Science of the Total Environment 987 (2025) 179790

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Changes in land capability for agriculture under climate change in Wales

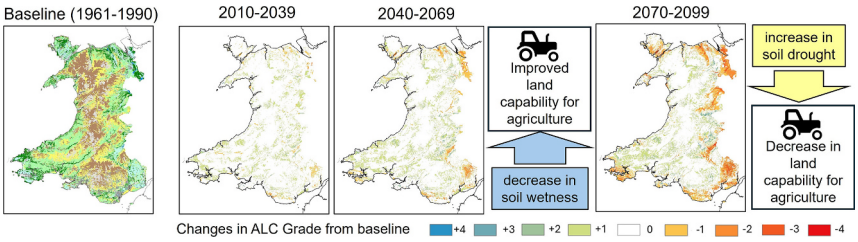
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HIGHLIGHTS

- We assessed the changes in agricultural land classification of Wales under climate change.
- Fewer limitations of soil wetness lead to improved land quality in 2020 and 2050.
- Reduction in land capability by 2080 was caused by increased drought limitations.
- Planning policy should consider future climate impacts on land capability.
- ALC can assess trade-offs between using land for food production and other demands.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Sergey Shabala

Keywords:
Land suitability
Agriculture
Climate change
Soil
Land use

ABSTRACT

Land capability assessments are key models that can identify current and future capacity of land for agricultural production. However, assessments of land capability under climate change do not fully consider climate-soil-crop interactions, are produced at scales too coarse for decision making and exclude key end users. We tackle these gaps by co-developing a predictive fine-scale spatial assessment of Agricultural Land Classification in Wales for baseline climate (1961–1990) and future climate scenarios. The findings revealed an increase in the proportion of land with better agricultural potential in 2020 (2010–2039) and 2050 (2040–2069) compared to the baseline, becoming more favourable for agriculture due to decreased soil wetness. However, by 2080 (2070–2099), there was a reduction in the proportion of higher grade and best and most versatile land for agriculture. During this period, an increase in accumulated temperature and decrease in rainfall during the growing season resulted in higher soil moisture deficits and increased risk of summer drought. We identified soil droughtiness as the most limiting factor for agricultural capability in 2080, resulting in a decrease in the best and most versatile land for agriculture (by 2 to 11% compared to the baseline). The transparency of the approach and prediction of land capabilities at local scale enabled effective policy implementation and decision making. The predicted future changes in land capability highlight that policy instruments used currently to protect high grade agricultural land should also consider the potential impacts of climate change.

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https://doi.org/10.1016/j.scitotenv.2025.179790
Received 13 August 2024; Received in revised form 23 May 2025; Accepted 27 May 2025
Available online 3 June 2025
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1. Introduction

Greenhouse gas emissions, if sustained at current or higher levels, are expected to intensify global warming and trigger substantial changes in the Earth's climate system during the 21st century, with impacts likely exceeding those recorded in the 20th century (Meehl et al., 2007). Climate model projections suggest that these changes could result in an average global temperature increase ranging from 1 °C to 7 °C and a rise in annual global precipitation by 0% to 11%, for different climate change scenarios (Tebaldi et al., 2021). Regionally, the UKCP18 climate projections from the UK Met Office indicate that the UK is likely to experience wetter, warmer winters and hotter, drier summers in the coming decades (Pope et al., 2022).

Climate change is projected to affect global crop productivity driven by elevated CO_2 concentrations, temperature increases, and changing patterns and extremes in precipitation and drought (Lesk et al., 2016; Vogel et al., 2019). Projections of global crop productivity by the end of the century indicate different crop responses such as reduced maize yield and increased productivity for wheat (Jägermeyr et al., 2021). These global figures however mask the regional variation of yield responses to climate change. Greatest yield reduction is projected for low latitude regions under the highest warming scenario but some high latitude areas will experience increased climatic viability for crops (Rosenzweig et al., 2014). In Africa reductions are predicted in yields of major crops (e.g. sorghum, maize) (Knox et al., 2012); In Europe, northern areas will show increased agricultural productivity and expansion in the range of crop types (Olesen and Bindi, 2002; Bindi and Olesen, 2011). Northward migration of agro-climatic zones has already been observed in Europe over the last 40 years under historical warming (Ceglar et al., 2019), including a significant increase in seasonal and annual temperature in the UK and Wales (Jenkins et al., 2008). In southern Mediterranean regions, loss in crop yields is expected in response to increased heat and drought (European Environment Agency, 2019; Abd-Elmabod et al., 2020). Increased crop losses and reduced livestock productivity are expected across most areas in Europe as a result of more frequent extreme weather and climate events (European Environment Agency, 2019).

Agriculture is the principal land use in the UK. In Wales it comprises 88% of land, of which 75% is dominated by grassland pasture (Armstrong, 2016). The current land use reflects the wet and cool climate and upland terrain of the country, showing potential sensitivity to climate change impacts on future land use potential. In the UK, arable land is projected to migrate to the north and west, demonstrating improved crop productivity in higher latitudes (Ritchie et al., 2019).

Whilst many studies show how crop productivity can shift under climate change (Brown and Castellazzi, 2015), they often do not account for the specific soil or site conditions that can limit agricultural production (Keay et al., 2014). Land suitability concepts consider biophysical conditions together with climate constraints for agriculture and can thus assess the potential of land for agricultural productivity (FAO, 1976; Eliasson, 2007). Agricultural land systems research has been concentrated in Asia and Africa (Viana et al., 2022). This emphasis may stem from the higher population and food demand, prevalent poverty, and consequently heightened vulnerability to the impacts of climate change in these regions (Richardson et al., 2018). Some of the studies considered additional factors in the land quality system, such as air and water quality (e.g. Liu et al., 2020), and socio-economic factors (Akpoti et al., 2019).

There is limited investigation of land capability schemes under future climate scenarios (Brown et al., 2008; Bonfante and Bouma, 2015; Ritchie et al., 2019). These assessments are often at scales that are too coarse (regional to km scale) for meaningful local decision making or are restricted to small case study areas or specific crops (Cengiz and Akbulak, 2009; Emadi et al., 2010; Akbari et al., 2019; Tashayo et al., 2020; Hassan et al., 2020). Land capability indices are often based on weighted factors or land suitability maps can be generated using machine learning and artificial neural networks (Møller et al., 2021; Taghizadeh-Mehrjardi et al., 2020). But the limiting factors for suitability cannot be determined using these methods, and interventions are difficult to propose that can potentially overcome or reduce the limitation.

