Barley Responses to Climate Change - Report

Report of developing capability in the spatial modelling of barley cropping under current and future climates.

RESAS Strategic Research Programme Theme 2.

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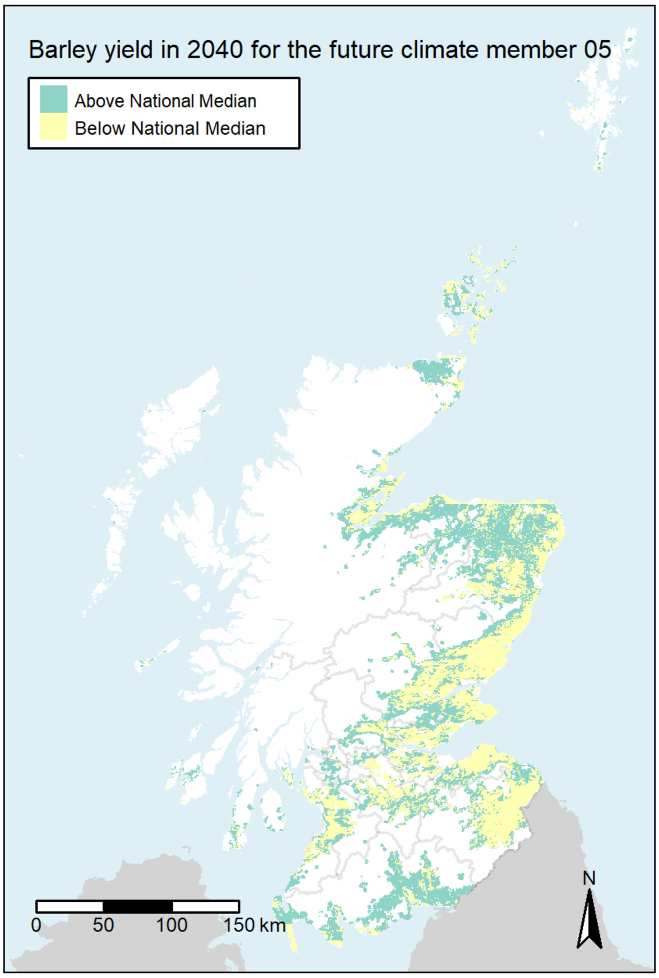

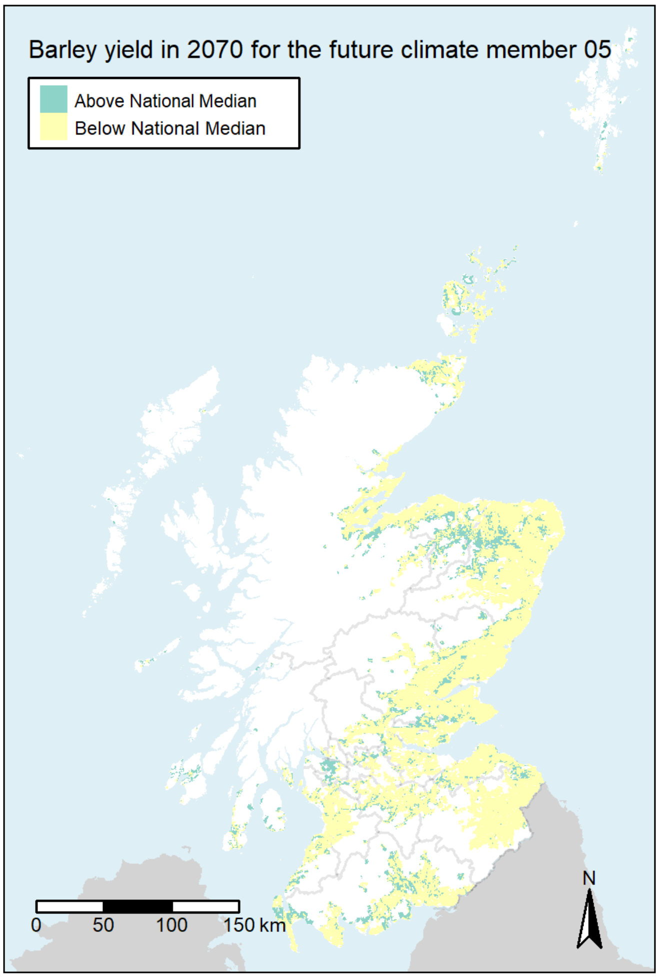

Barley responses to climate change – Executive Summary

This report details the results of using a crop simulation model and spatial weather, soil and land use data to estimate barley growth across Scotland for multiple years under current and 12 future projected climates. The research is part of the Rural Industries Work Package (WP) within Theme 2 of the Scottish Government's Strategic Research Programme.

The rationale for this project is to build capabilities in modelling barley growth and production responses to multiple drivers (e.g. climate change, policy or markets), as it is the most economically important crop in Scotland. This modelling platform will help: policy-makers; the agri-food industry; land managers and other rural stakeholders and researchers to better understand the biophysical and management processes determining barley yield on a spatial basis. This will aid future strategic planning (e.g. by farmers, cereal supply chains and barley users such as the whisky and brewing industries), identify areas of Scotland at risk or where opportunities exist and identify options for adaptation (e.g. by farmers) and define research gaps that need to be addressed (e.g. crop genetic trait selection).

The aim of this report is to present results for use with stakeholders so as to communicate risks and opportunities and to evaluate the utility of the projects' outputs and prioritise within the range of options for further research.

The project has used a crop simulation model (DSSAT) parametrised to model spring barley growth in Scotland using as inputs an integrated set of spatial data (weather, soils, and land use). The outputs from the simulations are visualised as maps using a geographical information system. Examples of mapped estimates of barley yield, phenology and soil properties (water holding capacity) are presented with a high spatial granularity national coverage.

Recommendations are made on future research development opportunities.

Key Findings: Climate Change Impacts

- With the high emissions scenario used (RCP8.5), climate change is likely to have both positive and negative impacts on barley growth and annual yields, but with an overall decrease in yields by the 2040s, which continues to worsen by the 2070s.
    - It should be noted that there is little difference in estimated climate change between the low and high scenarios until c. 2040 – 2050, after which they start to diverge.
- Under the twelve climate projections used (which leads to temperature increases ranging from 1 to 3.5°C and 7% increase to 14% decrease in growing season precipitation), barley yields are likely to decrease in many parts of Scotland.
    - This will likely be due to additional water stress, especially if water is limited in the spring to early summer periods.
    - Future higher temperatures and potentially reduced precipitation are likely to lead to an increased water deficit, where evapotranspiration loss of water to the atmosphere is greater than the precipitation input to soils.
    - Areas with better soil water holding capacity appear to be more resilient and could potentially experience increases in yield when favourable climatic conditions permit.
- There is good agreement between the climate projections as to where these changes in yield may occur.
- There is likely to be increased annual variability, with some years potentially experiencing good yields when conditions are favourable.
- The spatial extent and temporal frequency of yield decreases is likely to cause substantial challenges to the barley supply chain and end users.
- Earlier sowing appears to be a viable adaptation option.

Key Findings: Research capabilities

- The research capabilities have improved substantially during the project, as the crop model can now utilise multiple climate change projections and run on a High-Performance Computing platform to generate a diverse range of mapped outputs.
- These advances mean research now has improved capabilities to inform policy, farmers and the barley supply chain of the future risks and opportunities.
- However, a continuing major constraint on the utility of the modelling is the ability to validate modelled estimates using a diverse range of geographically dispersed site-specific observations.
    - There is need to develop a culture of collaboration between farmers and researchers to make historical and real-time data available, and develop the technical capabilities (e.g. phone apps and database) to facilitate data exchange.
    - To improve predictive skill, there is a need to improve the process of field scale data collection and organisation into a spatially references database. Desirable data include: yield, sowing date, fertiliser rate, growth stage (phenology: emergence, flowering, physiological maturity) and harvest date.
- Given the scale and extent of climate change impacts on barley production (which can also be analogous to other key crops in Scotland) and its associated economic value and role within the Scottish food system, there is an urgent need to further increase the research capabilities to improve risk and opportunity assessment to support adaptation planning.

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Acknowledgements and collaborations

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1 INTRODUCTION

About this document

This is a report on developing and applying new crop modelling simulation and spatial data integration capabilities to research the production of barley, spatially, for the whole of Scotland under future climate projections. This research is supported by the RESAS Strategic Research Programme 2016 – 2021 supported project within RD 2.4 Rural Industries work package. The research has improved on the existing ways of estimating future responses of barley to climate change and other key drivers by increasing the spatial resolution of representation and increase diversity of climate change projections used.

The objective has been to gain a better understanding of the biophysical and management processes determining yield and to use this with stakeholders to aid future strategic planning (e.g. by farmers and barley utilisers such as the whisky industry), identify spatially areas at risk or where opportunities exist and to explore options for adaptation (e.g. by farmers changing management). A further objective has been to define research gaps that need to be addressed (e.g. crop model calibration and validation data, crop genetic trait selection). The purpose of this report is to present results of what this new capability generates and how the research issues it addresses can inform stakeholders.

The results as presented are estimated projections of barley responses to a range of plausible climate projections. The results are not predictions, as there are a large range of uncertainty sources (e.g. atmospheric responses to greenhouse gas concentrations, modelling of climatic responses) that affect the amount of uncertainty (see Wallach et al 2015 for further details of uncertainty in agricultural impacts assessment). The scope of the study is therefore to explore the range of possible responses of barley to a range of future climates, rather than to attempt definitive predictions. The effects of this range of barley responses in terms of consequences on supply chains and impacts on economics is beyond the scope of this study.

Rational for this project

Barley is the most economically import crop in Scotland, the second most important in the UK and Europe and the fourth most important cereal in the world. In Scotland spring barley accounted for approximately 248,900 ha (54%) and winter barley 43,200 ha (9%) of the total cropped area in 2021. Barley underpins the distilling and brewing industries, and is a key feed source for livestock, and thus has an essential role in supporting economically significant supply chains. Whisky for example generates c. £5 billion in GVA to the UK economy.

There are emerging risks and opportunities for barley production due to climate change. In 2020 for example, The National Farmers Union annual crop survey (England and Wales) indicated winter wheat and barley yields down 18%, spring barley and oilseed rape down 6% and 15% respectively. The decrease in production was in part due to variable weather conditions, ranging from the wettest February on record (UKMO, 2020a) (restricting field access for pre-sowing preparation and sowing) to an exceptionally dry spring with May being the sunniest on record (UKMO, 2020b). Hence despite large increases in planted areas for some crops, e.g. spring barley was up 54%, there was little net gain (of 3.9%) on 2019 total yields (DEFRA 2020). Conversely in Scotland, 2020 saw increased production due to larger planted area and increased yields[1].

Hence there is need to better understand the consequences of climate change on barley production, both in terms of yield responses and identifying where yields may either increase or decrease, and why.

This project addresses the assessment of the sustainability of cropping systems under both present and future climates. Changes in climate will not, however, occur in isolation. To be useful to stakeholders the analysis of future sustainability needs to assess climatic effects in the context of other changes such as policy, markets and trade. This report focusses on the spatial climatic and biophysical determinants of yield change, the objective being to provide the production impacts basis to discussions on policy, market and trade responses.

[1] Cereal and oilseed rape harvest: final estimates - 2020 - gov.scot (www.gov.scot)

Context, aims and objectives

The research is part of the Rural Industries Work Package (WP) within Theme 2 of the Scottish Government's Strategic Research Programme. The aim of the project has been to build and deploy with stakeholders a capability to analyse the performance of cropping systems, in space, across Scotland. This capability has used an integrated analytical approach to bring together the relevant spatial data sets, simulation modelling, databases and High Performance Computing and spatial analytical tools such as geographical information systems (GIS).

The objective has been to present results and raise awareness of this new capability with stakeholders and to build on dialogue and collaboration with them in developing the project further.

We present a range of maps of estimated barley yields and soil water content to assess potential impacts of climate change. Estimates are based on simulations for three time periods (1994-2015, 2030-2049, 2060-2079, denoted thereafter as baseline period, 2040 and 2070, respectively). The scale of representation has sufficient granularity to allow the assessment of the implications for crop yield and other outcomes of specific localised combinations of soil and weather conditions.

2 RESEARCH CAPABILITY

The modelling of barley in this project has, to date, been undertaken using the Decision Support System for Agrotechnology Transfer (DSSAT) software platform, using a single barley model, applied with a high spatial granularity to simulate yield and other crop growth factors (soil water, nitrogen, responses to management etc.).

Unique combinations of weather and soil conditions are generated across the arable areas of Scotland (see Figure 1) for use in the model by combining high resolution weather data (1 km) from UK Met Office, the 1:250,000 scale soils mapping from the James Hutton Institute and data from the Scottish Soils Knowledge and Information Base (SSKIB). **There are 56,256 unique soil-climate combinations** generated for locations where barley has previously been grown and for areas adjacent (1km buffer zone) to these locations in which barley could hypothetically be grown, especially allowing for climate change. The locations on which barley has been grown are derived from field level reporting of land use by farmers in their annual Integrated Administration and Control System (IACS).

The DSSAT model used with the integrated spatial datasets represents a new capability in Scotland for spatial modelling at a national scale with high granularity. This will support the investigation of a diverse range of sustainable production system questions, including:

- Assessment of the impacts of drivers, e.g. climate change, on yields and the biophysical factors that determine this (e.g. soil water and nitrogen balances, crop phenology and timing of management operations etc.);
- Quantifying impacts in terms of risks and opportunities, including evaluations of uncertainty, to give indications of how likely impacts are to happen both in magnitude and return period.
- Spatial assessments to identify where changes in climate may be beneficial or pose increased risks.

Outputs from the barley modelling can also be combined with those from other aspects of the Scottish Government's Strategic Research Programme, for example spatial agrometeorological indicators and new computer-based estimates of future Land Capability for Agriculture[2]. This can be used to improve the utility of the barley modelling, e.g. including modelling of future soil trafficability to reflect changes in constraints on access to land by machinery.

The Agricultural Statistics group in RESAS have also commissioned a SEFARI Fellowship (starting April 2022) to develop crop yield forecasting capabilities, potentially including the use of the crop modelling developed here, to align with their Crop Map service[3].

[2] The Land Capability for Agriculture: building a tool to enable climate change assessments (climatexchange.org.uk)
[3] Scottish Crop Map 2019 (arcgis.com)

Additionally, outputs from the barley modelling can support other areas of research, for example: consequences on supply chains and economic analyses; changes in run-off, erosion and nitrate pollution and their implications for water quality; gene trait selection for crop variety breeding (‘climate ready crops’); management adaptation planning for farmers and options for greenhouse gas emissions reduction strategies.

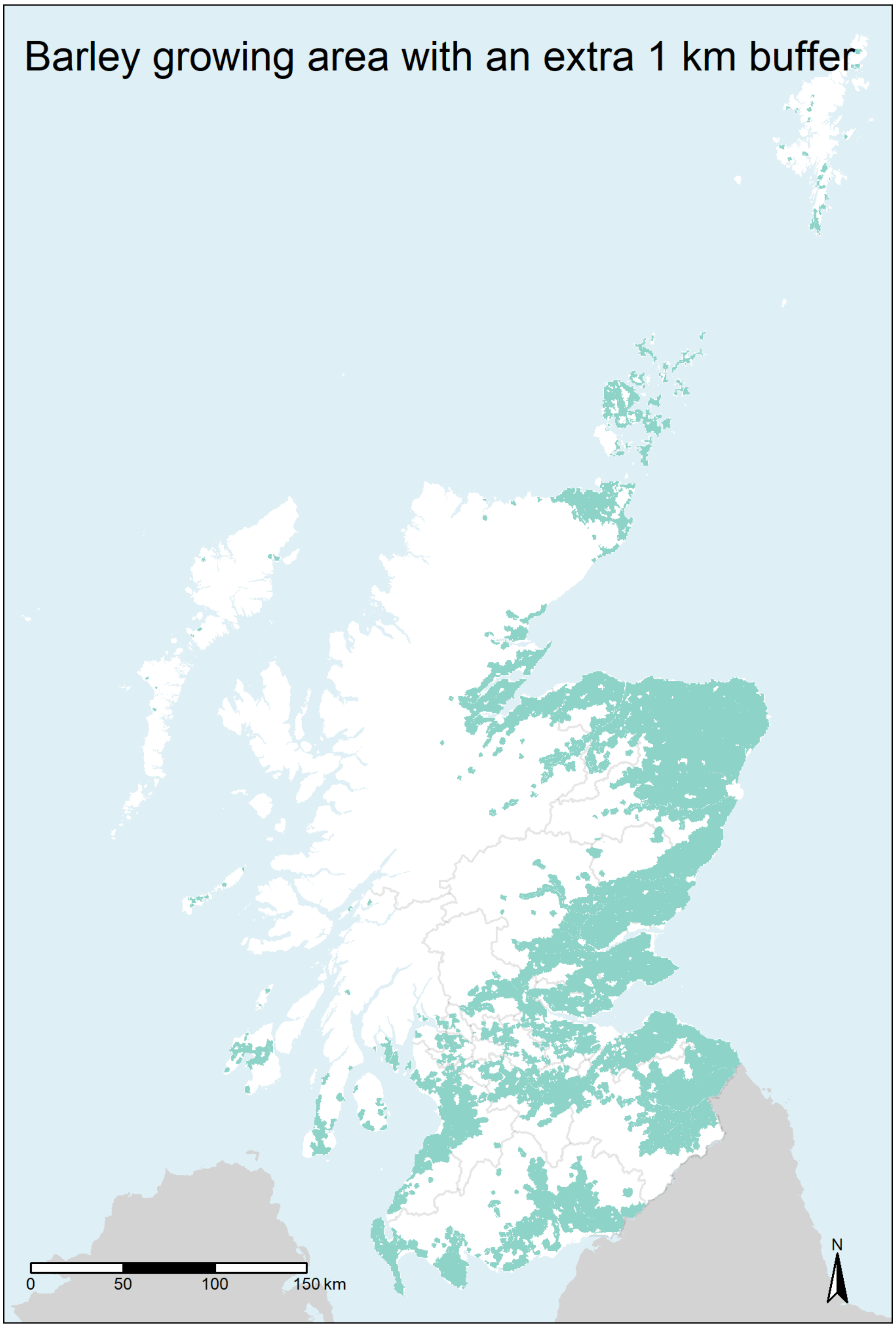


Figure 1: Known barley cropping area between 2003 and 2015. Note an additional 1km buffer area has been added to known cropped locations to indicate additional locations where the model has been applied.

Figure 1 shows the locations of fields in Scotland where spring barley had been grown and Common Agricultural Policy claims made during the period 2003 to 2015. To explore hypothetical barley growing area expansion, we have further added an extra 1 km buffer around the known locations where barley has been grown (all areas with protected status and no-agricultural lands were excluded from the 1km buffer). The white areas indicate where barley has not been grown during the last 12 years.

2.1 Refinements of earlier capabilities

An initial application of the spatial modelling capabilities within the project had been conducted in 2018 (Rivington et al 2018), which have been updated and detailed in Table 1.

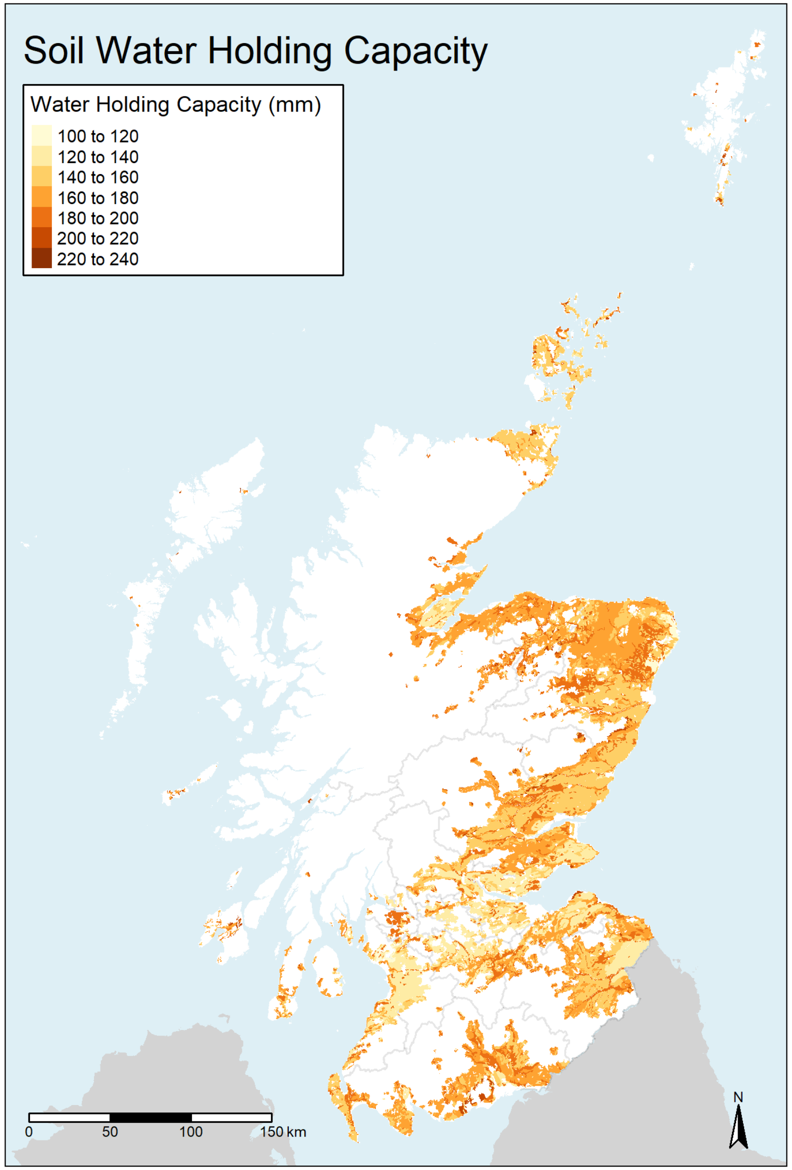
Table 1: Refinements in modelling capabilities from original model platform prototype.

Modelling capability, data input	Prototype (2018)	Current version (2022)
Number of climate projections used	x2 UKCP18 climate projections	x12 UKCP18 climate projections
Climate data spatial scale	5km grid	1km grid
Climate data bias correction method	Based on correction of means only	Based on correction of means and variance
Crop management – sowing date	4 sowing dates	5 sowing dates
Validation (yield)	10km aggregated	From 2017, holding level (IACS)
Simulation platform	PC	High Performance Computer

Initial yield response assessments using the modelling platform (Rivington et al 2018) and from field assessments (Cammarano et al 2019) had indicated the importance of soil water holding capacity in determining yield. On this basis additional emphasis was placed on assessing soil water.

Soil Water Holding Capacity

A key element learned in developing the crop modelling prototype platform was the importance of soil water holder capacity in influencing growth and yield. Additional research effort has been placed on improving this understanding. The soil data were retrieved from the 1:250,000 scale soils mapping from the James Hutton Institute and data from the Scottish Soils Knowledge and Information Base (SSKIB). Only the soil types with a satisfactory amount of detail that occur on the barley cropped area were selected. In total, 230 soil types with a depth of 100 cm and with soil information reported for four layers for each soil type were selected. The soil hydraulic properties (i.e. saturation (SAT), lower limit (LL), and drain upper limit (DUL) were estimated for each soil type and depth using the Hydraulic Properties of European Soils (HYPRES) pedotransfer functions. The soil water holding capacity (WHC) was calculated as the difference between DUL and LL and aggregated over 100 cm soil depth for each soil type. The WHC pattern is spatially variable (Figure 2) and varied between 104 to 222 mm with a median value of 159 mm. The 10th and 90th percentiles were 134 and 184 mm, respectively. The total barley cropped area can be classified based on the WHC as 6% of the total area with WHC being lower than the 10th percentile (Low, indicating locations that may be more vulnerable to future dry conditions), 90% between the 10th and 90th percentile (Average) and 4% with WHC above the 90th percentile (High).



