SP1104

# The Impact of climate change on the capability of land for agriculture as defined by the Agricultural Land Classification

**EVID4**

**Report Prepared for the Department for Environment, Food and Rural Affairs and the Welsh Government**

**September, 2014**

# The Impact of climate change on the capability of land for agriculture as defined by the Agricultural Land Classification

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Defra Contract No: SP1104

NSRI Contract No: WN32052E

RESPONSIBILITY FOR THIS DOCUMENT

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CHANGE HISTORY

| *Version* | *Date* | *Summary of change* |
|---|---|---|
| 1.0 | 27/08/2013 | |
| 2.0 | 13/11/2013 | |
| 3.0 | 17/02/2014 | |
| 4.0 | 07/05/2014 | |
| 5.0 | 24/09/2014 | |

*Reference to this report should be made as follows:*

KEAY, C.A.; JONES, R.J.A.; PROCTER, C.; CHAPMAN, V.; BARRIE, I.; NIAS, I.; SMITH, S.; ASTBURY, S. (2013).

SP1104 the Impact of climate change on the capability of land for agriculture as defined by the Agricultural Land Classification, DEFRA 138pp.

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# GLOSSARY

| | |
|---|---|
| AAR | Average Annual Rainfall |
| AAT | Average Daily Temperature over the year |
| ADP | Average Daily Precipitation |
| ALC | Agricultural Land Classification |
| AP | Available Water in the Soil Profile The total amount of soil water available to plants is the volumetric soil water content between 5 and 1500 kPa suction or, in the case of sands and loamy sands, 10 and 1500 kPa suction |
| AMSR | Average Monthly Summer Rainfall from April to September |
| AMST | Average Monthly Summer Temperature from April to September |
| ASR | Average Summer Rainfall (April to September) |
| AT | Accumulated Temperature |
| AT0 | Accumulated Temperature above 0°C - median value (January to June) |
| ATS | Accumulated Temperature above 0°C - median value (April to September) |
| AWC | Available Water Capacity to 1m (see AP) |
| AWR | Average Winter Rainfall (October to March) |
| BMV | Best and Most Versatile land – designated as ALC grades 1, 2 and 3a. |
| EFC | Date of the End of Field Capacity (see FC) |
| EP | Hydrologically effective precipitation |
| FC | Field Capacity is a meteorological condition when the soil moisture deficit is zero. Soils usually return to field capacity (zero deficit) during the autumn or early winter and the field capacity period, measured in days, ends in the spring when evapotranspiration exceeds rainfall and a moisture deficit begins to accumulate. |
| FCD | Duration of Field Capacity in Days from the start to end date (see FC) |
| MD | Moisture Deficit (see SMD) |
| MDPOT | Moisture Deficit for Maincrop potatoes (see SMD) |
| MDWHT | Moisture Deficit for Wheat (see SMD) |
| MORECS | The Met Office Rainfall and Evaporation Calculation System |
| MPT | Maincrop Potatoes |
| NSI | National Soil Inventory – data collected from 5829 sites on a 5km grid by the then Soil Survey of England and Wales in the early 1980's (McGrath and Loveland, 1992) |
| PSMD | Potential Soil Moisture Deficit, PSMD can be calculated for daily or monthly periods and the maximum value in any year used to indicate the shortfall in moisture supply for that year. For land classification purposes, the PSMD needs to be averaged over a period of years and selecting the median value of PSMD avoids the bias of extreme years. |
| PT (PE, PET, ETP and ET0) | Potential Evapotranspiration. The concept of potential evapotranspiration (PT) was introduced by Penman (1948) who defined it as the water transpired by a short green crop, such as grass, which completely covers the ground surface and has an ample supply of water around its roots. Different models for evapotranspiration use different acronyms which are broadly equivalent. |
| RFC | Date of the Return to Field Capacity (see FC) |
| SMD | Soil Moisture Deficit, a crop-related meteorological variable which represents the balance between rainfall and potential evapotranspiration calculated over a critical portion of the growing season. |
| TMAX | Maximum Daily Temperature |

TMIN Minimum Daily Temperature

UKCP09 UK Climate Projections, UKCP09 is the fifth generation of climate information for the United Kingdom. The UK Climate Projections data have been made available by the Department for Environment, Food and Rural Affairs (Defra) and Department for Energy and Climate Change (DECC) under licence from the Met Office, Newcastle University, University of East Anglia and Proudman Oceanographic Laboratory. These organisations accept no responsibility for any inaccuracies or omissions in the data, nor for any loss or damage directly or indirectly caused to any person or body by reason of, or arising out of, any use of this data. Climate scenarios data used in analysis:

| Climate scenario | Time period | Emissions scenario |
|---|---|---|
| 2020H | 2010 - 2039 | High |
| 2020M | 2010 - 2039 | Medium |
| 2020L | 2010 - 2039 | Low |
| 2030H | 2020 - 2049 | High |
| 2030M | 2020 - 2049 | Medium |
| 2030L | 2020 - 2049 | Low |
| 2050H | 2040 - 2069 | High |
| 2050M | 2040 - 2069 | Medium |
| 2050L | 2040 - 2069 | Low |
| 2080H | 2070 - 2099 | High |
| 2080M | 2070 - 2099 | Medium |
| 2080L | 2070 - 2099 | Low |

VP Vapour Pressure

WWT Winter Wheat

# 1 Executive Summary

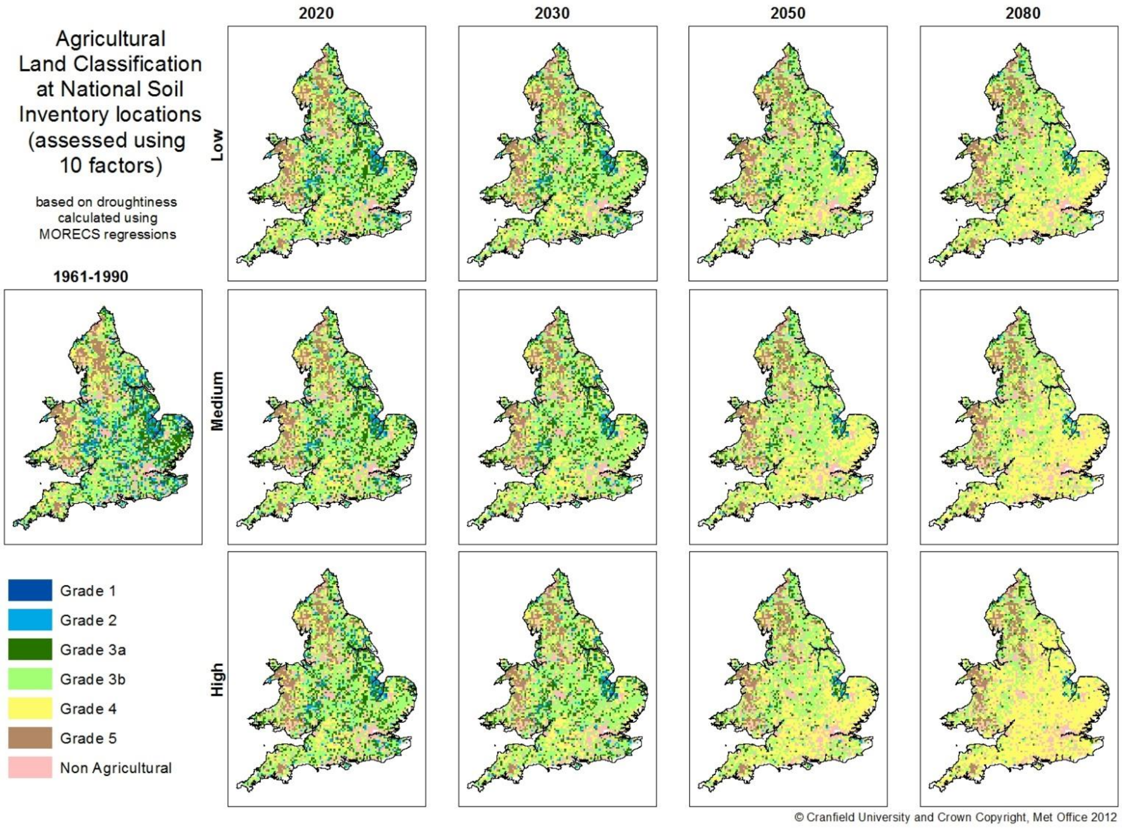
1. NSRI conducted a study for Defra and the Welsh Government (SP1104), in collaboration with ADAS (including input from the Meteorological Office), to assess how future changes in climate may affect agriculture in England and Wales using the Agricultural Land Classification (ALC) system as a surrogate measure. The study focuses on the time period 1961-1990 to generate a baseline from which relationships are derived to apply to the future climate change scenarios. Twelve UKCP09 climate change scenarios are investigated namely the medium, high and low emissions scenarios for 2020 (2010-2039), 2030 (2020-2049), 2050 (2040-2069) and 2080 (2070-2099) time periods.
2. The ALC system provides a framework for classifying land in England and Wales according to limitations placed upon it either through physical or chemical constraints. Land grading using ALC was first implemented in the 1960s for England and Wales, as documented in the MAFF Technical Report 11. The detailed ALC criteria that forms the statutory basis for the evaluation of agricultural land for land use planning in England and Wales was published by MAFF in 1988, and modifies earlier methodologies by taking advantage of new data and knowledge, to update the system without changing the original concepts.
3. For each of the 30-year periods, an assessment of the ALC grade was carried out, using existing soil and site parameters from the National Soil Inventory on a 5 km grid across England and Wales. The climate data for the NSI point were taken for the 5 km cell in which it resides. It is important to emphasise that the distributions portrayed in the maps, based on the soil properties from the NSI, are from single points in the landscape which do not necessarily represent the whole 5km square to which the climate data relate.
4. ALC classification was calculated for 10 criteria: climate (Annual Average Rainfall (AAR) and Accumulated Temperature above 0 °C (AT0) Jan-June), soil wetness, droughtiness, gradient, flooding, texture, depth, stoniness, chemical, and erosion). The climate, soil wetness and drought criteria are all assessed using climate variables and were calculated for the baseline and 12 future emission scenarios; the remaining seven criteria were assessed for each of the NSI sites from the original observed data as surveyed in 1979-1983. The final ALC grade given to a site is determined by the most limiting factor present from any of the 10 criteria.
5. The ‘overall climate’ limitation used in ALC is built on the premise that the warmer and drier the climate the better the grade. Although the AAR remains steady throughout the future scenarios there is an increase in AT0 which results in the ALC grade (by climate) improving with the proportion of England and Wales potentially in grade 1, based only on that criterion, increasing from 58% in 1961-90 to over 90% in 2070-99.
6. Soil wetness (based on the duration of field capacity and drainage status of the soil) was shown to be largely unaffected over most of England and Wales mainly because, even though the start and end dates of field capacity are likely to change, the duration remained constant. In order to address the broad changes in seasonality the calculation of field capacity duration was varied to use the average

summer and winter rainfalls rather than just the average annual rainfall. There is an overall drying of the soils resulting in fewer sites being downgraded by being too wet with the proportion of England and Wales potentially in Grade 1 based only on that criterion increasing from 24% in 1961-90 to over 30% in 2070-99.

7. The potential impact of the predicted change in climate only becomes significant when the effect on the droughtiness is considered. For ALC purposes the assessment of drought uses two crops, wheat and potatoes, as a general indication of average drought risk. Although the ALC model focuses on these two arable crops it should be noted that grassland will also be affected as it has characteristics which make it prone to drought over a large range of conditions, such as shallow rooting. Subsequent low grass yields will affect grazing, increasing the need for supplementary feeding or reduced stocking rates.
8. The current method for measuring and classifying drought results in the amount of grade 1 (based only on that criterion) land being downgraded from 37% in 1961-90 down to only 7.1% by the 2070-99 (high emission scenario) whereas the amount of land in grade 4 increases from 2.2% to nearly 66% of England and Wales. As the overall ALC grade is defined by the most limiting factor, the result is a very large area of England and Wales being downgraded to Grade 4.
9. Areas vulnerable to inundation or flooding, given the UKCP09 projections of how sea levels might change in the UK over the coming century, have been mapped using the topographic parameters. The number of NSI sites that could be affected by flooding, for which ALC has been calculated, was assessed. Assuming no defence against any marine incursion existed or was planned, of the current 96 Grade 1 sites, 13 could be potentially at risk from inundation as the sea level rises. By the 2080 period, there would only be 9 NSI sites remaining in Grade 1 of which 3 sites could potentially be lost to flooding.
10. As a result of the extreme changes predicted using the original ALC procedures, a number of alternate drought indices, recognised in the literature, were reviewed. The results of applying these indices suggest that there would be a significant increase in drought conditions in the South and East of England, with many areas shifting to a drier climate type.
11. However, these indices are mostly based on averages of annual meteorological parameters and, because they do not account for seasonality, their use is unlikely to reveal the full extent of droughtiness in the future. The moisture balance method for determining droughtiness used by the ALC system, uses rainfall and evapotranspiration during the summer months, which is more appropriate than using annual averages.
12. All the aridity indices evaluated show the same trend and add confidence to the results of Project Objectives 4 & 5 that levels of droughtiness will increase significantly in future, thus reducing land capability. The issue now is not the direction of change but the magnitude of these changes, taking account of the mitigating impacts of adaptation.
13. The net impact of climate change on cropping outcomes in the UK remains unclear, as there are potentially some positive effects related to warmer temperatures and

increased $CO_2$ concentrations as well as negative impacts due to increased water stress.

14. There is great potential for adaptation within the agricultural sector. This will either be planned adaptation as part of policy changes, or autonomous adaptation as individual farmers respond to local conditions. If the aridity zones shift northwards (as predicted by the aridity indices), there may be a geographical shift in the crops grown, including the introduction of crops not currently grown in the UK (and which are not currently represented in the ALC classification methodology).
15. Future UK climate projections (periods 2050 and 2080) show that areas of the UK are likely to experience similar climatic conditions to those in present-day Mainland Europe. For example by the 2050 period grain maize, which is currently widely grown in western France, could become an important crop in the UK. By the 2080 period areas of the UK, which currently grow wheat and potatoes, may experience a Mediterranean climate and be able to grow crops such as maize, olives and vines.




Projected ALC Grade (most limited of all 10 criteria) of the NSI sites with droughtiness using new MORECS regression and adjusted potato classification under different climatic scenarios. Reproduced as Figure 29 p66.

# 2 Project Objectives

The research objectives were to:

1. Evaluate the climate baseline data: 1941-70; 1961-90; and 1971-2000;

2. Generate appropriate digital future climate data using the UKCP09 scenarios;

3. Convert the original system[1], implemented for the NSI assessment in dBase, into an Oracle SQL environment and to adapt the system to be able to work with the various climate scenarios to return revised ALC classes;

4. Generate ALC classification maps for each of the 12 UKCP09 scenarios using the National Soil Inventory 5km gridded dataset;

5. Undertake a comparative evaluation of the existing and future maps and methodologies;

6. Take consideration of the effects of potential sea level rise;

7. Validate the findings and further research the models and data underpinning the outcomes to ensure they are scientifically robust.

## 2.1 The extent to which the objectives have been met

1. The historical climate baselines were evaluated comparing the climate data used in the original ALC system (Meteorological Office 1989) with 30 year summary data for 6 periods calculated from the Meteorological office's 5km monthly summary data from 1914 to 2000.

2. The UKCP09 datasets provided basic climate data on a 25x25km grid for each of the future climate scenarios. Different methods for calculating the agroclimatic variables required for assessing the ALC grade from these basic parameters were evaluated and the best method was chosen in each case. The parameters were then interpolated onto a 5x5km grid to match with the resolution of the NSI sites.

3. Functions were written in the LandIS Oracle database using the PL SQL language which enable the ALC subgrades and final grade to be determined for each of the site and climate input scenarios. These functions were used with both the historic and future climate scenarios.

4. ALC grade and subgrade maps were produced for each of the 12 UKCP09 scenarios using the National Soil Inventory 5km gridded dataset;

5. A comparative evaluation of the existing and future maps was carried out.

6. A brief look at the expected level of sea water rise was investigated to see how many of the NSI sites would be vulnerable. Due to the location of much of the best ALC grade land being in the Fens region of England this effect was found to significantly reduce the proportion of Grade 1 land in England even though only a few sites were likely to be inundated. As the Fens are already artificially drained however it was thought that this problem would probably be manageable, though a

[1] ADAS (1994)

risk remains if flood control and drainage measures are less effective due to rising sea levels.

7. The models used to calculate the various climatic variables in the original ALC programme were each investigated and compared with alternative approaches using different source data.

# 3 Background

## 3.1 The ALC system

The Agricultural Land Classification (ALC) system used in England and Wales was first defined by MAFF (1966). The purpose of the classification is primarily for land use planning in order to steer urban development away from those areas of land that have the greatest agricultural potential (Natural England, 2012). The limiting physical factors are identified as: climate (rainfall, transpiration, temperature and exposure); and soil (wetness, depth, texture, structure, stoniness and available water capacity). These factors are used to classify the land into five grades; Grade 1 being excellent quality and Grade 5 being of very poor quality (Table 1).

The system proposed in 1966 was implemented and became the basis of advice by MAFF (and subsequently Defra and Natural England) on land use planning matters. Between 1966 and 1974 provisional reconnaissance scale maps were published on an Ordnance Survey base at a scale 1:63,360. In 1976 a review of the system recommended that Grade 3 be sub-divided, because almost half the agricultural land in England and Wales (48.9 %) was classified in Grade 3 (MAFF, 1976). Three subdivisions were created, Grades 3a, 3b and 3c, and a programme of more detailed mapping was instigated in response to specific development proposals.