Land evaluation schemes should be accessible and usable by stakeholders (government, landowners, non-governmental organisations) for effective decision making. Predictions of land capability, land use or crop suitability under climate change are often developed without input from the primary beneficiaries of the outputs (stakeholders) and driven and limited by data and modelling capabilities. These limitations restrict the application of many land capability assessments for land use decision making by policy makers and land managers.

To address these shortfalls our approach co-develops a predictive system of agricultural land classification with policymakers. It is aimed primarily for use by policy stakeholders to provide a national scale assessment of the quality of agricultural land appropriate for national policy. It accounts for specific soil and climate limitations for agriculture under climate change scenarios that forecasts future land capability and inform land use, planning and agricultural policy. The outputs can also be useful for farmers to indicate where changes in land capability over their farm can affect the suitability and yield consistency of crops. It can guide decision making for current and future crop selection that considers the potential impacts of climate change.

The objectives of this study were to determine how future potential land capability for agriculture is affected by a changing climate using Agricultural Land Classification (ALC). We do this by calculating ALC grades in Wales under different probabilistic emission scenarios in 2020, 2050 and 2080 using UK climate predictions (UKCP18). We use local scale soil data and interpolated climate datasets to generate outputs at 50 m to enable effective decision making for future land use planning and policy scenarios. We co-produced the project outputs with government stakeholders who already use land capability assessment to inform national policy frameworks and for local planning decisions.

2. Data and methods

2.1. Data for the ALC baseline and climate scenario predictions

Fig. 1 provides an overview of the interactions between the data and

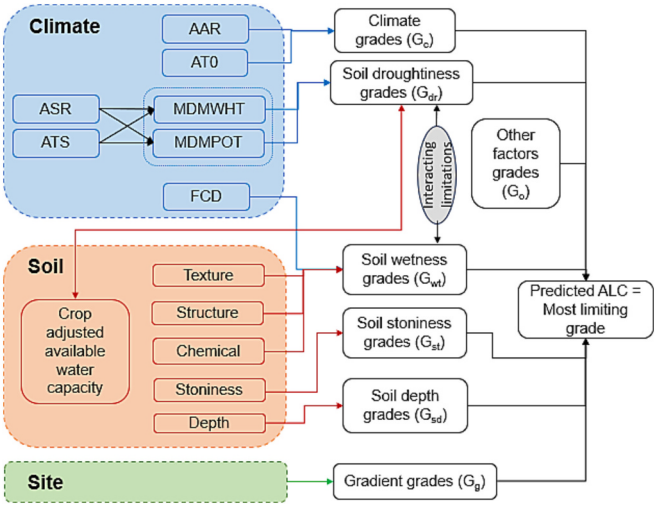


Fig. 1. Calculation of ALC limiting criteria from climate, soil, and site data. AAR: Average annual rainfall; ASR: Average summer rainfall (April to September); AT0: Accumulated temperature (January to June); ATS: Accumulated temperature (April to September); FCD: Field capacity days; MDMWHT/MDMPOT: Moisture deficit for wheat/potato. Please see supplementary information S1 for more information on these parameters.

calculated parameters necessary for determining the standard ALC criteria following (MAFF, 1988). Further details are described in the following sections.

2.1.1. Soil and topography data

Soil data for each 50 m grid was determined by identifying the dominant soil series for each grid cell using the National Soil Map of England and Wales (NATMAP) (Mackney et al., 1983) vector data or from detailed mapping soil products where available (approximately 50% of the area). Soil series property data required for ALC assessment was obtained from the LandIS database (Cranfield University, 2024; Keay, 2020).

Topography data was derived from Ordnance Survey (OS) at 50 m resolution (Ordnance Survey, 2013).

2.1.2. Climate data

The baseline climate data is standardised in the ALC approach and covers a thirty-year monthly timeseries between 1961 and 1990 and is provided on a 5 × 5 km grid for the whole of England and Wales. It was obtained from the Meteorological Office titled as 'Climatological data for Agricultural Land Classification' (The Met Office, 1989).

The future climate data used the HadUK 25 km gridded climate monthly time series projections (Met Office Hadley Centre, 2018). We used temperature and precipitation from the UKCP18 scenarios (Fung and Gawith, 2018) for the time periods 2010–2039 (represented as 2020), 2040–2069 (represented as 2050), and 2070–2099 (represented as 2080) for RCP 4.5, RCP 6.0, and RCP 8.5 emission scenarios (representative of low, medium and high emissions, respectively). The 25 × 25 km UKCP18 data was resampled to 5 × 5 km for comparison with the 1961–1990 baseline data. An average of the climate value for each 25 × 25 km grid cell was calculated. The original 5 × 5 km values were then divided by the baseline 25 × 25 km average to determine the proportion of the baseline climate value that makes up the average. These proportions were then used on the UKCP18 climate variable values to provide an estimate of the climate projections data at a 5 × 5 km grid cell resolution. This is the same method used in scaling the UKCP09 data where a number of approaches and methods were used to evaluate the robustness of the scaling method (Keay et al., 2013). All climate data for ALC was then interpolated to a 50 × 50m grid using interpolation methods (The Met office, 1989) in combination with easting, northing and altitude from the Ordnance Survey OS terrain 50 m product. The definitions and importance of different climatic parameters used for the ALC study are detailed in Table 1. Supplementary information S1 details the methods used to generate all the variables from temperature and precipitation of the future climate data based on formulae provided by Wilson and Hockridge (2019).

Table 1
Definition and importance of different climatic parameters used for ALC study.

