soil types present, topography, erosion and flooding risk to come to an overall assessment within the climatic framework. The LCA polygon lines generally followed those for soil types but were more generalised. The work was carried out in a systematic manner with some drive-by field validation to see if it made sense overall and to pick up any obvious errors, or where further detail was required.

Later, when the 1:50 000 scale LCA maps were produced there was more field assessment and validation and, in some cases, new soil mapping. This was followed subsequently by review by Scottish Government officials, and by research and agricultural organisations such as the Scottish Agricultural Colleges and the National Farmers Union of Scotland.

In the production of the 1:50 000 scale LCA maps, as with the 1:250 000 scale reconnaissance maps, the first consideration was the climate framework which set the limits to the maximum class the land could be in. This was followed by extensive fieldwork over 2 to 3 field seasons (April to October each year). The soil map units were assessed by digging inspection pits and noting any soil properties that would down-grade the land from the maximum class set by the climate such as stoniness, depth to induration or soil wetness based on the thresholds set in the LCA guidelines (Bibby er al.,1982). These observations were recorded on 1:25 000 sale soil maps and in notebooks, and were used to subdivide or amalgamate soil polygons as appropriate, into LCA classes. Specific attention was paid to land in poorer condition that the surround area to assess if there were additional constraints or whether it was due to a lower level of land management.

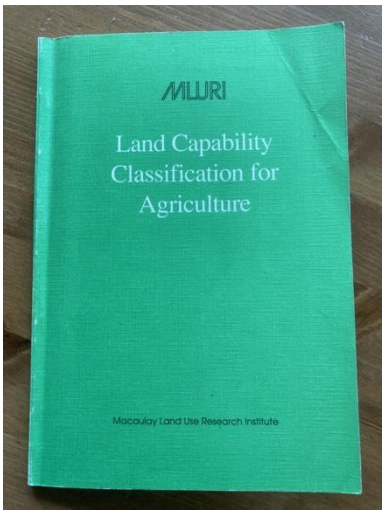
Areas where slope was likely to be limiting were checked in the field using a clinometer and topographic maps and local knowledge/observations were used to identify areas at risk of erosion or flooding and local factors such as exposure which could modify the broad-scale climatic framework also taken into account.

There were correlation discussions within and between teams to ensure the guidelines were being implement uniformly and the draft maps were sent to local advisory and Government offices for review with full-day field meetings to discuss any disagreements in the allocation of classes.

Appendix B: Platform technical development

The Land Capability of Scotland research platform is primarily a computer-based data integration, calculation, mapping and visualisation tool. Designing, building and running the platform has consisted of ten steps:

1. Develop a sound understanding of the original LCA guidelines (right) and the methods to calculate each individual constraint and what data is required.
2. Understand data issues of quality and utility.
3. Design the platform architecture and flow of data (Figure 12).
4. Identify appropriate programming, database and mapping / visualisation tools to use.
5. Design and create input and output database structures and referencing.
6. Acquire input data and populate the database.
7. Convert the LCA guidelines and methods for estimating constraints into code, run calculations for individual constraints and test results.
8. Integrate constraint calculations to derive LCA class.
9. Run calculations for 477,209 unique soil-climate combinations with historical and future climate projection data.
10. Produce map and graphical outputs and analytical methods.



The platform delivers a comprehensive set of climate and soil factors and the results of their biophysical interaction, e.g. soil workability, trafficability, poaching risk and droughtiness (see Glossary and Appendix A). These are based on a sequence of data manipulation and processing operations within the integrated model-database-GIS framework. The platform data integration allows soil data provided at 1:250 000 scale from the Scottish Soil and Knowledge Information Base (SSKIB) to be joined to climatic variables at a 1km grid cell resolution and daily time step. This enables spatially detailed assessments and visualization of what constrains capability at a high granularity.

This granularity is such that the soils database (SSKIB) can be manipulated for over 477,209 unique soil identities that comprised the 580 distinct soil map units in Scotland. Apart from a national scale representation, use of the platform can also manipulate and analyse data based on a user-defined area of interest across 14 attributes.

The structure of the platform ensures it is also capable of:

- Mapping the LCA class and constraint values at a high spatial granularity.
- Estimating the land area for each LCA class for any required scales, such as national, regional (e.g. a Local Authority or catchment) or land holding.
- Identification of the limiting constraint that determines the LCA class (e.g. soil feature or climatic).
- Estimation and visualisation of time series analysis of calculations used in the LCA process, for example soil moisture content (e.g. Figures 9 and 10)
- Spatial assessment of soil and climate interaction e.g., those factors that influence LCA constraints to agriculture such as droughtiness (susceptibility to drought) and potential soil moisture deficit (how dry a soil may become) and interactions that

determine soil how workable a soil is (workability) by machinery (trafficability) and whether access by livestock may damage soils (poaching risk).
- Visualising and interrogating the underpinning soils data.
- Estimation and spatial analysis of agroclimatic indicators including length of field capacity days.