In 1988 new methodologies for wetness and droughtiness assessment and climate data from the Meteorological Office, led to the publication of a revised Agricultural Land Classification (MAFF, 1988). In order to provide a more objective assessment of the climatic factors, a grid point data set with a 5 km resolution was produced, together with site specific interpolation procedures (Met Office, 1989). The revised classification updated the criteria for assessing the climatic limitations and those involving a climate-soil interaction, namely soil wetness class (Hodgson, 1976) and droughtiness (Thomasson, 1979). In addition to the new criteria the Grades 3b and 3c were combined to leave only two classes, 3a and 3b (Table 1). The new climatic data were developed in collaboration with the Meteorological Office and the Soil Survey and Land Research Centre, Silsoe (formerly Soil Survey of England and Wales based at Rothamsted Experimental Station (Harpenden)). The creation of these new data sets and interpolation procedures are described in Jones and Thomasson (1985) and Meteorological Office (1989).

Land is graded according to the degree to which physical or chemical properties impose long-term limitations on agricultural use. It is assessed on its capability at a good but not outstanding standard of management. Where limitations can be reduced or removed by normal management operations or improvements, for example cultivations or the installation of an appropriate underdrainage system, the land is graded according to the severity of the remaining limitations. Where an adequate supply of irrigation water is available this may be taken into account when grading the land.

## 3.2 The use of climate data for Agricultural Land Classification

Climatic limitations have a major, and in places overriding, influence on land quality for agriculture. Temperature and rainfall fundamentally affect plant growth, determining the energy available for photosynthesis and the water supply available to the roots. There are also direct effects on plants caused by exposure and frost. In climatic terms, the poorest land for crop production is found in the wettest and coldest areas. The original ALC methodology identifies two parameters chosen for the primary assessment of climatic limitations: 1) Average Annual Rainfall (AAR), as a measure of wetness and 2) Accumulated temperature above 0 °C (AT0), as a measure of overall warmth. Accumulated temperature is measured above the selected threshold (0 °C) and over a specified period. This threshold was chosen because research on grass and cereals showed that leaf extension could occur down to temperatures as low as 0 °C. The period from January to June was determined to be the critical period for most crops in the UK. A single grade was given for the overall climate limitation, which combines the AAR and the AT0.

Table 1 Generalised Description of the Agricultural Land Classification Grades (source MAFF 1988)

| Grade | Description of Agricultural Land | Detail |
|---|---|---|
| 1 | Excellent Quality | No or minor limitations on agricultural use. Wide range of agricultural and horticultural crops grown. High yielding and consistent. |
| 2 | Very Good | Minor Limitations on crop yield, cultivations or harvesting. Wide range of crops but limitations on demanding crops (e.g. winter harvested veg). Yields high but lower than Grade 1. |
| 3 (subdivided) | Good to Moderate | Moderate limitations on crop choice, timing and type of cultivation, harvesting or level of yield. Yields lower and more variable than Grade 2. |
| 3a | Good | Moderate to high yields of narrow range of arable crops (e.g. cereals), or moderate yields of grass, oilseed rape, potatoes, sugar beet and less demanding horticultural crops. |
| 3b | Moderate | Moderate yields of cereals, grass and lower yields other crops. High yields of grass for grazing/ harvesting. |
| 4 | Poor | Severe limitations which restrict range and/or level of yields. Mostly grass and occasional arable (cereals and forage), but highly variable yields. Very droughty arable land included. |
| 5 | Very Poor | Severe limitations which restrict use to permanent pasture or rough grazing except for pioneering forage crops. |

In addition to the direct effect of rainfall and temperature on crops, climatic variables are also involved in interaction with site and soil conditions. Soil wetness, droughtiness and erosion are all influenced by climate and the use of each of these variables in the ALC is outlined in the following section.

## 3.3 The assessment of soil conditions for Agricultural Land Classification

### 3.3.1 Soil Wetness

Excessive soil wetness adversely affects seed germination and survival and restricts the development of a good root system. It reduces the temperature of the soil and causes anaerobic conditions. The wetness of the soil also affects the sensitivity of the soil to structural damage, influencing the number of days when the site is accessible to farm machinery or livestock grazing. Soil wetness is assessed by a combination of the climatic regime, the soil water regime and the texture of the top 25 cm of the soil.

The wetness component of the climatic regime is determined from the duration of field capacity (FC). The start and end dates of FC are probably the most difficult of all the agroclimatic parameters to predict. A soil is said to be at FC when it holds the maximum amount of water against the force of gravity, which in a meteorological sense is when the soil is at zero moisture deficit. Soil moisture deficits were originally determined by (Smith, 1967) from the actual moisture deficit over the year calculated from the balance of biweekly rainfall and monthly potential transpiration. A simple water abstraction model was used to limit the transpiration from the soil to take into account the greater water retention of most soil material as it dries out. The start of the FC period was determined from the date at which the soil water was no longer in deficit i.e. there was a water surplus in the soil. This state often pertains in the autumn on agricultural land, but in drier areas of south east England for example it can be as late as the end of November. In the wettest areas at higher elevation the soil can be at FC throughout the year e.g. above 500 m in N Wales and N.W. England. Once the soil reaches FC it can fluctuate in and out for a few days or weeks depending on the weather but eventually settles down through the winter until the temperatures begin to increase in the spring, vegetation growth starts and the soil once again begins to dry out and a soil moisture deficit returns.

The start and end dates of FC were calculated for 97 sample stations across England and Wales (Smith, 1971). From these analyses, estimates of the start and end dates of FC were developed from algorithms based on actual soil moisture deficit at the end of specific months and the rainfall zone. England and Wales was divided into 70 areas of similar climate and a full range of agroclimatic parameters were determined for each of these zones from meteorological station data from 1941 to 1970 (Smith, 1976). For ALC purposes, regression algorithms were developed from these data to calculate the start and end dates of FC from the average annual rainfall and altitude (Jones and Thomasson, 1985). Spatial coverage on a 10 km and subsequently 5 km grid was developed and the start and end dates adjusted by the residual difference between the equation and the measured value at the nearest climate station (Ragg et al., 1988).

The soil water regime was determined using the soil wetness class (classes I to VI) (Hodgson, 1976) based on the depth and duration of water logging measured by monitoring dipwells in the field (Jones, 1985; Robson and Thomasson, 1977). The scale ranges from class I where the soil is not wet within 70 cm for more than 30 days in a year (and is usually recognised by the lack of any mottling) to class VI where the soil is wet within the top 40 cm for more than 335 days in most years. For ALC purposes wetness class of a soil is assessed by a decision tree approach based on the climate region (FC day zone), the presence or absence of a slowly-permeable layer or gleying within specified depths, whether the site is disturbed, and whether the soil is peaty, an organo-mineral or a red soil (MAFF, 1988).

### 3.3.2 Droughtiness

Soil droughtiness is determined separately for ALC purposes as a soil can be both waterlogged in the winter but very desiccated during the summer. Throughout the growing season it is important for a crop to receive an adequate supply of water to its roots. If at any point the crop demand for water exceeds the capacity of the soil to satisfy this demand, which is defined by (Thomasson, 1979) as the soil water available to plants (AP), then the crop plants will experience moisture stress and cease to grow, resulting in reduced yields. The degree of drought in a soil is influenced by three factors: rainfall amount, evapotranspiration and the store of water available in the soil. The ALC method to assess the drought is based on the concept of potential soil moisture deficit (PSMD), which describes the balance of rainfall and potential evapotranspiration (Thomasson, 1979). Moisture deficit (MD) in the soil builds up over the summer months in most of lowland Britain, the potential evapotranspiration increasing progressively from springtime onwards and peaks in July or August. The PSMD is the maximum recorded MD irrespective of the month in which it is recorded. For calculating ALC grade, the PSMD is adjusted for two reference crops, winter wheat and maincrop potatoes. These crops were chosen as they are widely grown and are representative of a broad range of crops in terms of their susceptibility to drought (MAFF, 1988). The method estimates the values of MD under various crops based on the soil moisture deficits attained at the end of key months in the plants life cycle (Thomasson, 1979). Arable crops use less water up until the point where they reach their maximum ground cover and transpiration is greatly reduced while they are ripening and after they attain senescence,

The crop-adjusted soil moisture deficits were calculated for 94 stations in the ‘Complete’ Agromet Data set (Field, 1983) from 1961 to 1980 which was extended to include a further 25 sites in Scotland and 2 sites in Northern Ireland (Harvey, 1983). From these records it was possible to devise regression equations which allowed MD for winter wheat and maincrop potatoes to be calculated from the Accumulated Temperature in Summer (ATS) and the Average Summer Rainfall (ASR). The ATS value was derived from a regression equation based on the AT0. The amount of water available in the soil that can be transpired by the crop is calculated as the water held in the soil between 15 bar (wilting point) and 0.05 bar (field capacity) (not to be confused with the field capacity period described earlier) to the rooting depth of the particular crop.

To calculate the droughtiness of the soil, the crop specific MD (mm) is subtracted from the water available to that crop in the soil (AP).

### 3.3.3 Site and Soil limitations

In addition to the parameters influenced by climate, the ALC classification is also based on the properties of the site and the soil of the area being investigated, such as: gradient; soil depth; stoniness; flooding risk; and erosion.

## 3.4 Development of spatial agroclimatic data for ALC

**Smith and Trafford 1976 method**

Much of the data and methods underlying the current ALC system originated from MAFF Reference Book 434; ‘Climate and Drainage’ (Smith and Trafford 1976) and include estimates of rainfall, temperature and field capacity duration. Initially, agroclimatic data for England and Wales were interpreted spatially for the period 1941 to 1970 (Smith, 1976). The agroclimatic properties were summarized for each of 70 areas of England and Wales delineated using parish and ADAS District boundaries combined into areas where farming systems were uniform, but not necessarily having similar climate. For mean air temperatures and potential transpiration, large amounts of station data were used to derive month-by-month 30-year averages.

**1988 MAFF method**

In 1985 a new agroclimatic data bank was created on a 5 km x 5 km grid (Jones and Thomasson, 1985) for the ALC (MAFF, 1988). Temperature data were collected for 109 stations recording daily data from 1959-78 across England and Wales. Regression equations were generated for calculating the Accumulated Temperature (AT), growing season and grazing season values from the Ordnance Survey Easting and Northing and the altitude of the site. Rainfall data were recorded at 970 stations, by the Meteorological Office, for the period 1961-75. However when compared with the original 1941-70 data, the differences were mostly very-small and therefore the original averages were retained (Jones and Thomasson, 1985).

However, the 1961-75 rainfall data were used to generate a new moisture deficit map by combining total monthly rainfall with monthly potential transpiration (PT) data calculated from 40 stations. For each rainfall station, the nearest PT station was selected and the PT adjusted by the difference in altitudes between the two sites. Potential Transpiration is much less variable than rainfall over short distances, thus use of a relatively small number (40) of PT stations compared to (970) rainfall stations was justified. The soil moisture balance was then calculated on a month by month basis over the 15 year period and means and standard deviations of month-end and maximum PSMD were calculated.

Table 2 Climatic datasets used in the Agricultural Land Classification of England and Wales

| Climate Parameter | 1988 Method | 2004 Method |
|---|---|---|
| Accumulated Temperature above 0°C, January to June (AT0) | Median 1961 - 1980 | Mean 1971 - 2000 |
| Accumulated Temperature above 0°C, April to September (ATS) | Median 1961 - 1980 | Mean 1971 - 2000 |
| Duration of Field Capacity Days (FCD) | Median 1941 - 1970 | Median 1971 - 2000 |
| Average Annual Rainfall (AAR) | 1941 - 1970 | 1971 - 2000 |
| Average Summer Rainfall (April to September) (ASR) | 1941 - 1970 | 1971 - 2000 |

For the 1988 ALC system, the data and methods used are described in ‘Climatological Data for Agricultural Land Classification’ (Meteorological Office, 1989). The climate data includes location, altitude, rainfall, temperature, moisture deficit and duration of field capacity datasets at 5km grid spacing. The 1988 revision of the climate data sets offered an improvement over previous versions, which used maps or meteorological station data to estimate climate data at a site. Introducing standardised gridded data in the classification reduced some of the subjectivity of earlier classifications, especially in areas where suitable, representative data from meteorological stations were not available. There was also a change to the method used to derive accumulated temperatures. However, the time periods used to derive the climate data sets are not consistent, with the rainfall analysis focusing on 1941 to 1970 and temperature the 1961-80 time period (Table 2).

**2004 method**

In 2005, monthly long-term climate averages on a grid were created by the Met Office for the 30-year period 1961-90 (Perry and Hollis, 2005a). Averages on a grid were created using new and improved interpolation methods and a much greater number of climate stations for 13 different meteorological variables (including the minimum, maximum and mean temperature, precipitation and sunshine duration). Weather station data were interpolated by multiple linear regressions of the station data to define relationships between the key climatic values and the easting, northing, altitude, terrain shape, and the proportion of sea and urban area within a 5 km radius. The density of the station network used varied between elements with 70 stations analysed for pressure, cloud and wind, 290 stations for sunshine, 540 stations for temperature and 4400 stations for rainfall; considerably more than used in the original agroclimatic assessments.

The Residual Differences between station data and the value by regression were interpolated onto a 1 km grid using an inverse distance weighting (IDW). At each point on the 1 km grid the climate parameters were calculated using the regression algorithm adjusted by the interpolated residual difference at that location. This method is easy to implement and generates maps that follow general UK climate patterns. Further monthly grid data sets were created for the period 1914- 2004 for a range of climatic variables (Perry and Hollis, 2005b). The maps were created using the same techniques as the 1961-90 datasets thus allowing direct comparison of changes in space and time. The long-term datasets are fundamental to assessing the effect of historical climate change on ALC classification and should provide a rational method for determining an appropriate baseline for assessing the changes in the predicted future climate scenarios also provided by UKCP09 (Meteorological Office, 2006).

Driven by the availability of this new 1km resolution climate data, in 2004 Defra commissioned ADAS to develop a modern, high resolution and robust climate database for use in the Agricultural Land Classification (LE0216) that would provide a consistent time period for all climatic data variables used in the ALC system (Table 2). There were also improvements made to the methods to calculate the derived climate variables, namely accumulated temperatures (AT0 and ATS) and duration of field capacity days, taking advantage of new knowledge and data. The methods are described in Barrie (2004).

# 4 Objective 1: Evaluation of historic climate data to establish a baseline

## 4.1 Summary

This section summarises the preparatory work required to select an appropriate baseline dataset to assess future projections of climate in England and Wales and its effect on Agricultural Land Classification. The aim was to calculate all the parameters from the source climate data using consistent methods in order to recreate a comparable set of average data for each of the six 30-year periods in the historic records. A common approach is required for calculating the necessary agroclimatic parameters over time to determine the effects of changes in the climate on land grading. Climatic parameters used in the ALC classification were calculated from a range of primary climate data, available from the UKCP09 monthly gridded data sets at 5km resolution for the period 1914 to 2000. Thirty-year averages of the various agroclimatic properties were created for 1921-1950, 1931-60, 1941-70, 1951-80, 1961-90 and 1971-2000. Soil records from the National Soil Inventory on a 5 km grid across England and Wales (McGrath and Loveland, 1992) were used to determine the required soil and site parameters for determining ALC grade. For more information on the NSI dataset go to http://www.landis.org.uk/data/nsi.cfm.

Over the 80-year period it was shown that the overall climate was coolest during 1951-80. However, the area of land estimated in retrospect as “best and most versatile land” (BMV) (Grades 1, 2 and 3a) probably peaked in the 1950s to 1980s as the cooler climate resulted in fewer soils being classed as droughty, more than offsetting the land that was downgraded by the climate being too cold. Overall there has been little change in the proportions of ALC grades between the six historical periods once all 10 factors (climate, gradient, flooding, texture, depth, stoniness, chemical, soil wetness, droughtiness and erosion) are taken into account. This is because the ALC methodology uses average climate data for 30-year standard periods, during which data for years with extreme weather events tend to be smoothed by the averaging process. Calculations of soil moisture deficit and field capacity days using current methods revealed that these methods are problematic for future projections. Further work was carried out in later phases of this project to determine better methods for calculating these parameters.

## 4.2 Aims

1. To create a complete and consistent set of historic agroclimatic parameters.

   The Meteorological Office has recently provided a 5 km x 5 km gridded data set of primary climate parameters for every month from 1914 to 2000. Using this information, a consistent set of 30-year average data will be created for the main ALC climate parameters for the periods: 1921-50, 1931-60, 1941-70, 1951-80, 1961-90 and 1971-2000.

2. To assess the implications of any historic changes in these parameters on the ALC.

   For each of the 30-year periods an assessment of the ALC grade will be carried out, using soil and site parameters from the National Soil Inventory on a 5 km grid across England and Wales. How the changes in the average climate parameters affects the grading will be analyzed to determine how the grading would have changed throughout this time.

## 4.3 Methods

The Meteorological Office produced a series of monthly summary weather data on a 5 km x 5 km grid for every month between 1914 and 2000 (Perry and Hollis, 2005b). The data provided were:

From 1914 - 2000 Average Monthly Rainfall (mm) *[rain]*

From 1914 - 2000 Average Daily Min, Max and Mean Temperature (°C) *[temp: Tmin, Tmax, Tmean]*

From 1929 - 1960 Sunshine – total monthly hours (hours) *[sun]*

From 1961 - 2000 Sunshine - average hours per day (hours) *[sun]*

From 1961 - 2000 Average daily Vapour Pressure (hPa) *[VP]*

From 1969 - 2000 Average Windspeed at a height of 10m (Knots) *[wind]*

This data set is referred to as the 'UKCP09' data. For comparison, the data set used in the published ALC classification is referred to as the 'Original' data (Met Office, 1989).

### 4.3.1 Calculating Average Annual Rainfall and Accumulated Temperature

Annual summaries for rainfall and accumulated temperature above 0 °C were calculated for each year in the period. The annual rainfall for each year is the sum of the monthly totals. The accumulated temperature function calculates how much of the minimum, maximum and mean temperatures for each day are above the given threshold and whether the record is between the specified dates as modified from Meteorological Office (1969) by Hallett and Jones (1993). The function returns the daily effective temperature (measured as degree-days above the threshold), which is then multiplied by the number of days in the month, and accumulated over the required period.