Climate parameter	Definition	Importance	Assessment in ALC
Accumulated Temperature above 0 °C January to June (AT0)	Daily effective temperature (measured as degree-days above 0 °C), multiplied by the number of days in the month, and accumulated from January to June	Temperature limiting factor on crop development and growth. Work has shown leaf extension occurs at temperatures of 0 °C	Climate
Accumulated Temperature above 0 °C, April to September (ATS)	Daily effective temperature (measured as degree-days above 0 °C), multiplied by the number of days in the month, and accumulated from April to September	Temperature limiting factor on crop development and growth. Used in calculation of soil moisture deficit.	Soil droughtiness
Average Annual Rainfall (AAR)	Mean total annual rainfall	Determination of wetness	Climate
Duration of Field Capacity Days (FCD)	The number of days (median or mean) between a return to and end of winter field capacity conditions (when soil moisture deficit is zero).	Soil wetness affects plant growth and germination, and can impose restrictions on cultivations and grazing by livestock	Soil wetness
Average Summer Rainfall (April to September) (ASR)	Mean rainfall total between April and September	Desiccated soils restrict crop growth during the growing season, causing moisture stress	Soil droughtiness
Moisture Deficit for winter wheat and potatoes (MDMWHT/ MDMPOT)	Represents the balance between rainfall and potential evapotranspiration related to two reference crop requirements (winter wheat and potatoes)	Droughtiness limits crop growth, especially in areas with relatively low rainfall or high evapotranspiration or where the soil holds a small amount of water.	Soil droughtiness. used in the calculation of moisture balance with crop adjusted available water capacity (AP)

2.2. Agricultural land classification predictive model

Agricultural Land Classification (MAFF, 1988) was developed as a field-based assessment of land capability that combined local long-term climate data and field observations of soil and site factors. Our predictive model replaces the field method with national spatial datasets to enable the prediction of ALC grades under a baseline climate and under future climate projection scenarios. ALC system grades land according to the principal biophysical limiting criteria of climate (temperature and rainfall), site (gradient, microrelief and flood risk), soil (depth, stoniness, texture, structure and chemical) and interacting limitations (soil wetness, soil droughtiness and soil erosion). These combined characteristics influence long term limitations on agricultural use, affecting the range of crops that can be grown, the level of yield, the consistency of yield and the cost of obtaining it. The system assumes a good but not outstanding level of agricultural management. Each limitation is individually graded and the overall ALC grade is defined by the most limiting criteria. The grades range from 1 to 5 with grade 3 split into 3a and 3b. Grade 1 has no or minor limitations on agricultural use, supports a very wide range of agricultural and horticultural crops that have high and consistent yields. Grade 5 has very severe limitations which restrict use to permanent pasture or rough grazing except for pioneering forage crops. In our predictive assessment, we did not use other limiting criteria such as microrelief, flood risk, soil chemical properties, and soil erosion because of unavailability of suitable data. In addition to the above, frost risk, exposure, and soil 'pattern' (where soil and site conditions vary significantly and repeatedly over short distances) limitations are considered in the field but were not part of our predictive assessment. The grades were calculated for the following criteria 1) gradient 2) soil depth 3) soil stoniness 4) climate 5) soil wetness 6) soil droughtiness and 7) other grades (limited by other factors such as sandy or loamy sand soils and some soils restricted by micro-relief issues) (Fig. 1).

2.3. Calculation of site, soil, and climate limitations for ALC criteria

The overall climate limitation is calculated from a relationship between average annual rainfall (AAR, mm) and accumulated temperature from January to June (AT0, Day °C) in the original ALC guidelines (MAFF, 1988). This was converted into a look up table and the grade determined from the combination of AT0 and AAR. More details on AT0 and AAR are included in the supplementary information S2. In addition to AAR and AT0, we derived Average Summer Rainfall (ASR, April to

September), accumulated temperature from April to September (ATS), moisture deficit for two main crops winter wheat and potato (MDMWHT and MDMPOT), and duration of field capacity days (FCD) from the climate (temperature and precipitation) data. The definitions of the climate parameters are described in Table 1.

Gradient plays a crucial role in mechanized farming, as machinery operates most efficiently on level ground. Gradient values were derived from OS raster topography data, with ALC Grade 1 assigned to slopes <7° and Grade 5 to slopes >18° (supplementary information S3). Soil stoniness can hinder cultivation, harvesting, crop growth, and reduce water availability, while soil depth directly affects available water capacity. Stoniness and depth data were obtained from soil series records, indicating stone content (% volume) in the topsoil and depth (cm). ALC grading reflects these limitations: Grade 1 corresponds to depths over 60 cm, while Grade 5 applies to depths under 15 cm (supplementary information S4). For stone content, grading depends on stone size (>2 cm or >6 cm) and percentage volume in the top 25 cm, with Grade 1 allowing <5% stones of either size (supplementary information S5). The full ALC grading criteria for these limitations are outlined in the ALC guidelines (MAFF, 1988).

Soil droughtiness provides an indication of drought risk to crops using interactions of soil and climatic factors for two reference crops (winter wheat and potatoes). It is based on Thomasson (1979) to estimate the moisture balance of the reference crops. It requires calculation of available water for potatoes (difference of water content at field capacity and the water content at wilting point for each horizon to a depth of 70 cm) and wheat (summation of total available water to 50 cm and easily available water (water content between 5 kPa and 200 kPa) to 120 cm). The water contents are calculated using pedotransfer functions (Hollis et al., 2015) from the soil series property data. Moisture deficit (MD) is calculated by the balance of evapotranspiration and rainfall over a portion of the growing season depending on when the crop attains full ground cover till when it is harvested (from April to mid-July for winter wheat and mid-May to August for potatoes), based on potential soil moisture deficits (supplementary information S6). In the ALC system (MAFF, 1988), moisture deficits are estimated from regressions with accumulated summer temperatures (ATS) and average summer rainfall (ASR) (supplementary information S1). ATS and ASR are calculated from daily and monthly temperature and rainfall data between April and September (supplementary information S1). The resulting soil droughtiness grade is calculated from the moisture balance (AP-MD) for wheat (WHT) and potatoes (POT).

Soil wetness can adversely affect plant growth or restrict the use of agricultural machinery or grazing opportunities. In the ALC system soil wetness is considered by factors of climate (FCD), soil water regime (wetness class) and topsoil texture (Fig. 1). Field capacity days are calculated by a regression between AAR, ASR, altitude (in metres above sea level) and location (British National Grid eastings and northings in metres) (supplementary information S1). Wetness class, the average duration of waterlogging at specified depths in the soil profile and soil texture were derived from the soil series property data. The wetness limitation grade is derived from a combination of the wetness class, topsoil texture and field capacity days detailed in the ALC criteria (MAFF, 1988), while considering for the adjustments for calcareous soils and organo-mineral/peaty soils (soil chemical data).