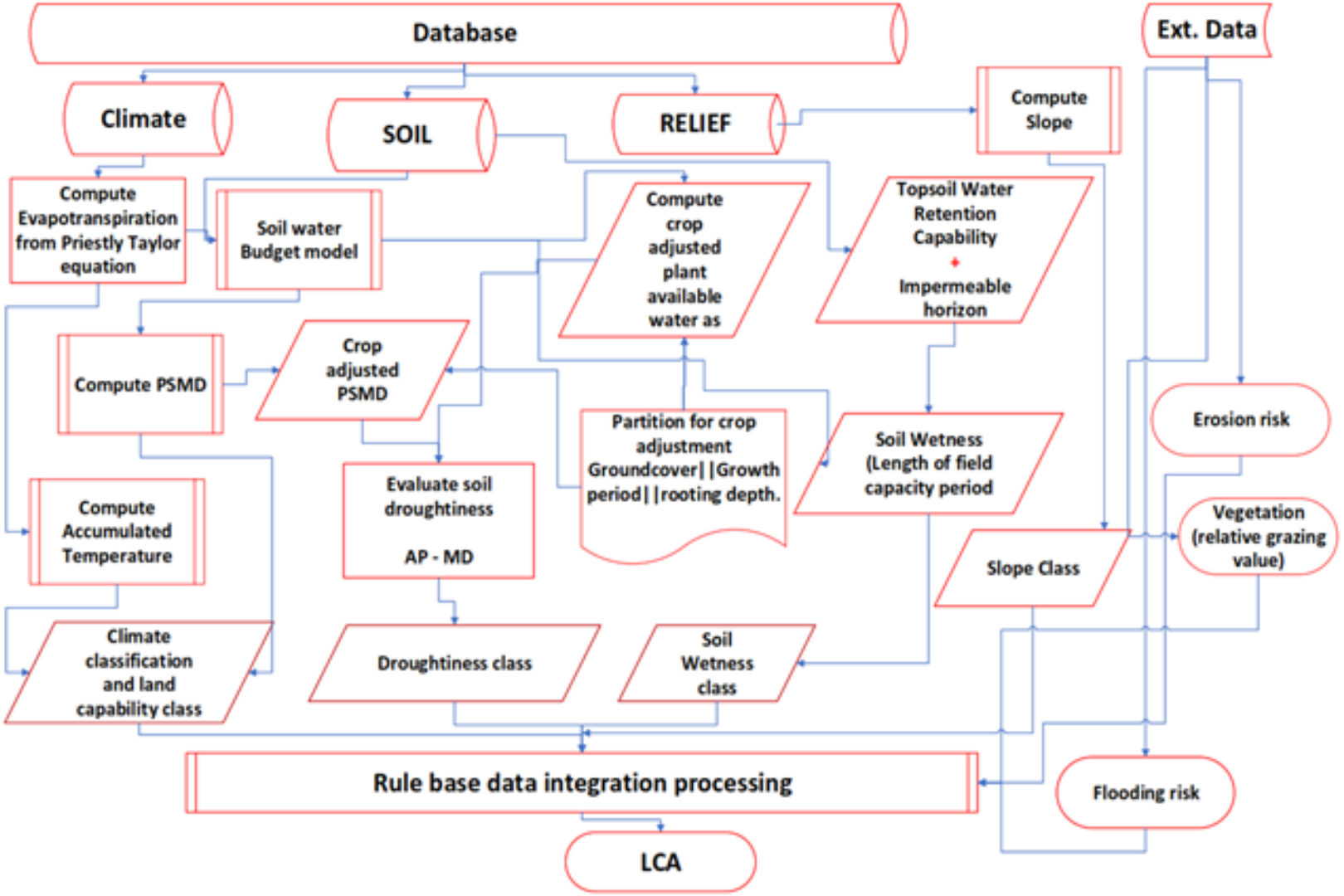


Figure 12: Schematic of the research platform design and data flows to estimate Land Capability for Agriculture classes.

Appendix C - Spatial and temporal evaluation of climate change impact on land capabilities

C1 Climate data

Climate data is critical to the estimation of the LCA classes as it determines constraints to land capability such as soil moisture deficits, wetness and workability.

Currently the platform database is populated with the UKCP18 climate projection data (UKCP18 2018). This data is estimated using a UK Meteorological Office Regional Climate Model (HadRM3) (CEDA 2021)[14]. There are 12 different projections of the future climate made using this model, providing 12 unique data sets to be input to the platform. Each projection is based on the same emissions scenario (below) but with slightly different model settings. This was done to capture the range of possible climate responses to the level of atmospheric greenhouse gas concentrations resulting from the emissions scenario. Each of the twelve HADRM3 simulations is referred to as an 'Ensemble Member'. To aid interpretation of platform results, it is important to understand the differences between the ensemble members' data in respect of their temperature and precipitation differences from the past climate (1960-1990). This is illustrated in Figure 1, which shows the differences between ensemble members for two future time periods: 2030-2049 (2040s) and 2060-2079 (2070s), with respect to a 1994-2015 baseline period, for the March to September growing season covering Scotland's class 1 – 3.1 areas.

For example, ensemble member 07 has a 1.4°C temperature increase by the 2040s period, but the same precipitation amount compared to the baseline period (i.e. no change). By the 2070s, ensemble member 07 becomes 2.5°C warmer and has 5% less precipitation. In contrast, ensemble member 13 is 2.1°C warmer and 9% drier by the 2040s, and 3°C warmer and 21% drier by the 2070s.

The emissions scenario under which the HadRM3 model was run is referred to as the Representative Concentration Pathway 8.5 (RCP 8.5) (Moss et al 2010, Raihi 2017). RCP8.5 is considered as a high and continued rate of emissions and reflects the current increasing rates of emissions (IEA 2021, NOAA 2022). This scenario may not be likely if mitigation efforts are intensified and targets are reached, but its overall atmospheric CO_2 concentrations may yet still remain feasible given risks of positive feedback responses by natural systems (e.g. carbon and methane emissions from melting Arctic tundra) and loss of natural carbon capture (e.g. reduced functioning of rainforests and phytoplankton activity in the oceans). The RCP8.5 UKCP18 data has been used as it is it the only high-resolution daily data currently available. This scenario represents a plausible 'worst case' but also sets a range of future conditions that are useful in respect of adaptation. It is important to also note that there are few differences in the climate projections up to c. 2040 between the high (RCP8.5) and low (RCP2.6) emissions scenarios.

The platform has been developed to enable the use of multiple climate model projections using other emissions scenarios and spatial scales when available.

[14] Dataset Collection Record: Met Office Hadley Centre Regional Climate Model (HadRM3-PPE) Data (ceda.ac.uk)

C.1.1 Assessing changes over time

Climate change means that land capability classification should have a dynamic temporal component; assessments should consider annual variability, rather than be based on the use of long-term averages (Brown and Castellazzi 2015).

Using the baseline observed climate data (1960 – 1990 and 1987 – 2017) at a 1km grid cell resolution and the soil series data, it is possible to assess changes over time. It is important to note here that some constraints are independent of the climatic factors and will not – or are unlikely to – change in the future, e.g. slope, soil depth and impermeable horizons.