For each of the 30-year periods: 1921-50, 1931-60, 1941-70, 1951-80, 1961-90 and 1971-2000, the Average (Mean) Annual Rainfall, the Median Accumulated Temperature (AT0) and Median Accumulated Summer Temperature (ATS) were calculated. For AT0 and ATS the threshold is 0 °C and the period is defined as January to June for AT0 and April to September for ATS. Monthly average rainfall (January to December) was also calculated to show seasonal changes. For ALC purposes ATS is used in the calculation of moisture deficit.

### 4.3.2 Calculating Evapotranspiration

The climate data provided by UKCP09 include all the variables required to make a reasonable approximation of evapotranspiration using the Penman-Monteith equation (Allen et al., 1998). The methodology used to calculate the evapotranspiration from the available climate variables is described in detail by Hess (2000).

$$ETo = \left[\frac{\Delta}{\Delta + \gamma^*} \cdot \frac{(R_n - G)}{\lambda}\right] + \left[\frac{86.4}{\lambda} \cdot \frac{1}{\Delta + \gamma^*} \cdot \frac{\rho cp}{ra}(ea - ed)\right]$$

Where:

| | |
|---|---|
| *ETo* | reference crop evapotranspiration (mm $d^{-1}$) |
| Δ | slope of vapour pressure curve (MJ $kg^{-1}$) - *ƒ(temp, VP)* |
| $\gamma^*$ | modified psychrometric constant (kPa °$C^{-1}$) - *ƒ(temp, wind, altitude)* |
| *Rn* | net radiation (MJ $m^{-2}$ $d^{-1}$) - *ƒ(temp, VP, sun)* |
| *G* | Soil heat flux (MJ $m^{-2}$ $d^{-1}$) – set to 0 for monthly data |
| λ | latent heat of vapourisation - *ƒ(temp)* |
| ρ | atmospheric density (kg $m^{-3}$) - *ƒ(temp, altitude)* |
| *cp* | specific heat of moist air (1.013 kJ $kg^{-1}$ °$C^{-1}$) |
| ra | aerodynamic resistance (s $m^{-1}$) - *ƒ(wind)* |
| ea | mean saturation vapour pressure (kPa) - *ƒ(temp)* |
| ed | actual vapour pressure (kPa) - *ƒ(VP)* |

It was necessary to estimate the missing values for vapour pressure (1914-1960), windspeed (1914-1968) and sunshine hours (1914-1928) to produce a contiguous data set. Analysis of the vapour pressure records from 1961-2000 shows a strong relationship between *VP* and *TMin* (Figure 1). This formula was used to populate the missing *VP* records from 1914 - 1960.

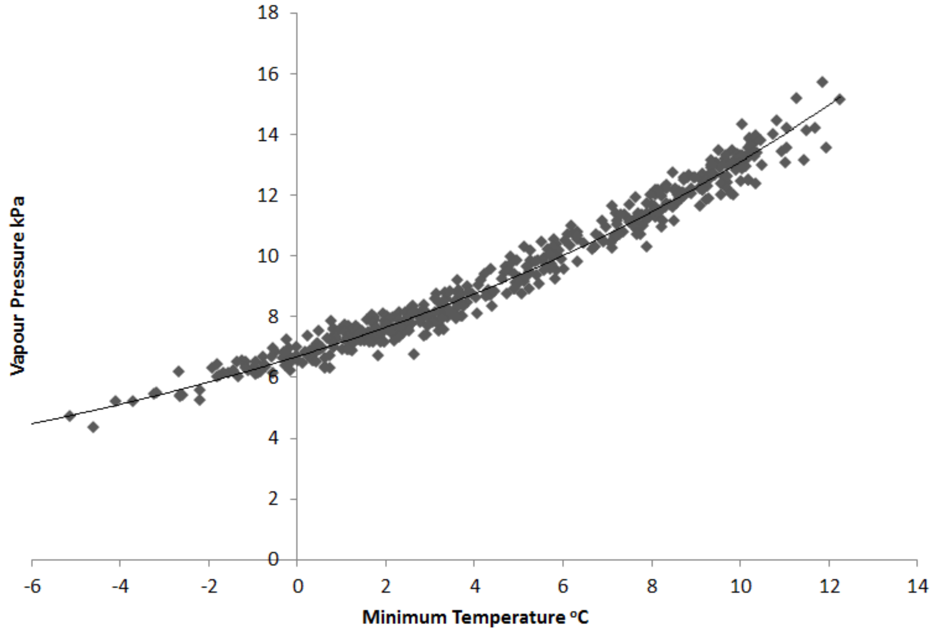



Figure 1 Relationship between Vapour Pressure (VP) and Minimum Temperature (MinT) from UKCP09, monthly data for 1961 to 2000. VP = $6.69e^{0.067TMin}$ ($R^2$ = 0.96)

The windspeed is measured at a height of 10m and thus for the purposes of the Penman-Monteith method it was adjusted down to the reference height of 2m. Windspeed is variable and there is no strong relationship with any of the other variables. In order to distinguish the exposed areas of Britain, such as the hills and coasts, from the less windy regions, the average windspeed was calculated for each individual grid point from the 1969 to 2000 records. This value was then used to populate the records before this date.

The missing sunshine records from 1914 to 1928 were estimated by calculating the average sunshine by month using regression to determine a polynomial equation (Figure 2).

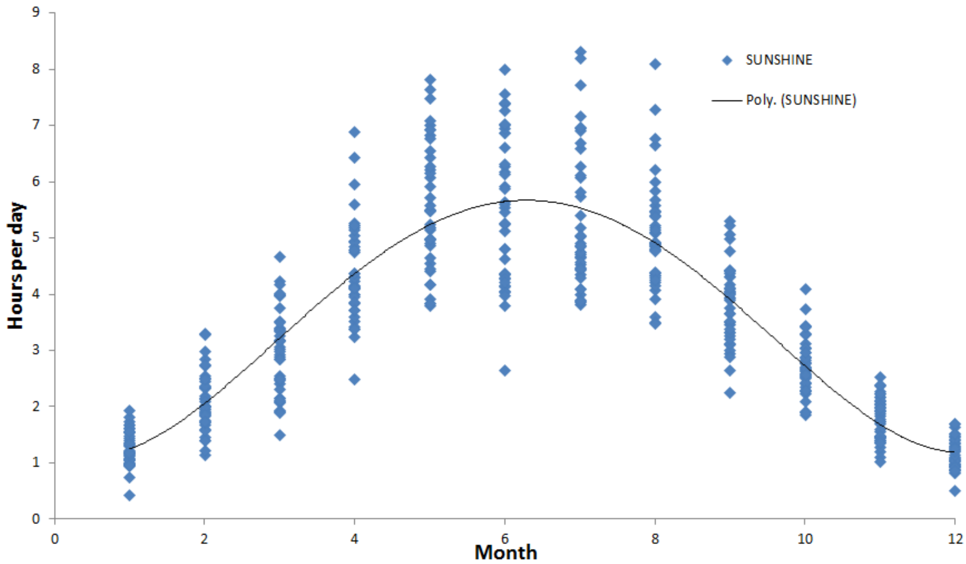



Figure 2 Mean number of sunshine hours per day for the UKCP09 monthly data (1961 – 2000). A polynomial curve was fitted to the data ($R^2$ = 0.79).

### 4.3.3 Calculating Potential Soil Moisture Deficit

Potential Soil Moisture Deficit (PSMD) was calculated for each month in each year throughout the period. The monthly moisture deficit equals the moisture deficit for the previous month plus the rainfall minus the potential evapotranspiration, where the balance rises above 0 (there is a moisture surplus) it is reset to 0. This calculation represents a potential climatic deficit but the actual deficit is modified by the amount of water available in the soil. For example, some areas in eastern England may occasionally experience potential deficit in January and February of the following year but to carry this deficit into the next spring period would distort the calculations in the following year. Therefore the PSMD is reset to 0 at the end of February each year. Over the 87-year period, the annual maximum PSMD showed a skewed distribution with a few years having very high values. To compensate for these extreme years, the median PSMD value was used to describe the PSMD for each 30-year period.

For calculating ALC grade, the PSMD is adjusted for two reference crops, winter wheat and maincrop potatoes. The crop-adjusted moisture deficit under winter wheat and maincrop potatoes can be calculated by one of two existing methods. The first (moisture balance method) calculates crop-adjusted PSMD from the relationships with specific monthly PSMD values (Jones and Thomasson, 1985) (Equations 1 and 2).

*MDWHT = mid-July PSMD - 1/3 April PSMD* Equation 1

*MDPOT = August PSMD - 1/3 June PSMD - 1/3 mid-May PSMD* Equation 2

Where,

MDWHT = potential moisture deficit under winter wheat

MDPOT = potential moisture deficit under maincrop potatoes

PSMD = potential soil moisture deficit for given month

The second method calculates MDWHT and MDPOT from relationships with annual summer rainfall (ASR) (April to September) and the accumulated summer temperature (ATS) from station data between 1960 and 1980 (Meteorological Office, 1989) (Equations 3 and 4).

$$MDWHT = 325.4 - 162.3\log_{10}ASR + 0.08022ATS \qquad \text{Equation 3}$$

$$MDPOT = 326.4 - 196.5\log_{10}ASR + 0.1127ATS \qquad \text{Equation 4}$$

The PSMD values computed using the first method are much more widely distributed than those calculated using the second method. The difference is likely to be the result of differences in the calculation of the reference crop evapotranspiration (ETo). The original ETo data were calculated using a pre-Penman-Monteith method, which produced smaller moisture deficit values than the complex Penman-Monteith equation adopted for the Meteorological Office Rainfall and Evaporation Calculation System (MORECS) (Thompson et al., 1981). This is probably because the later versions of the Penman-Monteith equation give more prominence to wind speed measured 2 m above ground. Deficiencies in the original documentation make it difficult to duplicate the original methods.

Applying the Penman-Monteith derived ETo in calculating the PSMD data that are subsequently used in the ALC classification results in a larger number of sites being limited by droughtiness than seems appropriate for the U.K. Applying the regression equations (3 and 4) calculated from the 1961-1980 ‘complete’ Agromet data set is also problematic as the range of values over the wider period goes beyond the range used in the regression equation and therefore beyond the advisable range of these equations. These issues are further investigated later in this report to determine if an improved methodology can be developed.

Figure 3 shows how the monthly PSMD calculated from the moisture balance (method 1) varies between each period when averaged across England and Wales. By the 1971-2000 period, the PSMD has increased markedly but only in August and September. Using Equation 1 to calculate the moisture deficit for winter wheat takes into account the mid July and April values when there is little to distinguish the different periods and the moisture deficit for winter wheat is highest in the earlier 1921-1950 period. Using Equation 2 to calculate the moisture deficit for maincrop potatoes on the other hand is mostly affected by the PSMD for August and is therefore highest in the 1970-2000 period.

Overall when both winter wheat and maincrop potatoes are taken into account in the assessment of droughtiness, more land is reduced in quality in the 1970-2000 period.

However if the moisture deficit results calculated using the 'Original' data had returned values as high as using the moisture balance method on the UKCP09 data, it is highly likely that the cut-off criteria for the classification of droughtiness would have been adjusted so that a similar area of land was being affected by drought. This is because cut-off values were selected subjectively to fit with the soil surveyors' knowledge of where drought was a problem in England and Wales rather by any objective means. We therefore propose to use the droughtiness results calculated using the second method rather than the results from the moisture balance, as the former better fit the known pattern of drought.

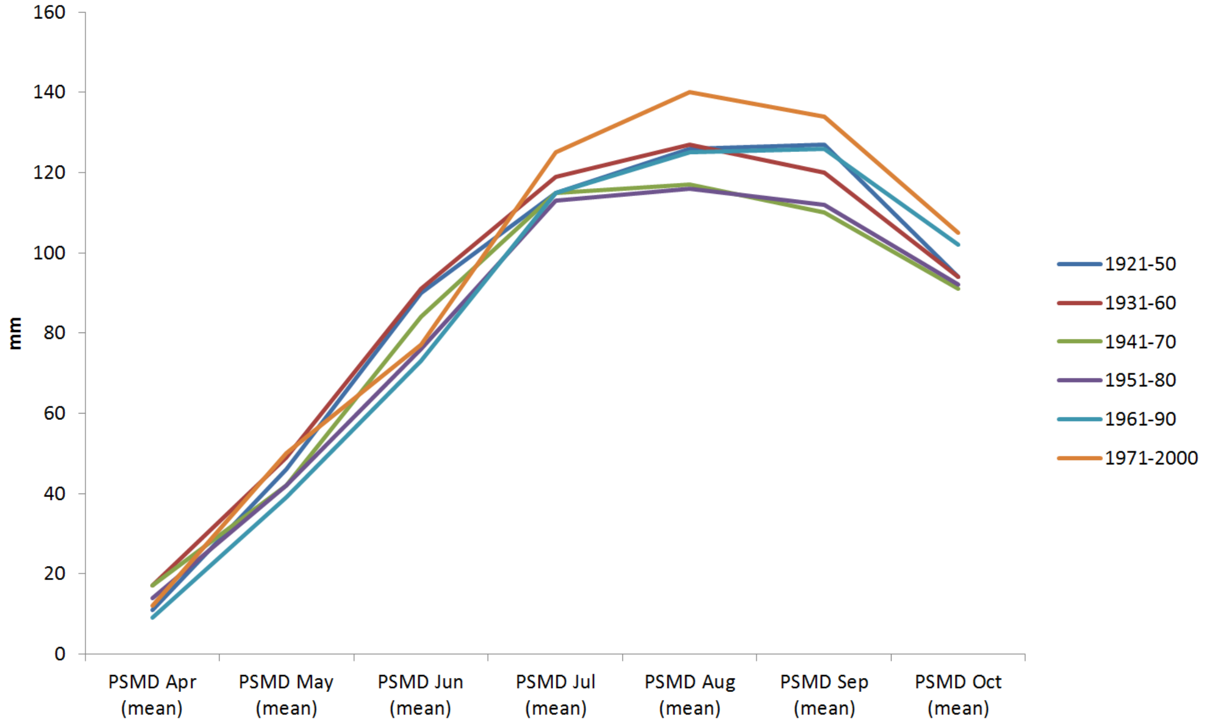



Figure 3 Average monthly potential soil moisture deficit (PSMD) for each Met Office 30-year period in England and Wales (calculated from moisture balance).

### 4.3.4 Calculating Field Capacity Days

The duration of field capacity was estimated from rainfall and evapotranspiration for regional areas of England and Wales (Smith and Trafford, 1976). A relationship between Field Capacity Days (FCD) and AAR was established and used to extrapolate the FCD across England and Wales. Calculating the water balance from monthly data to determine the start and end dates of field capacity (RFC and EFC respectively) was considered to be inherently inaccurate. Thus regression functions were developed that related the field capacity data to the easting, northing and Average Annual Rainfall (Table 3) (Jones and Thomasson, 1985). In the original ALC exercise the regression value was adjusted for the residual difference derived from measured values at the nearest weather station. To maintain continuity with the original methods, regressed FC dates were adjusted by the difference between the AAR of the original data (1941-70) and the AAR of the UKCP09 data multiplied by the coefficient for AAR from the original regression equation (Table 3).

$$xFC_{(ukcp09)} = xFC_{(original)}*AARcoeff * (AAR_{(ukcp09)} - AAR_{(original)}) \qquad \text{Equation 5}$$

Table 3 Field Capacity Parameters for original 5 km data set (provided by Dr Robert Jones)

| Field Capacity Date | Constant | Coefficient of AAR (AARcoeff) | North (100m) | East (100m) |
|---|---|---|---|---|
| RFC (wet quartile) | -40.4 | - 0.090450 | -0.008808 | 0.010756 |
| RFC (median) | 4.04 | - 0.101570 | -0.005068 | 0.006626 |
| RFC (dry quartile) | 57.39 | - 0.116837 | -0.003991 | 0.002854 |
| EFC (wet quartile) | 100.03 | + 0.058524 | 0.001963 | -0.004381 |
| EFC (median) | 72.47 | + 0.055301 | 0.001551 | -0.002725 |
| EFC (dry quartile) | 37.82 | + 0.062100 | 0.001399 | -0.000668 |

#### 4.3.5 Calculating Wetness Class

The Wetness Class at each of the NSI locations was calculated using the relevant duration of Field Capacity, the texture and the depth of the profile to a gleyed or an impermeable horizon (if it is within 150cm). The method for calculating wetness class is provided in (MAFF, 1988).

#### 4.3.6 Applying the ALC Classification

Once a complete set of Agroclimatic data had been created for each of the six 30-year periods, the ALC classification was applied and the differences resulting from changes in the climate assessed. In order to make suitable comparisons with the 'original' climate data, the UKCP09 climate data for the NSI point was taken from the value for the 5 km cell in which it resides; i.e. the data was not interpolated from the four surrounding sites and adjusted for the altitude at the NSI point.

The ten criteria used to calculate ALC grade are; (i) climate; (ii) droughtiness; (iii) wetness; (iv) gradient; (v) risk of flooding; (vi) soil texture; (vii) soil depth; (viii) stoniness of topsoil; (ix) soil toxicity; (x) soil erosion. Functions were derived to calculate the most limiting grade for each of the individual criteria (factors) as follows:

- **Climate** was calculated from AAR and AT0 using a formula (calculated by interpretation of the original graph in MAFF, 1988) for each of the five curves which separate the six classes (Figure 4). The formula for each line was checked and an adjustment was made to flatten each line once the rainfall fell below 350mm.