3. Results

3.1. Changes in ALC climate criteria

Changes in climate limiting criteria indicate increased accumulated temperature over the growing season (AT0; April to September) from the baseline to 2080, and increased soil moisture deficits and drought. By 2050 some areas showed accumulated temperatures that are not currently experienced in the baseline (>2000° days, Fig. 2, supplementary information S7). The total rainfall amount (AAR) showed little change (649–4980 mm in 1961–90 to 560–5210 mm in 2080), but decreased summer rainfall indicated the seasonal distribution of rainfall shifts to wetter winters and drier summers from the baseline (310–1895 mm) to 2080 (225–1771 mm) (Fig. 2, supplementary information S8, S9). Higher summer temperatures combined with lower summer rainfall increased moisture deficits for the two reference crops during the growing season (Fig. 3, supplementary information S10, S11). In the baseline there are very few areas where drought is limiting (total 187 km^2) (majority of Wales is Grade 1 for drought criteria). By 2080 however areas along the coast and areas in west Wales become limited by drought (total 6225 km^2) (Fig. 3, supplementary information S12).

3.2. Changes in agricultural land classification grade

The agricultural land classification for baseline climate and projected RCP 6.0 (medium) emission scenario for 2020, 2050 and 2080 are shown in Fig. 4 (please see supplementary information S13 for other scenarios). Under projected climate change the overall proportion of land in Wales under higher land quality grades (ALC grade 1, 2 and 3a termed Best and Most versatile land (BMV; Welsh Government, 2024)) increased in 2020 and 2050 compared with the baseline (Fig. 5). This trend reversed in 2080 where there were fewer areas with high grades and a greater proportion of poorer grades (Fig. 5, RCP 6.0 emission scenario). The total area of BMV land, which is protected under current planning policy, increased from 20% to 21–23% for different emission scenarios in 2020 and 2050 compared with the baseline (Fig. 5). By 2080, the total area of BMV land reduced to 18%, 16% and 9% for low, medium and high emission scenarios, respectively, (Fig. 5).

In 2020 and 2050 the total area of poor grade land (Grade 4) decreased from 24% to 17–19% under all emission scenarios (Fig. 5). In 2080, under the RCP 2.6 and RCP 8.5 scenarios, the total area of Grade 4 land increases to >34% (compared to 24% of total area for the baseline). The proportion of very poor (Grade 5) land showed little change (24%–27%) between the baseline and 2020, 2050 and 2080 for all emission scenarios.

Areas showing improved ALC grade in 2020 and 2050 are distributed across Wales and expand into upland peripheral regions by 2080 (Fig. 6). However, in 2050 and 2080 other areas show a significant reduction in ALC grades, with a decline by 4 grades (e.g. from excellent to poor) by 2080 in some areas. The areas with the greatest decline in ALC grade are concentrated in the border regions [B] (border between England and Wales), West Wales (Pembrokeshire) [P] and areas of North Wales (Anglesey [A] and Vale of Clwyd [C]) (Fig. 6).

Any changes in the ALC grade are determined by the most limiting criterion. This can change at each time period and emission scenario, depending on the grade. In the baseline the most limiting criteria are climate (35%) and soil wetness (50%). By 2080 droughtiness is a more limiting factor for ALC grade in a large portion of Wales going from 1% upto 30% of the country (Fig. 7).

4. Discussion

4.1. Climate driven impacts to future agricultural land potential

The agricultural land classification system reflects potential long term biophysical constraints to agriculture assuming good current crop and soil management practices and infrastructure. The predicted uplift in ALC grade in some areas in Wales in 2020 and 2050 was due to these regions becoming more climatically favourable, impacting on a reduction in wetness and workability limitations. This may lead to an expansion of land used for arable or horticultural crops and potential for new crops or new varieties of existing crops. In 2080, we observed land in western Wales continues to be more favourable whilst ALC grade in some eastern areas becomes limited by drought, unless water stress can be managed by irrigation, implying a switch to arable and horticultural cropping may not be sustainable by 2080. Improvement in agricultural