Climate change impacts on an LCA class (and their constraints) can now be evaluated using the future climate projections for any time slices required. It is also possible to consider issues of uncertainty, for example by comparison between the 12 climate model ensemble members. This facilitates assessments of how the LCA classes respond to variation in future climate conditions. For example, Figure 2 shows the differences between climate projections, hence it is possible to estimate the LCA classes for all 12 ensemble members and then assess their range.

C2 Advances on previous capabilities

The project has successfully constructed a computing platform on which future land capability can be projected through the integration of a range of new data sources and the implementation of the original guidelines as computer code. The architecture of the platform has been designed to be open-ended enabling potential for further development and inclusion of new data and application for other research purposes.

The platform now means there is potential to:

- Estimate the individual constraints and overall classes of future land capability with new climate projections, and / or updated soils data, as they become available. This means it is now possible to identify which constraint determines the LCA class, for example if it is one determined by the climate and can therefore change, such as accumulated temperature and / or potential soil moisture deficit, or remains a fixed constraint such as slope or soil depth.
    - Model soil water balance and evapotranspiration on a daily time step at a 1km climate and soils series level of granularity to enable location specific assessments of temporal variability.
    - Back-calculate the LCA to 1960 using interpolated climate data to estimate how LCA has changed over time in the past.
        - We used Machine Learning methods to estimate solar radiation data back to 1960 based on observed precipitation and temperature data, calibrated against solar radiation derived from satellite data (1994-2020).
- It is now possible to assess how the LCA classes and constraints have varied over time in the past and how they might vary in the future:
    - It is now possible to estimate the LCA constraints and classes per year and analyse the inter-annual variability.
- Refine, add to or develop new constraint calculation methods. This means we can adapt the platform to cover issues beyond just agricultural capabilities, or develop criteria for particular aspects of agriculture (e.g. crop specific).
- Use GIS software to map the classes, access the results for each individual constraint and the underlying data (e.g. soils, climate).

    - This means we can undertake spatial analyses (e.g. changes in land area per class over time or between climate model projections – see Figure 6).
    - This enables detailed site-specific analysis of underpinning data (soils, climate)
    - It is possible to overlay other spatial data, for example existing land use or cover (existing woodlands, wetlands, areas under protected status etc.), to explore land use options.
- The new platform enables the production of maps at multiple scales, from national down to a single map unit (soil series within a 1km grid cell).
- Integrate spatial data sets: High resolution topography (Digital Elevation Models – DEM), soils, climate and remote sensed data to enable more detailed analysis of multiple criteria that influence land capability and are impacted by the climate and what this means for land use decision making.
- Analyse specific constraints within the LCA. Scripts for individual constraints can be run independently, allowing assessment of a particular constraint to a change in input data.
- Potentially utilise remotely sensed satellite data as input, for example Sentinel-2[15] including soil moisture (Ambrosone et al 2020) and Normalized Difference Vegetation Index (NVDI) data.
- Develop additional land capability criteria and convert this into code. The platform has been developed to be open-ended to enable new types of assessments to be made.

C3 Soil water balance

The ability to model soil water is essential to understand how land capability may change under future climate conditions. Soil water content is a key determinant of what an area of land can be used for, as well as influencing the type and properties of soils. The amount of water in a soil is primarily determined by the weather and soil properties and influences the water available for use by crops and vegetation. This availability is a key part of how soils function and provide ecosystem services, e.g. carbon sequestration.

An important improvement in the platform is the ability to estimate daily soil water balance (SWB) to provide high-granularity spatial (map unit) and daily time-step level estimates of Potential Soil Moisture Deficit. This ability enables calculation of Field Capacity days and soil wetness (which are key LCA class constraints, as well as being useful indicators for land managers when access to land is possible) using unique soil-weather combinations at a 1km climate and soil series map unit level. In Scotland there are 477,209 unique soil-climate combinations, with corresponding SWB estimates made for each one, enabling detailed assessment at a high spatial resolution.

Figure 13 shows the overall method for estimating SWB values for each of these combinations. This is a new addition to the process of estimating land capability and has been coded within the platform enabling SWB values to be estimated independently of other LCA calculations, meaning it can be revised and rapidly re-run using any new data on soils and climate. The modelled data can also be used for other research purposes.

[15] Sentinel-2 - Data Products - Sentinel Handbook - Sentinel Online (esa.int)