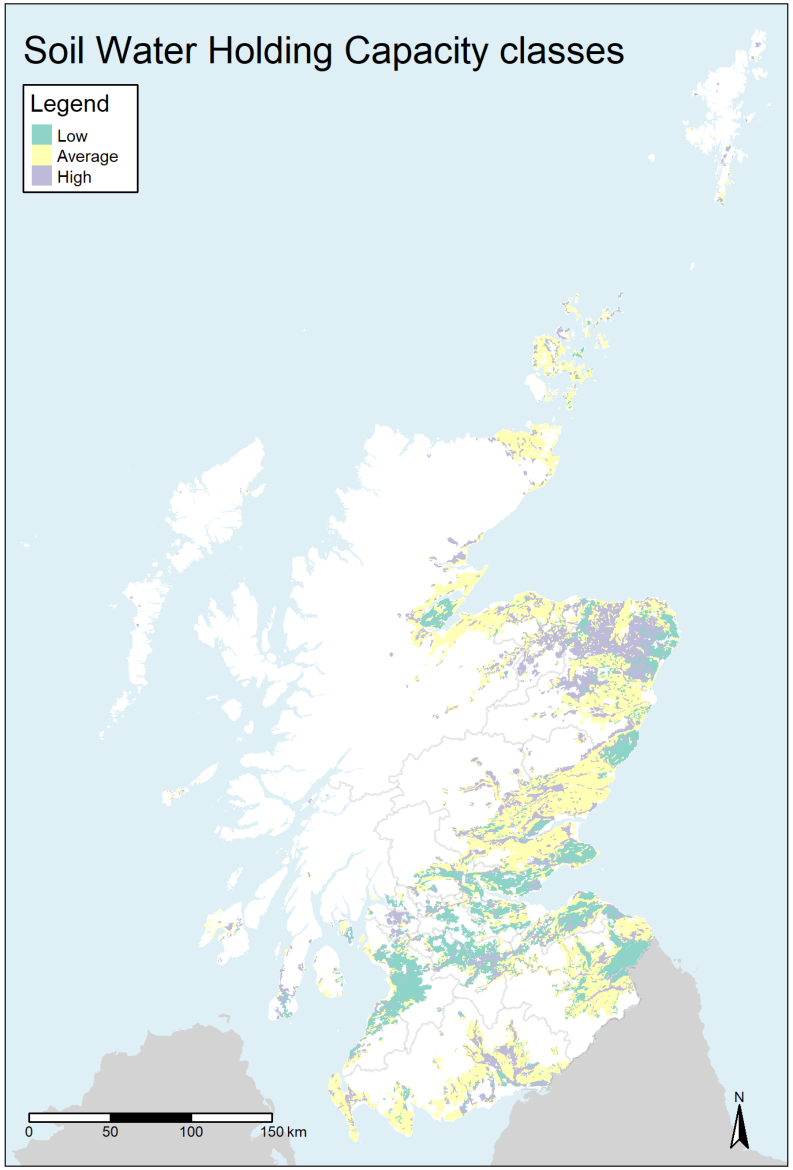


Figure 2. Spatial distribution of the soil water holding capacity (WHC) (left map) and the different WHC classes (right). The WHC classes were defined based on the 10th and 90th percentiles with the class 'Low' for WHC below the 10th percentile, 'Average' for WHC between the 10th and 90th percentiles, and 'High' for WHC above the 90th percentile

Climate Data

Reference climate data

Observed climate data were obtained from the UK Meteorological Office. The data consisted of interpolated daily data set for precipitation, maximum and minimum temperature at 1 km grid cell resolution. Daily solar radiation values for the period 1994 to 2015 were purchased from SolarGIS (www.solargis.com) and re-sampled at 1 km grid cells to match the resolution of the other climate variables.

Estimating available water

To visualise and map the availability of water, we have used a simple difference model between precipitation input and the amount of water returned to the atmosphere from evapotranspiration (evaporation from land surfaces and transpired by plants). A negative climate deficit means evapotranspiration is greater than the amount of precipitation.

The daily reference evapotranspiration (ETo) was calculated for each grid using the Priestley-Tailor equation. In total 28,054 1km grid cells were used to cover the whole barley cropped area over Scotland. The spatial pattern of the mean temperature, cumulative precipitation and the climatic deficit calculated as the difference between precipitation (P) and evapotranspiration (ETo) for the period between March and September, which represent the spring barley growing season in Scotland, are given in Figure 3. The average seasonal mean temperature ranged between 8 and 12.6 °C and can be as low as 6 °C in some areas. The seasonal precipitation ranged from 330 to 750 mm and can reach up to 1100 mm in some areas. The climatic deficit, which can be used as an indicator of water shortage (when values are negative), varied between -200 to 800 mm with about 26% of the total barley area prone to water shortage during the season. To help interpret maps of yields, it is worth noting where in Figure 3 has low precipitation and a negative climate deficit.

Note: The crop model used in the estimation of barley yield does simulate the soil water balance on a daily time step and for multiple layers in the soil profile. This date can be available for analytical and visualisation purposes, but due to the vast amount of data (365 days x 120 years x 12 ensemble members x 56,256 unique soil-climate combinations), it has not been stored during simulations.

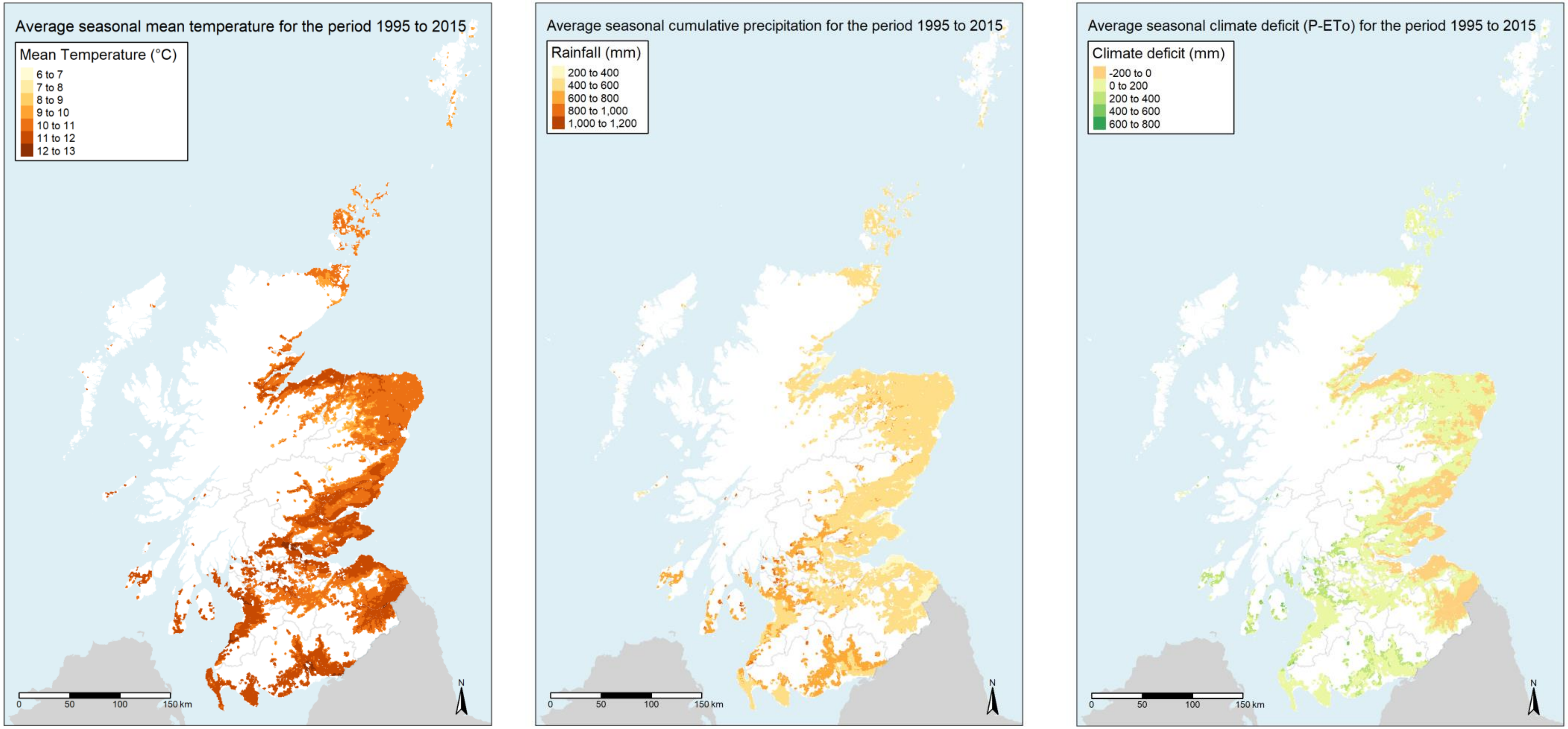


Figure 3. Spatial distribution maps of the average growing season (March to September) mean temperature (left), cumulative precipitation (middle) and climatic deficit (Precipitation – evapotranspiration) (right).

Climate projections

This study uses the UKCP18 climate projections (UKCP18 2018) from which the following published key messages can be summarised as:

- Hot summers are expected to become more common. The summer of 2018 was the equal-warmest summer for the UK along with 2006, 2003 and 1976. Climate change has already increased the chance of seeing a summer as hot as 2018 to between 12-25%. With future warming, hot summers (like 2018) by mid-century could become even more common, near to 50%.
- The temperature of hot summer days, by the 2070s, show increases of 3.7 °C to 6.8 °C, under a high emissions scenario, along with an increase in the frequency of hot spells.
    - For the RCP8.5 emissions scenario (used in this study) the estimated probabilistic temperature increase for the UK by 2070 ranges between 0.9 °C to 5.4 °C in summer, and 0.7 °C to 4.2 °C in winter.
- UKCP18 Global (60km), Regional (12km) and Local (2.2km) scale climate model simulations all project a decrease in soil moisture during summers in the future, consistent with the reduction in summer rainfall. Locally this could lead to an exacerbation of the severity of hot spells, although large-scale warming and circulation changes are expected to be the primary driver of increases in the occurrence of hot spells.
- The probabilistic projections (12-member ensemble) provide local low, central and high changes across the UK, corresponding to 10%, 50% and 90% probability levels. These local values can be averaged over the UK to give a range of seasonal average precipitation changes between the 10% and 90% probability levels. By 2070, in the high emission scenario, this range amounts to -47% to +2% in summer, and -1% to +35% in winter (where a negative change indicates less precipitation and a positive change indicates more precipitation).
- Overall increased drying trends in the future, but increased intensity of heavy summer rainfall events, indicating greater variability and increased frequency of extreme events.
- Change in the seasonality of extremes with an extension of the convective season from summer into autumn, with significant increases in heavy hourly rainfall intensity in the autumn.
- By the end of the 21st century, lying snow decreases by almost 100% over much of the UK, although smaller decreases are seen over mountainous regions in the north and west. It is unclear though how this will impact water availability in downstream parts of catchments.

This project used a new bias-corrected version of the UKCP18 climate projections. It consists of an ensemble of 12 climate projections made using variants of the HadGEM3 climate model (HardRM3-PPE) that were bias corrected against observed data for each 1km grid cell. The emissions scenario under which the climate models were run is referred to as the Representative Concentration Pathway 8.5 (RCP 8.5) (Moss et al 2010, Raihi 2017). This 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 targets are reached, but its overall atmospheric greenhouse gas concentrations may 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 ecosystem services such a climate regulation due to deforestation.

Considering the barley growing areas and seasons, on average, seasonal mean temperature is projected to increase for all 12 climate members with higher temperature increases ranging from 2.4 to 4.8 °C during the 2070's compared to the baseline period. However, the range for the relative seasonal precipitation change is comparable between the two future periods with the difference between climate members being clearer during 2070 (Figure 4). The relative seasonal precipitation change ranged from -21 to 7%. The ensemble members 12 and 13 have the lowest precipitation decrease during 2040 and 2070 respectively and climate member 10 being the wettest among the climate members for both periods. Ensemble members 15 and 12 have the lowest and highest mean temperature increase for both periods. These four ensemble members (i.e., 10, 12, 13 and 15) represent the extreme future weather conditions and will be considered when presenting some of the results relating to projected barley yield change in the next sections.

Variability in climate projections used

To help understand the range of crop model estimates, it is useful to understand the range of plausible future climate conditions. Figure 4 shows how all projections (ensemble members) available for use 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. Results are presented either as individual ensemble members, the ensemble mean, or agreement maps for different numbers of ensemble means.

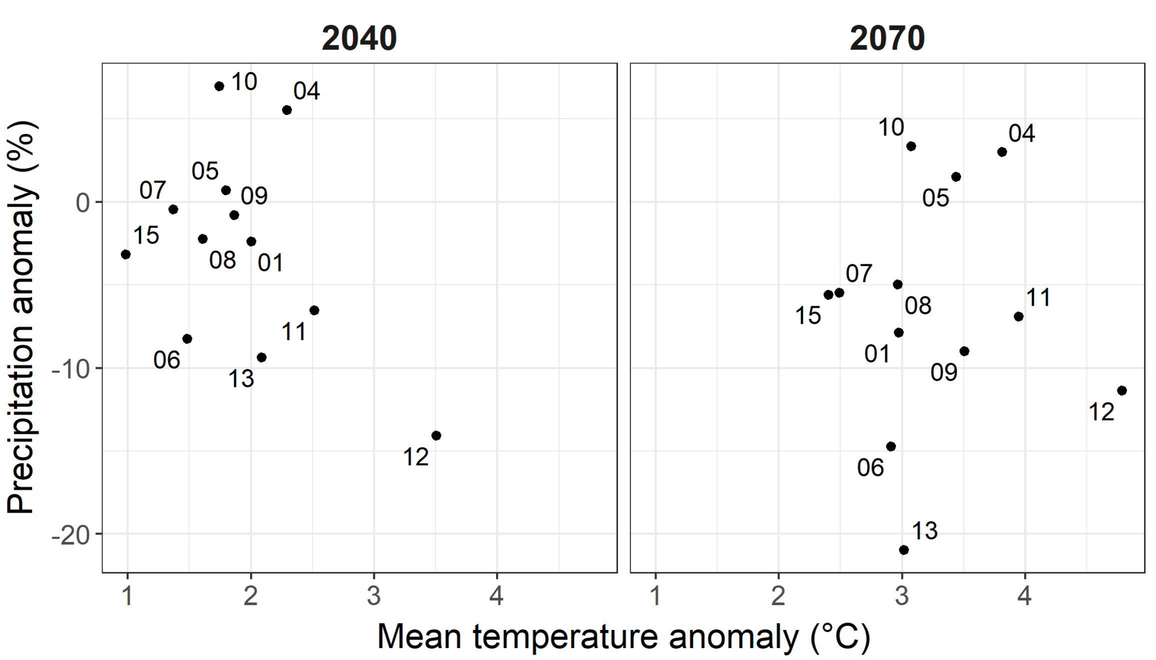


Figure 4. Comparison of the Scotland barley area-wide mean climate change signal in seasonal (March to September) precipitation and temperature under RCP8.5 for 2030-2049 ('2040') and 2060-2079 ('2070') with respect to 1994-2015 for the different climate ensemble members.

It is important to be able to put these projections and any beneficial impacts on barley growth in Scotland into context with their significance in terms of warming on a global scale: temperature rises above 2°C are considered to be very high risk for continued safe global scale ecosystem function. Temperature rises above 3°C are very likely to result in severe negatively impacts on global food production, ecosystem viability and economic activity, and substantial risks of irreversible climate breakdown (IPCC 2022).

Yield simulations

The modelling of spring barley has been undertaken using the Decision Support System for Agrotechnology Transfer (DSSAT) software platform, using the CERES barley model to simulate yield. DSSAT has been satisfactorily calibrated for barley in Scotland and the same calibrated parameters were used in this study. The model inputs were prepared for each single unique combinations of the high-resolution weather grid and soil series. There are 56,256 combinations generated for locations where barley has been grown between 2003 and 2015 and for the 1 km buffer area adjacent to these known locations.

The sowing date can have a significant impact on spring barley yield. Since no site-specific observations are available for the currently practiced sowing dates by farmers, the simulation was conducted five times, with each simulation using a different sowing date across the whole of Scotland. The five sowing dates considered are 15/Mar, 01/Apr, 15/Apr, 01/May and 15/May which represent a plausible sowing window for barley across Scotland. Barley yield was then simulated for each year of three time periods (1994-2015, 2030-2049, 2060-2079, denoted thereafter as baseline period, 2040 and 2070, respectively) using the five sowing dates.

3 RESULTS

Before presenting the results, it is important to note in providing information on climate change impacts on barley yields in Scotland, we are primarily concerned with the sign of the change, either positive (increase) or negative (decrease) and variability in yield compared to the baseline period, rather than the absolute amount. This is because there remain uncertainties in the simulation process and utility of the observed yield validation data. Use and validation of the DSSAT model indicated that it was able to usefully simulate the yield response to changes in nitrogen, water and temperature, but that the model had a systematic over-estimation of yield (the average was approximately 0.34 tons hectare, but with cases in excess of 1 t ha). Further to this, there are issues concerning the utility of observed yields, as agricultural census data was provided as an aggregated value to a 10km resolution for validation purposes from 2004 to 2016, which means direct site to model comparisons was not appropriate. Availability of yield data to a holding level from 2017 has improved validation, but still limits site-specific validation (i.e. a holding can include multiple fields with a wider geographic distribution, hence it has not been possible to align a yield value with a specific climate-soil combination).

Reading the maps

Yield values are modelled for each unique combination of climate and soil where spring barley had been grown in a 1km climate cell or an adjacent cell (Figure 1). A range of map formats are presented. For the crop yields, the values do consider the interactions of weather, soils, crop genetic coefficients and management in determining growth, including limitations such as drought or leaching of nutrients that limit growth. The crop model simulations do not reflect yield losses such as those from wind or pest and disease damage. The maps also do not reflect other management focused aspects, e.g. machine access limitations due to wet soils (trafficability), slope angle or other constraints since the effects of these can often depend on the specific assumptions on machinery used or manager preferences.

The maps for the baseline use a colour gradient to show the estimated yield (t/ha) for four groups: <3, 3-5, 6-7, >7 (Figure 5a and b). Since sowing date can strongly affect yield, the simulation was conducted five times, with each simulation using a different sowing date across the whole of Scotland. A map of the coefficient of variation (CV) is also provided. This is a statistical measure of the dispersion of yield data points for all sowing dates around the mean and indicates where there is more or less variation depending on sowing date, e.g. pale yellow = 0 to 2% variation, dark red = 10 to 12% variation, hence lighter coloured areas have less variation whilst darker areas have more. The white areas are those where barley has not been grown (between 2003 and 2015) and are outside of the 1km buffer applied to the growing areas.

Changes to the Median National Yield: to compare yield changes between observed and estimated futures, we use the Median National yield derived from Scottish Government statistics. Figure 8 shows the spatial distribution of where, for the baseline period, observed yield is above (green) or below (yellow) the median national yield, whilst Figures 9 and 10 provide future examples using two climate projections for the 2040s and 2070s. Increases in the yellow area indicates where in the future yield may fall below the current median national yield value.

Absolute yield change: whilst our preference for result presentation is to provide maps showing the sign of change (whether yield increases or decreases), we have also provided maps of absolute yield change (Figures 11 and 12 for the 2040s and 2070s respectively). These represent the actual yield estimates made by the model based on the average yield for all 12 climate projections. These maps indicate how much yield may change (in tons per hectare), but we repeat the caveat that we know the crop model tends to over-estimate yield. Maps of the standard deviation of absolute yield have also been provided. These indicate the range of variation in annual yields, with darker shaded areas potentially experiencing greater variance.

Uncertainty: A new form of uncertainty communication in yield projections is presented here in the form of Agreement Maps (Figure 13 and 14), illustrating where yield change (decrease = red, increase = blue, no change = yellow) based on 7 to 12 climate projections. The more projections where there is agreement on the sign of change, the more confident we can be that those locations may experience that change. The same approach is used in Figures 17-19 to illustrate where the climate projections agree of increases or decreases in future precipitation.

Interpreting the yield maps

Areas of high estimated yields occur due to favourable growing conditions, primarily through combinations of:

- Good soil water retention (and / or slow drainage) resulting in lower water stress to crops;
- High organic carbon;
- Nitrogen availability;
- The above and favourable weather conditions at key growth stages, particularly adequate rainfall, especially in the spring.

In the absence of cropping system constraints (physical and biotic damage, practicalities of management), this can lead to some locations (e.g. western Clyde Valley, Mull of Kintyre) having high modelled yields that do not necessarily reflect actual harvestable values.

Similarly, areas of low yield occur due to unfavourable conditions:

- Poor water retention (higher risk of water stress), such as soils with a high sand content; rapid drainage or high run-off (leading to nitrogen leaching);
- Weather conditions (primarily low rainfall and warmer temperatures leading to higher evapotranspiration rates and soil water loss).

An estimated yield value is mapped for any location where barley has been grown in the last 12 years, plus the additional 1km buffer zone around those locations. Thus, the mapped extent in the buffer zones does not reflect in detail the actual locations where barley could be grown, but does indicate areas with potential. This is important when looking at possible expansion of areas where barley could be grown under climate change due to an easing of climatic constraints (if other conditions, such as soil type and depth, are appropriate). Yield mapping in the buffer zone is thus included as it is simpler to later apply masks to remove areas considered unsuitable for reasons beyond those represented within the DSSAT model than it is to later add back in areas that have not been modelled.

Baseline yield

There is a large range in spatial and temporal variation in the barley yield estimates for the period 1994-2015 (Figure 5). Average yield ranged between 2.2 to 9.1 t/ha, which corresponds to the observed yield range from the Crop Survey Report data. The national average yield is estimated at 6.6 t/ha with a coefficient of variation of 12.3 % across the barley cropped areas. There is a difference in the estimated yield between the five sowing dates with sowing earlier having a slightly higher yield as compared to sowing late. However, there is a slight spatial variation between the response of the model to sowing date which is shown in Figure 5b (bottom right map).

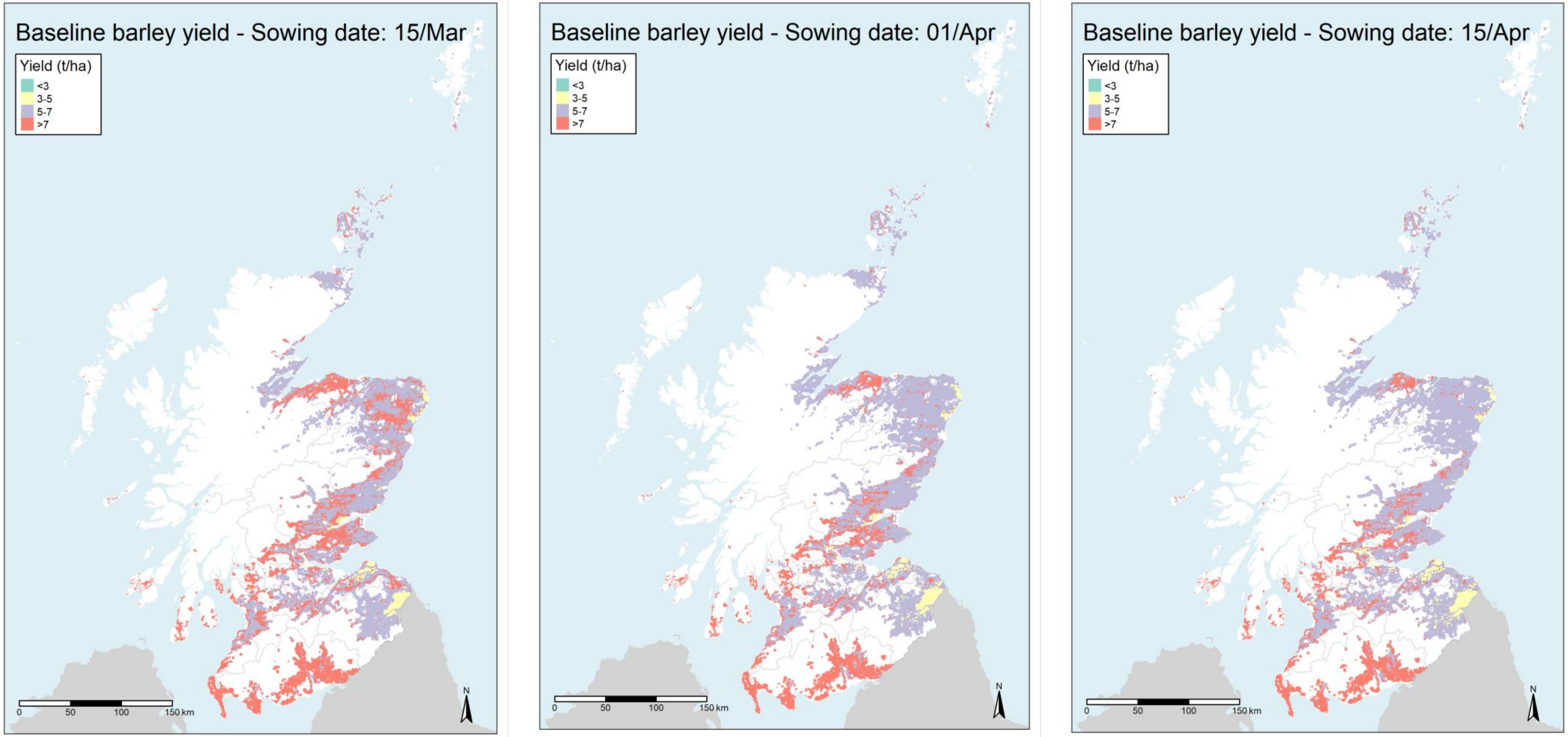


Figure 5a. Map of the averaged barley yields (t/ha) for Scotland for the five different sowing dates.