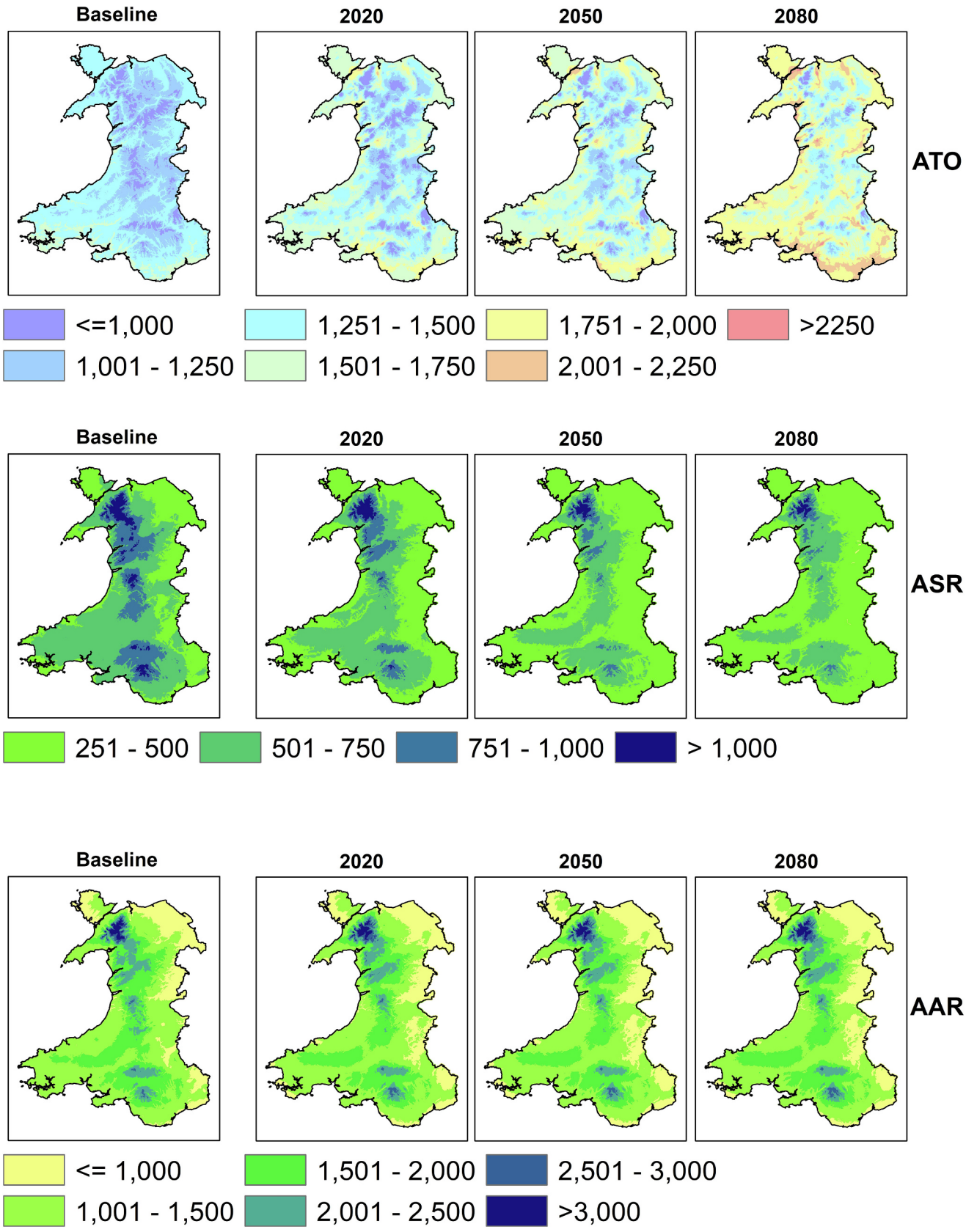


Fig. 2. Accumulated temperature above 0 °C January to June (AT0) (upper), average summer rainfall (ASR) (mm) (middle), and average annual rainfall (AAR) (lower) for baseline climate (1961–1990), 2020, 2050 and 2080 for RCP 4.5 emission scenario. Source image: Keay and Hannam, 2020.

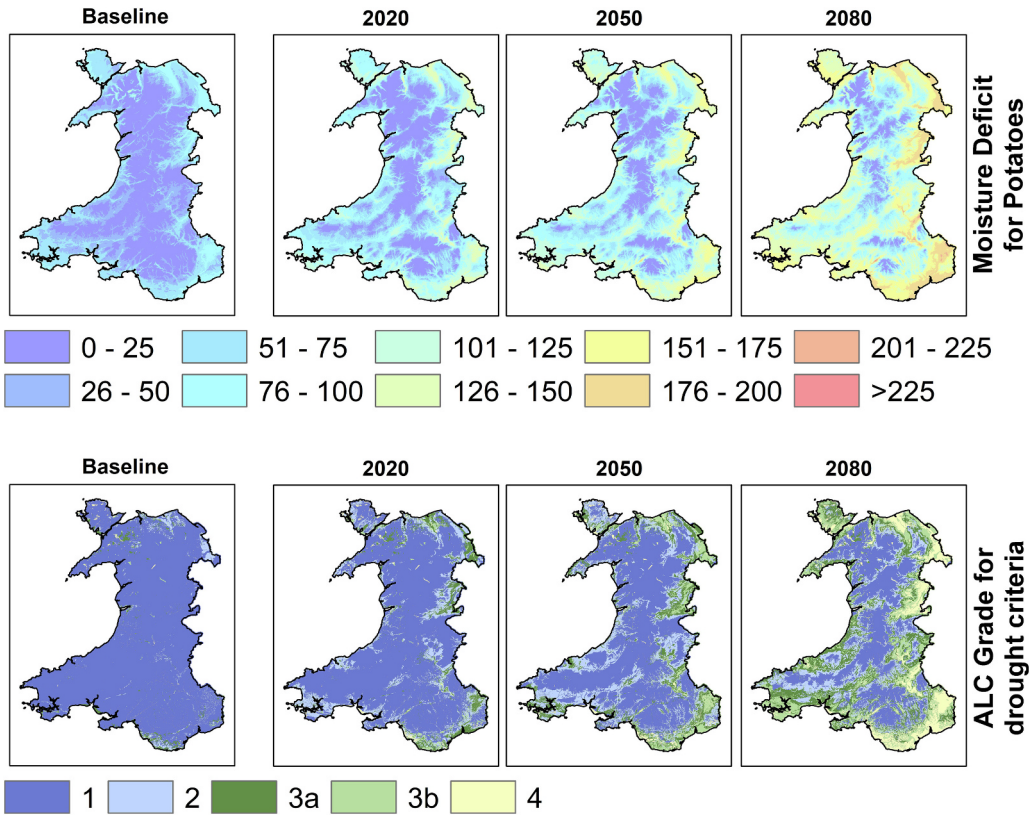


Fig. 3. Moisture deficit (mm) for potatoes (above) and ALC grade for drought criteria (below) for baseline climate (1961–1990), 2020, 2050 and 2080 for RCP 4.5 emission scenario.
Source image: Keay and Hannam, 2020

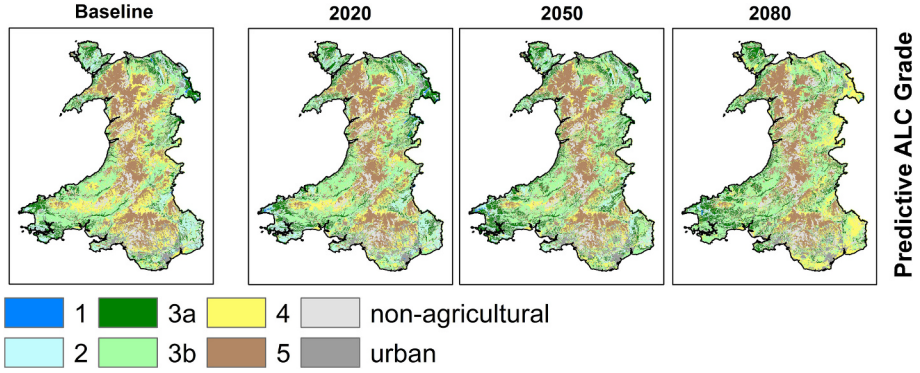


Fig. 4. Agricultural Land Classification grades for baseline (1961–1990), and projected (2020, 2050 and 2080) under RCP 6.0 emission scenario. ALC: grade 1 (excellent) to 5 (very poor).
Source image: Keay and Hannam, 2020.

potential has predicted arable land migrating to the north and west of the UK under climate change (Ritchie et al., 2019; Olesen and Bindi, 2002). But some parts of the UK show vulnerability of agricultural areas to drought and a decreasing risk from wetness under future climate scenarios (Brown et al., 2011; Brown, 2017; Daccache et al., 2011; Knox et al., 2010). Other global regions have predicted changes in suitability for specific crops under climate change, such as a reduction in land capability for rice cultivation in West Africa (Akpoti et al., 2022); variable effects on cocoa suitability in Ghana and Cote d'Ivoire where current areas become both less suitable and more suitable by 2050 (Läderach et al., 2013) and global soyabean potential was predicted to become unsuitable in large areas of low latitudes under future climate scenarios (Feng et al., 2021).