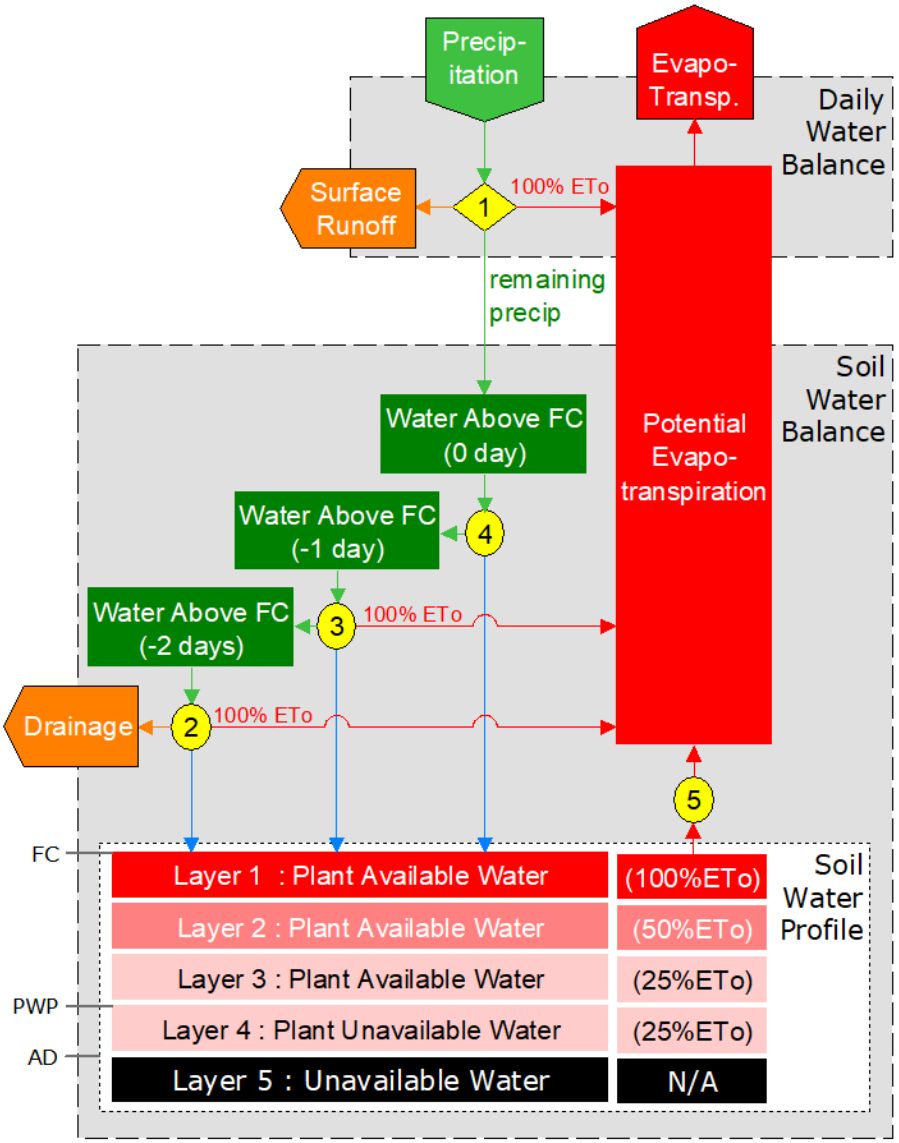


Figure 13: Schematic of the Soil Moisture Balance model used to estimate Potential Soil Moisture Deficit and Soil Wetness class constraints. FC = Filed Capacity, PWP = Permanent Wilting Point, AD = Air Dried, ETo = Evapotranspiration

The implementation of this new soil water balance modelling capability to better estimate the LCA constraints means it is now possible to assess the variability of soil water balance within- and between years and on a daily basis to observe changes over time, for examples see Figures 9 and 10.

Appendix D: Additional results

The following tables provide details of the annual variability in LCA constraints and classes for two soil types and two ensemble members.

Table 5 Annual variability in constraint values and LCA classes for a noncalcareous gley soil with no surface peat (unique_ID 116379) estimated using two ensemble members (01 and 13).

	Ensemble Member 01									Ensemble Member 13								
Year	Total Precip (mm)	ATo (degree days)	SMD (mm)	FC days	Workability Limit	Poaching risk	Wetness	LCA limiting factor	LCA Class	Total Precip (mm)	ATo (degree days)	SMD (mm)	FC days	Workability Limit	Poaching risk	Wetness	LCA limiting factor	LCA Class
2020	779	1338	182	58	3	b	2	s	3.1	663	1648	217	18	3	b	2	s	3.2
2021	828	1422	171	94	3	b	2	s	2	749	1281	154	29	3	b	2	s	2
2022	640	1538	151	38	3	b	2	s	2	704	1346	175	54	3	b	2	s	2
2023	601	1626	201	57	3	b	2	s	2	818	1398	148	66	3	b	2	s	2
2024	967	1347	140	36	3	b	2	w	2	760	1348	141	24	3	b	2	s	2
2025	641	1384	195	46	3	b	2	s	3.2	856	1321	151	56	3	b	2	s	2
2026	760	1650	194	65	3	b	2	s	2	866	1372	154	108	3	a	2	w	3.1
2027	999	1413	84	107	3	a	2	w	3.1	573	1634	226	59	3	b	2	s	3.2
2028	848	1499	143	37	3	b	2	s	2	781	1299	159	38	3	b	2	s	2
2029	675	1224	163	41	3	b	2	s	2	895	1391	157	64	3	b	2	s	2
2030	1259	1309	138	91	3	b	2	s	2	692	1423	147	58	3	b	2	s	2
2031	1024	1299	135	101	3	a	2	w	3.1	636	1396	179	5	3	b	2	s	2
2032	829	1388	202	74	3	b	2	s	3.2	907	1560	147	43	3	b	2	s	2
2033	698	1469	175	53	3	b	2	s	2	754	1439	197	53	3	b	2	s	2
2034	686	1625	156	32	3	b	2	s	2	506	1444	227	0	3	b	2	s	3.2
2035	846	1369	116	17	3	b	2	s	2	714	1546	180	6	3	b	2	s	2
2036	806	1598	144	72	3	b	2	s	2	855	1580	168	25	3	b	2	s	2
2037	822	1466	143	41	3	b	2	s	2	779	1594	185	70	3	b	2	s	3.1
2038	699	1542	176	47	3	b	2	s	2	849	1438	166	64	3	b	2	s	2
2039	652	1586	189	29	3	b	2	s	2	570	1304	184	19	3	b	2	s	2
2040	720	1486	172	0	3	b	2	s	2	845	1593	136	35	3	b	2	s	2
2041	802	1553	138	26	3	b	2	s	2	973	1520	140	68	3	b	2	s	2
2042	730	1708	167	39	3	b	2	s	2	789	1618	172	80	3	b	2	s	2
2043	899	1662	154	47	3	b	2	s	2	709	1630	194	49	3	b	2	s	3.1
2044	725	1500	161	42	3	b	2	s	2	783	1422	187	61	3	b	2	s	2
2045	926	1383	140	73	3	b	2	w	2	858	1581	228	65	3	b	2	s	3.2
2046	888	1376	130	56	3	b	2	s	2	705	1299	185	36	3	b	2	s	2
2047	603	1705	200	44	3	b	2	s	2	797	1685	128	53	3	b	2	s	2
2048	701	1823	203	3	3	b	2	s	3.1	747	1286	187	40	3	b	2	s	3.1
2049	735	1442	194	47	3	b	2	s	3.1	570	1674	217	44	3	b	2	s	3.2
2050	897	1383	132	96	3	b	2	s	2	787	1444	153	8	3	b	2	s	2

Table 6. Annual variability in constraint values and LCA classes for a peaty alluvial soil with surface peat (unique_ID 104) estimated using two ensemble members (01 and 13).