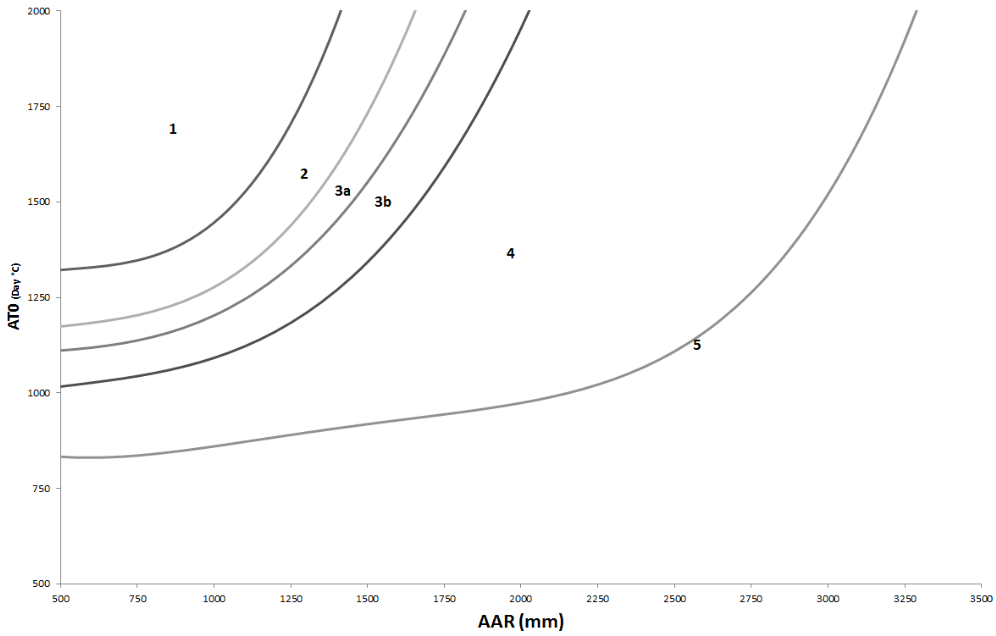



Figure 4 Limitation according to climate

- **Droughtiness** was assessed by taking the Available water of the soil profile identified at the NSI site and subtracting the PSMD at the location for winter wheat and maincrop potatoes and selecting the class using the defined limits (Table 4). The methodology for calculating the crop-adjusted soil available water capacity (AP) followed the procedure described in Appendix 4 of (MAFF, 1988) and is provided in detail in (Jones et al., 1994).

Table 4 Limitation according to Droughtiness

| **Grade/ Subgrade** | **Moisture balance limits (mm)** Winter wheat | | Maincrop potatoes |
|---|---|---|---|
| 1 | +30 | and | +10 |
| 2 | + 5 | and | -10 |
| 3a | -20 | and | -30 |
| 3b | -50 | and | -55 |
| 4 | <-50 | or | <-55 |

- **Wetness** was assessed from the FCD, topsoil texture and wetness class of the soil, where wetness class was calculated using the varying FCD and soil properties from the NSI profile data.
- The **gradient** of the site affects the ability of machinery to safely and efficiently operate and steeper slopes are also at increased risk of soil erosion. When assessing local sites it is also relevant to consider aspects of micro relief such as rock outcrops or an intensely undulating landscape which would reduce its manageability. The gradient was assessed at each NSI site at the time of survey.

Table 5 Limitation according to gradient

| Grade/ Subgrade | Gradient limits (degrees) |
|---|---|
| 1 | |
| 2 | 7 |
| 3a | |
| 3b | 11 |
| 4 | 18 |
| 5 | >18 |

- The **risk of flooding** is ideally assessed based on the history of floods, and their duration and frequency at the site. This information is not available for the NSI sites, but as in the original exercise in the 1994 work for ADAS/MAFF, sites with a risk of flooding were identified as those where there is evidence of inundation as indicated by their classification as alluvial soils. These sites are assigned to ALC grade 2 at best.
- **Soil texture** affects workability and the water available to plants and is therefore used to determine the soil droughtiness and wetness. In addition to these criteria, sites with sand topsoil are restricted to grade 3b or below and loamy sands are limited to grade 2 due to rapid drying effects.
- The **soil depth** influences the available water capacity of the soil, crop growth and cultivation options and limits defining the subgrade are shown in Table 6.

Table 6 Limitation according to soil depth

| Grade/ Subgrade | Depth limits (cm) |
|---|---|
| 1 | ≥60 |
| 2 | ≥45 |
| 3a | ≥30 |
| 3b | ≥20 |
| 4 | ≥15 |
| 5 | <15 |

- The **stoniness of the topsoil** affects the mechanical cultivation and harvesting possibilities at a site as well as reducing the available water in a soil. Therefore the abundance and size of stones in the top 25 cm is used to grade the site.
- The effect of **soil toxicity** is also considered, and for the NSI sites the levels of five key elements have been measured: lead, cadmium, zinc, copper and nickel. On sites where these elements exceed a given threshold (Table 7), then the site is automatically limited to grade 3b (CEC, 1986).

Table 7 Threshold limits for acceptable heavy metals concentrations in soil (ppm).

| Heavy Metal | Threshold (ppm) |
|---|---|
| Pb | 300 |
| Cd | 3 |
| Zn | 200 |
| Cu | 80 |
| Ni | 50 |

- The last criterion considered by the ALC classification is the presence of **soil erosion** at the site. This was assessed by the soil surveyors at the NSI site and documented if the evidence of actual wind or water erosion was considered significant. For this exercise if evidence of erosion was recorded, the site is limited to grade 2 at best.

After all ten criteria were assessed, the most limiting criterion determined the overall ALC grade for each site (i.e. the worst-case grade).

## 4.4 Results and Discussion

### 4.4.1 Analysis of the changes in agroclimatic parameters

The 30-year Average Annual Rainfall reached its lowest point in the period 1961-90 (879 mm) but increased to 893 mm in 1971-2000 (Table 9). There is variation in AAR of only 30 mm over the six periods. It is clear that the general rainfall pattern in England and Wales has not changed significantly over this time. Figure 5 shows how the AAR has fluctuated over the period with a very slight trend downwards (-27 mm). Table 8 shows that the downward trend is repeated in every region in England and Wales, with the biggest decrease in the North East region. Interestingly there is an upward trend in AAR in Scotland over the same period (up 5 % since 1914).

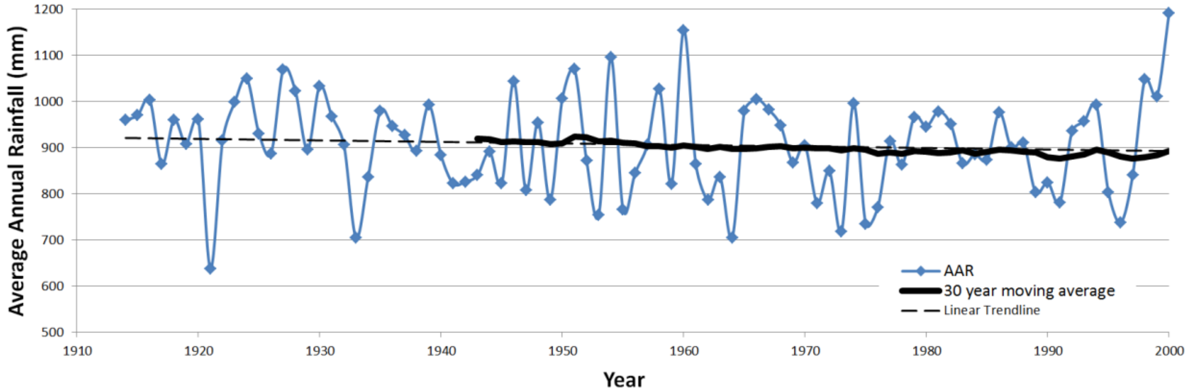



Figure 5 Mean average annual rainfall (AAR, mm) for England and Wales between 1914 and 2000. The long term trend is represented by the 30 year moving average.

Accumulated Temperature above 0 °C (January – June) dropped by 66 °C days, reaching its lowest point in 1951-80 (1314), but has climbed again since, reaching its highest point in 1971-2000 (1381). Figure 6 shows the annual variation across England and Wales with a general upward trend of 61 °C days over the whole period from 1914 to 2000. Although the overall trend has been upwards, the moving 30-year average (thick line) shows that the mean AT0 dropped until the end of the 1990's and has shown a substantial increase in the last decade of the 20th century.

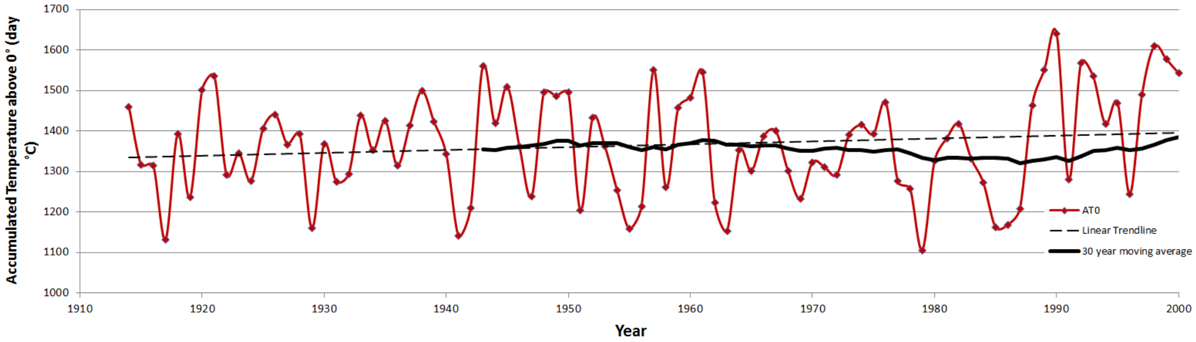



Figure 6 Mean annual accumulated temperature above 0°C (AT0) for England and Wales between 1914 and 2000. The long term trend is represented by the 30 year moving average.

The Duration of Field Capacity (FCD) has decreased slightly over this time in line with the changes in AAR from 1914 to 2000. The mean moisture deficit for winter wheat, calculated using method 2, was lowest (89 mm) in 1941-70 and 1951-80 and highest (96 mm) in 1971-2000 and for field potatoes it was lowest (77 mm) in 1951-80 and highest (86 mm) in 1971-2000. Table 8 shows the regional trends for moisture deficit from 1914-2000. The increase was most marked in the area around London, probably due to the heating effect of the city on the air temperature. The East Midlands and Eastern regions have shown the least increase in moisture deficit.

Although the average annual rainfall has remained reasonably stable over the six periods, the seasonal pattern of that rainfall has shown noticeable variation, with March and June rainfall getting higher (20-37 %) and July rainfall decreasing (by over 40 %) (Figure 7). By comparison the monthly temperatures have all tended to increase over the 87 years. The increase in AT0 in March is very high (20 %) while in May and June it is very slight.

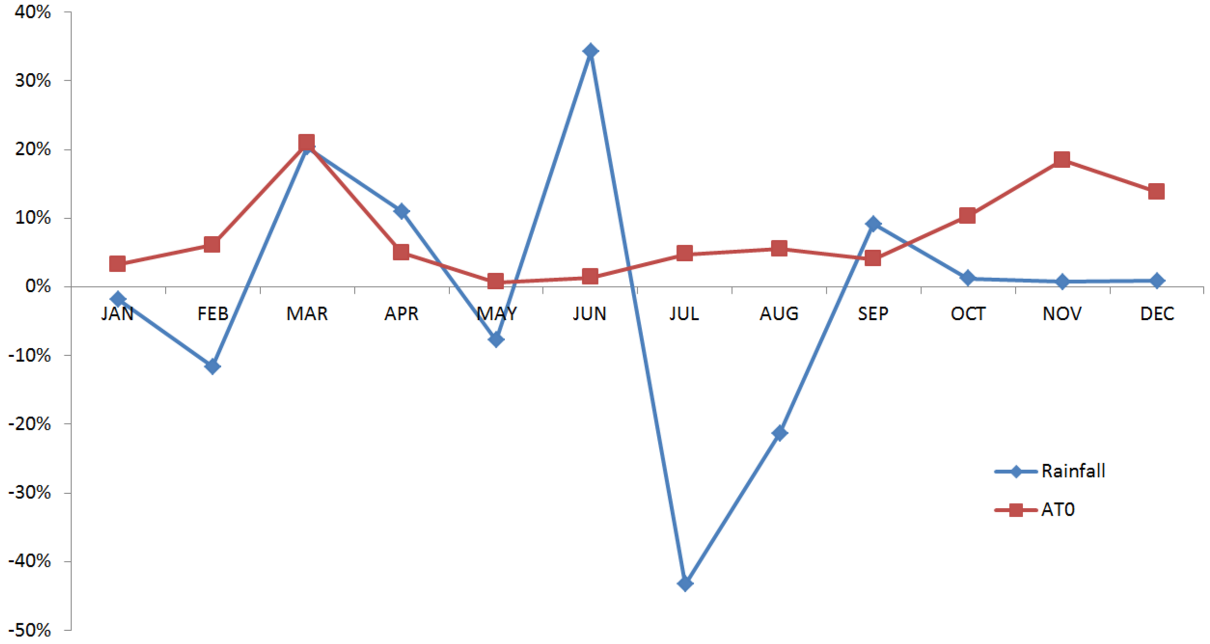



Figure 7 Percentage change in average monthly rainfall and accumulated temperature above 0°C (AT0) for England and Wales between 1914 and 2000.

The implications of this seasonal change in rainfall pattern is not being accounted for in the method used here to define the FCD for the different climate periods as they are being adjusted only by the AAR, which has not changed significantly over this time. However, looking at the general trends in seasonal rainfall and temperature, two conclusions can be drawn. Firstly, the increased rainfall in March and June could result in a delay in the end of FC date, which would have a significant effect on the workability of the land in that crucial spring window. Secondly, in the autumn the rainfall pattern is not changing significantly from October to December but there is a considerable rise in accumulated temperature over this time. This will result in the return date of field capacity being delayed until later in the year. Although the overall duration of field capacity might not change much, it will start later (in autumn) and end later (in spring) meaning that cropping patterns may need to change to more autumn sown crops.

Table 8 Overall trends in climatic variables between 1914 and 2000, by region: Average annual rainfall (AAR, mm); Accumulated temperature above 0°C (AT0); Reference crop evapotranspiration (Eto,mm); Potential soil moisture deficit (PSMD, mm); moisture deficit of wheat (MDwht, mm) and potatoes (MDpots, mm), data based on averages of the 5km points within each region.

| | Overall Trend from 1914 to 2000 | | | | | |
|---|---|---|---|---|---|---|
| REGION | AAR | AT0 | Eto | PSMD | MDwht | MDpots |
| East Midlands | -13 | 76 | 10 | 23 | -3 | 39 |
| Eastern | -15 | 66 | 35 | 40 | 3 | 39 |
| London | -29 | 104 | 121 | 108 | 40 | 82 |
| North East | -74 | 75 | 21 | 40 | 11 | 51 |
| North West | -46 | 78 | 65 | 41 | 17 | 47 |
| South East | -15 | 61 | 35 | 52 | 13 | 54 |
| South West | -13 | 24 | 36 | 52 | 18 | 59 |
| Wales | -27 | 49 | 62 | 47 | 24 | 43 |
| West Midlands | -26 | 73 | 20 | 37 | 9 | 52 |
| Yorkshire | -55 | 83 | 60 | 54 | 17 | 56 |
| England and Wales | -27 | 61 | 41 | 44 | 13 | 49 |
| Scotland | 74 | 42 | 73 | 29 | 13 | 23 |
| Ireland | 22 | 62 | -5 | 28 | 15 | 36 |

Table 9 Summary Statistics of Agroclimatic Parameters for Whole of England and Wales (6055 sites)

| Agroclimatic Parameter | 1921-50 | 1931-60 | 1941-70 | 1951-80 | 1961-90 | 1971-2000 | Original data |
|---|---|---|---|---|---|---|---|
| AAR (mean) mm | 909 | 904 | 899 | 890 | 879 | 893 | 907 |
| AAR (min) mm | 488 | 496 | 510 | 524 | 507 | 498 | 525 |
| AAR (max) mm | 3852 | 3754 | 3757 | 3854 | 4134 | 4199 | 3938 |
| AAR (sd) mm | 375 | 366 | 364 | 353 | 357 | 369 | 371 |
| AT0 (mean) °C days | 1381 | 1381 | 1339 | 1314 | 1321 | 1381 | 1348 |
| AT0 (min) °C days | 586 | 596 | 555 | 538 | 540 | 555 | 480 |
| AT0 (max) °C days | 1816 | 1814 | 1772 | 1732 | 1704 | 1767 | 1664 |
| AT0 (sd) °C days | 168 | 158 | 157 | 158 | 159 | 164 | 153 |
| FCD (mean) days | 190 | 189 | 188 | 187 | 186 | 187 | 190 |
| FCD (min) days | 83 | 85 | 86 | 86 | 82 | 81 | 85 |
| FCD (max) days | 365 | 365 | 365 | 365 | 365 | 365 | 365 |
| FCD (sd) days | 64 | 63 | 63 | 62 | 62 | 63 | 64 |
| MDMWHT (mean) mm | 91 | 92 | 89 | 89 | 92 | 96 | 86 |
| MDMWHT (min) mm | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| MDMWHT (max) mm | 152 | 153 | 146 | 139 | 143 | 148 | 133 |
| MDMWHT (sd) mm | 32 | 32 | 32 | 30 | 30 | 30 | 31 |
| MDMPOT (mean) mm | 80 | 82 | 78 | 77 | 81 | 86 | 73 |
| MDMPOT (min) mm | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| MDMPOT (max) mm | 160 | 160 | 152 | 142 | 145 | 153 | 133 |
| MDMPOT (sd) mm | 38 | 38 | 37 | 36 | 35 | 36 | 36 |
| ATS (mean) °C days | 2321 | 2342 | 2326 | 2295 | 2301 | 2338 | 2281 |
| ATS (min) °C days | 1374 | 1378 | 1363 | 1352 | 1343 | 1374 | 1299 |
| ATS (max) °C days | 2754 | 2762 | 2754 | 2714 | 2711 | 2753 | 2552 |
| ATS (sd) °C days | 193 | 191 | 191 | 188 | 185 | 189 | 182 |
| RAIN Jan (mean) mm | 95 | 91 | 86 | 86 | 88 | 92 | 91 |
| RAIN Feb (mean) mm | 68 | 67 | 64 | 65 | 63 | 66 | 62 |
| RAIN Mar (mean) mm | 54 | 57 | 58 | 64 | 71 | 72 | 62 |
| RAIN Apr (mean) mm | 58 | 54 | 57 | 55 | 58 | 59 | 69 |
| RAIN May (mean) mm | 63 | 62 | 65 | 62 | 62 | 58 | 67 |
| RAIN Jun (mean) mm | 55 | 60 | 60 | 62 | 62 | 64 | 62 |
| RAIN Jul (mean) mm | 78 | 77 | 72 | 68 | 60 | 55 | 70 |
| RAIN Aug (mean) mm | 80 | 80 | 88 | 82 | 74 | 70 | 80 |
| RAIN Sep (mean) mm | 76 | 78 | 81 | 80 | 76 | 78 | 84 |
| RAIN Oct (mean) mm | 93 | 90 | 82 | 79 | 84 | 90 | 75 |
| RAIN Nov (mean) mm | 100 | 99 | 96 | 94 | 89 | 91 | 99 |
| RAIN Dec (mean) mm | 88 | 88 | 89 | 93 | 93 | 99 | 87 |

### 4.4.2 Analysis of the changes in ALC grading

Although the climate was, on average, drier in the 1951-80 period it was also considerably cooler. ALC grade based on the climate criteria alone showed around 15 % of the grade 1 land (i.e. land not limited by climatic factors) would have reduced to grade 2 from its peak in 1930-60 to its lowest point in 1951-80 (Figure 8). In this period 1102 out of 6055 NSI sites were limited by climate, which reduced to 704 during the 1971-2000 decades.