4.2. *Implications for grassland productivity in upland areas*

The drought criteria in ALC only considers two reference crops (winter wheat and potatoes) and not grassland, which is currently the largest land use area in Wales. Whilst higher temperatures and increased CO_2 concentrations are projected to increase grassland productivity, this may be offset by drought stress (Rounsevell et al., 1996; Hopkins and Del Prado, 2007). As areas become more suitable, migration of more intensively managed, improved grassland for agricultural production into upland areas is possible as climatic criteria become more favourable from 2020 to 2080. This could increase pressure on semi-natural habitats that currently occupy a transitional zone between permanent pasture, rough grazing and semi natural habitats. These areas have large

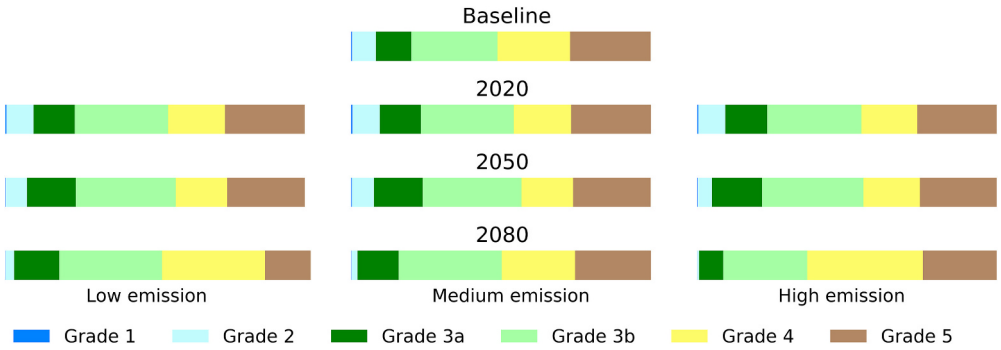


Fig. 5. Percentage of land area under different ALC grades for baseline, 2020, 2050 and 2080 for low emission (RCP 4.5), medium emission (RCP 6.0) and high emission (RCP 8.5) scenarios (UKCP18 data).

soil carbon stocks (Histosols or organo-mineral soils with a peaty topsoil) and the change in bioclimatic conditions (warmer temperatures) can alter environmental conditions affecting the accumulation of organic matter and formation of peat (Clark et al., 2010). However, soil or terrain conditions could ultimately limit the land capability for extensive grassland productivity in these semi-natural areas, indeed the ALC grade in core upland areas remains relatively unchanged throughout the future scenarios.

4.3. Influences of seasonal climate on agricultural suitability

Whilst most criteria are based on seasonal influences on productivity (e.g. temperature over the growing season; AT0), some ALC criteria are based on relationships with annual climate summaries that can mask other potential seasonal changes. Field capacity days, the number of days when soils are wet in the period between autumn and spring, is determined by a regression with average annual rainfall. As average annual rainfall does not change significantly over the scenarios, the number of field capacity days was also little affected by climate change in our predictions. However, it is likely that the field capacity period would reflect changes observed in the seasonal distribution of rainfall (drier summers and wetter winters) affecting the timing of the start and end of the field capacity period (Rivington et al., 2013). Soils showed greater moisture deficit at the end of the summer and would therefore take longer to return to field capacity in the autumn. This means greater opportunity for access to land in the autumn for grazing and increased opportunity of autumn sown crops. However, soils may take longer to dry out in the spring, due to increased winter rainfall, with reduced access to land for spring cropping, cultivations or grazing. These seasonal changes are important considerations in local decision making by farmers for cropping and grazing opportunities, as well as adoption of new crop (or grass) types or varieties.

4.4. Policy and land manager considerations for agricultural land

Agricultural land classification is considered in the UK planning process when planning proposals for the development of agricultural land are submitted to local authorities. Under national planning policy (Welsh Government, 2024) developers must consider the agricultural land quality of the site. This offers protection for high quality agricultural land: the 'Best and Most Versatile' agricultural land (BMV), which is considered the most productive and flexible to deliver future crops for food and biomass. The increased proportion of BMV land in 2020 and 2050 indicated that land currently not graded as BMV may improve sufficiently in the future to be protected under planning policy. These areas should be considered under planning policy now, so their future agricultural potential is protected. In 2080, some BMV areas are lost, primarily due to drought limitations, although this could be mitigated by irrigation, depending on the severity of the drought. These interventions should be aligned with policies to support the uptake of sustainable water use, efficient irrigation systems and minimise any unintended consequences on soil functions by the change in land use from grassland to arable systems.

The spatial change in ALC indicates where to direct current and future policies that prioritise land for food production whilst considering additional demand for land for bioenergy, infrastructure and development. This conflict is particularly pertinent in Wales where expansion of existing urban areas or infrastructure in north and south Wales correspond to the areas of best agricultural land. The ALC system indicated in the future where areas would be most reliable for food security (i.e. where ALC grade improves compared to the baseline) and others where adaptation strategies are needed under future climate change (e.g. increased irrigation demand). These insights are also useful for decision making for land managers to inform future land use. For example if land would support a change from grassland to arable systems in the future, how vulnerable areas may be to limitations such as drought, and where best to implement non-agricultural land uses, such as woodland, to areas less suitable for agricultural production.

4.5. Limitations of the current approach

There are a number of assumptions and limitations of the ALC criteria. For example, it does not take into account soil and crop management interventions, or the current state or land use of the area. We did not observe significant differences in the percentage of poor-quality land across the different climate scenarios. One possible explanation is that the primary criterion affected by climate change is droughtiness, which does not have a grade 5 classification; grade 4 represents the most severe level of droughtiness (supplementary information S6).

Another weakness is the period chosen for the baseline climate (1961–1990), which may have been appropriate when the protocols were determined, but we are already seeing significant deviation over the last 5–10 years from this baseline period. Keay et al. (2014), based on a study on the implications of historical climate change (1914–2000) on agricultural land classification, highlighted that 1961–1990 period, designated as the international standard reference period for climate averages, was one of the coldest in the study period. According to IPCC (2013), globally, the period after 1983 was found to be the warmest over the last 1400 years. Therefore, a revision of the climate baseline dataset (e.g. using a baseline reference period of 1991–2020) criteria is needed to account for current climate and soil-climate-land suitability relationships in ALC.