	Ensemble Member 01									Ensemble Member 13								
Year	Total Precip (mm)	ATo (degree days)	SMD (mm)	FC days	Workability Limit	Poaching risk	Wetness	LCA limiting factor	LCA Class	Total Precip (mm)	ATo (degree days)	SMD (mm)	FC days	Workability Limit	Poaching risk	Wetness	LCA limiting factor	LCA Class
2020	1166	1397	149	239	6	e	5.3	w	5.3	871	1717	198	166	4	e	5.3	w	5.3
2021	1269	1504	139	220	6	e	5.3	w	5.3	1081	1388	79	290	6	e	5.3	w	5.3
2022	1174	1628	73	278	6	e	5.3	w	5.3	1014	1458	150	216	6	e	5.3	w	5.3
2023	1063	1684	196	178	5	e	5.3	w	5.3	1013	1513	159	185	5	e	5.3	w	5.3
2024	1318	1423	0	360	6	e	5.3	w	5.3	1068	1472	117	258	6	e	5.3	w	5.3
2025	1086	1514	160	245	6	e	5.3	w	5.3	1231	1411	78	323	6	e	5.3	w	5.3
2026	1079	1735	164	199	5	e	5.3	w	5.3	1215	1478	77	310	6	e	5.3	w	5.3
2027	1369	1534	25	351	6	e	5.3	w	5.3	854	1753	242	153	4	e	5.3	w	5.3
2028	1113	1558	58	269	6	e	5.3	w	5.3	1127	1375	176	235	6	e	5.3	w	5.3
2029	1167	1314	84	264	6	e	5.3	w	5.3	1191	1436	125	263	6	e	5.3	w	5.3
2030	1244	1477	111	259	6	e	5.3	w	5.3	1288	1464	0	360	6	e	5.3	w	5.3
2031	1147	1392	47	313	6	e	5.3	w	5.3	1021	1532	175	204	6	e	5.3	w	5.3
2032	1043	1536	179	195	5	e	5.3	w	5.3	1189	1644	113	253	6	e	5.3	w	5.3
2033	1061	1573	130	221	6	e	5.3	w	5.3	941	1495	195	179	5	e	5.3	w	5.3
2034	1150	1699	62	310	6	e	5.3	w	5.3	892	1460	207	184	5	e	5.3	w	5.3
2035	1371	1468	0	360	6	e	5.3	w	5.3	1095	1595	110	227	6	e	5.3	w	5.3
2036	1138	1606	87	283	6	e	5.3	w	5.3	1153	1674	194	205	6	e	5.3	w	5.3
2037	1196	1568	105	253	6	e	5.3	w	5.3	1031	1633	213	214	6	e	5.3	w	5.3
2038	967	1610	156	161	4	e	5.3	w	5.3	1152	1536	167	214	6	e	5.3	w	5.3
2039	937	1661	175	193	5	e	5.3	w	5.3	896	1400	176	202	6	e	5.3	w	5.3
2040	1066	1599	90	270	6	e	5.3	w	5.3	1118	1680	80	279	6	e	5.3	w	5.3
2041	1000	1657	135	211	6	e	5.3	w	5.3	1328	1624	23	339	6	e	5.3	w	5.3
2042	1253	1763	101	249	6	e	5.3	w	5.3	1084	1687	175	231	6	e	5.3	w	5.3
2043	1349	1717	101	270	6	e	5.3	w	5.3	1247	1683	178	201	6	e	5.3	w	5.3
2044	1126	1595	40	330	6	e	5.3	w	5.3	988	1490	147	185	5	e	5.3	w	5.3
2045	1182	1534	56	277	6	e	5.3	w	5.3	1227	1682	246	199	5	e	5.3	w	5.3
2046	1095	1504	65	258	6	e	5.3	w	5.3	906	1373	139	241	6	e	5.3	w	5.3
2047	880	1722	192	171	4	e	5.3	w	5.3	994	1689	114	258	6	e	5.3	w	5.3
2048	1077	1893	195	160	4	e	5.3	w	5.3	923	1456	192	208	6	e	5.3	w	5.3
2049	1020	1513	147	220	6	e	5.3	w	5.3	710	1769	251	147	4	e	5.3	w	5.3
2050	1192	1490	160	242	6	e	5.3	w	5.3	1276	1576	96	230	6	e	5.3	w	5.3

Appendix E: Additional spatial information

There are a range of spatial data products that have been created within the project on the Land Capability platform, such as the Field Capacity days (Figures 6 and 7), as well as complementary information from parallel research projects. Some of these are provided below as examples of how value can be added to the Land Capability research.