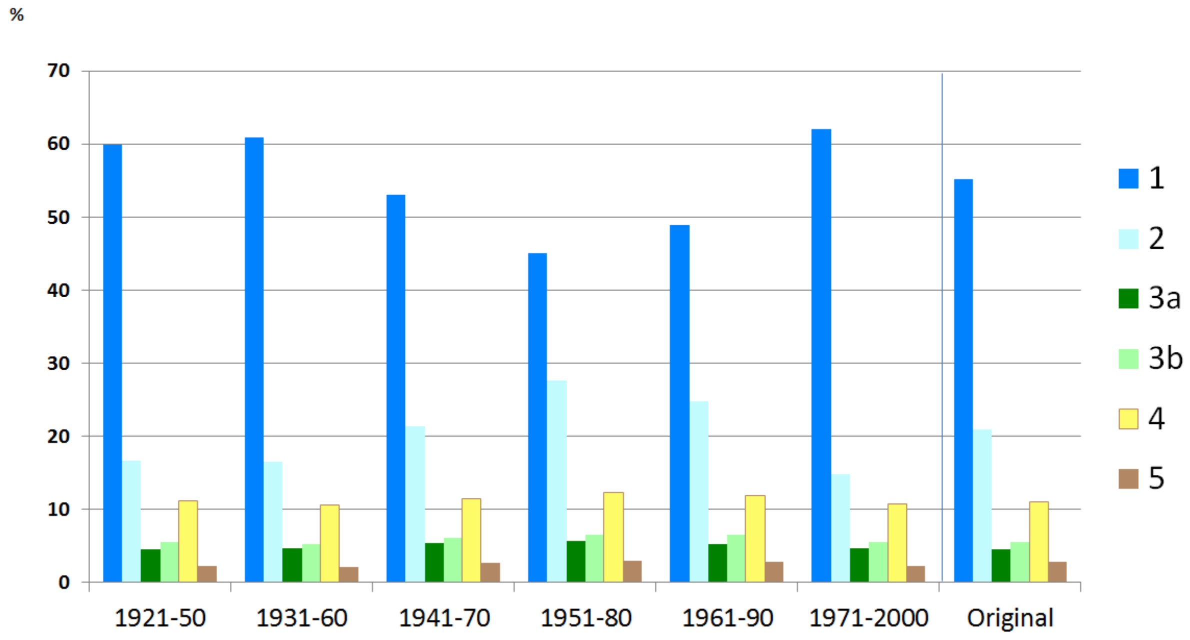



Figure 8 Proportion of land in England and Wales assigned to each ALC grade, if the grade is derived from the climatic criteria only, for each 30-year period, and for the 'original' ALC climate data (MAFF 1989).

In contrast to the climate classification, the area classified as droughty decreased as the temperature cooled and evapotranspiration reduced but increased in the warmer 1971-2000 period (Figure 9).

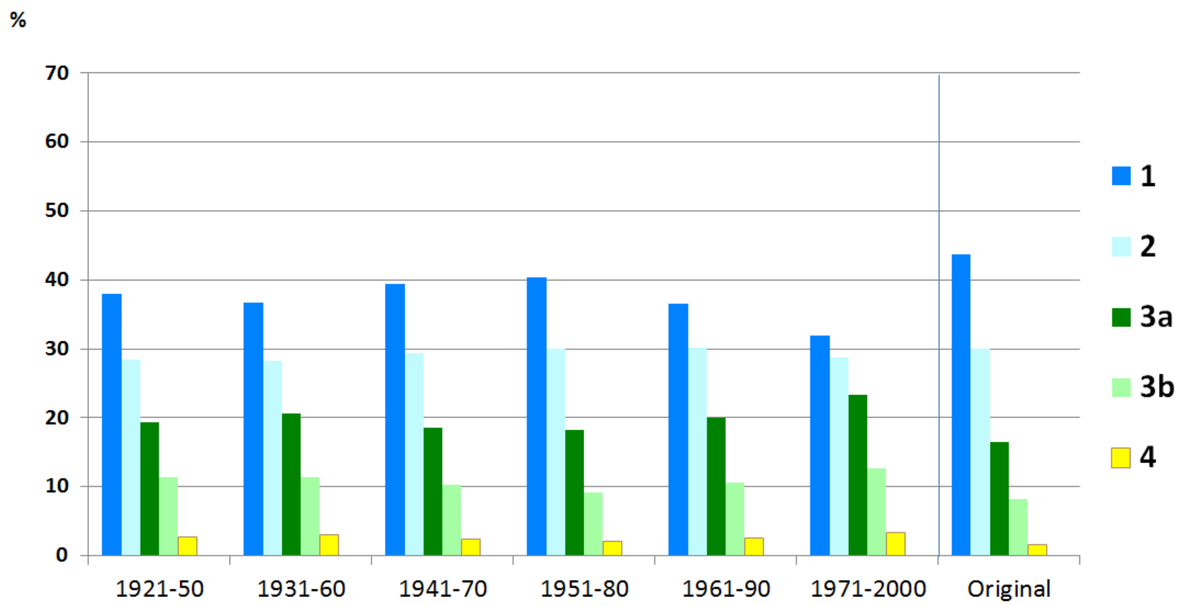



Figure 9 Proportion of land in England and Wales assigned to each ALC grade, if the grade is derived from droughtiness criteria (where moisture deficit is calculated from regression equation from ASR and ATS), for each 30-year period, and for the 'original' ALC climate data (MAFF 1989).

The small change in FCD over the 87-year period results in minimal change in the wetness class of the soils at each NSI site because wetness class is based on soil properties that have not been perturbed during this study. The ALC classification for wetness class is little affected by the changing climate (Figure 10) because it is related to AAR, which has not changed significantly.

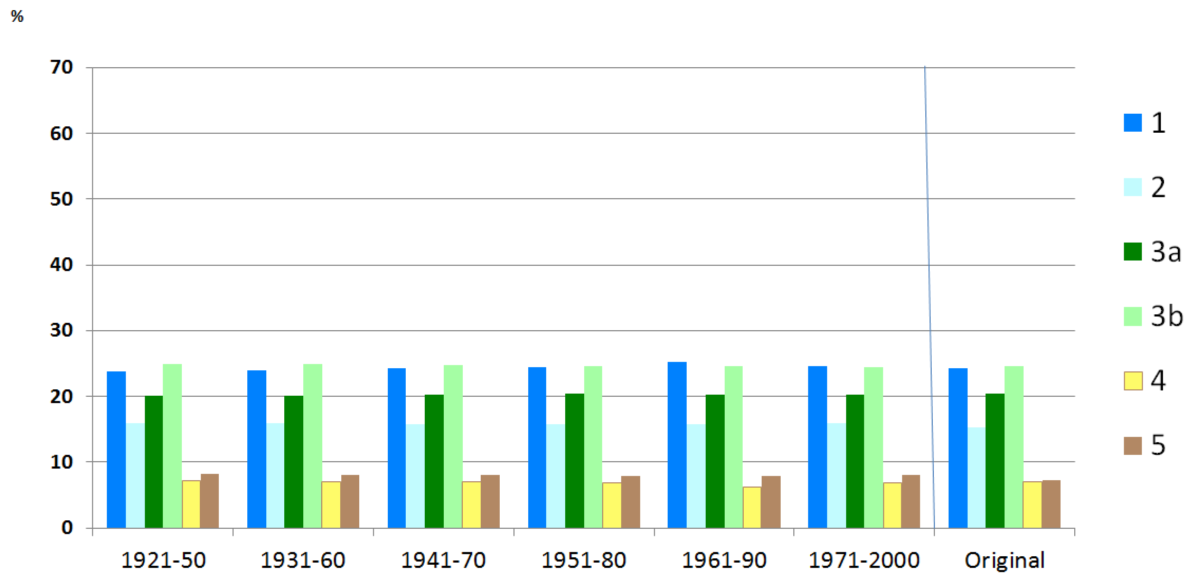



Figure 10 Proportion of land in England and Wales assigned to each ALC grade, if the grade is derived from wetness criteria only, for each 30-year period, and for the 'original' ALC climate data (MAFF 1989)..

Figure 11 shows the ALC classification for the other seven factors taken into account for determining the overall ALC grade and the proportion of NSI sites in each grade for each factor.

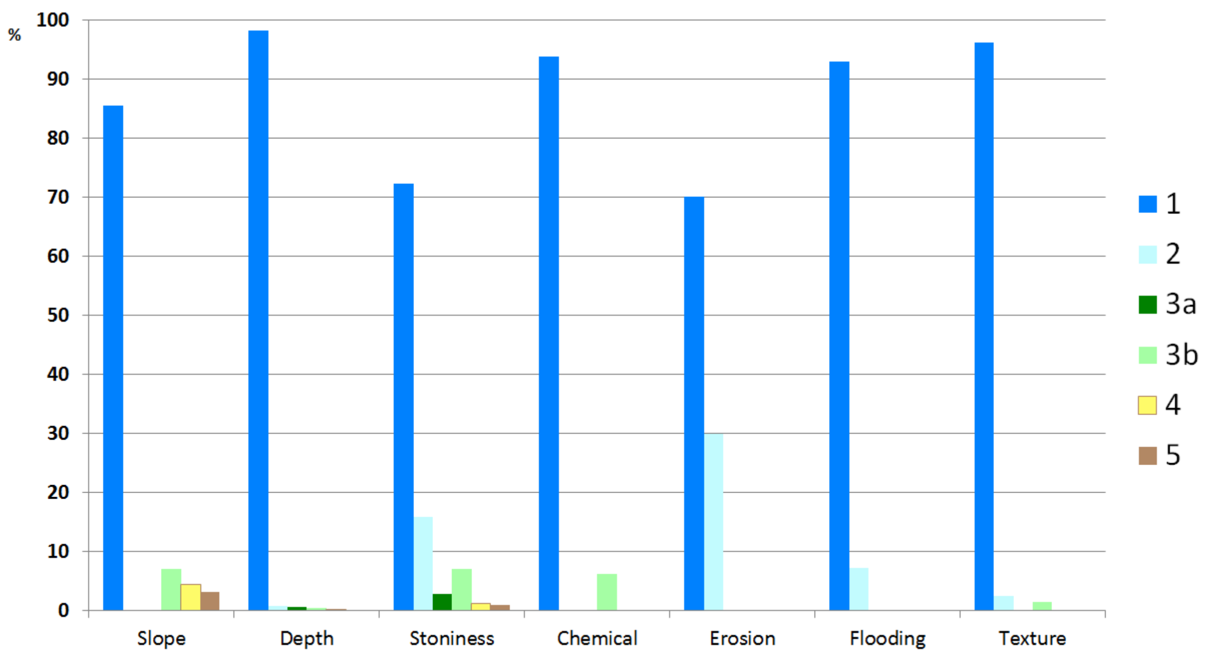



Figure 11 Proportion of land in England and Wales assigned to each ALC grade, when each of the remaining seven non climate criteria are taken into account in turn (these factors are considered not to have changed over the entire period (1921-2000)).

Once each NSI site had been assessed individually for the 10 criteria, the lowest (most limiting) ALC grade in terms of quality was selected as the overall ALC grade for that site.

Figure 12 shows the proportions of sites within each grade for each 30-year period. The first thing to note is just how few sites are classified as grade 1 once all the criteria have been applied. One factor or another will usually succeed in lowering the grade, especially as some of the factors are almost exclusive, for example sites failing due to climate are different to those failing due to drought. Others however have considerable overlap, for example the sites affected by wetness are similar to those affected by climate. The most limiting factors at each site were determined and Table 10 shows the percentage of sites limited by each factor. Wetness limits more sites than any other factor, with over one third of sites in England and Wales having this as one of the most limiting factors. This is followed by droughtiness, which affects around one quarter of the sites. The most noticeable difference is the amount of grade 4 land in 1971-2000 when method 1 is used, with most of East Anglia being classified as grade 4 on droughtiness. As previously discussed, method 1 seems to overestimate ETo.

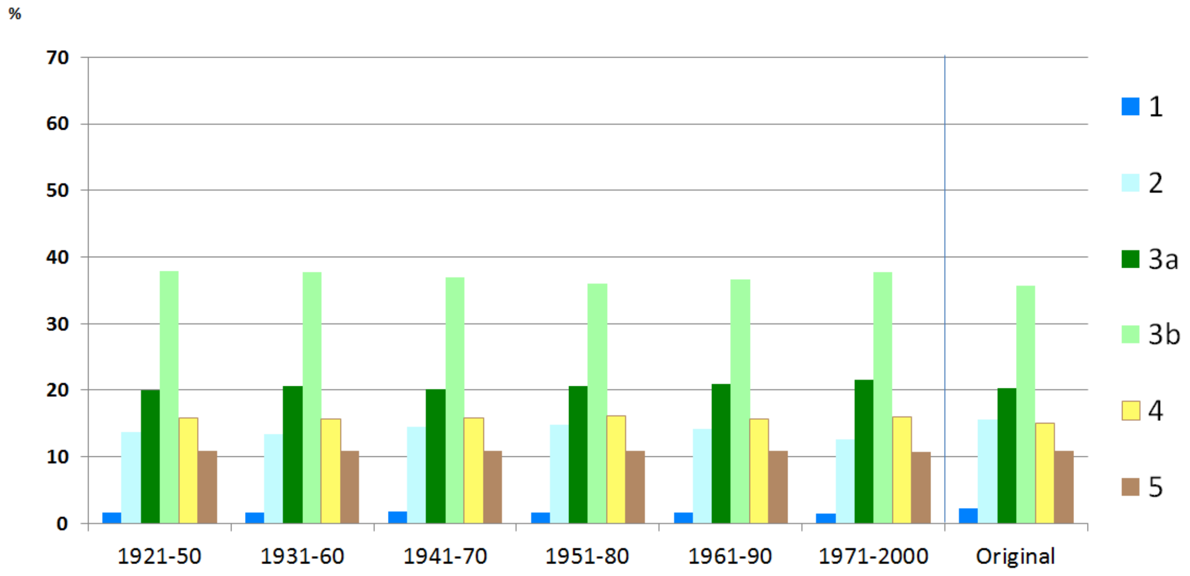



Figure 12 Proportion of land in England and Wales assigned to each ALC grade when all 10 factors were taken into account (including moisture deficit calculated from regression for the droughtiness factor), for each 30-year period, and for the original ALC period.

Figure 13 shows the spatial distribution of the most limiting ALC Grade of all 10 factors with droughtiness calculated using moisture deficit (MD) calculated by the moisture balance method (Method 1). Figure 14 shows the most limiting ALC Grade with droughtiness calculated using moisture deficit (MD) calculated from average summer rainfall (ASR) and accumulated summer temperature (ATS) (Method 2). As portrayed in these two figures, it is important to emphasise that the soil properties from the NSI used for this analysis are from single points in the landscape and do not necessarily represent the whole 5km square to which the climate data relate.

Table 10 Percentage of sites where factor(s) are the most limiting

| Factor | 30 year Period | | | | | | |
|---|---|---|---|---|---|---|---|
| | 21-50 | 31-60 | 41-70 | 51-80 | 61-90 | 71-00 | Original |
| None | 1.7% | 1.7% | 1.8% | 1.7% | 1.7% | 1.5% | 2.3% |
| Climate | 14.8% | 13.6% | 17.8% | 21.4% | 19.6% | 13.7% | 16.7% |
| Wetness | 54.8% | 55.0% | 54.6% | 54.4% | 53.1% | 53.6% | 55.6% |
| Drought | 31.2% | 31.9% | 29.6% | 28.2% | 31.0% | 34.7% | 26.8% |
| Erosion | 2.8% | 2.7% | 2.8% | 2.8% | 2.7% | 2.5% | 3.0% |
| Flood | 2.6% | 2.6% | 2.7% | 2.7% | 2.7% | 2.5% | 2.6% |
| Slope | 8.7% | 8.8% | 8.6% | 8.5% | 8.6% | 8.8% | 8.6% |
| Depth | 0.7% | 0.6% | 0.7% | 0.7% | 0.6% | 0.5% | 0.8% |
| Stones | 9.0% | 9.1% | 9.3% | 9.5% | 9.2% | 8.7% | 10.1% |
| Chemical | 3.5% | 3.6% | 3.5% | 3.7% | 3.7% | 3.7% | 3.8% |
| Texture | 1.2% | 1.2% | 1.2% | 1.3% | 1.3% | 1.1% | 1.5% |
| Best and Most Versitile Land | 35.4% | 35.7% | 36.4% | 37.1% | 36.8% | 35.5% | 38.2% |

### 4.4.3 Uncertainty

Due to the nature of the data and methods used within this study, an element of uncertainty is inevitable. Each dataset carries with it its own limitations and assumptions, all of which must be acknowledged within the results.