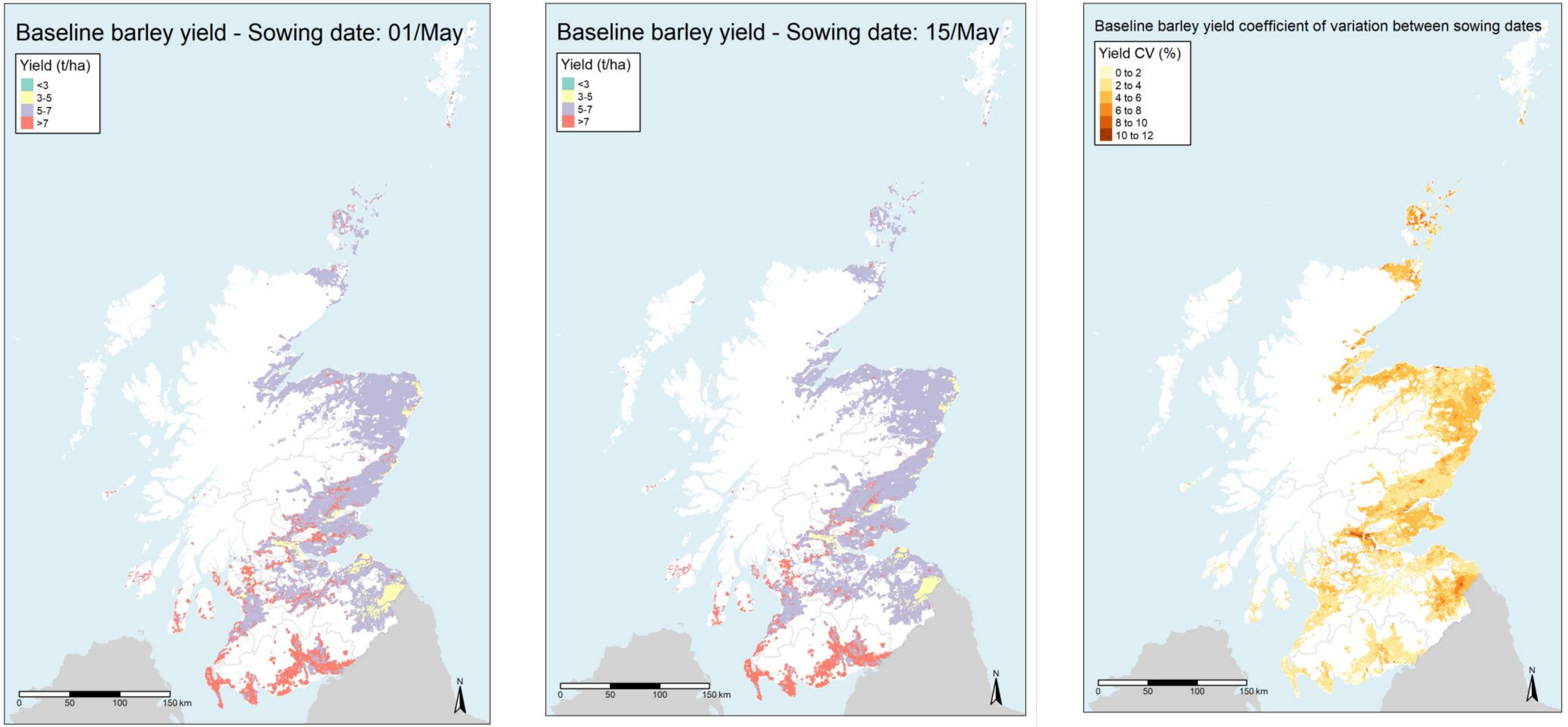


Figure 5b. Map of the averaged barley yields (t/ha) for Scotland for the five different sowing dates and the coefficient of variation of yield between sowing dates (right hand map).

Yield projections

The future grain yield estimates vary considerably between climate ensemble members both spatially and temporally with some areas seeing substantial decreases and others seeing substantial increases (Figure 6). The variation is likely to be due to the differences in precipitation spatial and temporal distribution.

The mid-century sees both gains and losses in mean yields, however more yield declines are projected towards the 2070's and this is true for the different climate ensemble members and sowing dates. For instance, yield projection using the climate member 10 which has the highest increase in seasonal precipitations (7 %) and a mean temperature increase of about 1.7 °C resulted in yield increase in more than 67 % of the barley area. This yield increase benefited from good crop growing conditions as a result of the increase in both precipitation and mean temperature. However, the increase in mean temperature by 3 °C with precipitation being comparable to the baseline period during 2070 resulted in an increase in reference evapotranspiration and hence crop water demand. Under these conditions, the total area with yield increase shrank to 36 % during 2070 as compared to 67 % during 2040.

Please Note: three of the four ensemble members used for examples are the more extreme cases (ensemble members 10, 12 and 13), whilst 15 represents the projection with the least combined precipitation and temperature change (see Figure 4).

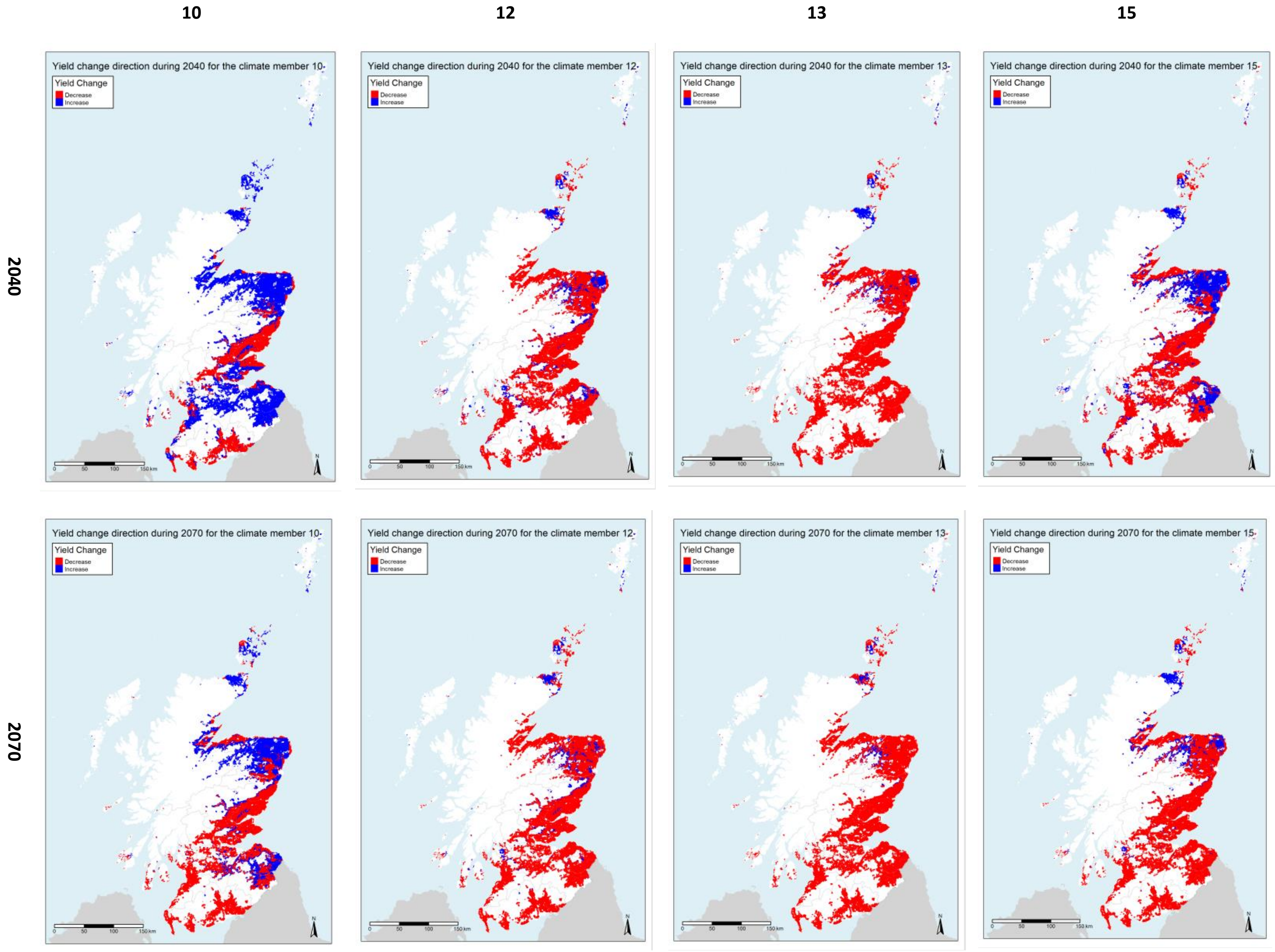


Figure 6: Average barley yield change sign during 2040 and 2070 for the four extreme climate ensemble members as compared to the baseline period 1994-2015. Blue = yield increases; Red = yield decreases. The maps are shown for the sowing date 01/Apr.

The modelled yield increase or decrease responses to changes in mean temperature and precipitation varied substantially between the different climate ensemble members (Figure 6). Both temporal and spatial variability of the changes in weather played a role in the model response and hence in yield change projections.

From the four projection examples it is possible to identify barley growing areas that could potentially have consistent yield increases, e.g. the far north and parts of north-east Scotland. Conversely, areas with projected yield decreases are also consistent between projections, with a close corresponding decreases in June precipitation (Figure 17).

This issue of variation between projections is discussed in more detail in the section Addressing Uncertainty.

Variation due to sowing date

The date on which a crop is sown can have a large influence on the eventual yield. In this study five different dates were used for each soil-climate combination, to capture the range of plausible possibilities as there is a diverse geographical range.

Figure 7 highlights the difference between the average barley yield at the national scale during the baseline and each of the future climate models for the five sowing dates. It shows that in general there is a tendency of yield decrease despite the response variation among the different climate models (as can be seen from the boxplots) and that the decrease is more pronounced in 2070 compared to 2040.

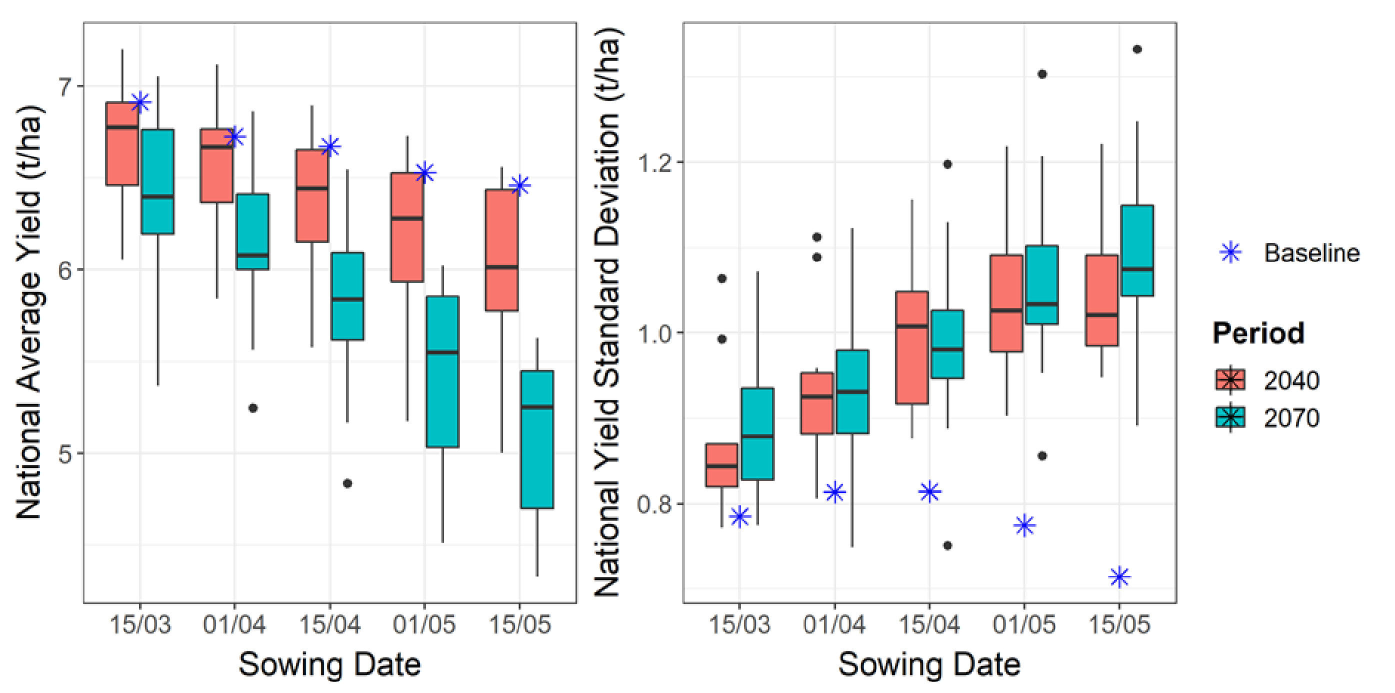


Figure 7. Average and standard deviation of barley yield across whole of Scotland during the baseline period and each of the future climate members of the periods 2040 and 2070 for different sowing dates.

The national yield standard deviation also shows that there is likely to be greater variation, which increases with later sowing dates. Figure 7 (right plot) suggests a variation in the future climate signal across the whole of Scotland with locations affected more than others with climate change.

The implications are that an adaptation strategy in the future is to plant earlier to avoid possible water stress issues in late spring during crop emergence and initial growth stages. This adaptation approach however has to assume that access to land is possible (e.g. soils are workable, when the soil water is below field capacity, which may be more likely under future climates – see Appendix A Figures 27 and 28). A trade-off risk may be that an earlier sown crop may be more vulnerable to frosts, however analysis of the climate projection data indicates that the last spring frosts will likely occur earlier and less frequently.

Changes in the national median yield

The median for the national barley yield during the baseline period is 6.7 t/ha. We can use this value as a threshold to locate the areas where the barley yield will be lower or higher than the national median for the baseline (Figure 8, left) and the probability of the yearly baseline yield being less than the median national yield was calculated (Figure 8, right). The median yield is used instead of the average as it is less affected by outliers.

Figures 9 and 10 illustrate whether the estimated future yield is above or below the baseline national median for two climate projections:

- Ensemble member 05 (2040's = 1.8°C increase, same precipitation amount, 2070's = 3.4°C increase, 2% increase in precipitation).
- Ensemble member 06 (2040's = 1.5°C increase, 8% decrease in precipitation, 2070's = 2.8°C increase, 15% decrease in precipitation).

Both projections indicate an overall decline in area where yield is above the national median, instead yield decreases drive the value to be below the baseline.

For ensemble member 05, in the 2040's there is a small decrease in the area where yields are above the national median compared to the baseline, but is overall similar indicating the spatial distribution of yields above or below the national median may remain equivalent to the present. This projection has little change in precipitation from the historical baseline but 1.8°C warmer. This slight decrease in area below the national median continues into the 2070's to the extent that more than 80% is below the national median (Figure 9). In the 2070s this projection is about 2% wetter but substantially warmer at about 3.4°C, driving greater evapotranspiration rates and reduced water availability.

For ensemble member 06, approximately 80% of the barley area is below the baseline national median yield by the 2040's and continues to decrease to more than 90% by the 2070's (Figure 10). This projection is about 8% drier and 1.5°C warmer in the 2040's than the historical baseline, increasing to about 15% drier and 2.9°C warmer in the 2070's. Reduced water availability is the primary cause in the reduction in yield.

Note: the sowing date for these simulations is 1st April. Some of the negative effects of future projections may be reduced by an earlier sowing date.

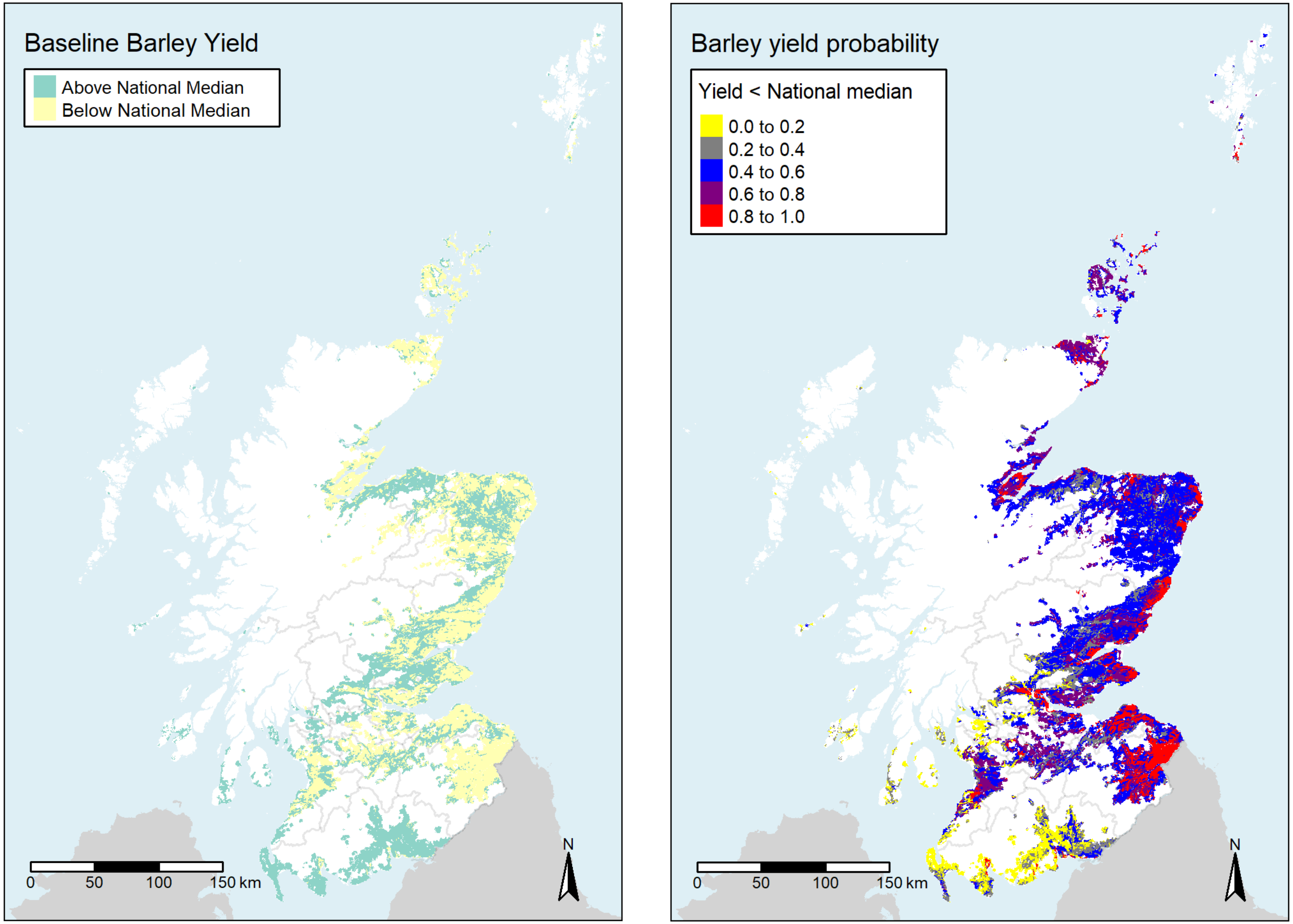
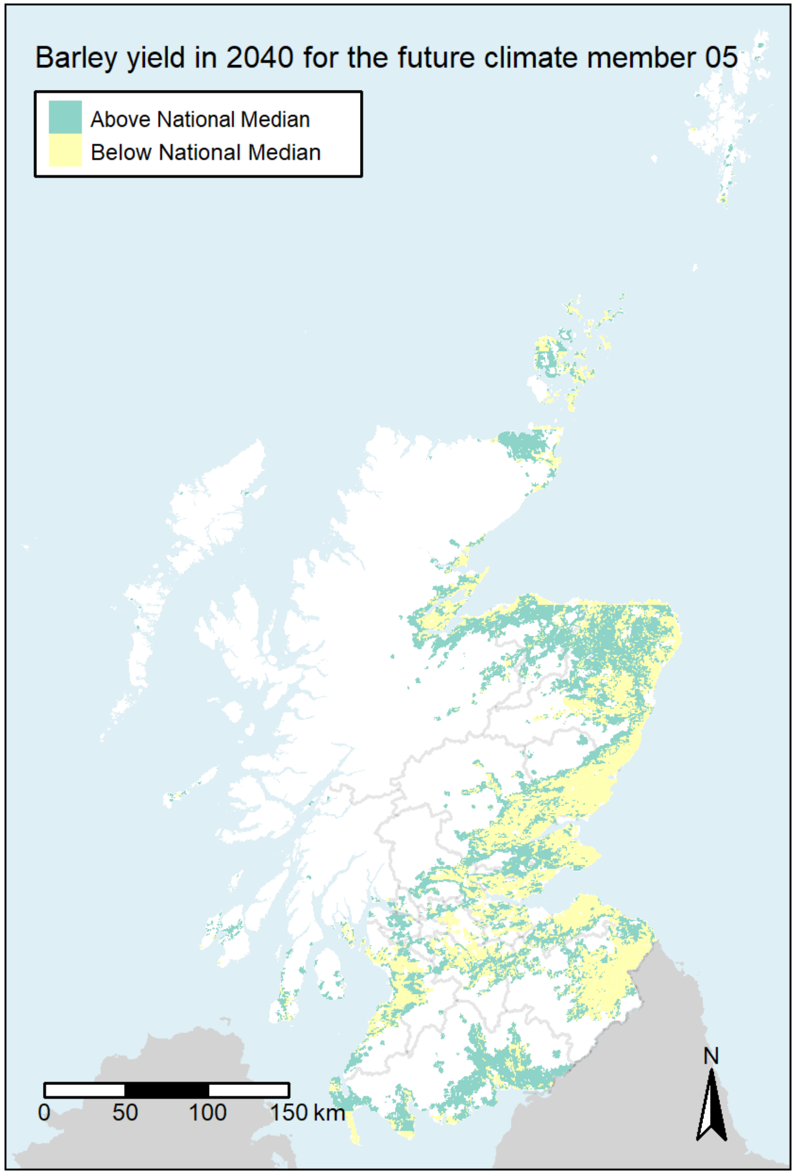


Figure 8. Spatial distribution of the baseline barley growing area based on the median national yield (left) and the probability of the yearly yield being less than the median national yield (right) when sowing date is 01-Apr.