E1 Soil water holding capacity

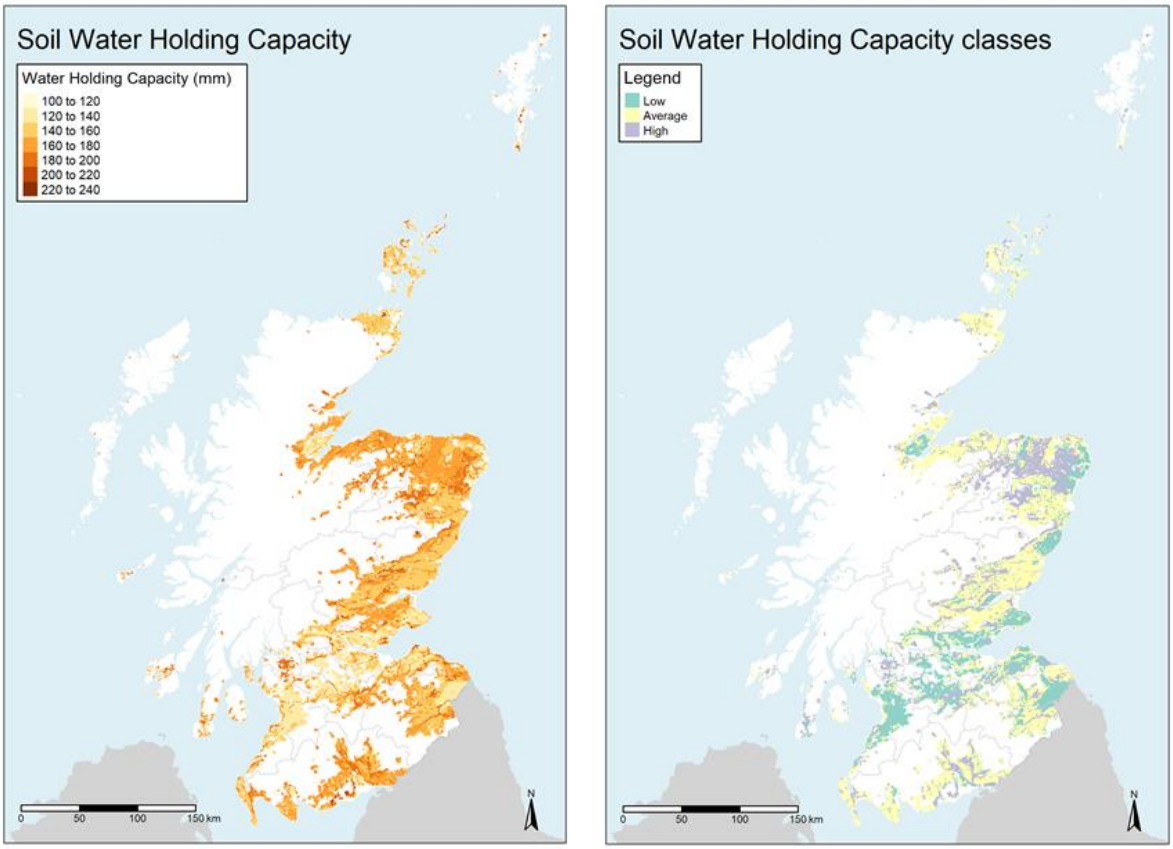


Figure 14. Spatial distribution of the soil water holding capacity (left map) and the different WHC classes (right) for the arable areas of Scotland. The WHC classes were defined based on the 10th and 90th percentiles with the class 'Low' for WHC below the 10th percentile, 'Average' for WHC between the 10th and 90th percentiles, and 'High' for WHC above the 90th percentile (Credit: Mohamed Jabloun, James Hutton Institute, 2021)

Mapping the soil water holding capacity and the water balance helps us to align a key soil characteristic with changes in the climatically driven changes in Potential Soil Moisture Deficit and wetness classes and overall LCA class.

E2 Crop yield mapping

A parallel area of research with the Scottish Government Strategic Research Programme has utilised the application of a crop simulation model applied to the arable areas of Scotland. This research has used the same climate and soils data meaning results can be linked to add value to the outputs from the Land Capability platform. Mapping crop responses to the same soil-weather unique combinations used to produce

the LCA classes means we can compare crop productivity with land capability. This adds a substantial refinement to the LCA system by enable exploration of the relationships between land capability and productivity. Figures 10 and 11 below illustrate the outputs from the crop simulation modelling research for the observed period and future projections.

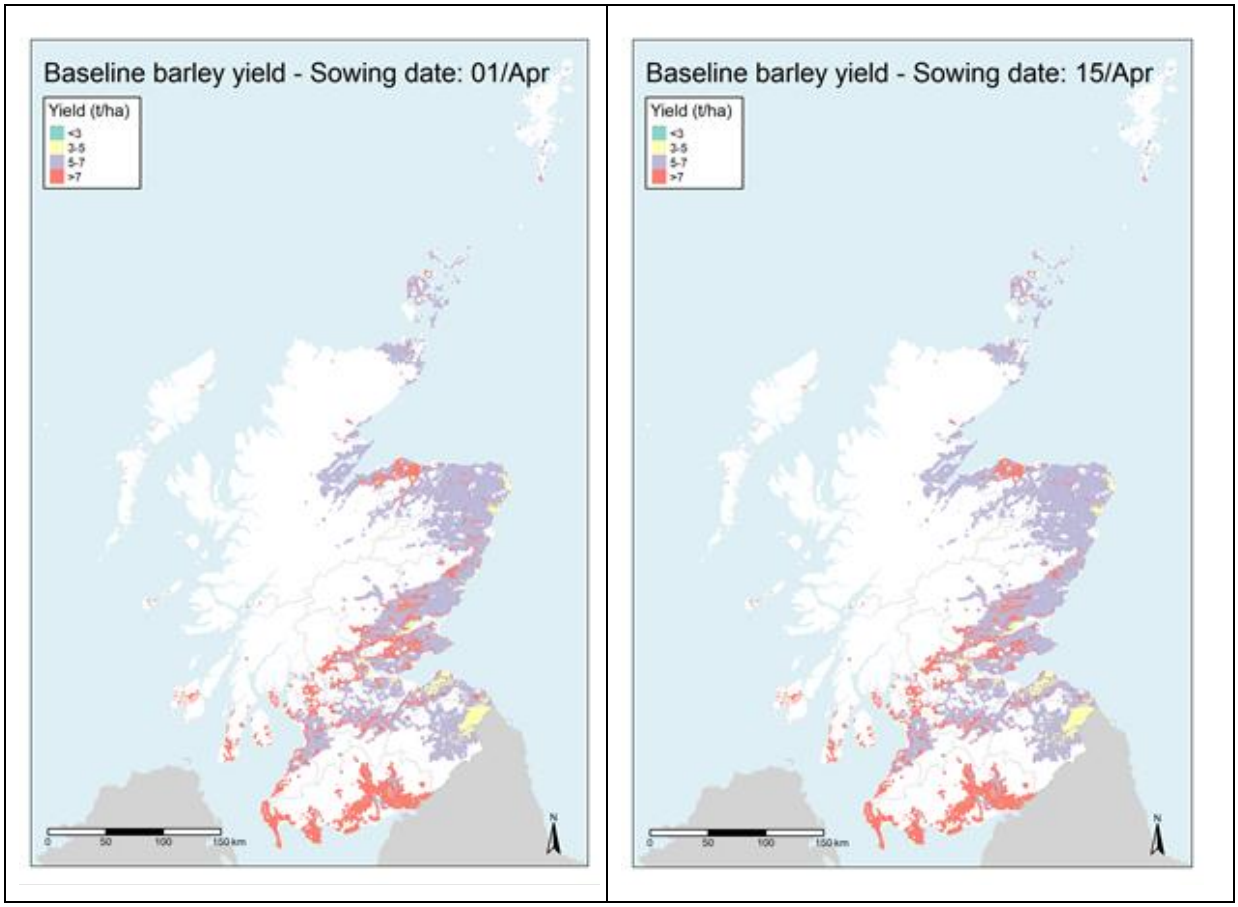


Figure 15. Map of simulated averaged barley yields (t/ha) for Scotland for two sowing dates. (Credit: Mohamed Jabloun, James Hutton Institute, 2021)