The data used for long-term climate is an interpolated layer derived from a large number of monitoring stations. The interpolated value at each 5km grid square is a representation of the parameter, but should not be interpreted as an absolute value. Inevitable gaps in long-term monitoring data are filled by synthetic values, again introducing scope for variation. Our methods utilise fixed cut-offs for climate parameters (e.g. AAR) and as such on a cell by cell basis, there is a scope for mis-categorisation.

Coupling the climate data to soil parameters introduces some scope for further uncertainty. The NSI data are not necessarily representative of the 5km square. The parameters recorded in the NSI dataset are therefore a sample value, but do not portray any variation within the square. We therefore make use of soil parameters such as soil depth or texture as a single variable in the 5km cell.

The uncertainty of our input parameters means that results should not be interpreted at a local scale. Outputs should be considered at a regional level at best and provide a statistical estimate of the ALC breakdown; they should not be viewed as a mapped product for purposes other than general overviews.

### 4.4.4 Analysis of changes in Best and Most Versatile Land

The National Planning Policy Framework (DCLG, 2012) defines the “Best and Most Versatile” (BMV) agricultural land as land in grades 1, 2 and 3a and instructs that when determining planning applications local authorities should seek to use areas of poorer quality (grades 3b, 4 and 5) in preference to that of higher quality. Although climate criteria are the most sensitive components of ALC, climate change has been shown to have the greatest effect on the area classified as grades 1 and 2. Thus the effect on the BMV pool is small, especially as the area graded as 3a that changes to grade 3b on the basis of climate factors alone lies mostly on the margins of the uplands where sites are already downgraded on slope and/or soil wetness. However the reduction in the number of droughty soils in the East of England due to the cooler climate in 1951-80 resulted in an increase in the amount of land classified as BMV so that the period 1951-80 had a larger proportion of good quality land than any other period.

## 4.5 Conclusions of the Historical Climate Analysis

1. The weather in the UK is very variable from year to year and therefore 30-year averages are appropriate to characterise the principal agroclimatic parameters and allow an assessment of suitability for particular crops and other land uses. A 30-year period is considered long enough to accommodate most variation in regional climates. Over the 87-year period analysed, the climate in England and Wales has been shown to be changing, but the change has not all always been consistent.
2. When the mean annual AT0 for England and Wales was analysed for 1914-1990, there was found to be a decrease of 18 °C days. The four warmest years for AT0 occurred in the last decade (1991-2000) and all except two of the ten years were above average AT0. This resulted in the overall trend from 1914 to 2000 being an increase of 61 °C days. Summarising the climate for the 20 years 1981-2000 gives a mean AAR of 913mm (up 20mm from 1971-2000) and a mean AT0 of 1438 °C days (up 57 °C days), which means the next 30-year period (1981-2010) is well on its way to being the warmest and wettest yet.
3. The current ALC system (MAFF, 1988) does not incorporate direct seasonal effects except in the calculation of the duration of field capacity. However it is likely that the increase in spring rainfall and warmer autumn periods could change the number of days in each of the spring and autumn workability periods, when machinery can safely work on the land without risking damage to the soil structure. This would be worth investigating in a future study.
4. The 30-year period 1961 to 1990 has been designated as the international standard reference period for climate averages by the World Meteorological Organization. This period was one of the coldest in the 87 year span and therefore has been chosen as the study baseline to emphasise the predicted changes in climate into the future.

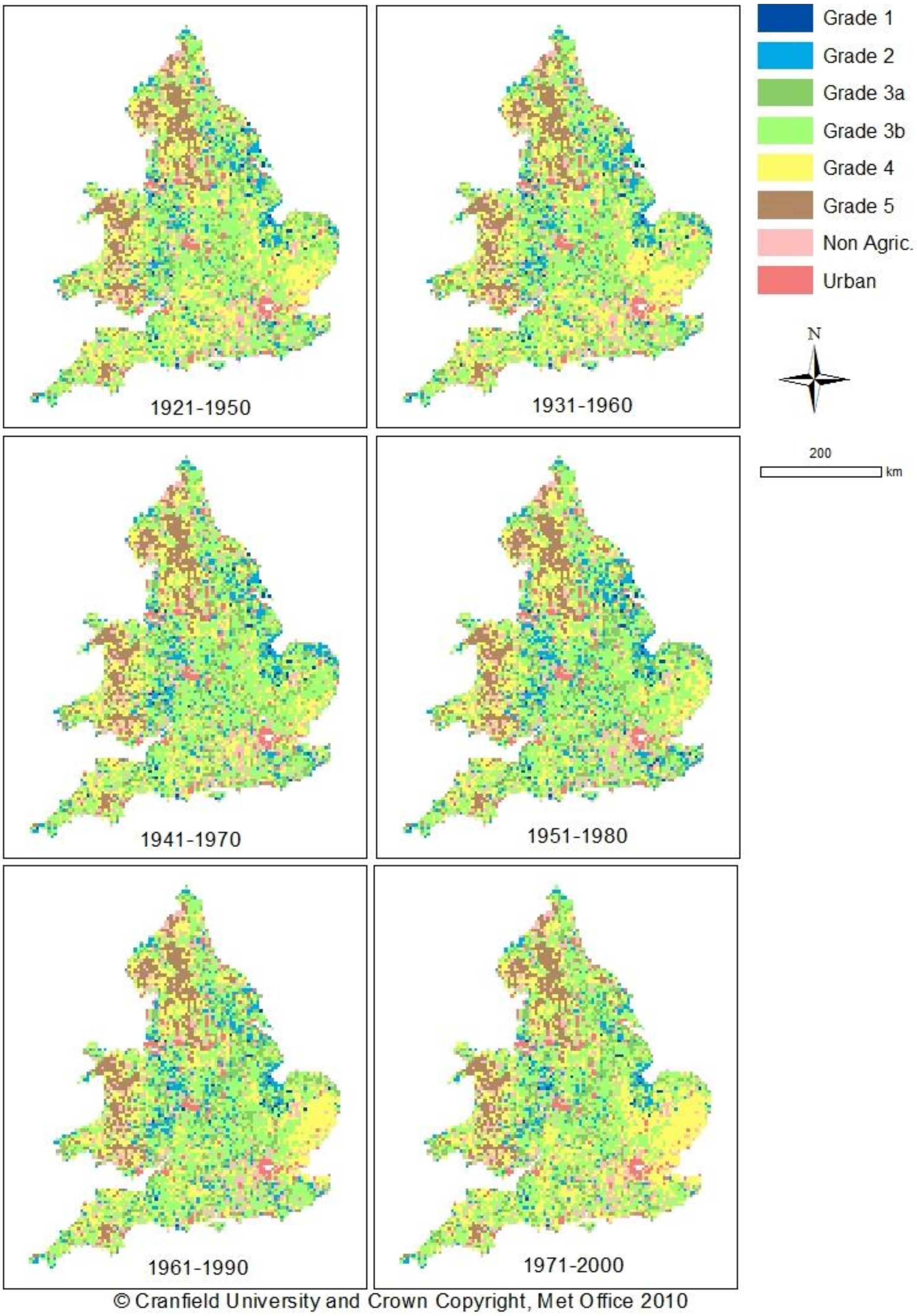



Figure 13 Most limiting ALC Grade of all 10 factors with droughtiness calculated using moisture deficit (MD) calculated by the moisture balance method (Method 1).

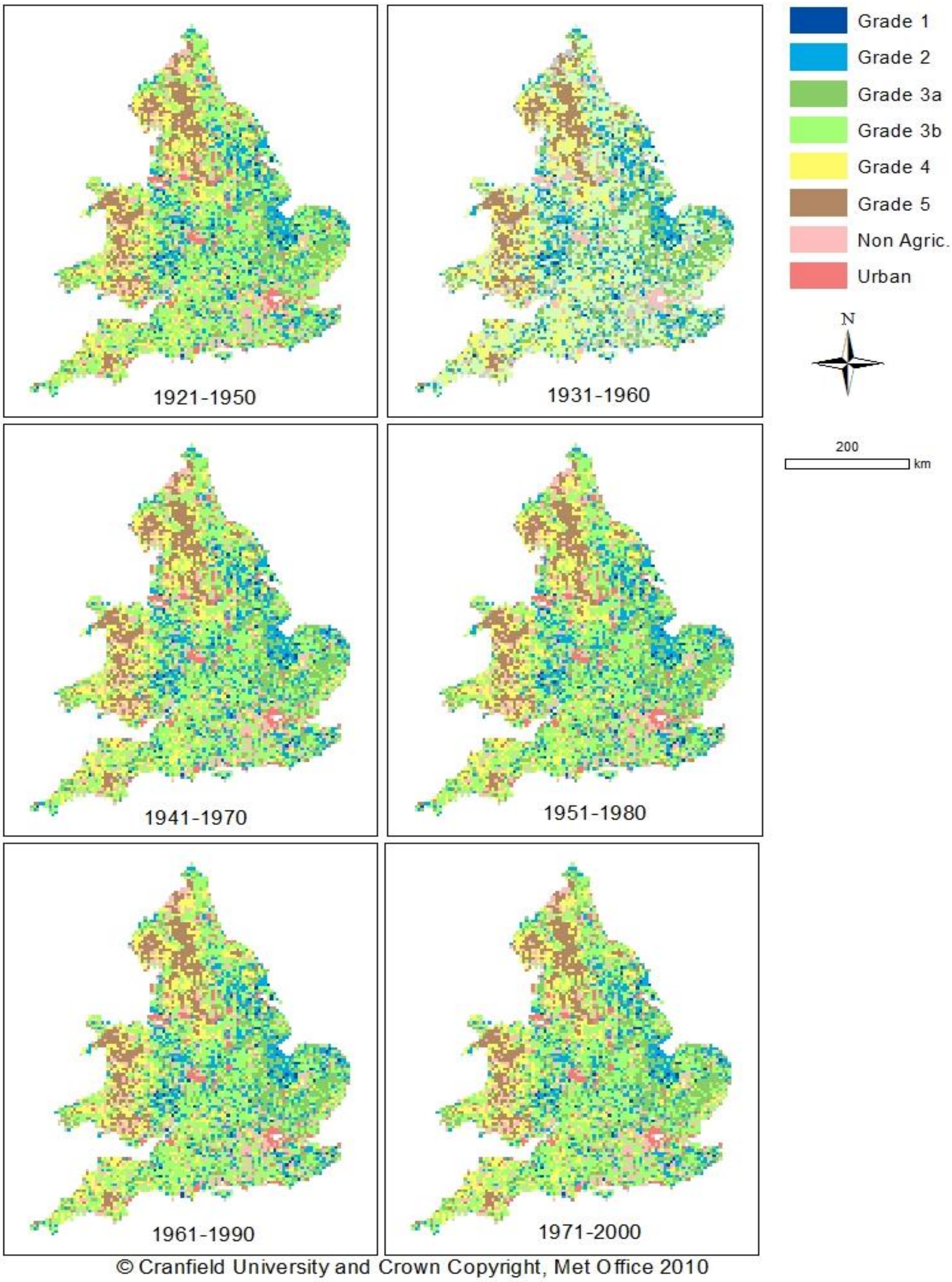



Figure 14 Most limiting ALC Grade of all 10 factors with droughtiness calculated using moisture deficit (MD) calculated from average summer rainfall (ASR) and accumulated summer temperature (ATS) (Method 2).

# 5 Objective 2: To generate appropriate digital future climate data using the UKCP09 scenarios

## 5.1 Summary

Climate data plays an important role in ALC system and the key variables include average annual and summer rainfall, accumulated temperatures, field capacity duration and moisture deficits for winter wheat and potatoes. The methods presented in the published Agricultural Land Classification of 1988 remain the statutory basis for the ALC, but further work in 2004 and in 2010 was conducted with the aim of improving the data and methods used in the derivation of the climate data sets. This section reviews the methods available to generate the derived climate data variables, and provides independent verification and justification for the chosen technique.

The methods for estimating the climate parameters were applied to the 1961-1990 baseline, which represents a standard World Meteorological Organisation (WMO) international climate period. The equations were also applied to the 12 UKCP09 climate scenarios representing the 2020s, 2050s and 2080s under low, medium and high emissions. The climate data were processed to take account of the 11 model runs, and downscaled from 25km x 25 km resolution to 5km x 5km resolution. Spatial variations in the baseline 1961-1990 climatology were used to scale the climate projections to 5km x 5km, rather than using a weather generator. This is because of time constraints on the project, and because the independence of each 25km x 25km grid may lead to discontinuities at the boundaries of the 5km x 5km grids.

A summary of the climate parameter methods are as follows:-

- Previous methods for determining January to June and April to September **accumulated temperatures** above 0 ºC were reviewed and the potential for improvements investigated. Analysis of observed Meteorological Station data revealed a significant underestimation in the original '1988 method'. The '2010 method', derived for this project was based on the '2004' investigation and used data from 29 Met Stations. Both the 2004 and 2010 provide technical advances to the 1988 method in an independent validation of the methods. The '2010' method was used to generate the baseline and future climate change accumulated temperature climatology for this study.
- Various methods for calculating **Field Capacity Days** were assessed based on 'Climate and Drainage' data (Smith and Trafford 1976) and daily Met Office Rainfall and Evaporation model (MORECS) data. A new '2010' method, derived for this project, was based on the '2004' revision but used data from 65 agroclimatic areas increasing the number of areas used three fold, to derive the relationship between summer and winter rainfall and field capacity days. A further improvement to the '2004' method was the inverse transformation of the rainfall data to remove the need for the separate wet and dry equations. Independent validation on 'Climate and Drainage' data showed a small RMSE of 17 days for the '2010' method. The '2010' inverse transformation method was used to generate the baseline and future climate Field Capacity Days climatology.

- The MORECS method to estimate Field Capacity Days uses set criteria to define the end of and return to field capacity from daily Soil Moisture Deficit data. Comparisons with the ‘2010’ Climate and Drainage method showed similar results, with a RMSE of 30 days. This independent verification increased the confidence in the use of the ‘2010’ inverse transformation approach derived from ‘Climate and Drainage’ data.
- Whilst the relationship between rainfall and field capacity days derived from MORECS data could have been used in this work, it was concluded that following the ‘Climate and Drainage’ ‘2010’ methods provided greater transparency. The main disadvantages to the ‘Climate and Drainage’ approach are that it is based on the 1941-1970 time period and cannot be adapted for temperature influences, which are clearly important under the climate change scenarios.
- MORECS also provides daily rainfall and potential evaporation on a 40km x 40km grid. This could be used to update the **Potential Soil Moisture Deficit (PSMD)** equations for winter wheat and maincrop potatoes. However, should these data be used to update the original methods, the threshold criteria for the classification of droughtiness would most likely need to be changed. As Potential Soil Moisture Deficit represents an index of droughtiness, and because accumulated temperature values will vary under climate change, the equations will provide a relative measure between the baseline and the scenarios. It is therefore unlikely that an update to the moisture deficit equations would benefit this work, in light of the extra resource required to produce the equations and examine the threshold criteria.

## 5.2 Accumulated Temperatures

### 5.2.1 Calculation of Accumulated Temperatures

Three methods for deriving January to June (ATO) and April to September (ATS) accumulated temperatures were assessed namely, the original ‘1988 method’, the ‘2004 method’ (Barrie 2004) and an improved ‘2010 method’. Each are subsequently described, and formulas for each of the methods are summarised in Table 11.

.

Table 11 Methods for Calculating Accumulated Temperatures

| Year | Parameter | Equation | Summary |
|---|---|---|---|
| 1988 | Accumulated temperature (January to June) | *1708 - 1.14(A) - 0.023(E) - 0.044(N)* | A is the altitude (m) at the grid intersection<br>E is the national grid Easting (EEEE)<br>N is the national grid Northing (NNNN) |
| | Accumulated temperature (April to September) | *611 + 1.11(AT0) + 0.042(E)* | |
| 2004 | Daily Mean Accumulated Temperature | *ATj = (0.42+0.49 (Txj)+0.48(Tnj))* NDIM* | ATj is the daily mean accumulated temperature for month j (°C days)<br>Txj is mean maximum daily temperature for month j<br>Tnj is mean minimum daily temperatures for month j<br>NDIM is the number of days in the month |
| 2010 | Daily Mean Accumulated Temperatures | ATj > 0ºC = (0.4476 + (0.4854*Tmax) + (0.4804*Tmin)) * NDIM | ATj is mean monthly accumulated temperature above 0 ºC for month j<br>Tmax is daily mean maximum temperature for month j<br>Tmin is the daily mean minimum temperature for month j |

**1988 Method:** Daily air temperature records between 1961 and 1980 from 94 climatological stations were used to derive the relationship between the median January to June accumulated temperature and altitude, latitude and longitude. The median accumulated temperature for April to September was derived from a relationship with the derived January to June accumulated temperatures and easting. The accumulated temperatures were subsequently interpolated across England and Wales onto a 5km x 5km grid following the 'calculate then interpolate' principle.

**2004 Method:** Daily air temperature records between 1971 and 2000 from 24 climatological stations were used to derive a relationship between mean monthly accumulated temperature above a base of 0 °C and the mean monthly maximum and minimum air temperatures. The relationship was then applied to the standard, gridded, Met Office 1971-2000 maximum and minimum temperatures following the 'interpolate then calculate' principle. The April to September and January to June accumulated temperatures are a sum of the six monthly totals.

**2010 Method:** The method developed for this project is based on the 2004 method. For the time period 1961 to 1990, a total of 29 stations (Figure 15) with complete station data (>95% completeness) were used to generate the relationships between the mean monthly accumulated temperatures above a base temperature of 0 ºC and the mean maximum and minimum monthly temperatures. The April to September and January to June accumulated totals were a sum of the relevant monthly totals. The derived relationship has an $R^2$ of 0.999, which is similar to the 2004 method.