The baseline data only uses annual summaries in many of the criteria (e.g. average annual rainfall) but the change and shift in the seasonality of climate variable may be more appropriate to consider (Reilly, 2002; Brown and Castellazzi, 2015), particularly as these have a significant impact on crop productivity. The stability of the ALC grade in each year across the 30-year climate baseline could be useful to indicate the

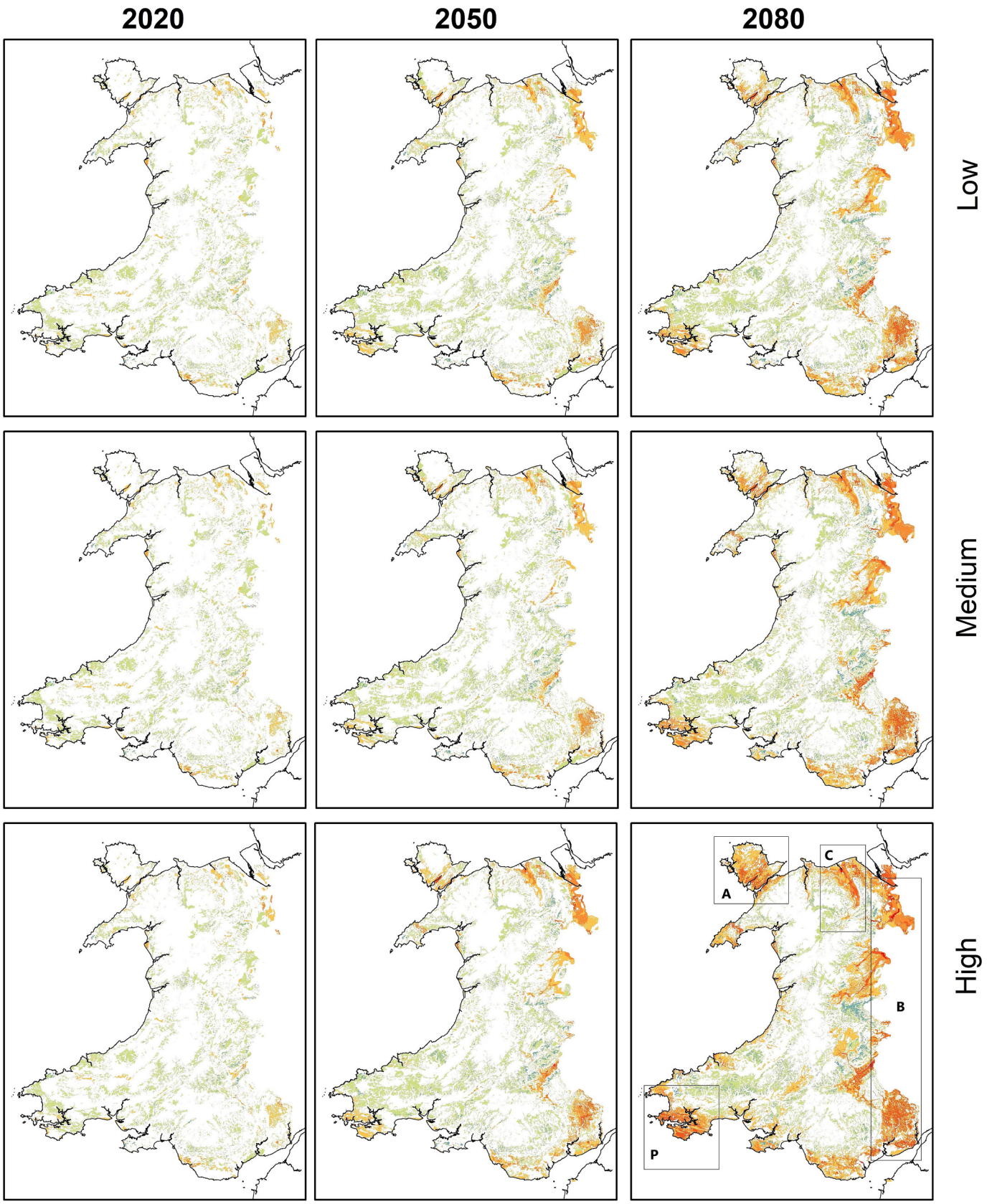


Fig. 6. Change in ALC grade between baseline and 2020, 2050 and 2080 for RCP 4.0 (upper), RCP 6.0 (middle) and RCP 8.5 (lower) emission scenarios. Greatest decline areas: [A] Anglesey, [B] Wales-English border, [C] Vale of Clwyd, [P] Pembrokeshire.
Source image: Keay and Hannam, 2020.