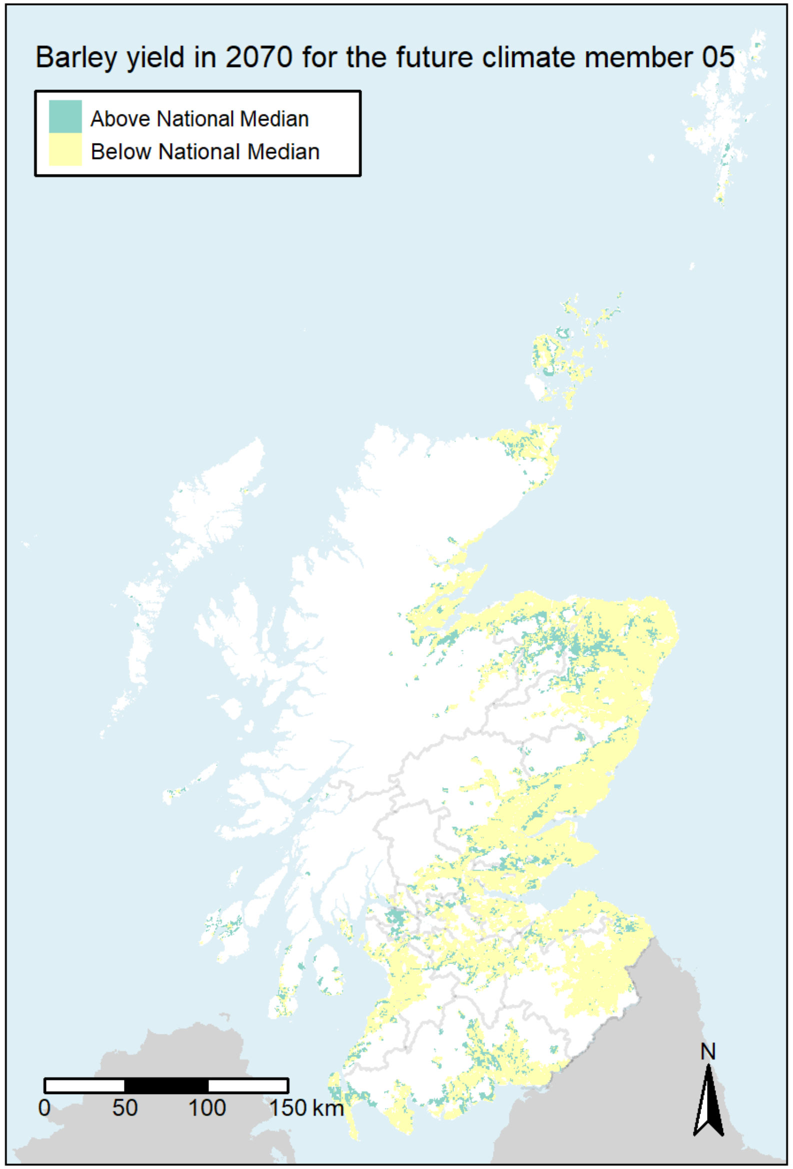
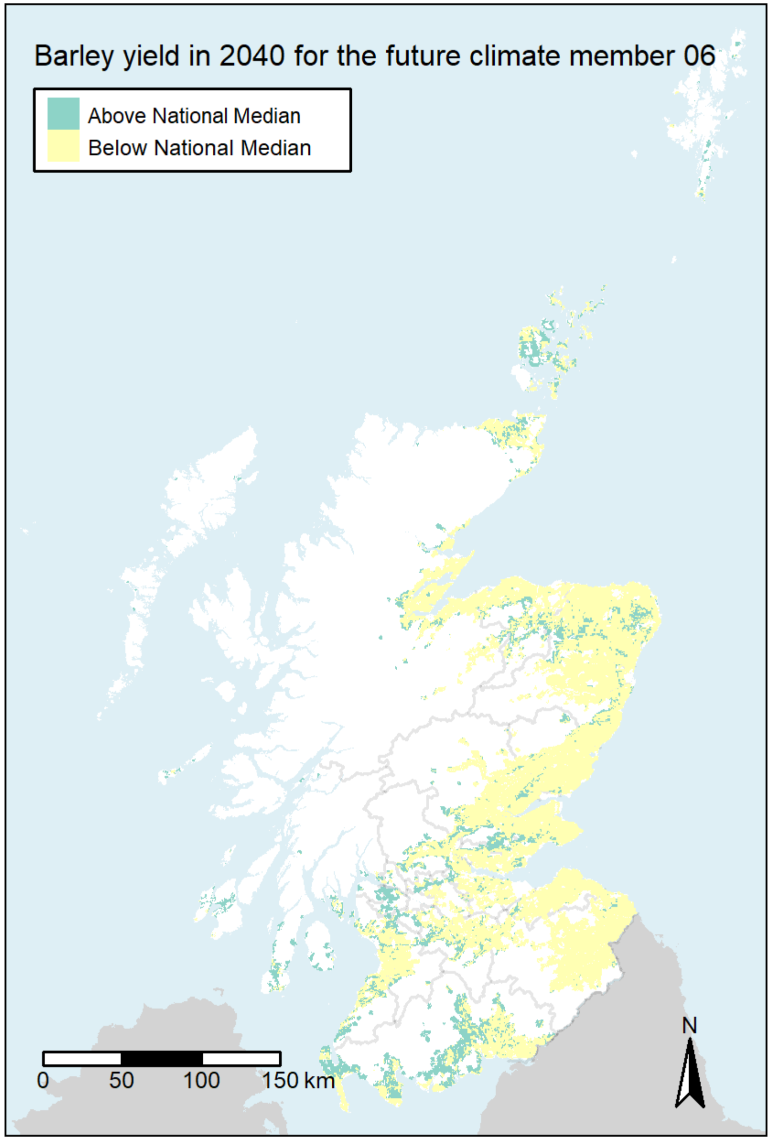


Figure 9. Spatial distribution of the future barley growing area for 2040 and 2070 based on the median national yield when sowing date is 01-Apr for the future climate member 05.



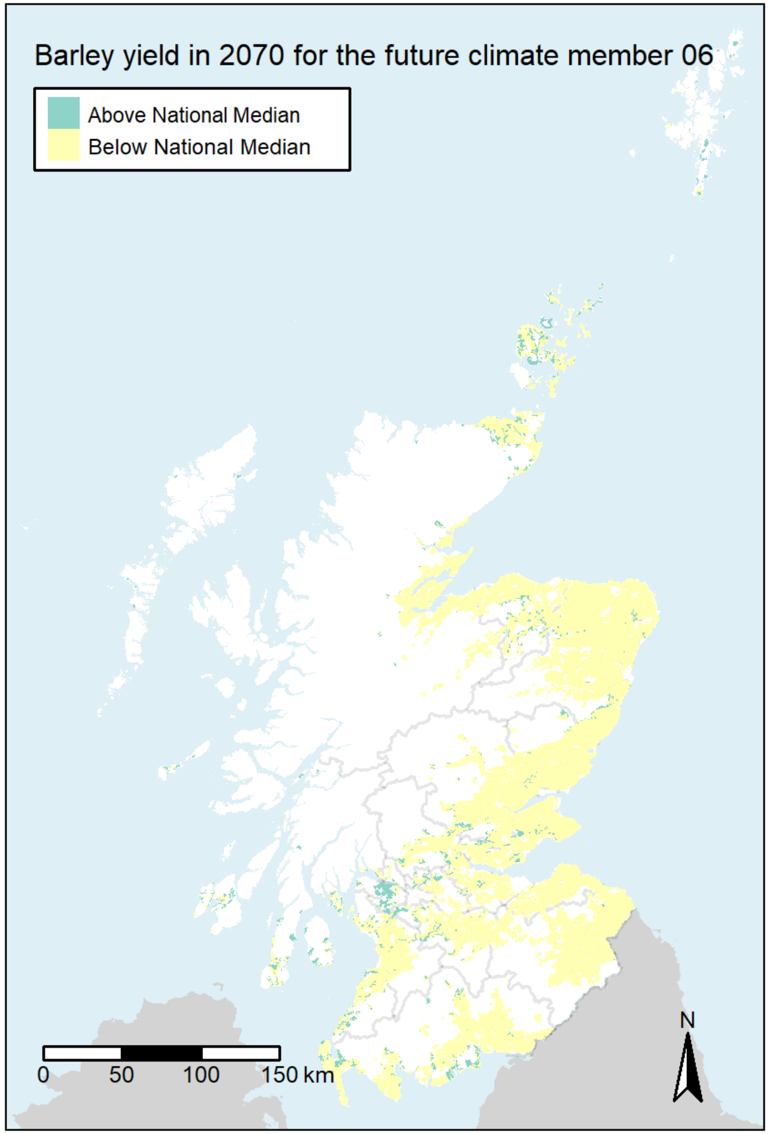


Figure 10. Spatial distribution of the future barley growing area for 2040 and 2070 based on the median national yield when sowing date is 01-Apr for the future climate member 06.

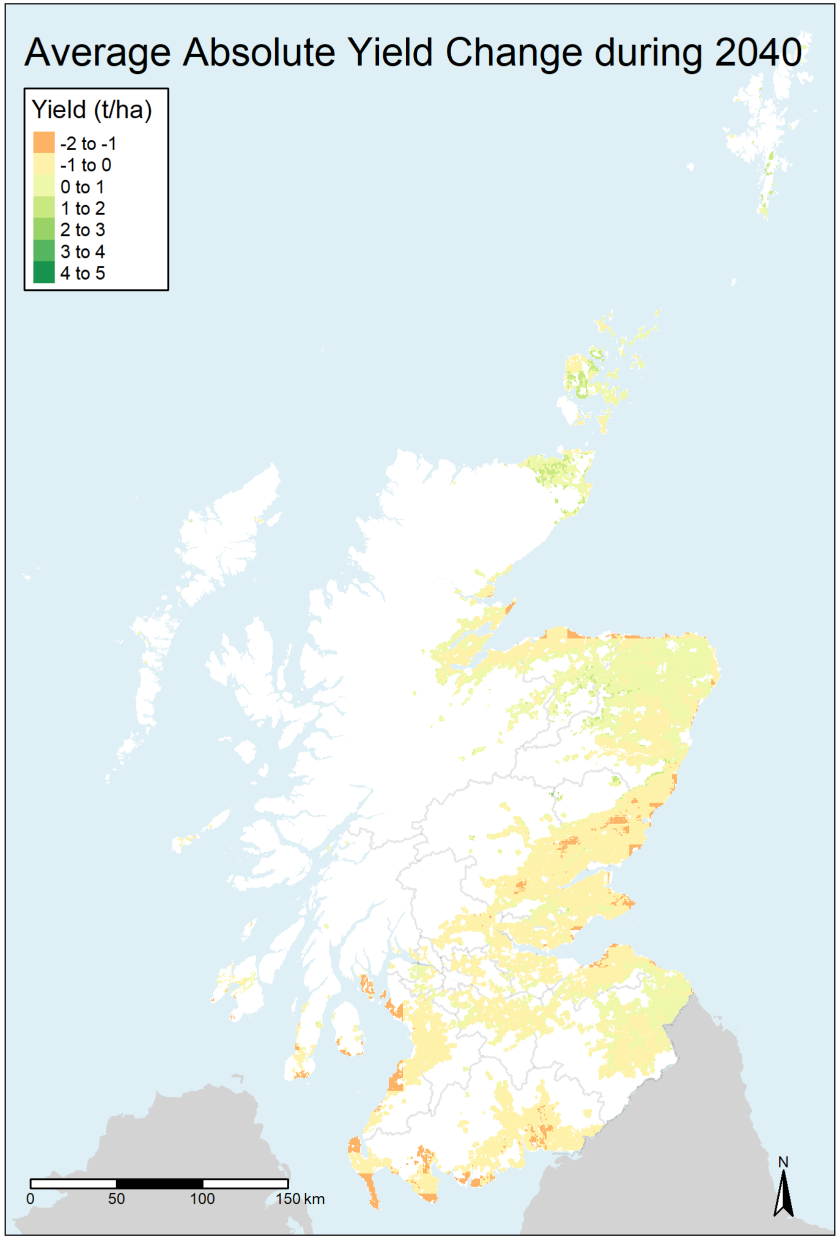
Absolute Yield Changes

There are modelling uncertainties associated with making estimates of absolute yield change (e.g. simulating precise yield values for any one of the 56,256 unique-climate soil combinations). This is primarily due to limitations in available calibration and validation data for all the soil-weather combinations. The results presented here are based on calibration and sensitivity analysis of the model used (see Methods section) at only two sites in Scotland (Mylnefield and Balruddery experimental farms), as well as use of national statistics and established growth guides. Hence we are cautious about making actual yield projections. Based on previous iterations of the modelling research, we found that the model tends to over-estimate yield. However, we are confident that the model responds appropriately to climatic, soil and management inputs and that the signs (+/-) of yield responses (as illustrated in Figure 6) are reliable.

The following two mapped examples illustrate the absolute change and variation in yield for the 2040s and 2070s periods for the climate projections based on an April 1st sowing date (Figures 11 and 12). The data presented is the average yield change between the baseline and the mean of the 12 climate projections. The standard deviation maps indicate where there is less or greater variability in yield responses.

For the 2040's (Figure 11), there is relatively little change from the current period absolute yields, but with several areas (e.g. the south-west) potentially having a decrease of between 1-2 tons hectare. The larger yield variability shown by the standard deviation occurs primarily in the Inverness – Elgin north-east coast and south-east Borders areas. These generally correspond to the average to low soil water holding capacity (Figure 2) and higher growing season temperature and negative climatic deficit (precipitation – evapotranspiration) areas seen in Figure 3.

By the 2070s, absolute yield shows a general shift to a reduction of 0 - 2 t ha, but with some areas in the north-east and north potentially seeing increases between 0 – 2 t ha (Figure 12). The spatial variation of larger variance is again seen in the Black Ise, Inverness – Elgin coastal area, and the southern central belt, Dumfries and Borders.



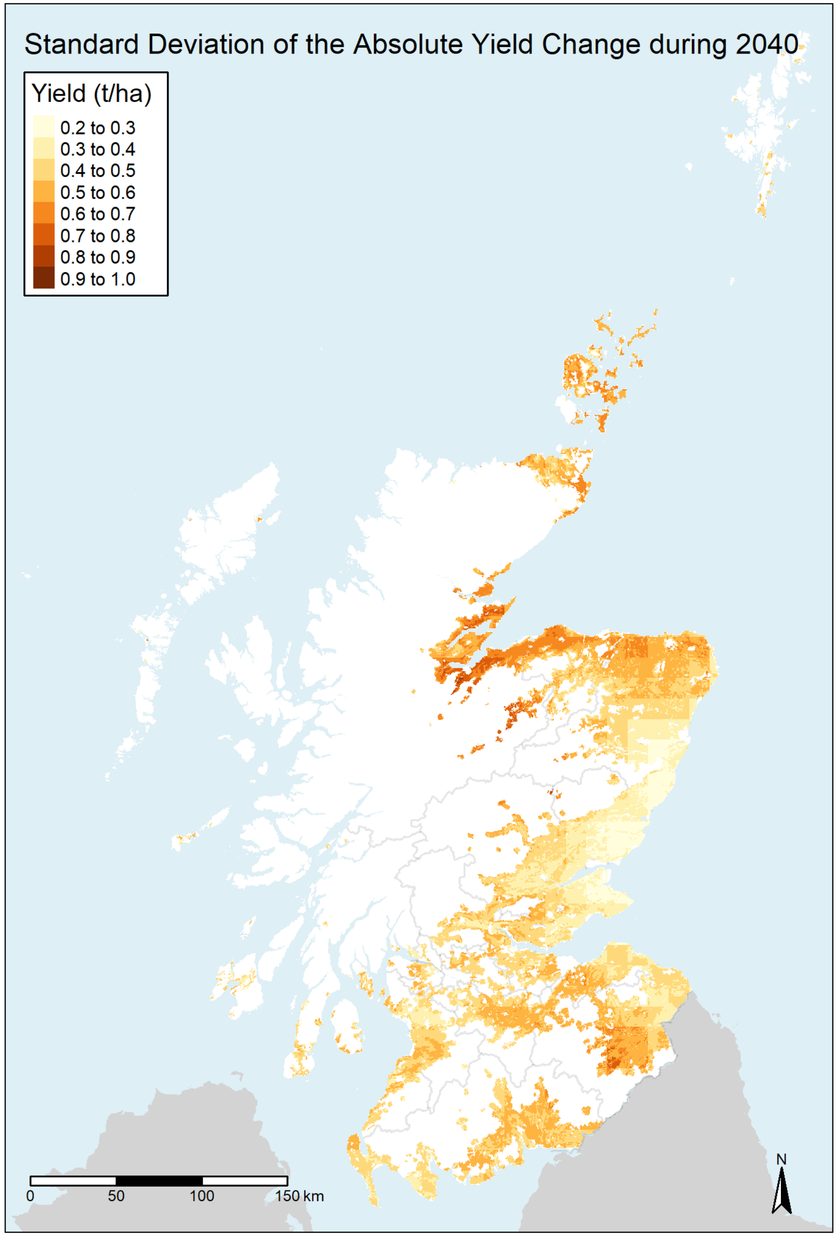


Figure 11. Spatial variation of the average absolute (left) and the standard variation (right) of the barley yield change among the different future climate models for the 2040s period for sowing on April 1st.

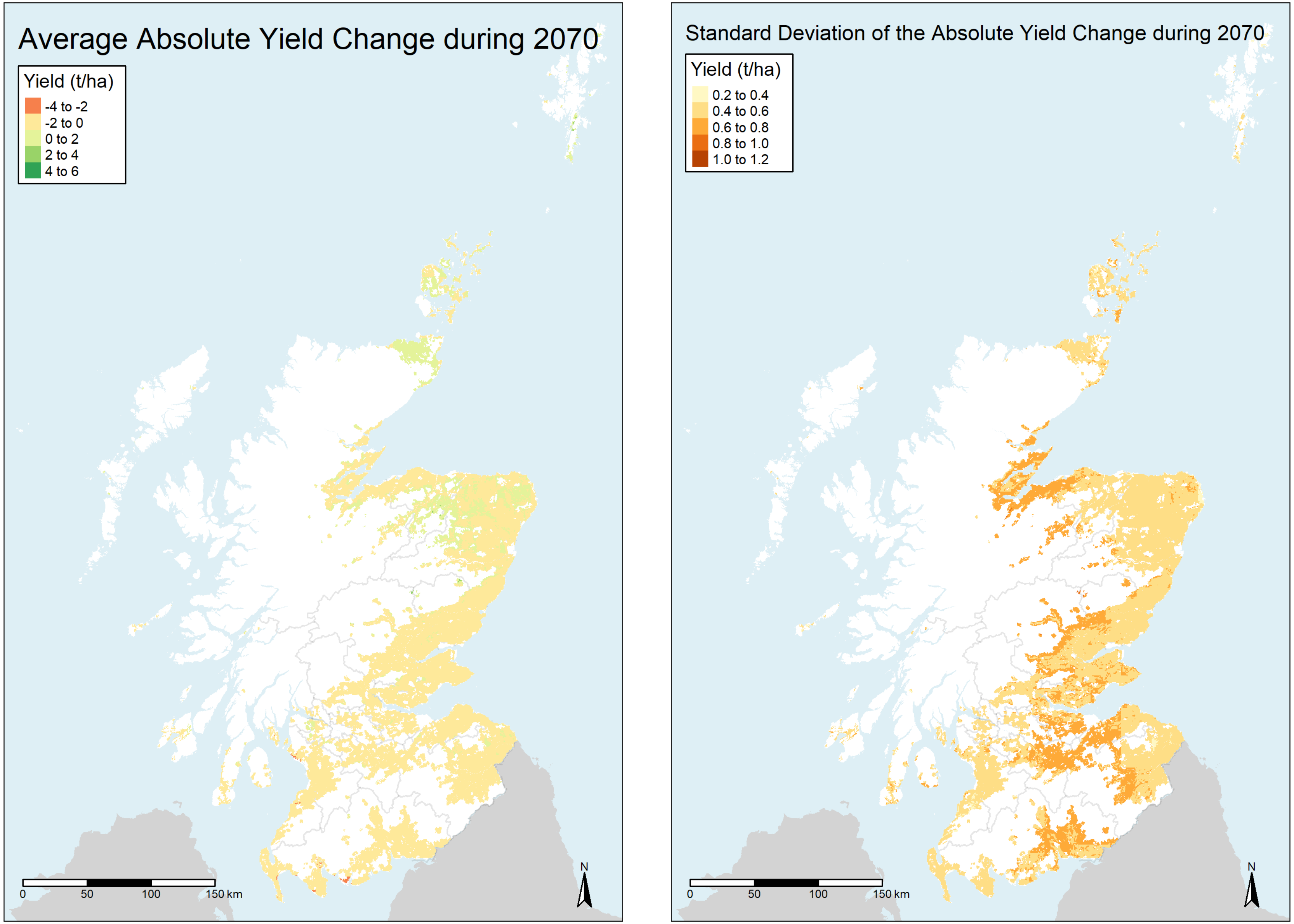
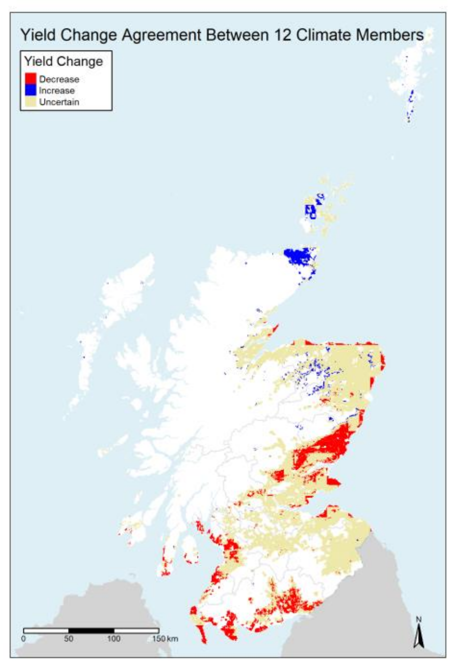


Figure 12. Spatial variation of the average absolute (left) and the standard variation (right) of the barley yield change among the different future climate models for the 2070s period for sowing on April 1st.

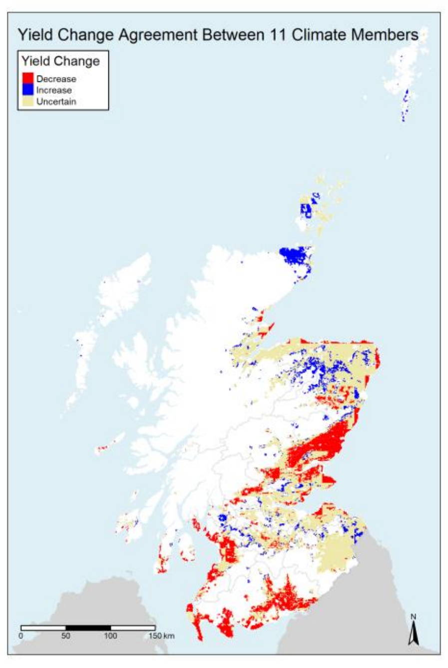
Addressing uncertainty

To locate 'hotspots' where there is a higher probability of the estimated change occurring, maps detailing the level of agreement between ensemble members were developed (see Figures 13 and 14). The purpose of generating agreement maps is to communicate that there are differing levels of certainty and uncertainty in space and time when using the UKCP18 projections.