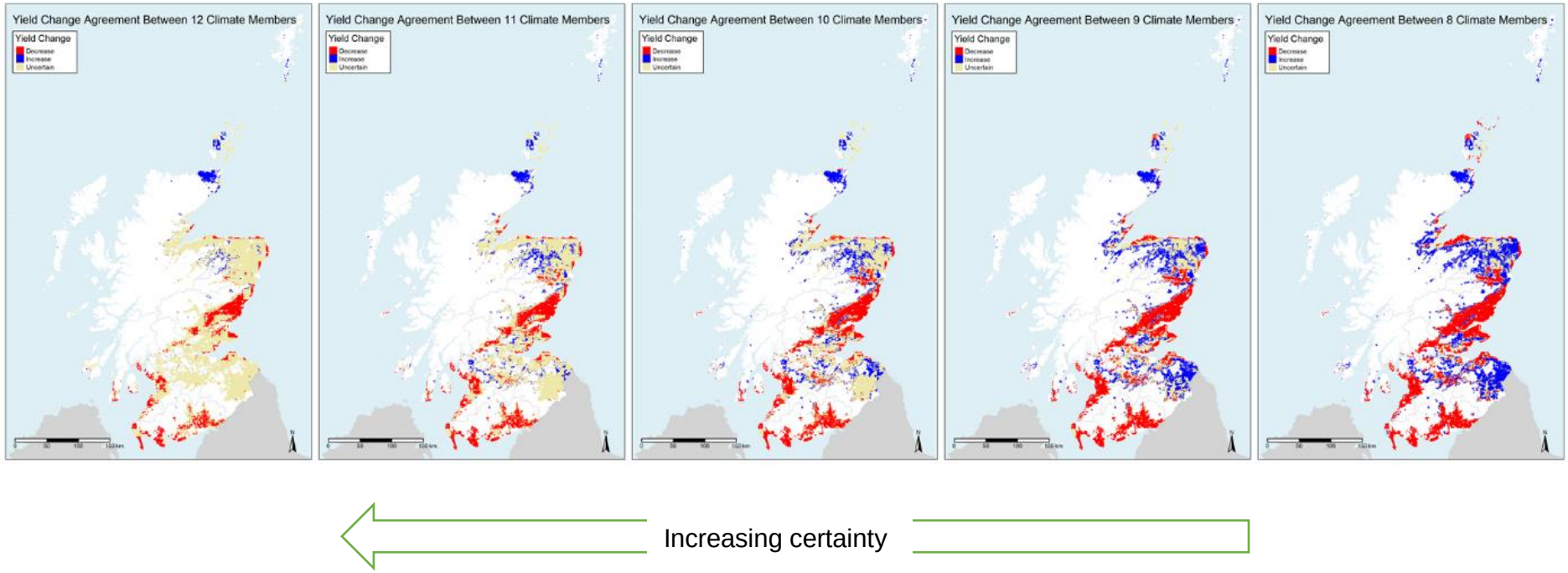


Figure 16. Maps of simulated averaged barley yields (t/ha) for Scotland for the period 2030 - 2039 produced using 8 (right) to 12 (left) UKCP18 ensemble members, illustrating the increasing certainty (with more ensemble members) as to where yields may increase (blue) or decrease (red). (Credit: Mohamed Jabloun, James Hutton Institute, 2021)

In Figure 16, the probability that areas identified as having an increase or decrease in yield becomes more certain with the numbers of climate model ensemble members used. This ‘agreement map’ method could be used with the LCA estimates as well to illustrate where there is more certainty that a locations LCA class (or constraint) may change.

E3 Spatial agrometeorological indicators

Another parallel area of research within the Scottish Government Strategic Research Programme has used the same input climate projection data, and therefore complementary to the land capability platform, is the production of Agrometeorological Indicators. These are things like the length of growing season, occurrences of frosts in spring and autumn, the date when soil water falls below field capacity etc. These have been estimated at a 1km resolution for the whole UK, enabling comparison of impacts in Scotland in a wider context. An example, Plant Heat Stress, is illustrated in Figures 17 (two historical baseline periods) and 18 (projections for three ensemble members).