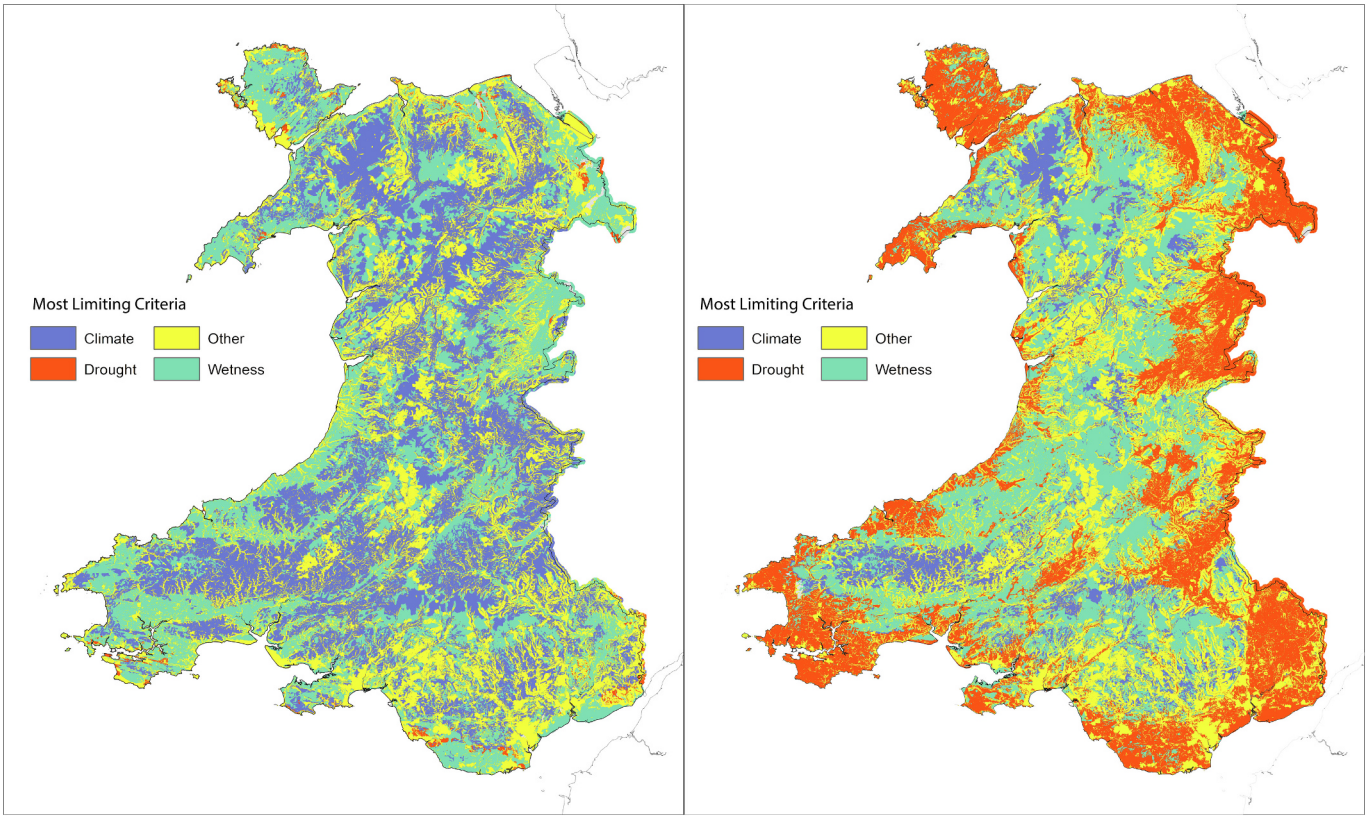


Fig. 7. Most limiting ALC criteria for baseline 1961–1990 (left) and 2080 high emission scenario (right).
Source image: Keay and Hannam, 2020.

probability of grades over time, providing a better representation of the likely grade. For example, Brown and Castellazzi (2015) explored the dynamic relationship between land capability classification and climate change in Scotland, highlighting the importance of both long-term averages and shorter-term spatiotemporal patterns.

Notably, the future predictions come with uncertainties (Steptoe and Murphy, 2024) and therefore the climate-related limitations should be considered within this context. For example, drought impact may change when new climate scenarios are available, or we get closer to the timelines of the predictions and the uncertainty can be reduced.

The ALC system does not consider grass crops, and grassland suitability models (Rounsevell et al., 1996) could be incorporated into the ALC classification to determine land capability for grassland. Further research is required to calculate and account for uncertainties (in climate and soil data) in the system.

5. Conclusions and recommendations

- The ALC system is a key tool to inform trade-offs between using land for food production against other demands such as development, tree planting, or habitat restoration.
- The predictive ALC system provides insight into long-term biophysical constraints on agriculture, with climate change influencing shifts in land suitability across Wales. Projected improvements in ALC grades by 2020 and 2050 suggest greater potential for arable and horticulture expansion in Wales.
- In some areas in the future, it may be difficult to sustain arable agriculture or horticulture without implementing irrigation. Where suitability increases under climate change, tipping points in the limitations should be considered before a major switch in land use.
- These future projections, especially in the longer-term periods (e.g. to 2080), have greater uncertainty, and the changes in ALC grade should be considered within this context. Predictions should be revised as uncertainty decreases as we get closer to the time periods or when new climate projections are developed.
- Where ALC is used in policies, such as national planning policies that consider development on good quality agricultural land, these future shifts in land quality should be considered to safeguard future agricultural potential.
- The future predictions of land suitability can also be used to inform land managers in decision making for changing land use from grassland to arable, determining the potential future limitations that may need interventions such as irrigation and highlight areas that will remain unsuitable for agricultural production to target for other uses such as woodland creation.
- While ALC remains a valuable tool for land-use planning, it has some limitations, and future refinements should incorporate climate datasets that reflect current baselines, consider the uncertainties in soil and climate data, improve drought assessments, and integrate grassland models to enhance decision-making.

CRediT authorship contribution statement

Jacqueline A. Hannam: Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Formal analysis, Conceptualization. **Caroline A. Keay:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Kriti Mukherjee:** Writing – review & editing, Visualization, Validation, Methodology, Formal analysis. **Ian Rugg:** Writing – review & editing, Conceptualization. **Arwel Williams:** Writing – review & editing, Conceptualization. **James Cooke:** Writing – review & editing, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, KM used 'chatgpt' in order to refine the language in some sections. After using this tool, all authors reviewed and edited the content as needed and take responsibility for the content of the publication.

Funding

This project was part of the Climate, Capability and Suitability Programme funded by the Welsh Government through the European Agricultural Fund for Rural Development (EAFRD) from the Welsh Government Rural Communities - Rural Development Programme 2014–2020.

Data statement

Data supporting this study is included within the article and in 'Appendix A: Supplementary data'.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to acknowledge ADAS and Environment Systems for stimulating discussions during the development of the scenario mapping. Data related to the project can be requested from Welsh Government (LQAS@gov.wales).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.179790.

Data availability

Soil data used in this project can be accessed from www.landis.org.uk.

Topography data is available from https://www.ordnancesurvey.co.uk/products/os-terrain-50, Baseline climate data is available from https://publications.naturalengland.org.uk/publication/6493605842649088 climate projection data is available from https://catalogue.ceda.ac.uk/uuid/9f8dfaf790644dbcb2c3f69f409a70d6.

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Hannam, Jacqueline A.; Keay, Caroline A.; Mukherjee, Kriti; Rugg, Ian; Williams, Arwel ...

2025-07-25
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https://doi.org/10.1016/j.scitotenv.2025.179790
Hannam JA, Keay CA, Mukherjee K, et al., (2025) Changes in land capability for agriculture under climate change in Wales. Science of The Total Environment, Volume 987, July 2025, Article number 179790

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