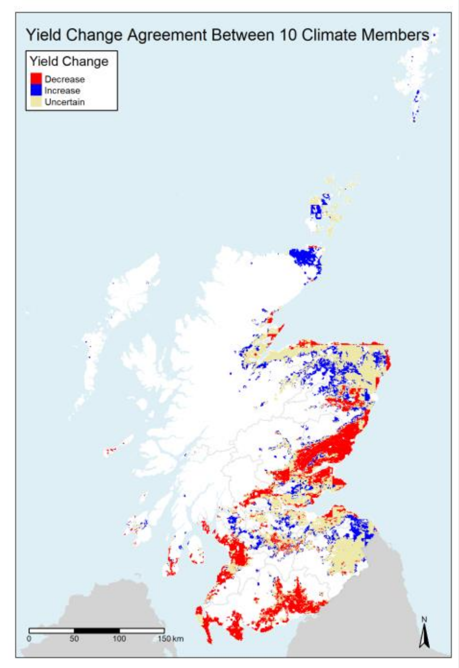
12 Ensemble Members



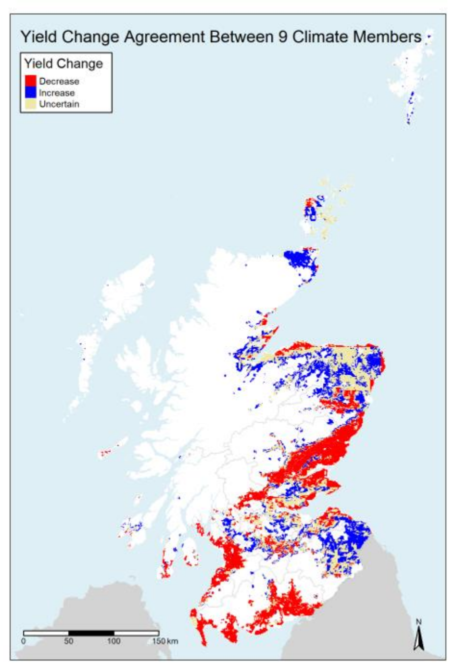
11 Ensemble Members



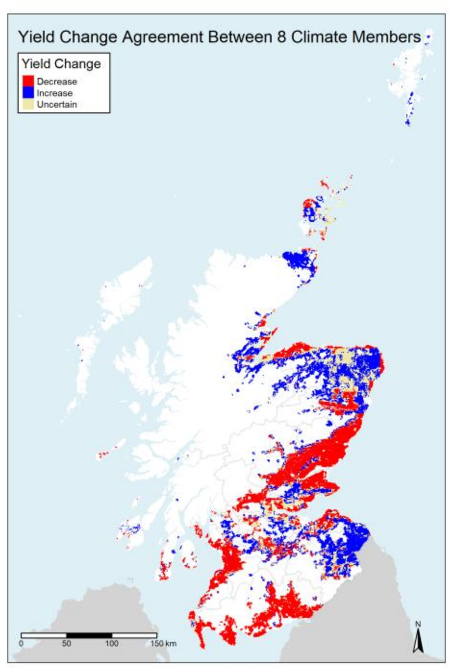
10 Ensemble Members



9 Ensemble Members



8 Ensemble Members



7 Ensemble Members

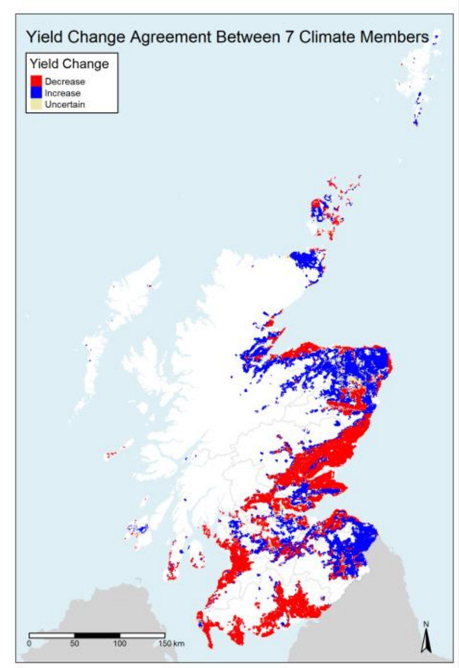
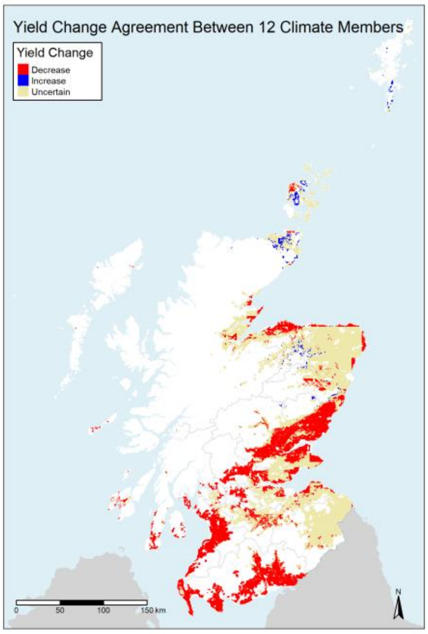


Figure 13. Spatial distribution of the level of agreement between climate projections in the barley yield change over the period 2030-2049 as compared to the baseline period 1994-2015. Yellow = variable probability of change; Blue = yield increases; Red = yield decreases. The number of climate members considered for the agreement maps are, from top left to bottom right: 12, 11, 10, 9, 8 and 7. The maps are shown for the sowing date 01/Apr.

For these levels of agreement maps, where there is either increase or decrease, then we can be more confident with more that the projected yield change is likely to occur. Where there is no change, then we can be confident that there is less likely to be much change. The uncertain areas indicate a variable probability of change (could be either decrease or increase). The agreement maps are provided for agreement between 7 ensemble members and above.

12 Ensemble Members



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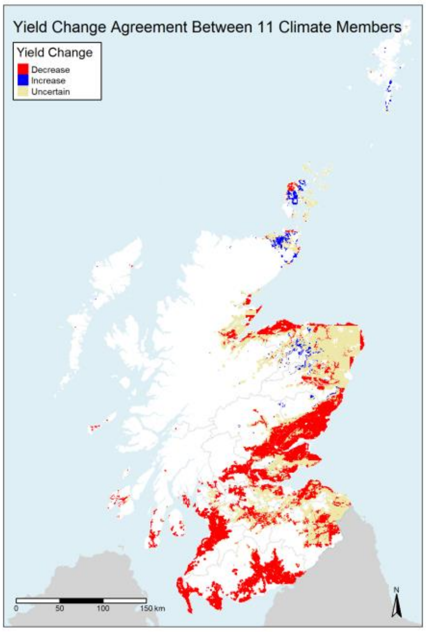
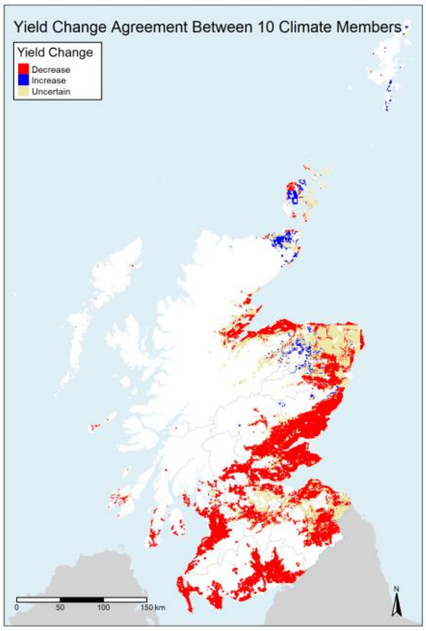


10 Ensemble Members



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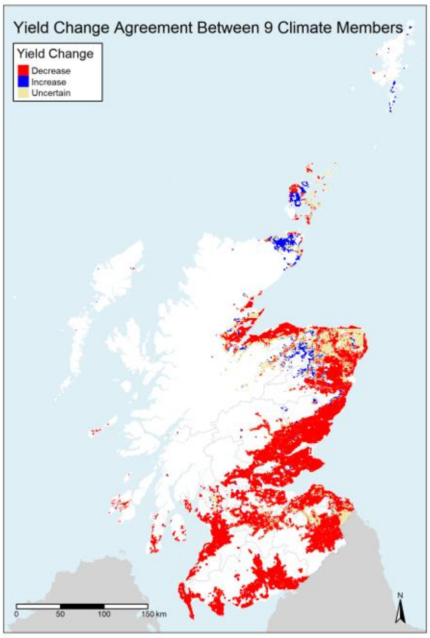

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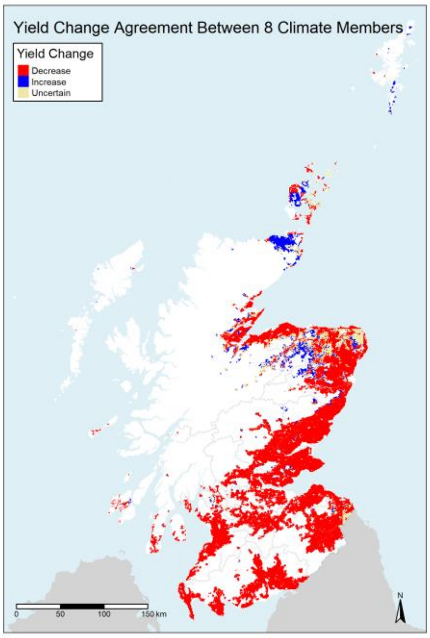

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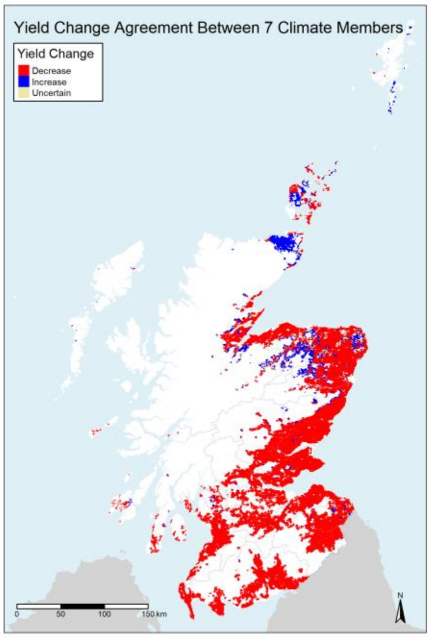


Figure 14. Spatial distribution of the level of agreement between ensemble member projections in the barley yield change over the period 2060-2079 as compared to the baseline period 1994-2015. Yellow = variable probability of change; Blue = yield increases; Red = yield decreases. The number of climate members considered for the agreement maps are, from top left to bottom right: 12, 11, 10, 9, 8 and 7. The maps are shown for the sowing date 01/Apr.

When a location is identified as potentially having yield increases or decreases by all 12 climate projections, we can be more certain about the estimates. As the number of projections is reduced, it is possible to identify locations where increases or decreases are consistent. Locations that consistently appear as potentially having a yield decrease can be seen as more vulnerable to climate change impacts.

For the 2040s period (Figure 13), when at least 9 climate members are considered and 1st April as sowing date, yield change patterns become more clustered and it is likely that yield is projected to increase in Northern and South Eastern parts of Scotland. Overall, yield will increase in about 19.6 % of the total barley area. However, yield is found to decrease in the middle and the South Western part of Scotland during the 2040s. The yield decrease would be estimated in about 46.7 % of the total barley area.

By the 2070s (Figure 14), there is a consistent occurrence of areas with yield decreases, regardless of the number of ensemble members used, as the area classified as uncertain decreases with increasing number of climate projections.

The barley cropped area with projected yield decrease is likely to be higher when at least 7 climate members are considered for the agreement map (Figure 8). However, there is more agreement during 2070 that yield will predominantly decrease across Scotland for the five sowing dates. Sowing late during May will result in more yield decrease (Figure 9).

These observations can also be easily seen when the results are summarized by percentage of each of the yield change signs for the total barley growing area per sowing date in Figures 15 and 16. These results show that whilst the amount of area that is classes as uncertain (could be either yield increase or decrease) gets larger with more climate projections used, the amount of area potentially experiencing yield decreases are consistently larger than areas with an increased yield.

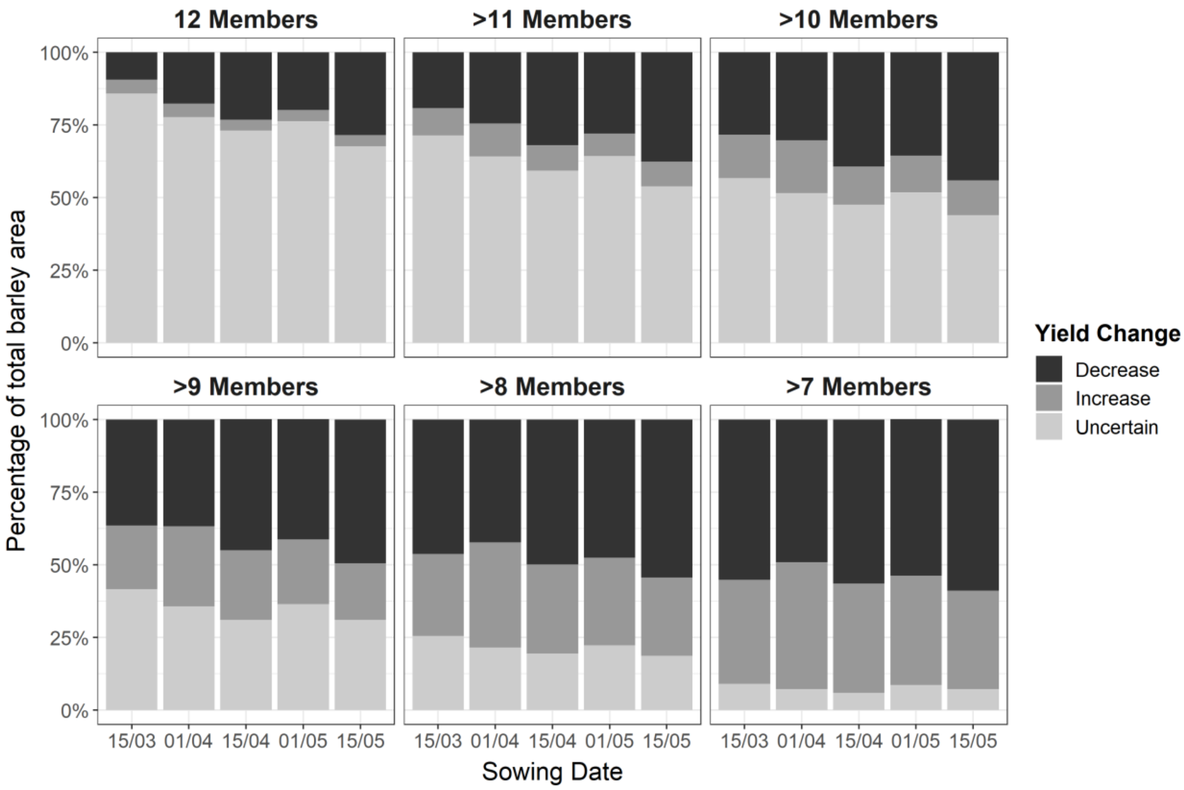


Figure 15. Total barley area shares between the projected yield change agreement among different number of climate ensemble members during the period 2030-2049 and for the different sowing dates.

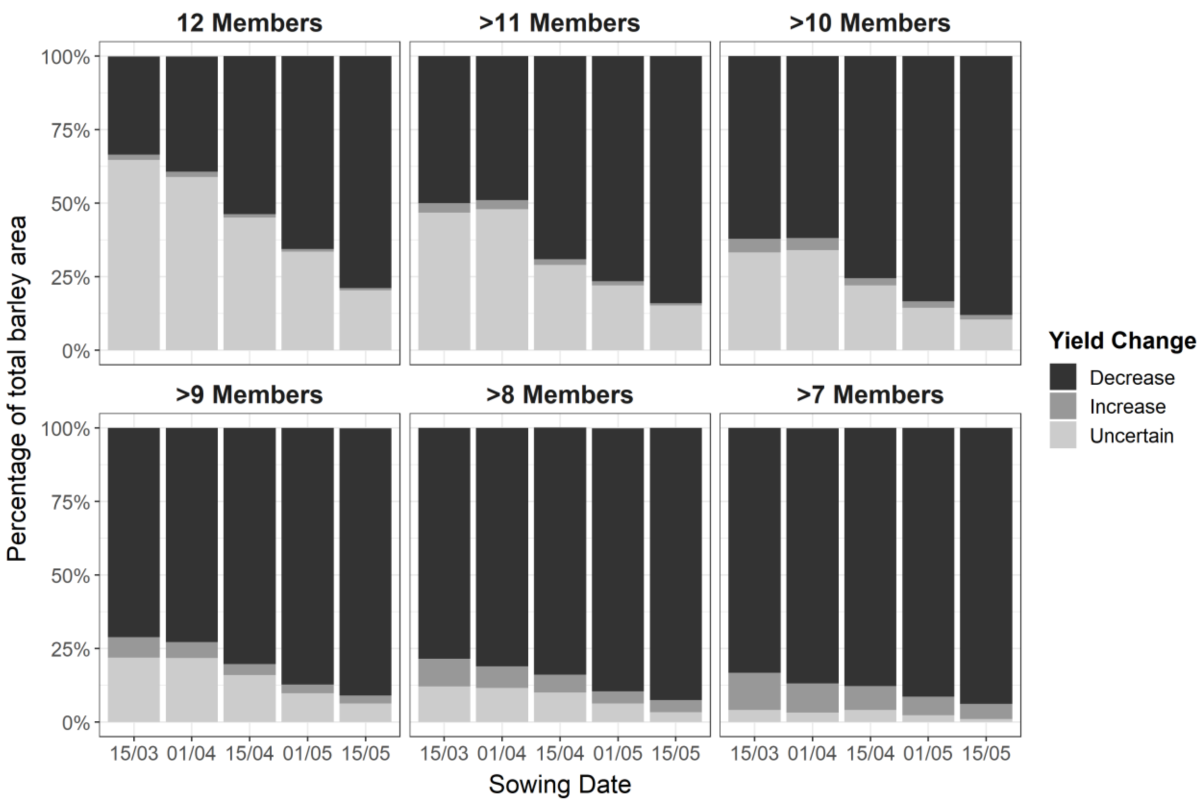


Figure 16. Total barley area shares between the projected yield change agreement among different number of climate ensemble members during the period 2060-2079 and for the different sowing dates.

By the 2070s the percentage area where yield increases may occur is considerably less than where decreases occur. **The consequence is that it becomes increasing likely over time that the total national yield amount will decrease.**

Precipitation change

Using the same approach as above to assess uncertainty in yield projections, we can also consider the range of certainty on how precipitation may change in the future, compared to the baseline. Figures 17 and 18 below indicate for the 2040s period that there is good agreement between all ensemble members that March's rainfall amount will increase across most barley growing areas. In April the level of uncertainty increases in the far north and north-east Scotland, but there is good agreement that the other barley growing areas will experienced an increase in precipitation. As the growing season progresses into May and June the areas seen to be uncertain increases, with large areas in the east and south-west experiencing a decrease in precipitation. In July only the far north and a few areas of north-east Scotland may experience increased precipitation, whereas the remaining barley areas are either uncertain or see a decrease. In August, most of Scotland may experience a decrease in precipitation, but with some uncertainty in the north-east. There is good agreement between the ensemble members where in September will have either an increase or increase in precipitation.

These results indicate that there may be increasing issues concerning crop establishment if planted in March or April, with potentially wetter soils. Conversely, if the soils remain workable and water availability in Spring is adequate, then crop growth may be good, and if followed by dry conditions at harvest, lead to a successful productive crop. These results are however the mean for the 2040 period, and hence mask the inter-annual variability, meaning some years may experience dry springs and wet summers as well as those when conditions are favourable.

Comparison of the growing season precipitation change agreement maps for 12 to 7 ensemble members (Figures 17 and 18) with those of the change in yield (Figures 6, 14 and 15, 19) however, highlights the alignment of locations with decreased precipitation and yield and that precipitation change, as a function of the soil water holding capacity (Figure 2) and climate deficit (Figure 3, precipitation – evapotranspiration) is driving the yield change response.

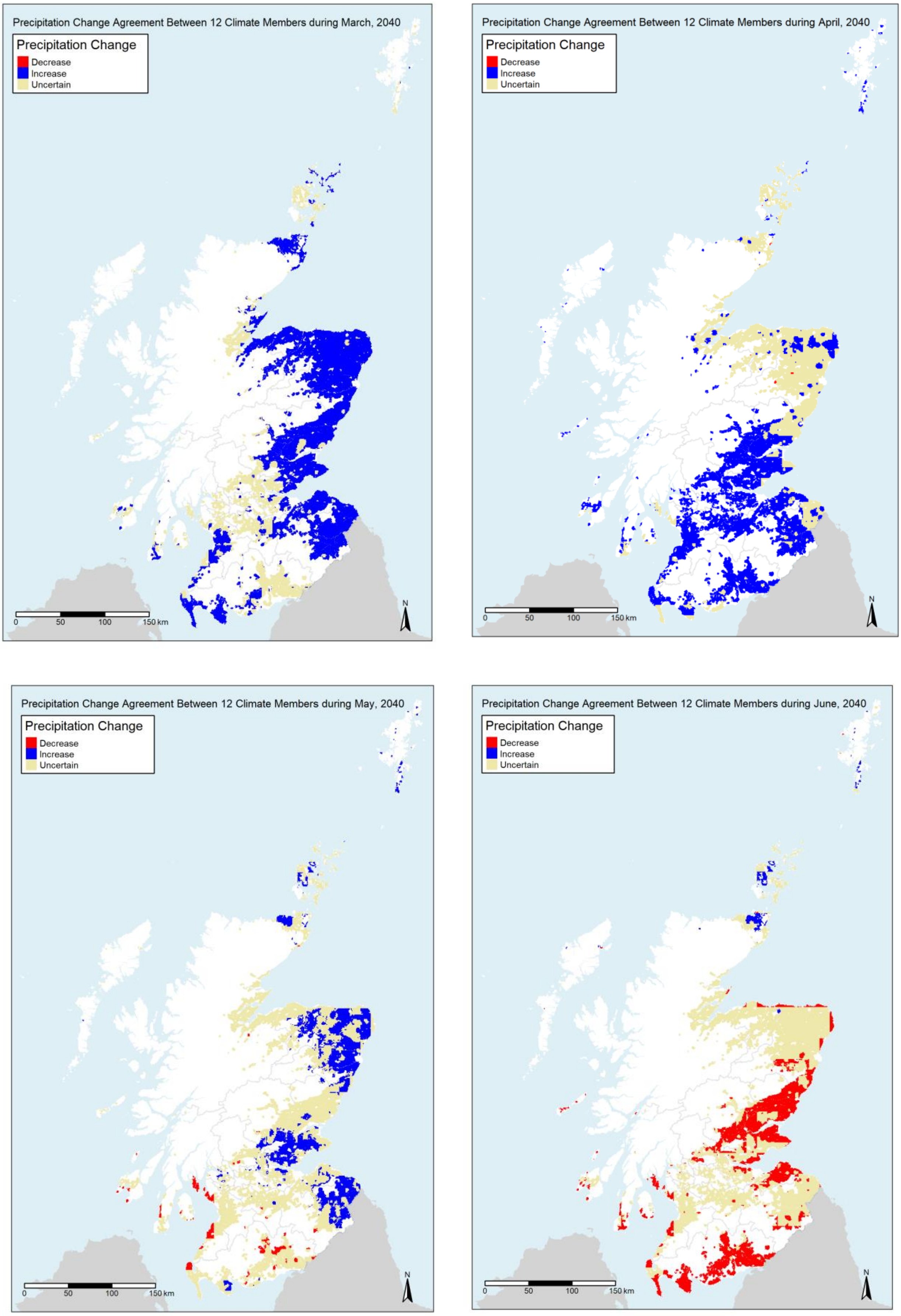
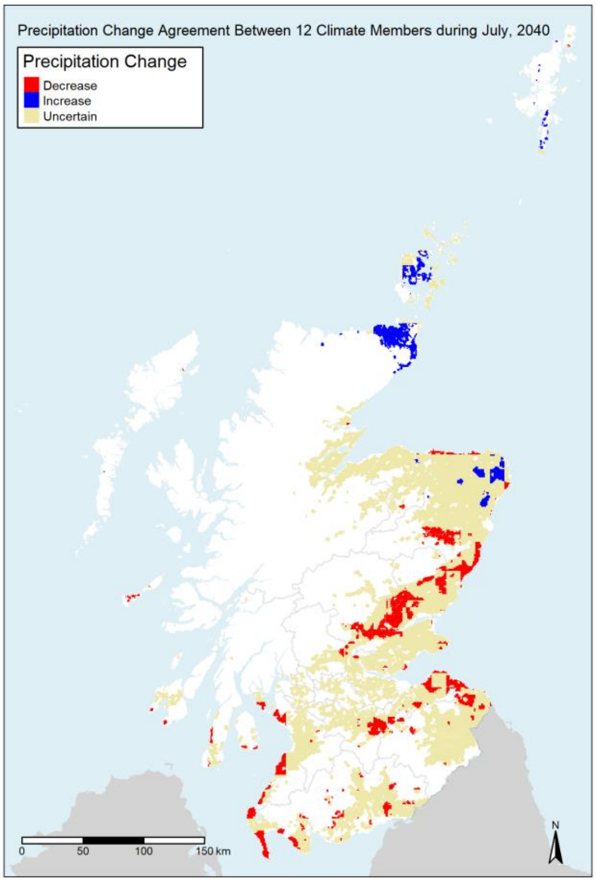
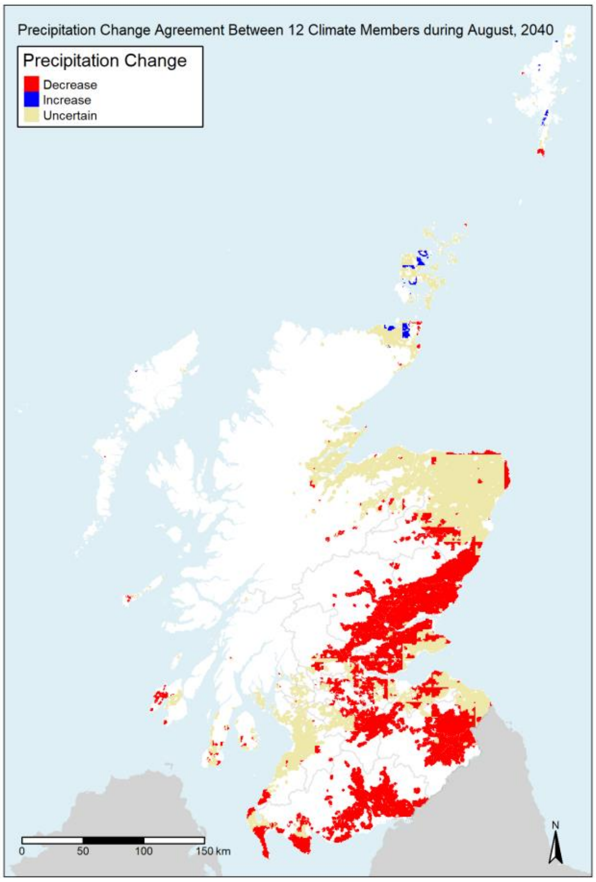


Figure 17. Agreement maps of the change in increase or decrease in monthly precipitation (March, April, May and June, 2040s) for all 12 climate model ensemble members.