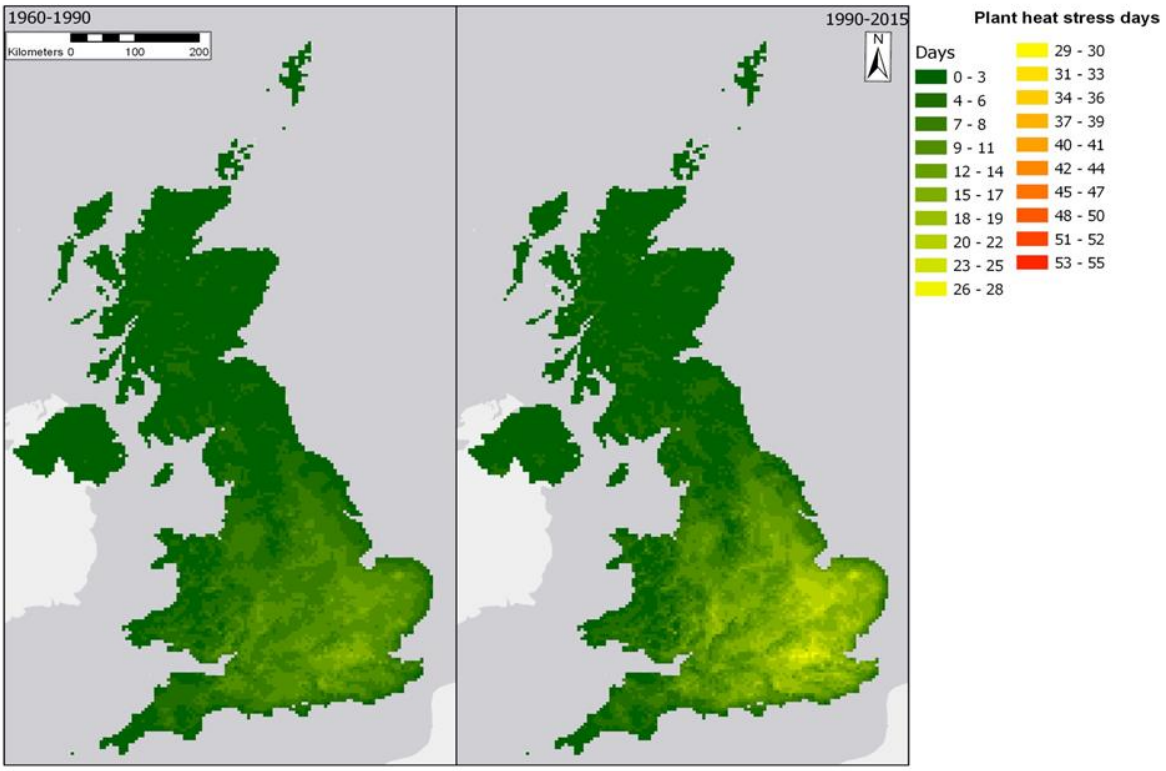


Figure 17. Observed changes in the mean Plant Heat Stress Indicator (number of days in a year when the maximum temperature is greater than 25°C) between 1960 – 1990 and 1990 – 2015.

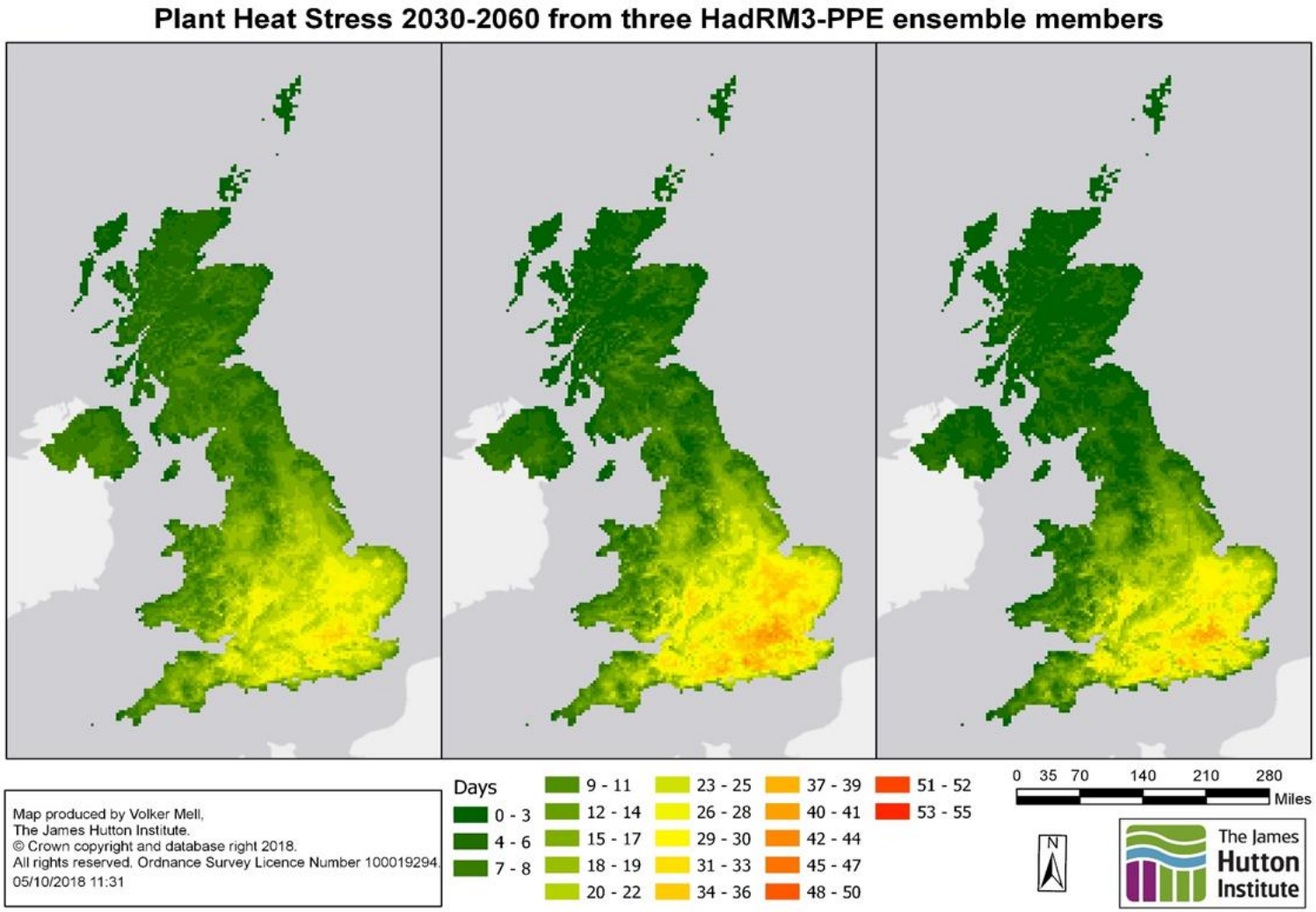


Figure 18. Projected changes in the mean Plant Heat Stress Indicator (number of days in a year when the maximum temperature is greater than 25°C) for the 2030 - 2060 period for three ensemble members.

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