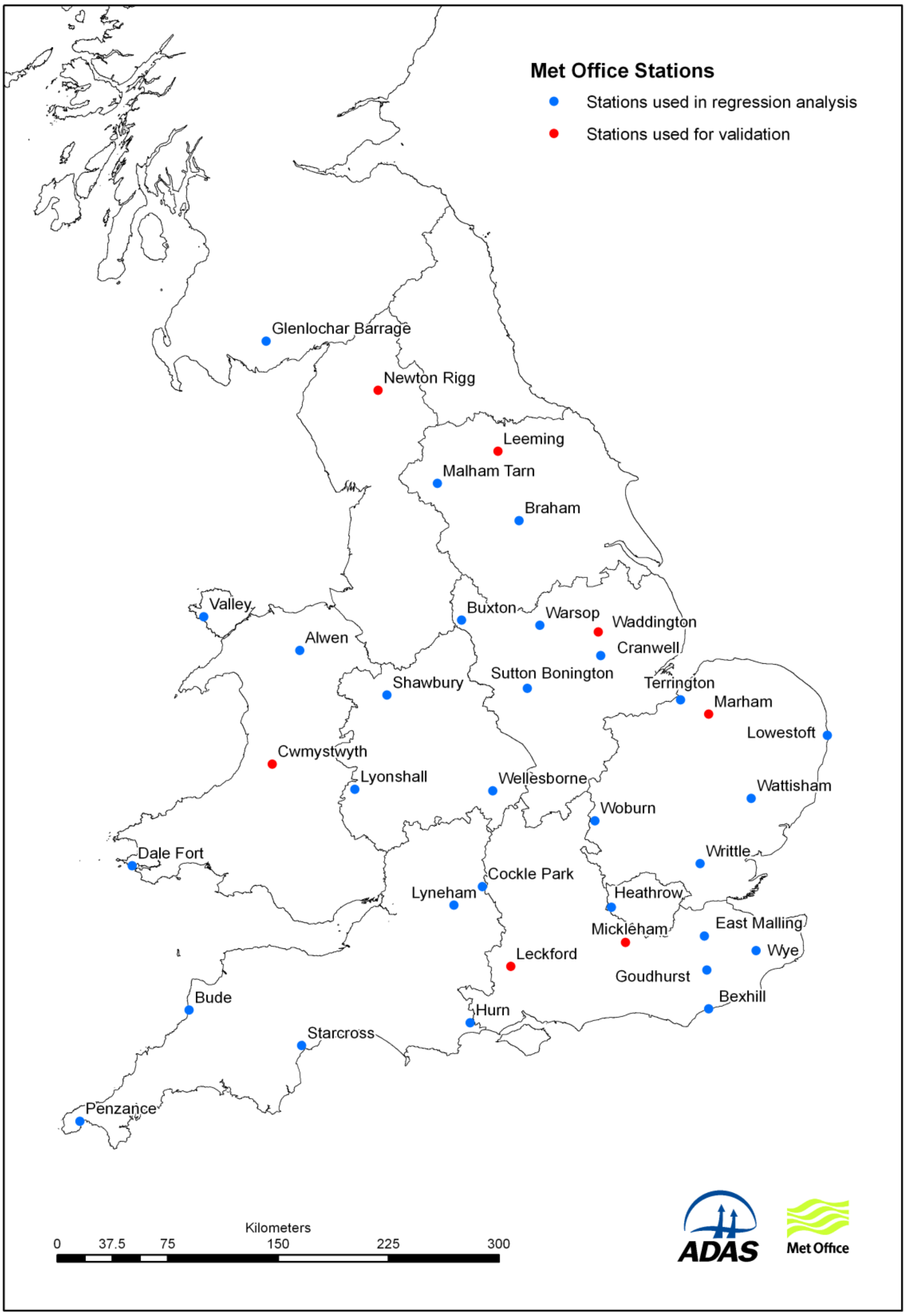



Figure 15 Location of the 29 Meteorological Office stations used in the regression analysis and the 9 stations used in the validation analysis

### 5.2.2 Validation of Accumulated Temperature Methods

All three methods outlined in Section 5.2 were subsequently applied to the climate data for the 29 stations used to derive the relationship in the ‘2010’ method (Figure 15). The derived estimates of accumulated temperature were compared to the observed/ actual accumulated temperature for each of the stations for 1961 to 1990 time period. The mean bias and root mean square error for each method are shown in Table 12. For April to September accumulated temperatures, the ‘2010 method’ performed best, producing a mean bias of -1.6 °C days and root mean square error of 7 °C days.

The ‘2010’ method as expected outperformed the other methods, since the relationship applied was derived from the same 29 stations data. The ‘2004’ method also performs well with a bias of 8.4 °C days and RMSE of 10.7 °C days, although some of the stations were also included in the derivation of this relationship for an overlapping climate period (1971-2000). Slightly higher errors are noted for the January to June accumulated temperatures. The ‘2010’ and ’2004’ method produces a root mean square error of 14.3 °C days and 15.1°C days respectively. In contrast, the ‘1988’ method significantly underestimates the actual accumulated temperatures for April to September, with a mean bias of 101.8 °C days and root mean square error of 147.6 °C days. There is also a large root mean square error of 118°C days for the January to June accumulated temperatures calculated from the ‘1988’ method.

Table 12 Mean Biases and Root Mean Square Errors of the 1988, 2004 and 2010 method when compared to the 29 stations used in the 2010 regression analysis. Based on the 1961-1990 time period.

| | **Accumulated Temperatures April to September** | | | **Accumulated Temperatures January to June** | | |
|---|---|---|---|---|---|---|
| **Station** | **Method 2010** | **Method 2004** | **Method 1988** | **Method 2010** | **Method 2004** | **Method 1988** |
| **Mean Bias** | -1.64 | 8.43 | -101.76 | -1.18 | 3.73 | -39.82 |
| RMSE | 7.00 | 10.69 | 147.64 | 14.3 | 15.13 | 118.26 |

* Statistics are based on the differences between the 3 methods for predicting accumulated temperatures and actual accumulated temperatures observed at the Meteorological stations.

An independent validation dataset for the ‘2010’ method, used data from seven meteorological stations (with >80% complete data) that were not included in the regression analysis. However, some of the seven stations were included in the derivation of the ‘2004’ method for the overlapping climate period (1971-2000). The location of the independent stations are marked by a red dot in Figure 15 and Table 13 provides the mean bias and root mean square error for each of the 3 methods.

The results show the ‘2004’ method slightly outperforms the ‘2010’ method for these stations, and this is expected given that some of the stations were used in the derivation of the relationship. The ‘2010’ method has Root Mean Square Errors of 18.9 °C days and 14.4 °C days for April to September and January to June totals, whilst the ‘2004’ method errors are 16.9 °C days and 12 °C days respectively. The ‘1988’ method does not perform well, with a RMSE of 450 °C days for April to September accumulated temperatures and 202 °C days for January to June totals. There is a significant underestimation of accumulated temperatures using the 1988 method.

Table 13 Mean Biases and Root Mean Square Errors of the 1988, 2004 and 2010 method when compared to the 7 independent Meteorological Stations

| | **Accumulated Temperature April to September** | | | **Accumulated Temperature January to June** | | |
|---|---|---|---|---|---|---|
| | **Station Biases (°C days)** | | | **Station Biases (°C days)** | | |
| **Station** | **2010 Method** | **2004 Method** | **1988 Method** | **2010 Method** | **2004 Method** | **1988 Method** |
| Mean Bias | -6.45 | 5.44 | -363.54 | -6.45 | -0.57 | -165.25 |
| RMSE | 18.94 | 16.87 | 449.92 | 14.35 | 11.97 | 201.45 |

It can be concluded that both the '2010' and '2004' methods perform significantly better than the '1988' method for the estimation of accumulated temperatures. The '2010' method was subsequently applied to the Met Office 5km$^2$ temperature climatology (1961 to 1990) and the derived accumulated temperatures for the grid squares coinciding with the 29 stations used in the regression were retrieved. The mean bias for April to September and January to June accumulated temperature totals for the 29 stations are 10.5 °C days and -17.8 °C days, whilst the Root Mean Square Errors are 67 °C days and 55 °C days respectively. These are larger differences when compared to the predicted values using station data, which is expected because the gridded 5km value represents the centre point of each 5 km x 5 km grid and is derived from interpolated station data, rather than a specific point value which the station data represents. However, the mean biases are small, providing confidence in the '2010' method for application to the 1961-1990 climate baseline and the climate change scenarios.

## 5.3 Field Capacity Days

Field capacity occurs when the soil holds the maximum amount of water it can hold against gravity. A return to field capacity, when the soil moisture deficit is zero, normally occurs during autumn or early winter, whilst it ends in spring when evapotranspiration exceeds rainfall. Estimation of the number of days that a soil is at Field Capacity is notoriously difficult to derive; there is no optimum system, but rather a choice of methods that all approximate to coarse field observations. The method used to describe the calculation of FCD is also not clearly documented for the earlier '1988' classification, hence a new method was derived for the '2004' revision and the '2010' method derived this project based on Climate and Drainage data for the 1941-1970 time period. In addition, the Met Office Rainfall and Evaporation Calculation System (MORECS), which provides a daily soil moisture deficit for the 1961-1990 time period, has been used as an independent check of the Field Capacity Days estimation. Each of the methods are subsequently discussed in detail:-

### 5.3.1 Calculation of the number of Field Capacity Days

**1988 Method:** This approach is based on the work of Smith (1967), who used bi-weekly rainfall and monthly potential transpiration in a water abstraction model to limit transpiration as the soil dries out. The start of field capacity was defined as the date at which the soil moisture was no longer in deficit, whilst the end was defined as the date when soil moisture deficit returned.

**2004 Method**: The median dates for return to and departure from field capacity, average summer and average winter rainfall for the 1941 to 1970 time period were extracted from the 'Climate and Drainage' reference book for 22 agro climatic areas (MAFF reference book 434). Subsequently, relationships between Field Capacity Days and Eastings, Northings, altitude and rainfall (average summer and winter rainfall) were derived for high and low rainfall areas (as defined by average annual rainfall below above 800mm). The equations are summarised in Table 14.

Table 14 Methods for Calculating Field Capacity Days (FCD)

| Year | Parameter | Equation | Summary |
|---|---|---|---|
| 2004 | FCD dry | **-78.62+ 0.2221*ASR+0.3085*AWR+0.2152*ALT+0.00082*E+0.00794*N** | Where FCD is median field capacity duration (days)<br>ASR is average summer rainfall (April to September) (mm)<br>AWR is average winter rainfall (October to March) (mm)<br>ALT is altitude in metres<br>E and N are Easting and Northings |
| | FCD wet | **47.50+0.0519*ASR+0.1856*AWR+0.1198*ALT+0.0054*E+0.00394*N** | |
| 2010 | FCD | **367.14-(55007.8*INVASR) + (25867.3*INVAWR) + 0.000564*EEEE + 0.004383*NNNN + 0.1*ALT** | Where FCD is median field capacity duration (days)<br>INVASR is the inverse transformation of average summer rainfall (April to September) (mm)<br>INVAWR is the inverse transformation of average winter rainfall (October to March) (mm)<br>ALT is altitude in metres<br>EEEE and NNNN are Easting and Northings |

**2010 Method:** A number of approaches were investigated to account for the seasonal trends in rainfall and temperature in the calculation of field capacity days. However, for transparency, the same principles to the '2004' revision was utilised for the '2010' method and subsequently applied to the baseline and climate change scenarios. The 1941-1970 median values of return to and end of field capacity from 'Climate and Drainage' were extracted, but for a larger number of agro climatic areas (in total 65 areas). Furthermore, average summer (April to September) and winter (October to March) rainfall components were normalised to eliminate the need for separate equations for dry and wet areas.

A number of transformations were investigated, but the inverse transformation worked best. The median duration of field capacity days were subsequently regressed against the normalised average summer and winter rainfall, location, and altitude. The resulting equation is shown in Table 14, and has an $R^2$ of 0.98 and a small standard error of 6.4 days.

There are a number of limitations to this method. Firstly, as no temperature data is provided in ‘Climate and Drainage’ it could not be included in the predictive equation. Therefore changes in temperature under climate change will not be accounted for in the calculation of field capacity days. Secondly, the predictive equation is based on areal averages from Climate and Drainage rather than the more accurate station values. Furthermore, the altitude data for the percentile data in ‘Climate and Drainage’ is estimated from a range, which provides a source of error. Thirdly, the method for deriving return to and end of field capacity in terms of the definition of soil moisture deficit and how fluctuations in and out of field capacity are accounted for is not clearly documented in Smith and Trafford (1976).

It is also noted that while the soil moisture balance models produce a good estimate of the return to field capacity in autumn, it is ‘far more difficult to specify or estimate the end of capacity in spring’ because it is an ill-defined intermittent process. Therefore, the ending of field capacity dates data in Climate and Drainage are ‘the best that can be estimated on the basis of past weather, but it must be stressed that the April rainfall and the April transpiration are very nearly equal in most farm areas. Therefore, any small change in either parameter will have a major effect on the dating of the end of capacity’ Smith and Trafford (1976, p9).

**MORECS Method**: The MORECS system uses input from daily observations from 130 synoptic stations, and uses a complex Penman Monteith equation to calculate evapotranspiration, soil moisture deficit and excess rainfall over Great Britain. Outputs are averages over 40 x 40 squares and daily estimates are available from 1961 to the present day. MORECS is fully described in the Met Office Hydrological Memorandum 45 (and updates).

For this work, the MORECS estimates were used to validate the Field Capacity Days estimates from the ‘2010’ method for the time period 1961-1990. MORECS was also used to derive new predictive equations, based on the 1961-1990 time period and the predictive equations could also include temperature data. However, for this project, these predictive equations were not used to estimate Field Capacity Days for the baseline and climate change scenarios, to ensure consistency with previous revisions of the Agricultural Land Classification and greater transparency in the work.

The definition of the end and start date of Field Capacity from soil moisture deficit is subjective, and two published methods (Francis 1981 and Smith and Trafford 1976) were used as the basis for defining the start and end dates in the daily soil moisture estimates (assuming a grass crop and medium available water content soil). The **End of Field Capacity** is defined as the start date of a drying sequence of 10 days or more with a soil moisture deficit of 5mm or more. The 5 mm threshold is consistent with the published methods of Francis (1981) and both Smith and Trafford (1976) and Francis (1981) use 10 day sequences. The **Return to Field Capacity** was defined as the start date of a wetting sequence of 10 days or more with a soil moisture deficit of less than 5mm. From these two dates, the median or 50th percentile value for the start and end dates were calculated for the 30 year period and used to validate the ‘2010 Method’.

### 5.3.2 Validation of the 2010 'Climate and Drainage' method

Two independent data sets were used in the validation exercise of the '2010' method. Firstly, independent early and late quartile data from 'Climate and Drainage' were extracted for arable areas with average annual rainfall less than 1000mm for 10 agroclimatic areas, providing a sample of 15 Field Capacity Days estimates. The mean bias (the difference between the Climate and Drainage printed values and the predicted values from the '2010' method) from the 15 sample points was 17 days.

The second stage of validation compared the '2010' and '2004' method Field Capacity Day estimates with the MORECS median estimates of field capacity and the results are shown in Figure 16. MORECS estimates from soil moisture deficit provide a lower number of field capacity days in drier areas compared to the '2004' and '2010' methods. However, for Field Capacity Days greater than 100, all the methods do fairly well.

In ALC, there are a number of classes between 100 and 225 Field Capacity Days, and for this range of data the predictive methods compare favourably with MORECS data. This produces a positive mean bias of 22.3 days for the '2004' method and 17.6 days for the '2010' method. In terms of root mean square error, the '2004' method has an error of 37 days, whilst the '2010' method performs better with an error of 30 days. A linear regression between the MORECS estimates and each of the predicted estimates of Field Capacity Days shows a strong relationship with an $R^2$ of approximately 0.93 for the '2010' method.

In conclusion, the '2010 method' derived from median percentile data presented for 65 agroclimatic areas produces good results when compared to the independent percentile data from Climate and Drainage and the MORECS estimates of Field Capacity Days. The '2010' predictive equation was subsequently applied to the 1961-1990 baseline and the climate change scenarios.

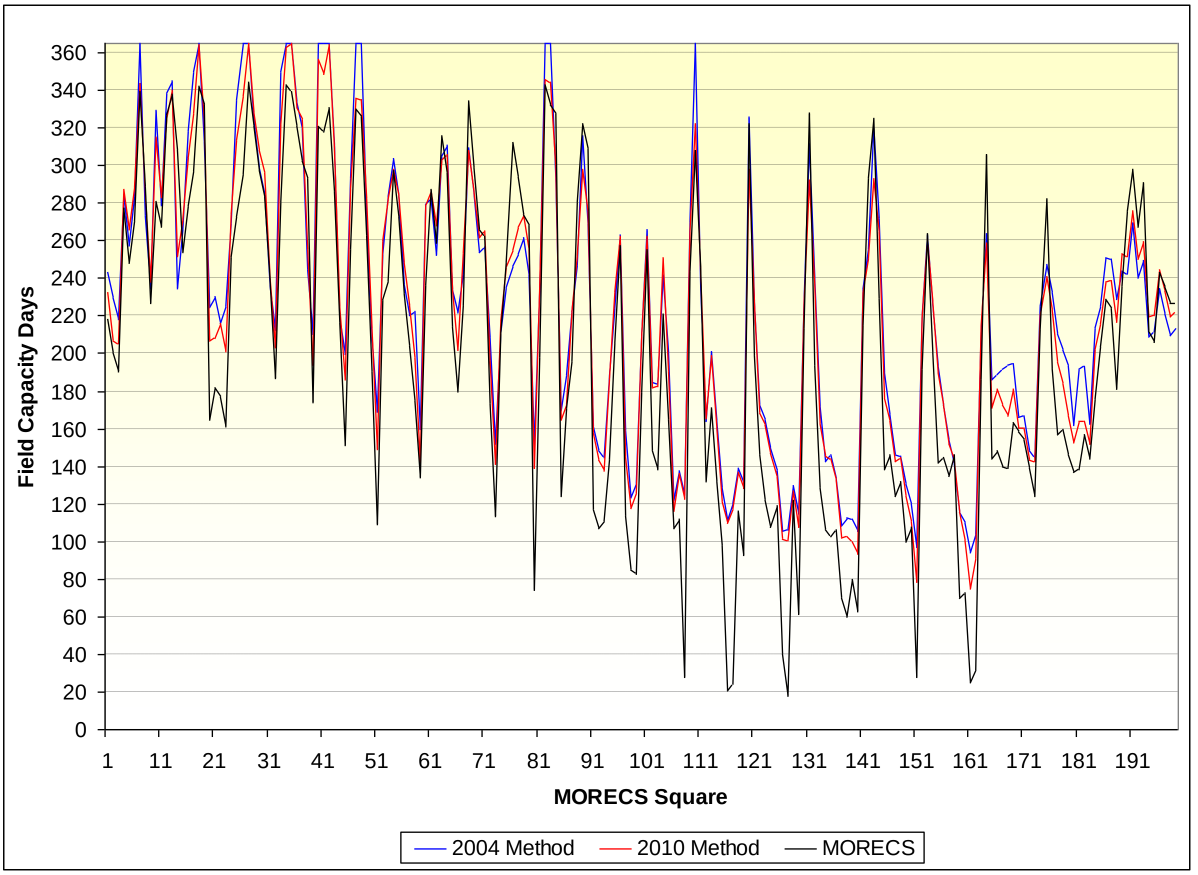



Figure 16 Comparison of MORECS and Climate and Drainage Predicted Median Field Capacity Days for the 1961-1990 time period

## 5.4 Soil Moisture Deficit

Soil moisture deficit for potatoes and winter wheat represent a droughtiness factor in the derived climate variables. Moisture deficit refers to the balance between rainfall and potential evapotranspiration during a critical portion of the growing season and is a crop related variable. Potatoes and winter wheat are representative of a broad range of crops grown in the UK.