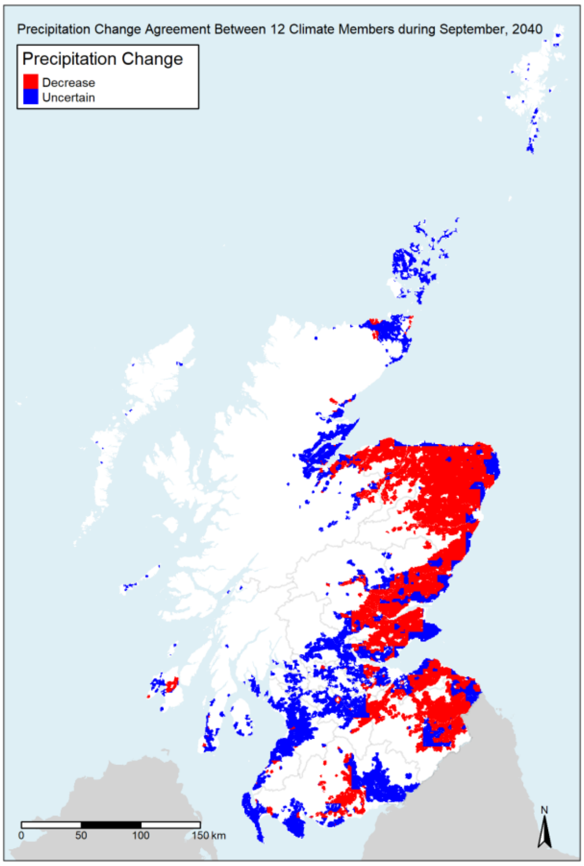


Figure 18. Agreement maps of the change in increase or decrease in monthly precipitation (July, August and September, 2040s) for all 12 climate model ensemble members.

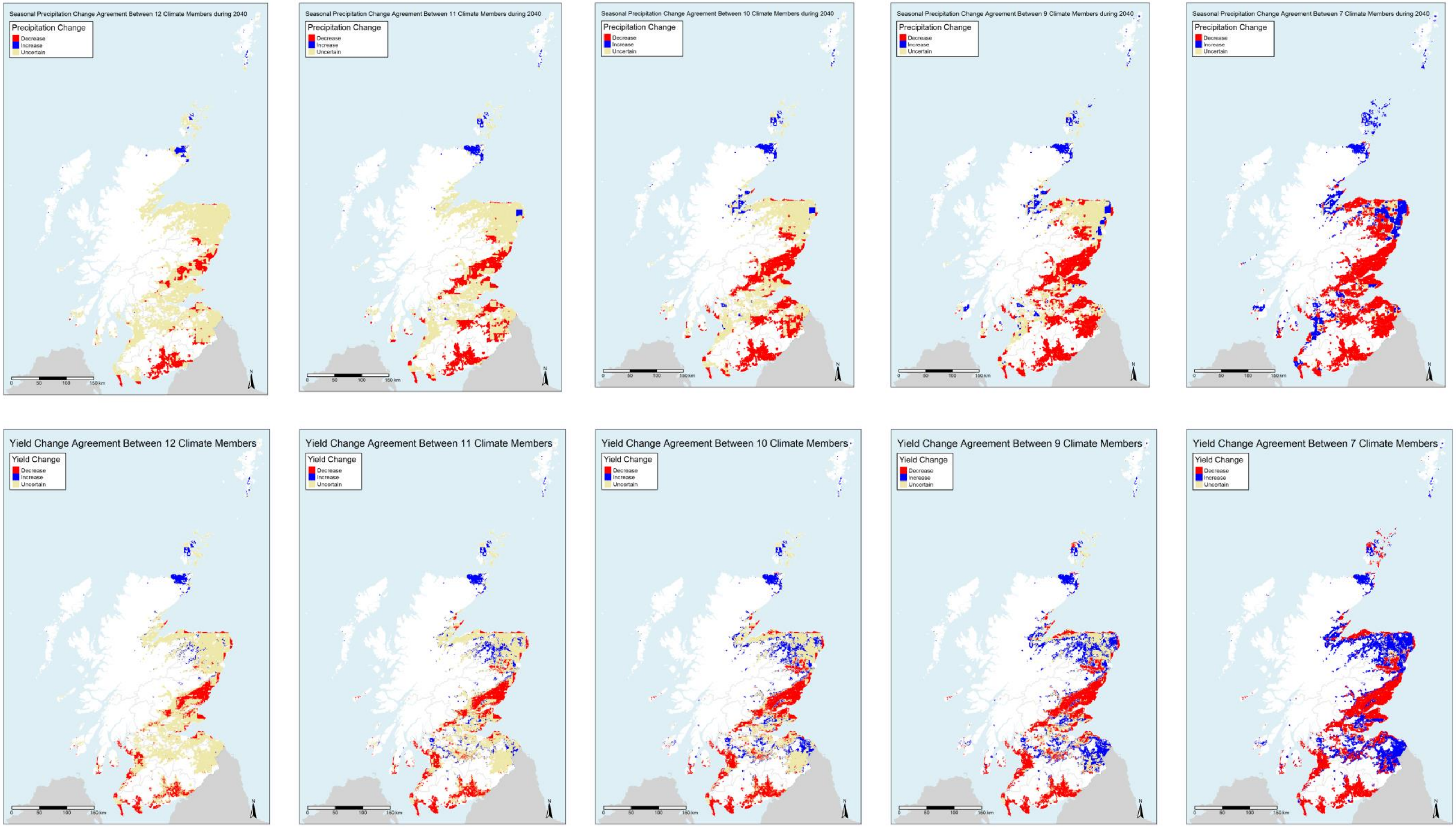


Figure 19. Growing season precipitation (top row) and estimated yield (bottom row) change agreement maps for all 12 ensemble members (left column) and reducing number (11, 10, 9 and 7) of ensemble members (right column) for the 2040's period.

Figure 19 highlights the spatial alignment of the agreement between climate projections of decreases in precipitation (top row) and decreases in barley yield (bottom row).

Water Stress Indicator

A Water Stress Indicator (WSI) is calculated as $1 - Y_w/Y_p$ where Y_w is water limited yield and Y_p is potential yield where water is not limiting and yield is mainly driven by solar radiation. A WSI value of 0 represents no water stress and 1 is high water stress leading to crop failure. Values in the mid-range imply stress can occur that reduces yields. It is important to note that the timing of when water stress occurs in relation to the crop growth stage during a growing season is critical, e.g. if low water availability between crop emergence and flowering will likely have more of a yield impact than if between flowering and harvest. High temperatures occurring during flowering (anthesis) however, especially if water for canopy cooling is not available, can have substantial impacts on grain formation and therefore yield (Ferris et al 1998). The WSI for the baseline climate period is mapped in Figure 20.

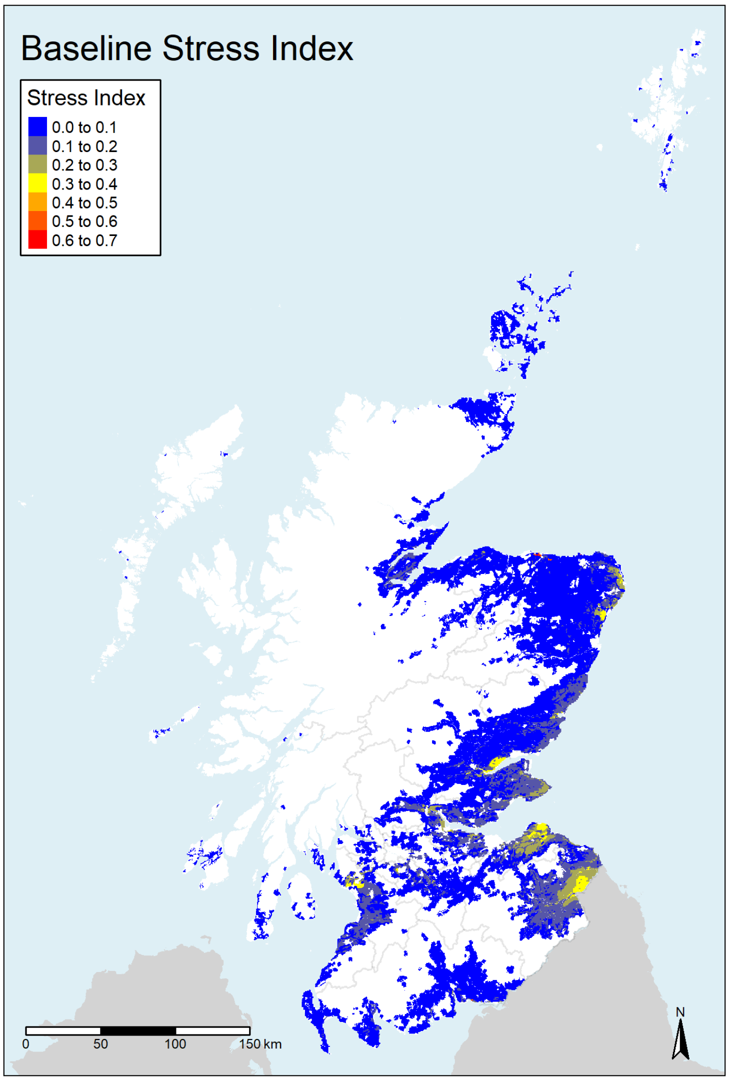
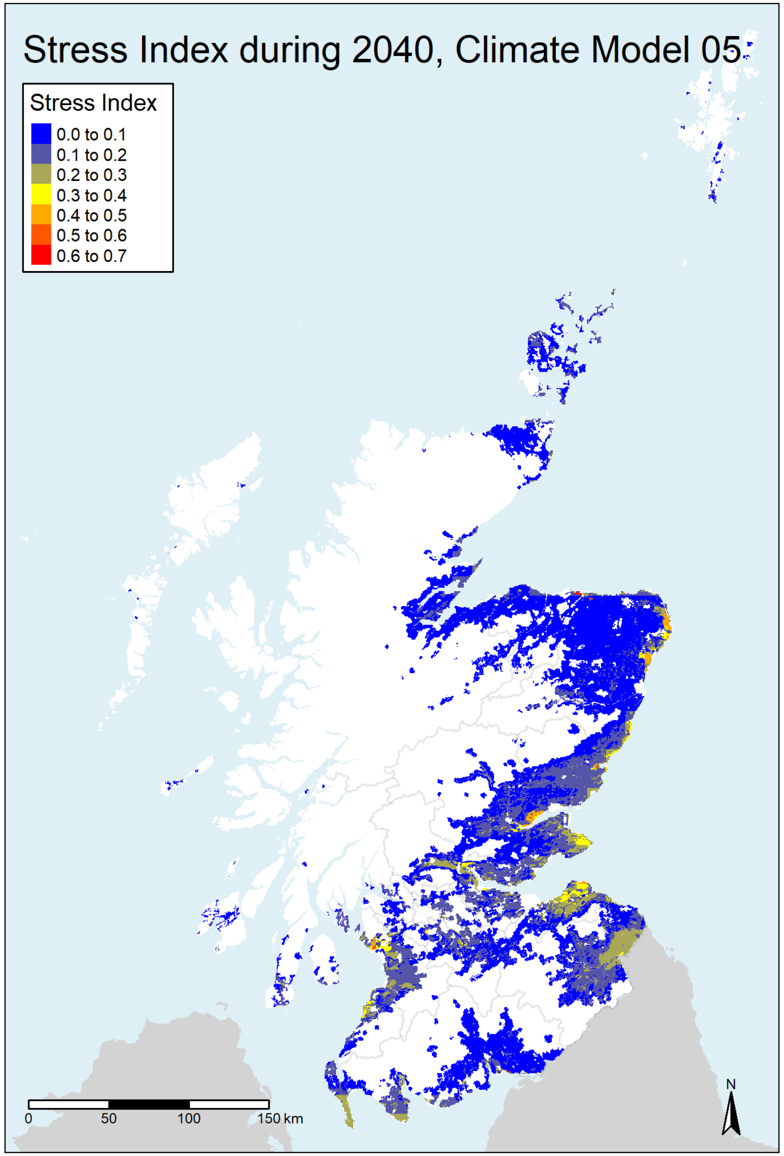


Figure 20. Spatial distribution of the Water Stress Index (WSI) across Scotland during the baseline period.

In figure 20, yellow and red indicate areas where yield is more impacted by water stress. By comparison with the soil water holding capacity (WHC, Figure 2), there is alignment in higher WSI values in the south-east, Haddington / East Lothian, parts of the central belt and southern Fife, Saltcoats – Irvine – Kilwinning and east coast parts of Aberdeenshire. The level of alignment between WSI and WHC becomes increasing apparent when considering the climate projections (Figure 21a and b), especially for the drier 06 ensemble member.



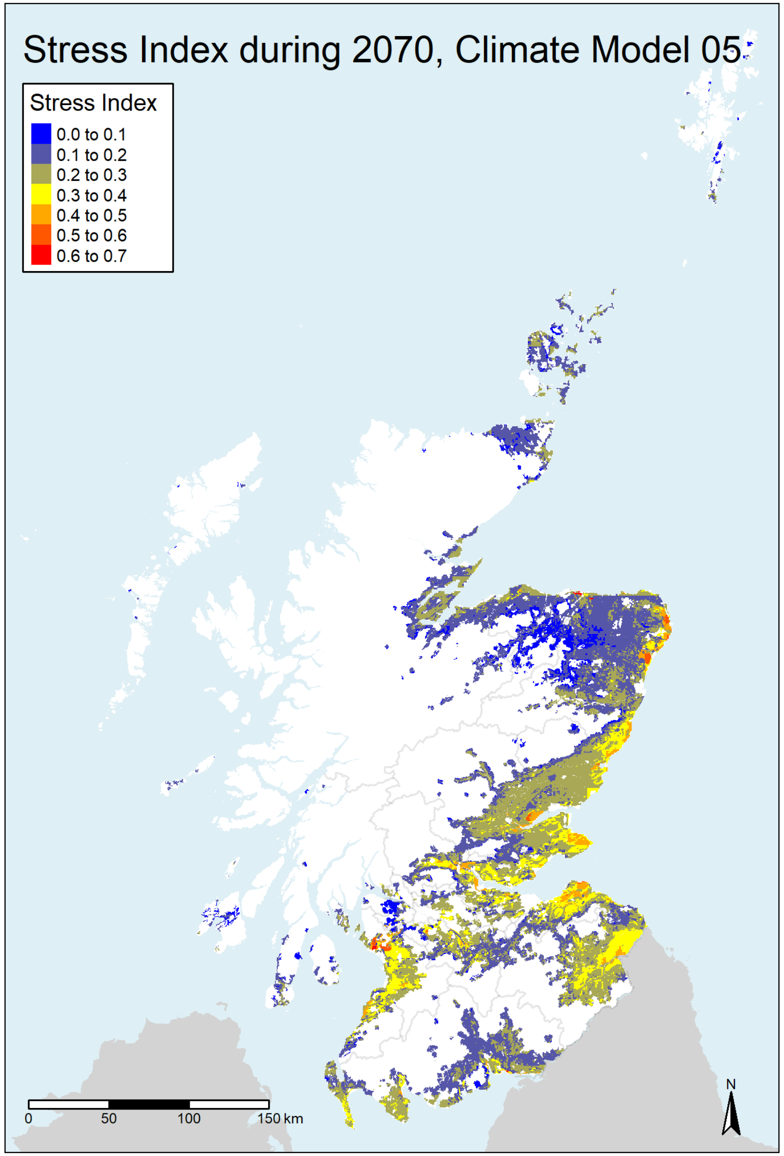
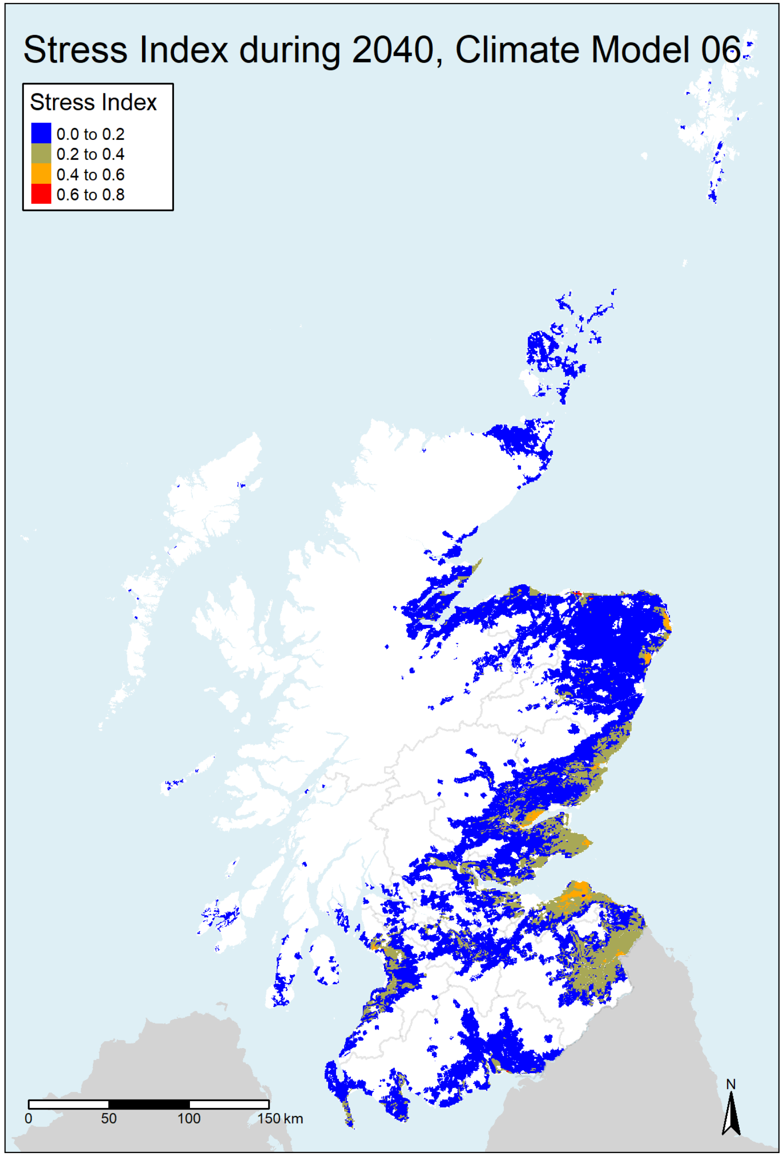


Figure 21a. Spatial distribution of the Water Stress Index (WSI) across Scotland during 2040 and 2070 for the ensemble member 05



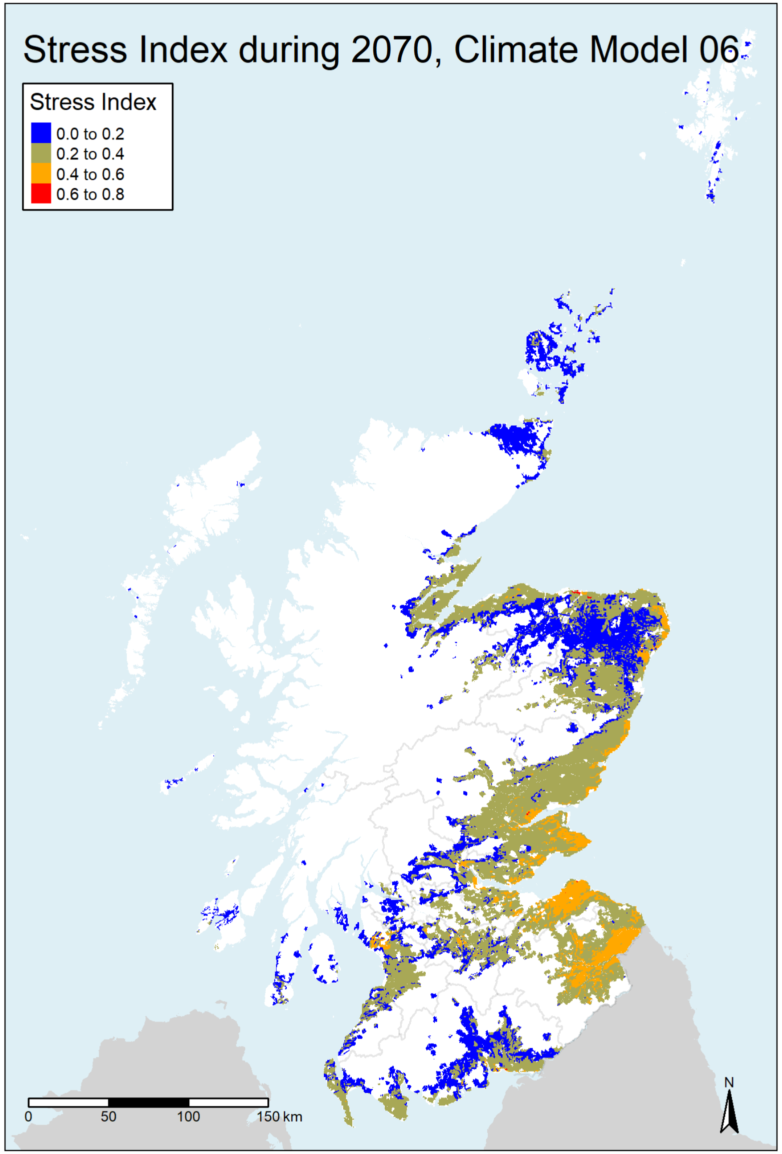


Figure 21b. Spatial distribution of the Water Stress Index (WSI) across Scotland during 2040 and 2070 for the ensemble member 06

The areas of higher water stress in Figure 21b spatially align closely with those areas consistently appearing as having decreases in yield (Figures 6, 14 and 15) and precipitation (17, 18 and 19).

A key point to note here is that in the 2040s both example climate projections show that areas considered as prime agricultural land (e.g. east of Edinburgh) all show higher WSI, indicating that land currently considered as highly flexible and productive land may experience reductions in yield. This situation is projected to worsen considerably by the 2070s.

Seasonal Water Stress

Having considered the overall spatial distribution of water stress, the next aspect is the seasonal distribution of available water, indicated by the climatic deficit (precipitation – evapotranspiration). Here, when evapotranspiration water loss to the atmosphere is greater than the input precipitation, there is a deficit. Figure 22 highlights that on average the barley reproductive phase will likely suffer from water shortage for most of the future climate members. The soil capacity to hold water will determine how barley yield is affected as soils with high water holding capacity will benefit from water surplus during the vegetative phase and the surplus can be used during the grain development. The climatic deficit and mean temperature were averaged across ensemble members and the barley growing area in Scotland.

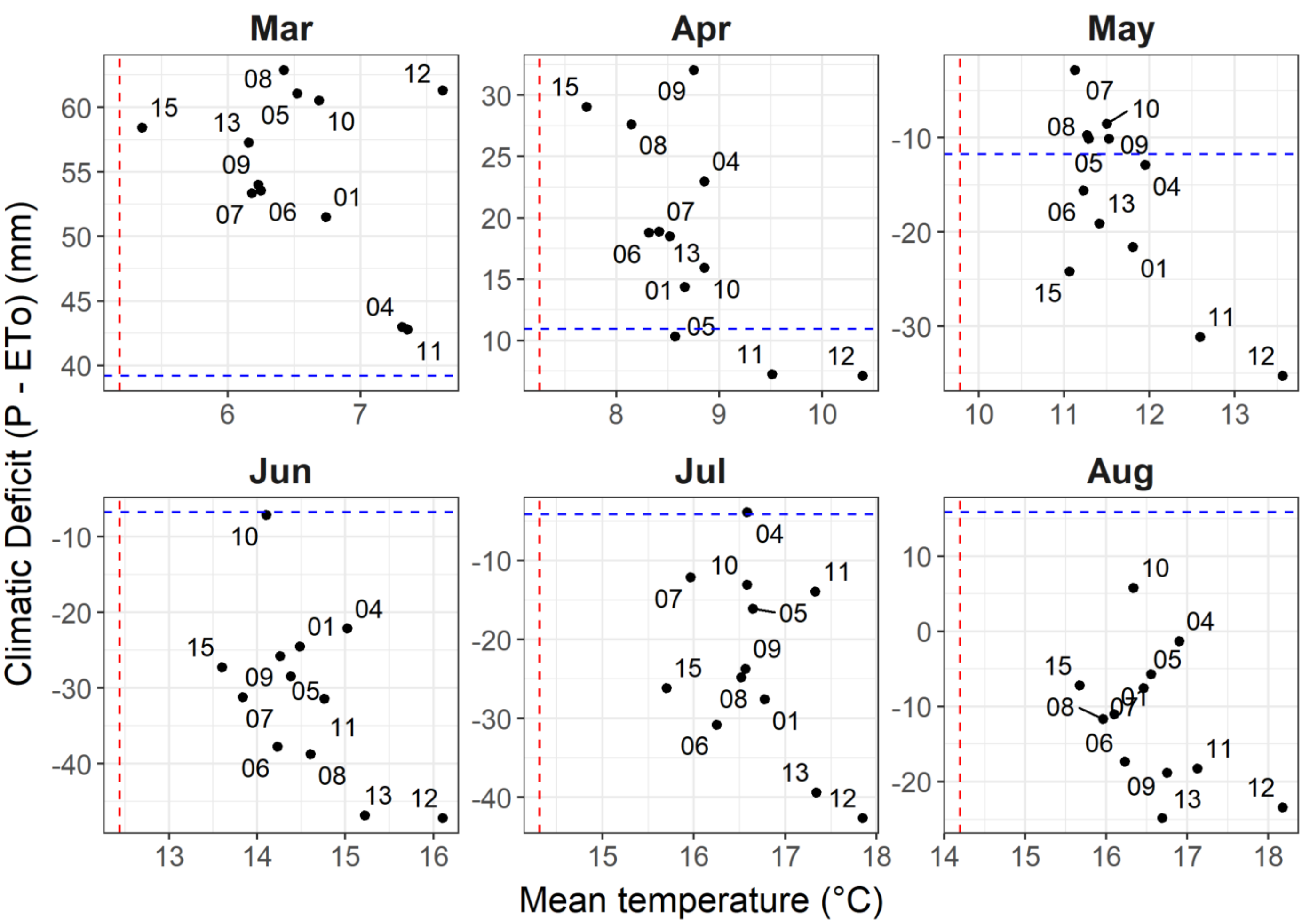


Figure 22. The climatic (water) deficit and mean temperature per ensemble member for each month in the growing season. The vertical red dotted line is the mean temperature for the baseline period, the horizontal dotted blue line is the baseline climatic (water) deficit).

In March all climate projections are warmer than the baseline but that there is a larger excess of water (no deficit) than the baseline period by between 43 – 65mm (Figure 22), and in April there is estimated to be a continued excess for 9 of the 12 projections. This raises several issues, particularly that of potential increased soil wetness and reduced workability, and the possible risk of surface ponded water and or runoff impacting crops when they are vulnerable at the time of emergence.

By May, the climate projections are generally below the baseline climate deficit, hence soils are more likely to be drier at a key time of crop growth and biomass accumulation. In June all climate projections are below the baseline climate deficit and remain so through to July and August. This means a substantial reduction in the amount of water available for crop growth (e.g. 10 – 45 mm in June) and increased risk of extreme temperature damage during flowering and grain filing. A benefit of a larger deficit in August may be that harvest conditions may be more favourable and that grain drying cost are reduced, however, it is projected that summer precipitation events are likely to be more intense (UKCP18 2018), so this benefit may be negated.

Changes in crop phenology

The warmer temperatures associated with future projections will mean that crops progress through their growth stages more rapidly, as phenology is determined by temperature accumulation (also referred to as thermal time accumulation).

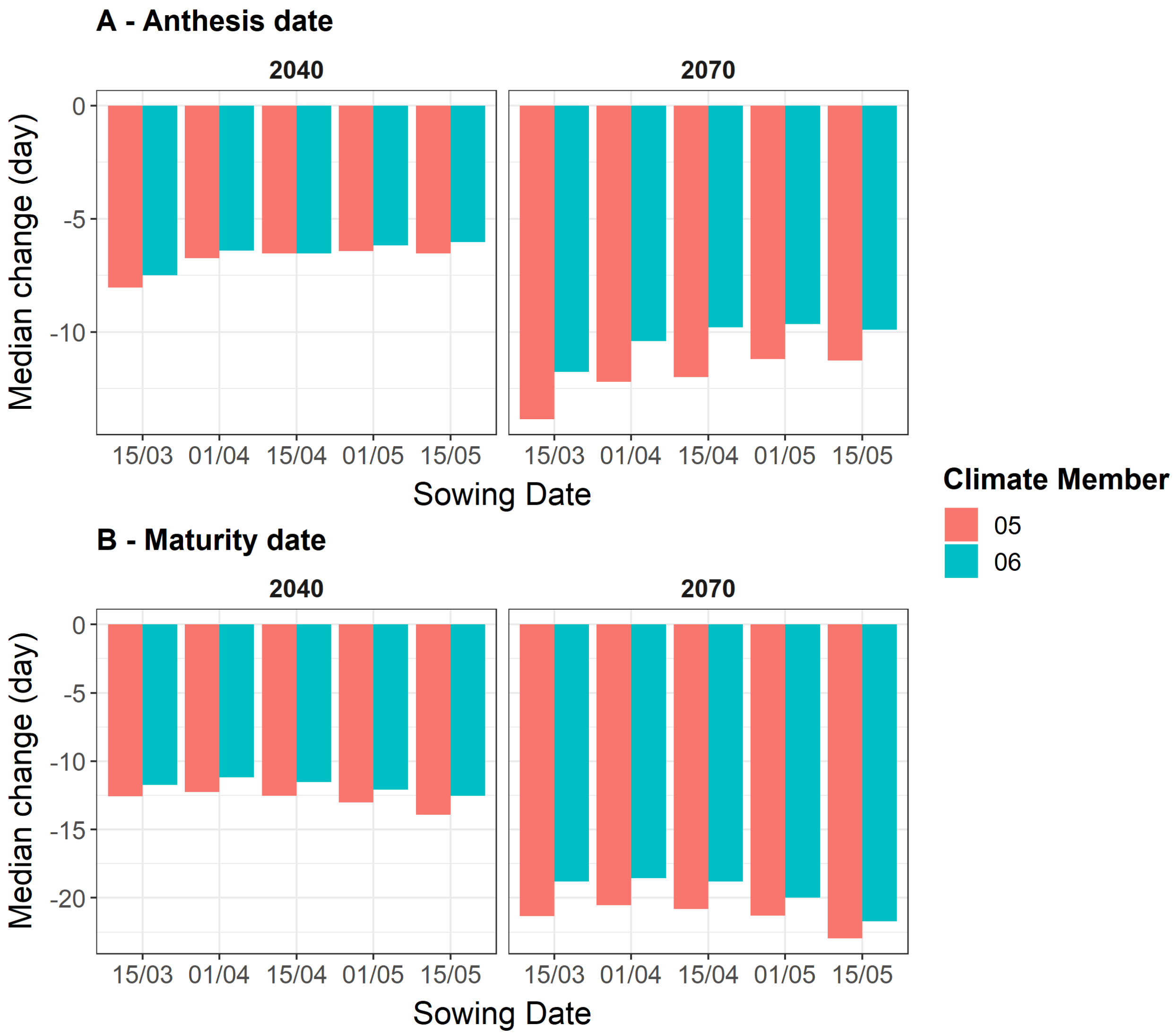


Figure 23. Variation in anthesis and maturity day of year per sowing date for two climate projections (ensemble members 04 and 05).

For the two ensemble member examples shown in Figure 23 (05 and 06), both indicate anthesis and maturity dates occurring earlier in the growing season, and this varies with sowing date. This more rapid phenological development means that overall, the crop has less time to accumulate biomass and thus less material to translocate from leaves and stems to grains.

Note: when interpreting Figures 24 and 25 below, there are differences between the scales and colours used for phenological change in the legends used in the maps, hence comparison between maps just by colour is not appropriate (e.g. red on the anthesis 2040s 05 ensemble member = -9 to -8 days, and for 2070s = -16 to -15 days).

Anthesis spatial variation:

There is a large degree of spatial variation in phenological response to reach anthesis (flowering stage), with some areas, e.g. the south-west in the 2040s experiencing less of change to crop development (e.g. 4-5 days earlier in the south-west) compared to locations on the boundaries of existing barley growing areas (e.g. 8-9 days earlier at higher elevations) (Figure 24, ensemble members 05 and 06).

Physiological maturity spatial variation:

The spatial variation of changes to when physiological maturity is reached is similar to that of anthesis. The larger changes occur at higher elevation areas (e.g. Land Capability for Agriculture classes 3.2 and 4.1).

It is useful to note that the thermal time accumulation basis for determining phenological development for barley is similar to other crops, vegetation and also insects. Hence these estimated and mapped changes are also applicable to a wider range of relevant research applications.

2040

2070

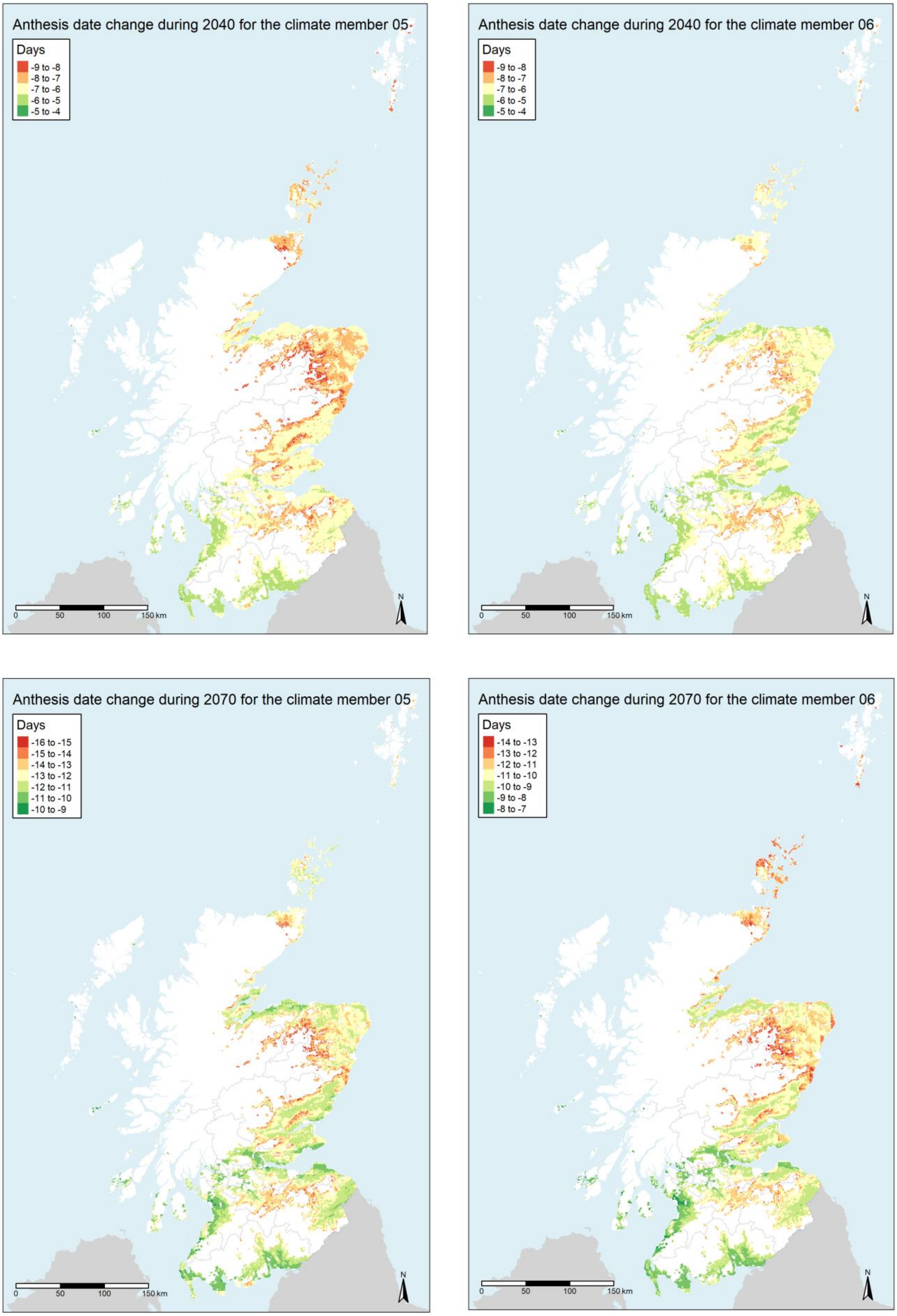


Figure 24. Anthesis date change of the periods 2040 and 2070 for the future climate members 05 (left) and 06 (right) for the sowing date 01 April.

2040

2070

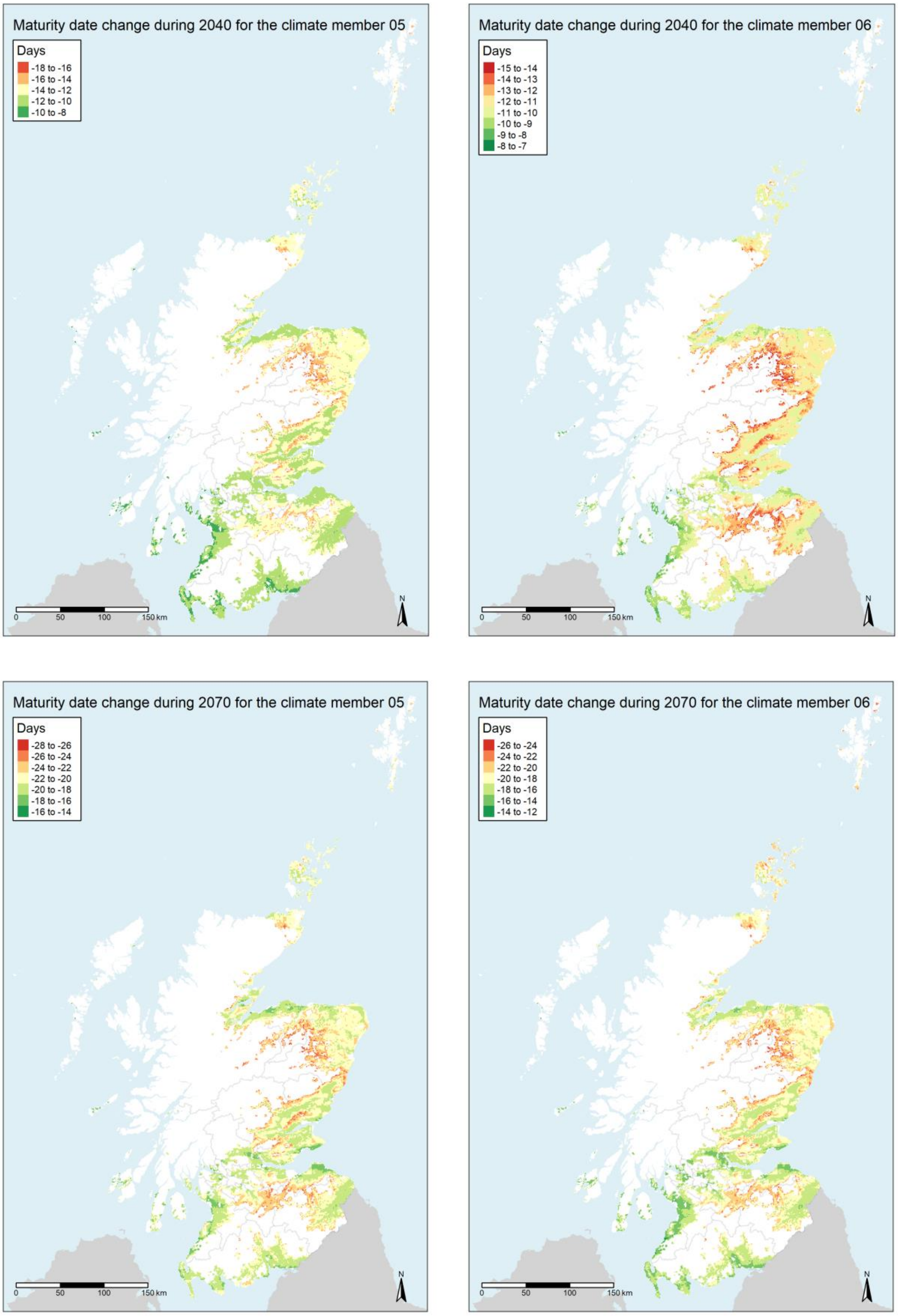


Figure 25. Maturity date change of the periods 2040 and 2070 for the future climate members 05 (left) and 06 (right) for the sowing date 01 April.

4 DISCUSSION

Utility of the modelling

The research developed by the RESAS Strategic Research Programme has enabled a substantial improvement in the capability to spatially model barley growth and to understand the potential spatial and temporal variation in impacts due to climate change. The level of spatial (1km) and temporal resolution (annual yield based on daily timestep simulations) means that individual farm businesses have the potential to assess a range of plausible future conditions and identify adaptation options and strategic plans. The complete coverage of the arable area of Scotland (plus the addition 1km surrounding buffer zone) enables the aggregation of the high-resolution data to assess impacts at a regional and national level.

Mapping yield, precipitation, soil water holding capacity, climatic deficit (precipitation – evapotranspiration) and phenology enables a more comprehensive understanding of spatial variation. Mapping the agreement in estimated yield increases or decrease using multiple climate projections is novel and helps to improve the reduction in uncertainty: we can be more certain where yields increase or decrease when there is agreement between an increasing number of climate projections used.

The combination of mapping the multiple factors determining yield and the sign of change (increase or decrease) agreement maps means it is now possible to identify locations that may be more vulnerable to climate change impacts and which ones may be more resilient.

Validation remains a substantial limitation: Whilst the increased spatial resolution of the modelling and the ability to utilise multiple climate projections has been achieved, a major limiting factor for the utility of the modelling remains the lack of appropriate observed data for calibration and validation purposes. As inputs to the model we are confident that the soils and climate data are adequate. However, the model parameters have only been calibrated using a limited number of locations and short temporal period, thus representing only a few of the 56,256 unique soil-climate combinations. This restricts the ability to demonstrate that the model is able to make reliable estimates in multiple locations under varying conditions. Sensitivity testing in the initial phases of the project indicated that the model responded well to variations in nitrogen, water, temperature, carbon and different sowing dates for the locations where data was available, hence we have good confidence that the model responds well overall to observed climate conditions.

Despite the lack of validation data, we are confident that the sign of yield changes under future climate conditions and spatial representation is sufficiently reliable to enable meaningful interpretation of risks and opportunities.

Result communication challenges

Simulating crop growth on a daily time step at the map unit level (unique soil-climate combinations) for multiple sowing dates and x12 climate projections raises two key challenges: the amount of data generated (the crop model can output many, c. 20-30, useful outputs detailing growth, resource use (e.g. nitrogen and water), soil water balance, phenology, root development etc.); and how best to present results, given the number of combinations and detail available. We have presented a range of possibilities with the aim of creating a comprehensive picture of impacts. However, presenting results for means from multiple climate projections often masks extremes and the range of annual variability. Conversely, presenting results from simulations using individual climate projections leads to many maps making comparison and interpretation problematic.

5 CONCLUSIONS

The increased crop modelling capabilities developed during the project has increased the research quality to assess multiple climate change projections and associated impacts on crop production. The research shows that:

- With the high emissions scenario used (RCP8.5), climate change is likely to have both positive and negative impacts on barley growth and annual yields, but with an overall decrease in yields by the 2040s, which continues to worsen by the 2070s.
    - It should be noted that there is little difference in estimated climate change between the low and high scenarios until c. 2040 – 2050, after which they start to diverge.
- Under the twelve climate projections used (which leads to temperature increases ranging from 1 to 3.5°C and 7% increase to 14% decrease in growing season precipitation), barley yields are likely to decrease in many parts of Scotland.
    - This will likely be due to additional water stress, especially if water is limited in the spring to early summer periods.
    - Future higher temperatures and potentially reduced precipitation are likely to lead to an increased water deficit, where evapotranspiration loss of water to the atmosphere is greater than the precipitation input to soils.
    - Areas with better soil water holding capacity appear to be more resilient and could potentially experience increases in yield when favourable climatic conditions permit.
- There is good agreement between the climate projections as to where these changes in yield may occur.
- There is likely to be increased annual variability, with some years potentially experiencing good yields when conditions are favourable.
- The spatial extent and temporal frequency of yield decreases is likely to cause substantial challenges to the barley supply chain and end users.
- Earlier sowing appears to be a viable adaptation option.

Whilst yields overall may decrease, there may be individual years when climatic conditions are favourable and higher yields may be attained. When feasible, earlier sowing may help to reduce risks of yield decreases. Barley production and utilisation will need to adapt to cope with increased annual and spatial variability. The analysis has not included potential yield loses due to pests, diseases or physical damage (e.g. wind). Climate projections indicate an increase in storm intensity, hence physical damage may be more frequent, as well as more droughts.

6 RESEARCH DEVELOPMENT RECOMMENDATIONS

The work undertaken to improve the modelling capabilities to understanding climate change impacts on crops in Scotland has helped identify the following issues and recommendations.

- Observed data limitations restrict the ability to calibrate and validate models: There is need to improve the collection and availability of data, ideally yield / biomass, phenology, management and soil water at the field scale and over a wide geographic distribution.
    - Development of phone apps will enable farmers to provide observations and receive back information on possible climate risks.
    - There are substantial opportunities for using remote sensed Earth Observation data to provide both historical and real-time spatial and temporal variation in soil moisture.
- Develop capabilities to forecast harvest time yields: The development of High-Performance Computing capabilities can now enable real-time simulation to be combined with use of satellite or other remote sensed data for harvest time yield forecasting.
    - This will facilitate improved regional and national level yield predictions.
    - Forecasting capabilities have the potential to enable improved forward planning by the brewing and distilling sector, and the livestock sector in terms of feed availability.
- A key issue for barley is grain quality for malting grade, hence there is need to improve the modelling capabilities to include indications of climate change impacts on quality.
- There is need to develop capabilities to model physical damage to crops arising from storm events.
- Research has focussed on barley: there is need to calibrate and validate models for broader range of crops.
- Grass is a major crop in Scotland yet there is poor capability to assess climate change impacts: Potential exists to implement existing grass models within the research platform developed in this project.

- Climate change, as both impacts and the need for mitigation, is likely to drive substantial changes in land use and management: There is need for greater integration of foresight modelling tools, for example the new Land Capability for Scotland platform[4], to increase the research capability to understand the spatial context of land use change.
- The impacts of climate change on crops in Scotland needs to be seen in the context of impacts elsewhere in the world: There is need to improve real time monitoring of crop growth and assessment of productivity internationally to identify emerging risks of supply not meeting demand.

[4] The Land Capability for Agriculture: building a tool to enable climate change assessments (climatexchange.org.uk)

7 METHODS AND MATERIALS USED

The output maps are the product of four components operating within an integrating framework. The components are: spatial data; crop simulation models; model calibration, testing and validation processes; and visualisation tools (especially as maps). Each component is set out in summary in the table below and detailed in the *Spatial Barley Modelling - Technical Documentation.*

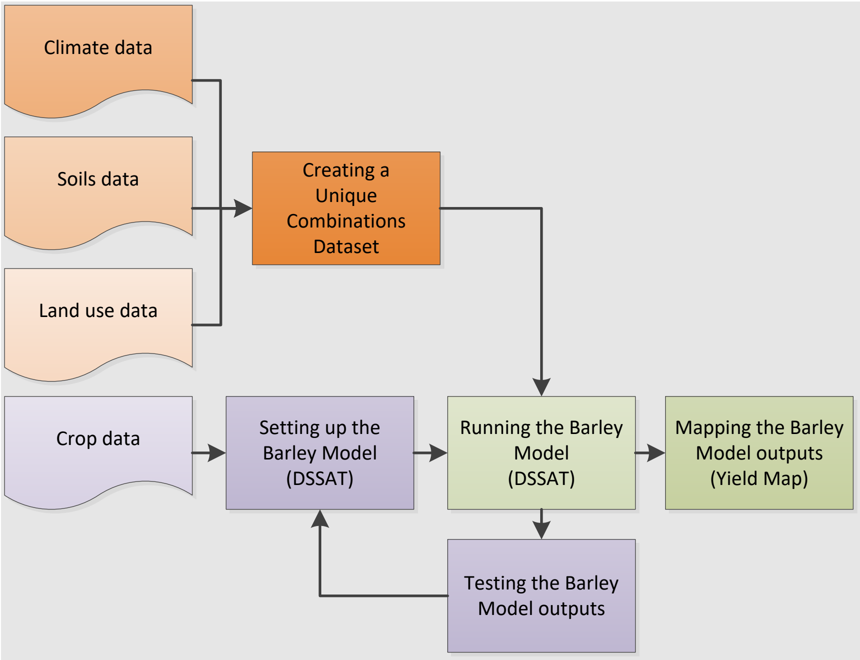


Figure 26: Overview of the method of generating yield maps.

Table 2: Description of overall modelling approach

Factors included	Assumptions and issues
Analytical Step: Creating a Unique Combinations Dataset	
This dataset provides the inputs needed to run the model across Scotland. Climate, soil and land use data were combined to generate unique combinations. This preserves the granularity of the analysis while keeping the number of model runs feasible (~56,256).	• The climate data used, (UKMO 1km gridded, daily precipitation and max and min temperature), is interpolated from observation stations, plus satellite derived estimates of solar radiation. • Soils data combines the 1:250,000 scale soil map with physical and biochemical data from the Scottish Soils Knowledge and Information Base (SSKIB). • Information on where barley could be grown was taken from the IACS data for the period 2003 - 2015.
Analytical Step: Setting up the Barley Model	
A barley specific process-based model (operating within the DSSAT modelling platform) simulates daily crop growth and development as a function of crop genetic coefficients and environmental inputs (soil, weather) plus a crop management regime (e.g. amount and timing of fertiliser applied). The crop model was run for each of the unique combinations for each individual year to generate estimates of crop biomass and grain yield (t/ha). A large range of other	Calibration, sensitivity testing and validation are necessary to underpin the credibility in the model outputs. Calibration of model parameters to test spatial and temporal responses for the unique combinations used four steps combined within an iterative review-and-refine process: • Calibration to match crop growth (accumulation of biomass) and development (e.g. flowering and physiological maturity) using the Barley Growth Guide, associated field trials and the scientific literature.

model estimates can also be recorded as outputs from DSSAT, some of these are presented for the Balruddery example in the *Spatial Barley Modelling - Technical Documentation*.	• Use of experimental data (covering factors determining crop growth) in combination with previous researcher experience. • Ability to match the aggregation of the simulated values with national level yield statistics, including temporal variation. • A subsequent phase of evaluation and re-calibration was performed using observed data from 10 farms on a North-South transect of Scotland. • A detailed sensitivity analysis programme was undertaken to test the model against combinations of carbon, temperature, water and nitrogen. See the Technical Documentation for more details.
Analytical Step: Running the Barley Model	
Yield values were simulated or each year from 1994-2015 using five sowing dates (15/Mar, 1/ Apr, 15/Apr, 30/Apr, 15/May). The model was run for all 5 km cells in which cereals had been grown in 2014 plus a buffer that included all adjacent 5 km cells.	The cereal fields for 2014 are mapped in this report (Fig. 1). The buffered region expands the mapped yield area to where barley could potentially be grown but does not reflect current land use, competing crops or practical constraints (e.g. slope angle).
Analytical Step: Testing the Barley Model	
The aim for validation was for the model to be able to achieve satisfactory total biomass, grain yield, crop phenology (flowering and maturity dates), soil water and nitrogen balance results at multiple scales (site specific based on experiments and in-field surveys, regional and national based on Scottish Government statistics).	In aiming to achieve these targets there are a range of caveats, limitations and assumptions that need to be recognised. These centre around issues of data availability and quality for calibration and validation, model skill in representing complex growth responses, and requirements to achieve useable estimates over a large range of soil-weather (and management) combinations. See the Spatial Barley Modelling - Technical Documentation for a full discussion of Caveats and Limitations.
Analytical Step: Mapping the Barley Model outputs	
Barley yield has been estimated for 56,256 unique climate soil combinations, 5 sowing dates, a baseline period and using 12 future climate projections. Maps have been produced for a range of these, including individual climate projections (ensemble members) and aggregation / means of these, plus representations of the climatic input (temperature, precipitation, water deficit etc.)	There are challenges in presenting and communicating interpretations of the multiple maps for different estimates made by the crop model and analysis of inputs (climate and soils) and outputs. Efforts have been made (e.g. production of the agreement maps) to represent uncertainties, which arise from the crop modelling process and in the climate projections. The research presents a diverse range of outputs with the aim of helping to tell a more comprehensive story of the potential impacts of climate change on barley production.

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APPENDIX A – ADDITIONAL MAPPED DATA

The UKCP18 climate projection data has been used to estimated field capacity days, defined as the number of days per year when soil water is at or above field capacity (the maximum water amount in mm a soil can hold against gravity. Figure 27 shows the mean for two baseline periods, Figure 28 shows the mean for two projections (ensemble member 04 and 05) for the period 2020 – 2050. Both projections indicate a decrease in the number of field capacity days, particularly in the south-east, suggesting an increased drying of soils. This is despite ensemble member 04 having higher growing season precipitation than the baseline period (1994 – 2017) (Figure 4).

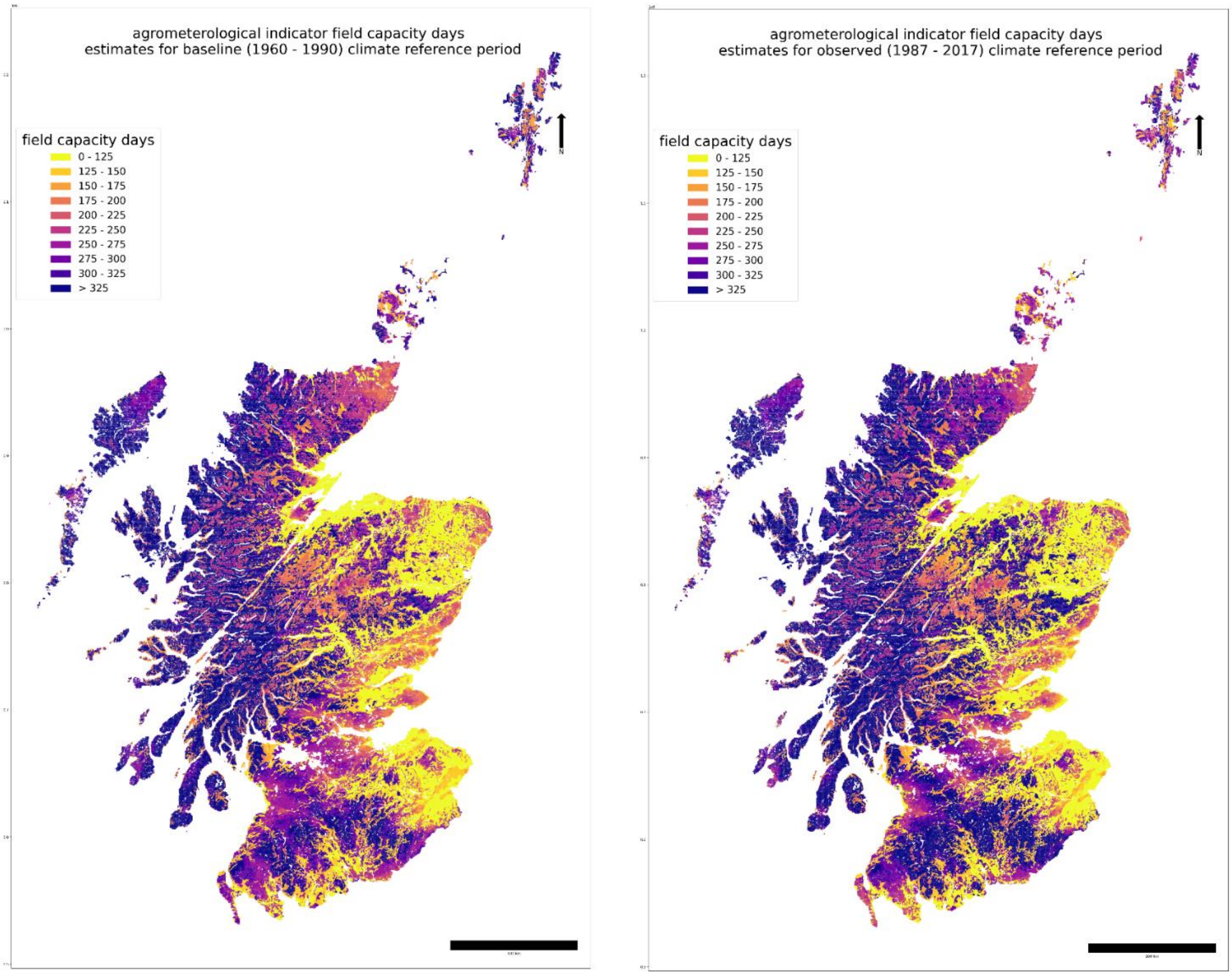

Figure 27. The number of days when a soil is at or above Field Capacity for two baseline periods, 1960 – 1990 (left) and 1987 – 2017 (right).

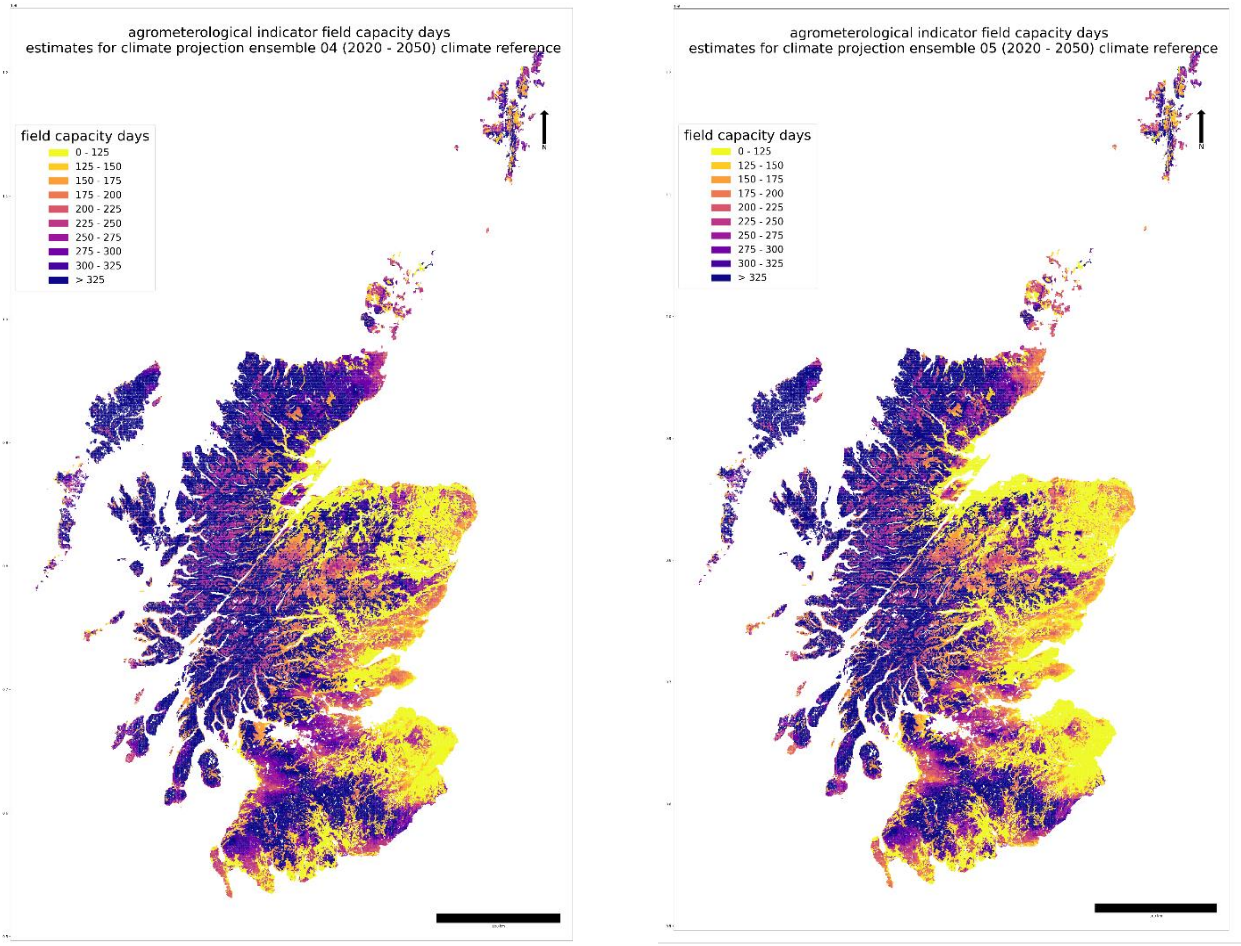

Figure 28. Estimated number of days in the future when soils are at or above Field Capacity for two ensemble members: 04 (left) and 05 (right).

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 29 (two historical baseline periods) and 30 (projections for three ensemble members).

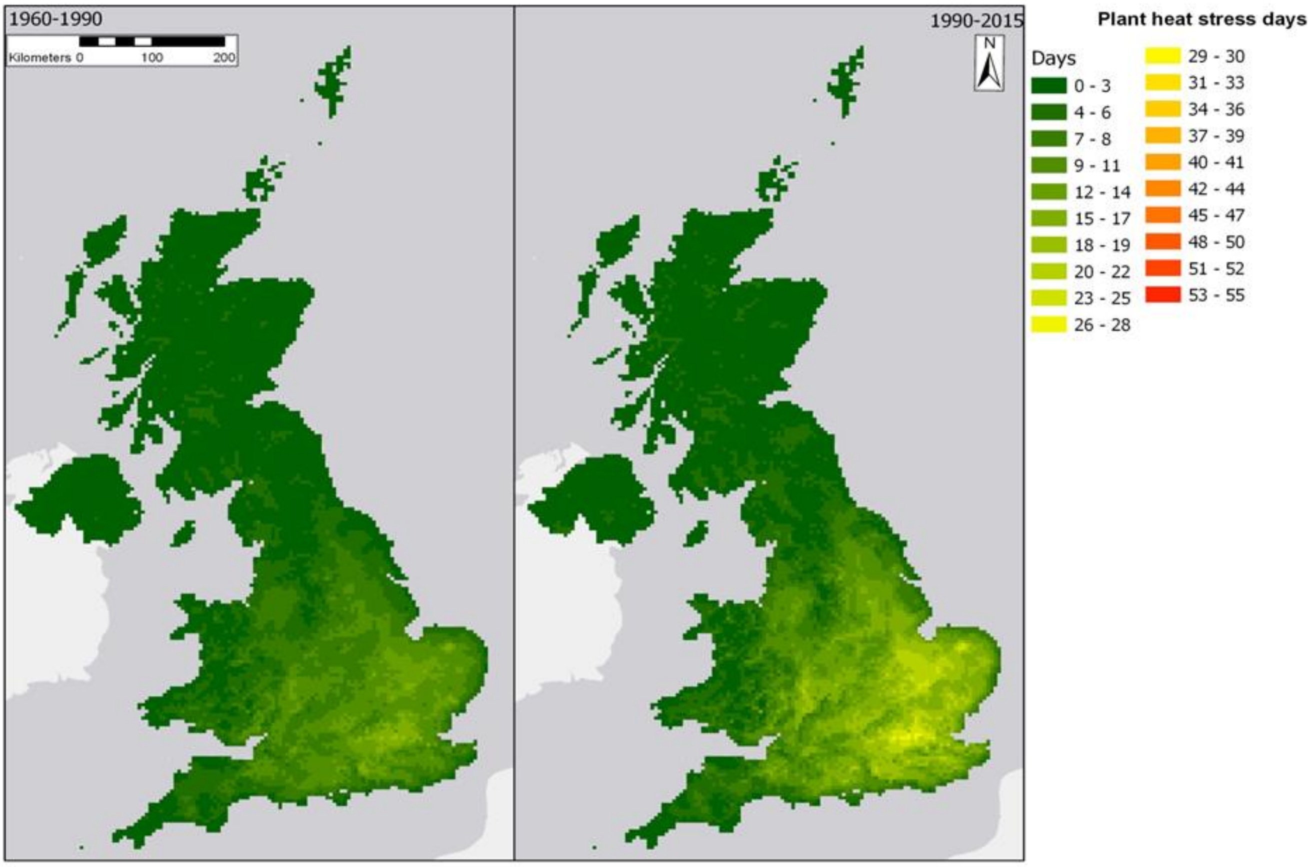

Figure 29. Observed changes in the mean Plant Heat Stress Indicator (number of days in a year when the maximum temperature is greater than 25°C) between 1960 – 1990 and 1990 – 2015

These indicators, in conjunction with the crop model estimates, provide a detailed indication of where and how climate change will have an impact.

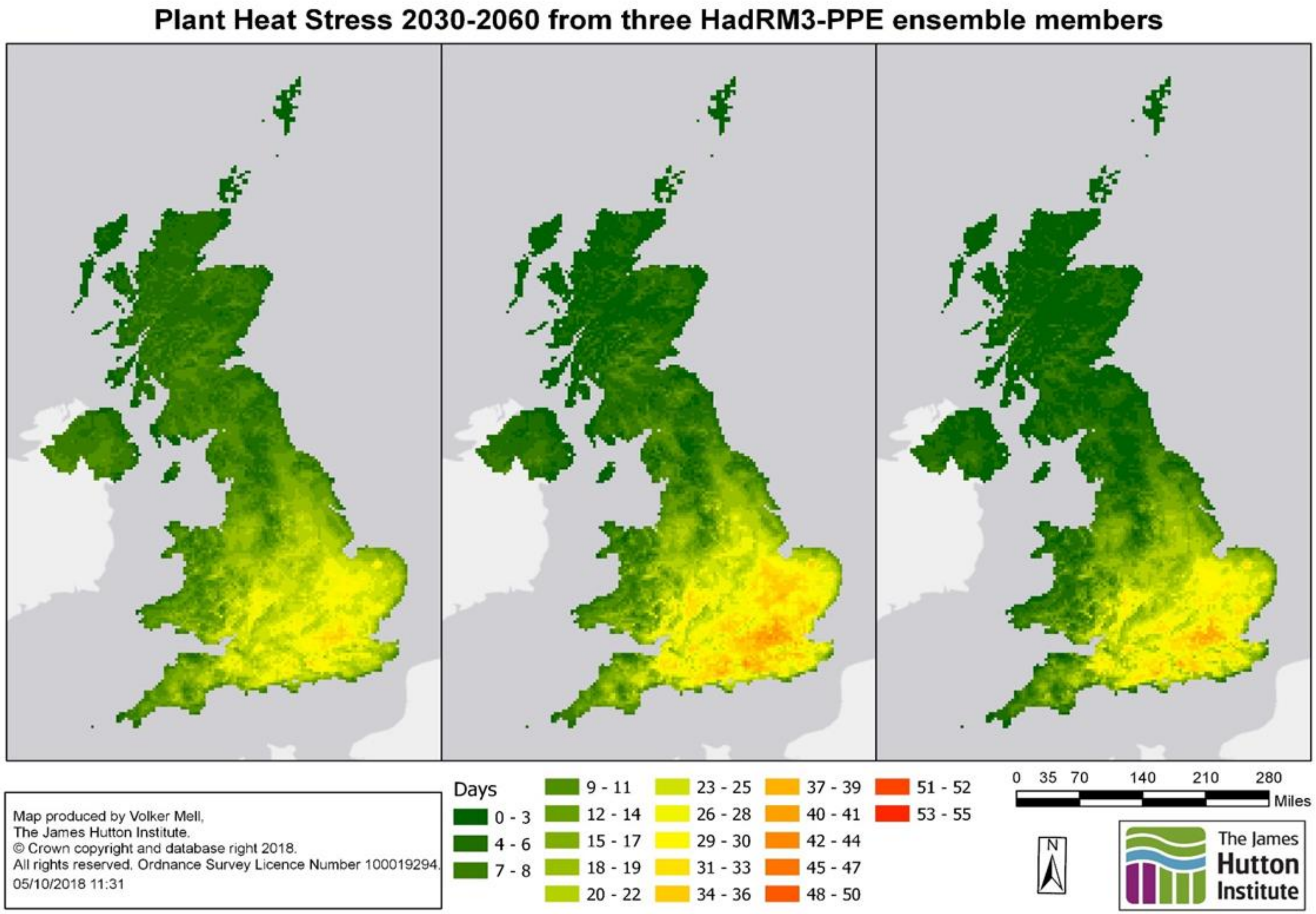

Figure 30. Projected changes in the mean Plant Heat Stress Indicator (number of days in a year when the maximum temperature is greater than 25°C) for the 2030 - 2060 period for three ensemble members

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