### 5.4.1 Calculation of Soil Moisture Deficit Winter Wheat and Main Crop Potatoes

**1988 Method:** When the climate scenario data was first constructed the analysis of the calculation of the soil moisture deficit component concluded that the original regression equations based on accumulated summer temperature (ATS) and Average Summer Rainfall (ASR) would be most appropriate (see Equations 3 and 4 in Section 4.3.3). However it was soon shown that when these equations were extrapolated into the future climate scenarios the results were extreme and by the 2080s the whole country would have been assessed at grade 4 at best. As a result of this a project extension was undertaken to focus on droughtiness (see Section 8). From the work during this extension the MORECS data was examined and new more robust regression equations were established. These equations are discussed here and the resulting equations were then used in the assessment of ALC into the future.

**MORECS Method**: The Met Office Rainfall and Evaporation Calculation System (MORECS) has been used to define the winter wheat and main crop potato predictive equations for the application to the 1961-1990 baseline and climate change scenario data. The average July and August soil moisture deficit for main crop potatoes and winter wheat on medium available water content soils between 1971 and 2000 was extracted. The monthly average soil moisture deficit was used rather than end of August soil moisture deficit for main crop potatoes or mid-July soil moisture deficit for winter wheat to smooth out sudden changes in the data. The sensitivity to using monthly averages rather than traditional mid, or end of month values has been tested and was found to be small. The soil moisture deficit for both crops were regressed against normalised monthly average summer rainfall (April – September) and temperature. Other variables including location, altitude, available water content, wind speed and sunshine were also analysed to test if they could explain a proportion of the variance but the correlations were either low or already represented in the rainfall and temperature variables. The resulting equations are presented in Table 15. The soil moisture deficit and main crop potato predictive equations show high $r^2$ values of > 0.9.

Table 15 Methods for Calculating Soil Moisture Deficit for Winter Wheat and Main Crop Potatoes and Estimating Average Monthly Summer Temperature

| Parameter | Equation | $R^2$ |
|---|---|---|
| Winter Wheat Soil Moisture Deficit | 271.4754 + (-168.802 x LOG10 Rainfall) + (10.00217 x Temperature) | 0.91 |
| Main Crop Potatoes | 337.8238 + (-185.614 x LOG10 Rainfall) + (5.849057 x Temperature) | 0.90 |
| Average Monthly SummerTemperature | 0.00547 * ATS – 0.04 | 0.999 |

### 5.4.2 Validation of the MORECS Predictive Equations

The new regression equations (Table 15) were used to recalculate the moisture deficits for winter wheat and maincrop potatoes based on the original published 1989 climate data (Met Office, 1989). As the raw climate data required for the predictive equations was not available from this source, it was assumed that the monthly average summer rainfall between April and September is represented by 1/6$^{th}$ of the average summer rainfall total. Monthly average summer temperatures were also not available from this source, so the UKCP09 accumulated summer temperature estimates on a 5km grid data between 1971-2000 was used to derive a relationship, that had a high $R^2$ value of 0.9999 based on 310,710 sample data points. This equation is shown in Table 15. The derived rainfall and temperature variables were calculated and compared to the original published moisture deficit values (Met Office, 1989). The results show that the new MORECS predictive equation for winter wheat had a strong $r^2$ of 0.99. However, the relationship is less strong for main crop potatoes ($r^2$ of 0.94), which would result in different classification cutoffs being applied to get the same levels of drought. The original classification was ground truthed by drainage experts in the field and should be considered as accurate as was possible at the time. A correction factor was therefore created and applied to the cutoff levels required to classify the ALC grade by droughtiness for potatoes as shown in Table 16.

Table 16 Correction factor used to adjust threshold of Droughtiness Classification for Potatoes

| ALC | Old | New |
|---|---|---|
| 1 | 10 | 17 |
| 2 | -10 | 3 |
| 3a | -30 | -12 |
| 3b | -55 | -30 |

In conclusion, whilst the MORECS method provides the potential to update the soil moisture deficit equations for winter wheat and maincrop potatoes, a change in the threshold criteria for the classification of droughtiness would most likely need to be made. As potato soil moisture deficit represents an index of droughtiness, and because accumulated temperature values will vary under climate change, the equations will provide a relative measure between the baseline and the scenarios. It is therefore unlikely that an update to the moisture deficit equations would benefit this work, in light of the extra resource required to produce the equations and examine the threshold criteria.

## 5.5 Production of Climate Change Scenario Datasets

Projected climate data were sourced from the UK Climate Projections (UKCP09) for a total of twelve climate change scenarios, including high (H), medium (M) and low (L) emissions scenarios for the time periods 2020s, 2030s, 2050s, and 2080s (Table 17). The data were named after the central decade of the time period e.g. 2020s is derived from model runs from 2010-2039. The emissions scenarios used by UKCP09 were derived from the IPCC Special Report on Emissions Scenarios (SRES), which is based on a number of potential future storylines from factors such as population change, energy use, and continued emissions of greenhouse gases and aerosols. The high emissions scenario uses the A1F1 storyline, medium the A1B1 storyline, and low the B1 storyline.

Table 17 UKCP09 climate scenarios data used in analysis

| Climate scenario | Time period | Emissions scenario |
|---|---|---|
| 2020H | 2010 - 2039 | High |
| 2020M | 2010 - 2039 | Medium |
| 2020L | 2010 - 2039 | Low |
| 2030H | 2020 - 2049 | High |
| 2030M | 2020 - 2049 | Medium |
| 2030L | 2020 - 2049 | Low |
| 2050H | 2040 - 2069 | High |
| 2050M | 2040 - 2069 | Medium |
| 2050 L | 2040 - 2069 | Low |
| 2080H | 2070 - 2099 | High |
| 2080M | 2070 - 2099 | Medium |
| 2080L | 2070 - 2099 | Low |

### 5.5.1 Data Description

UKCP09 used the emissions scenarios to model the projected change in climate from the 1961-1990 baseline, and calculate average climate values for a series of 30-year time periods. The global data has been downscaled by UKCP09 with the Met Office Hadley Centre's regional climate model (HadRM3) to produce 11 model runs at a 25 km x 25 km resolution on a rotated-pole grid. The data obtained from the UKCP09 archive for analysis was from the spatially correlated projections (SCP) dataset, which is available as monthly averages for each of the 11 HadRM3 runs. The 11 model runs in the SCP data have no likelihood attached, so each projection is equally plausible. The variables extracted from this dataset for processing were minimum air temperature, maximum air temperature and daily precipitation rate.

### 5.5.2 Data Processing

In order to provide one data set representative of each 11 HadRM3 runs and downscaled to 5 km x 5 km resolution, the data were processed as follows:

To account for any variation between the 11 HadRM3 projections, the 25km x 25km grid values for each parameter were averaged to give a single monthly value for each of the 12 climate scenarios.

The 25 km x 25 km UKCP09 data was then downscaled to 5 km x 5 km for comparison with the 1961-1990 baseline data. Whilst weather generators are available, the independence of each 25 km x 25 km grid may lead to discontinuities at the boundaries of the 5 km x 5 km grids. Spatial variations in the baseline 1961-1990 climatology were used to scale the climate projections to the 5 km x 5 km scale. The method is as follows:-

- Assign the rotated UKCP09 grid IDs to the baseline grid, with an ID selected where the centroid of a 5km x 5 km cell falls within the boundaries of a 25 km x 25 km grid cell.
- Group the baseline by the assigned 25 km x 25 km grid IDs, and calculate the average climate value. Divide the original 5 km x 5 km values by the 25 km x 25 km average climate value to determine the proportion of the baseline climate value that makes up the average.
- The 5km x 5 km proportions were then applied to the 25 km x 25 km data to downscale the projected climate values to 5 km x 5 km resolution.

# 6 Objective 4: Generation of ALC classification maps for NSI sites under future Climate Scenarios and Objective 5: Comparative evaluation of the existing and future maps and methodologies

## 6.1 Summary

The climate data, derived as part of Objective 2 of this project, were applied to the National Soil Inventory (NSI) site data to evaluate the ALC grade under the varying climatic conditions. The results are presented in map and tabular form, with a discussion of the implications for the future of agriculture in England and Wales.

## 6.2 Methods

For each of the 30-year periods, an assessment of the ALC grade was carried out using soil and site parameters from the National Soil Inventory on a 5 km grid across England and Wales. The climate data for the NSI point were taken for the 5 km cell in which it resides. In order to make suitable comparisons with the original climate data, the data were not interpolated from the four surrounding sites and adjusted for the altitude at the NSI point, as described in Met Office (1989).

ALC classification was calculated using 10 criteria: climate (AAR/AT0), soil wetness, droughtiness, gradient, flooding, texture, depth, stoniness, chemical, and erosion. The first three criteria are influenced by climate and were calculated for the baseline and 12 future climate scenarios; the remaining seven criteria were assessed for each of the NSI sites from the original observed data as surveyed in 1979-1983. The overall ALC grade given to a site was the lowest grade (i.e. the most limiting grade) from the 10 criteria.

### 6.2.1 ALC Grade by Climate

The assessment of ALC grade for climate was based on the Annual Average Rainfall (AAR) and Accumulated Temperature above 0 °C from January to June (AT0). AT0 was calculated using the 2010 method described in Section 5.2.1 where the accumulated temperature is calculated for each month using a regression equation based on the daily mean minimum and maximum temperatures multiplied by the number of days in the month and then summed to give the annual figure. The Annual Average Rainfall is provided directly for the UKCP09 scenarios and does not need to be derived and only needed to be interpolated onto a 5km grid as described in section 5.5.

### 6.2.2 ALC Grade by Soil Wetness

The Soil wetness class was assessed using the procedure in Appendix III of MAFF 1988. This method uses the duration of field capacity days, the presence of a gleyed horizon and the depth to a slowly permeable layer to determine the wetness class of the soil. The ALC grade is then based on wetness class, the texture of the topsoil and FCD.

### 6.2.3 ALC Grade by Droughtiness

The ALC system uses moisture deficit for winter wheat (MDWHT) and maincrop potatoes (MDPOT) as part of the assessment of soil droughtiness. The moisture deficit at each of the NSI sites was calculated using the regression equations produced by assessing the MORECS data as defined in section 5.4.1 which used Average Monthly Summer Rainfall (AMSR) and Average Monthly Summer temperature (AMST). The water available to each of the two crops at the NSI sites was calculated and this was used to counter the moisture deficit and calculate the droughtiness according to the criteria in Table 8 MAFF, 1988.

## 6.3 Results

### 6.3.1 ALC Grade by Climate

Figure 17 shows the predicted change in AAR over the future periods, which is very subtle on an annual basis. Figure 18 shows the changes in AT0, which are much more obvious, with the temperature predicted to get warmer over the years. The grading of ALC by climate is built on the premise that the warmer and drier the climate the better the grade (Figure 4). Even though the AAR is predicted to remain steady, the predicted increase in AT0 means the ALC grade based only on climate across England and Wales would improve (Figure 19), with 1703 new grade 1 sites by 2080 (Table 18).

Table 18 Percentage of NSI sites in each ALC Grade by climate

| ALC | 61-90 | Scenario | 2020 | 2030 | 2050 | 2080 |
|---|---|---|---|---|---|---|
| 1 | 57.5% | low | 79.6% | 81.8% | 85.0% | 86.7% |
| | | medium | 80.3% | 82.6% | 86.8% | 88.7% |
| | | high | 80.7% | 83.5% | 88.0% | 90.2% |
| 2 | 17.9% | low | 7.8% | 6.8% | 6.2% | 5.7% |
| | | medium | 7.5% | 6.9% | 5.6% | 5.2% |
| | | high | 7.4% | 6.6% | 5.4% | 4.5% |
| 3a | 5.0% | low | 3.3% | 3.2% | 2.7% | 2.5% |
| | | medium | 3.3% | 3.2% | 2.6% | 1.9% |
| | | high | 3.2% | 3.0% | 2.2% | 1.6% |
| 3b | 5.8% | low | 4.0% | 3.7% | 2.5% | 1.8% |
| | | medium | 3.8% | 3.1% | 1.8% | 1.6% |
| | | high | 3.8% | 2.8% | 1.6% | 1.5% |
| 4 | 11.4% | low | 5.1% | 4.3% | 3.4% | 3.1% |
| | | medium | 4.9% | 4.0% | 3.0% | 2.5% |
| | | high | 4.7% | 3.9% | 2.7% | 2.0% |
| 5 | 2.4% | low | 0.2% | 0.2% | 0.2% | 0.2% |
| | | medium | 0.2% | 0.2% | 0.2% | 0.1% |
| | | high | 0.2% | 0.2% | 0.1% | 0.2% |

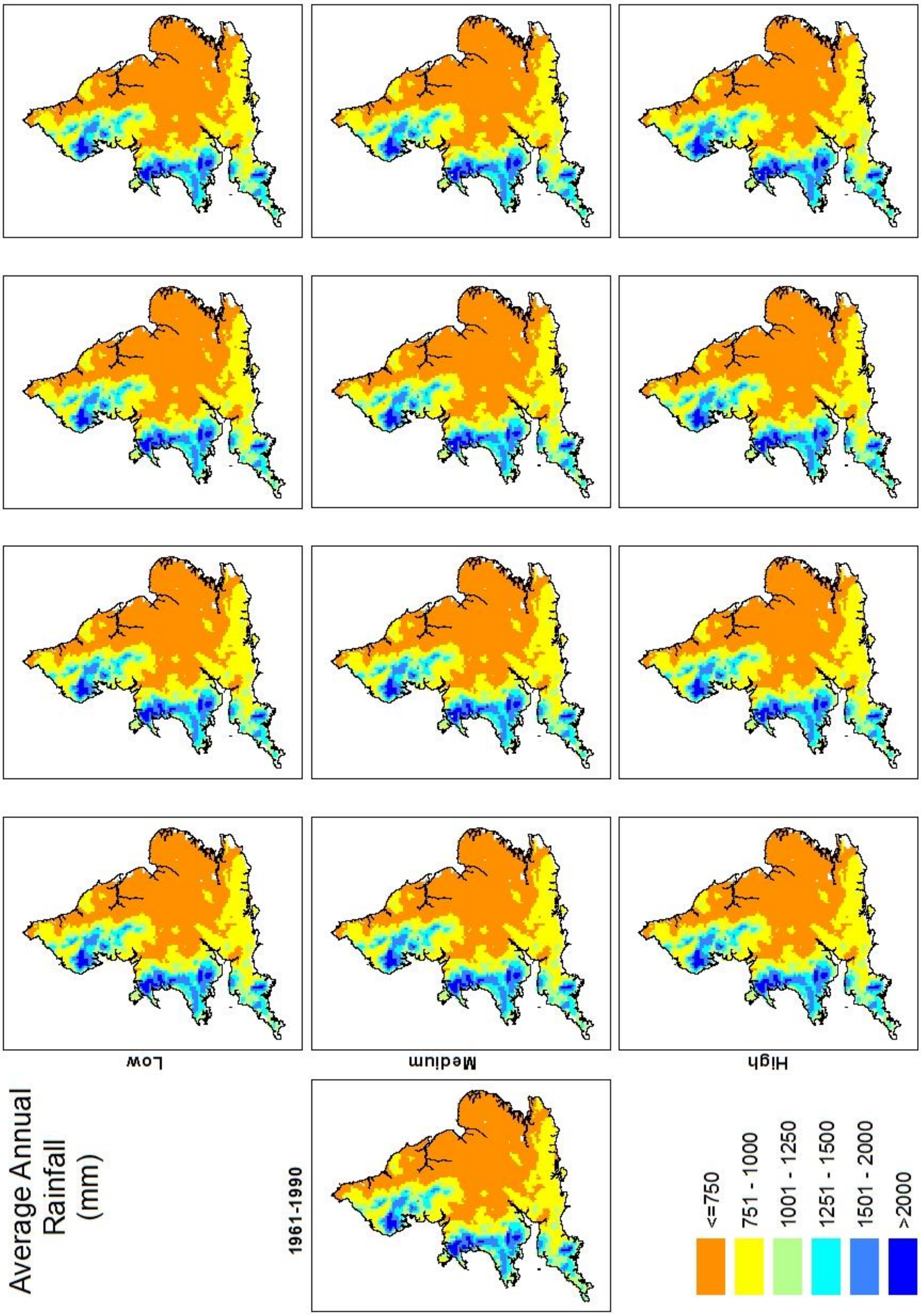



Figure 17 Average Annual Rainfall (mm) interpolated for each of the NSI points from the UKCP09 projections © Crown 2011

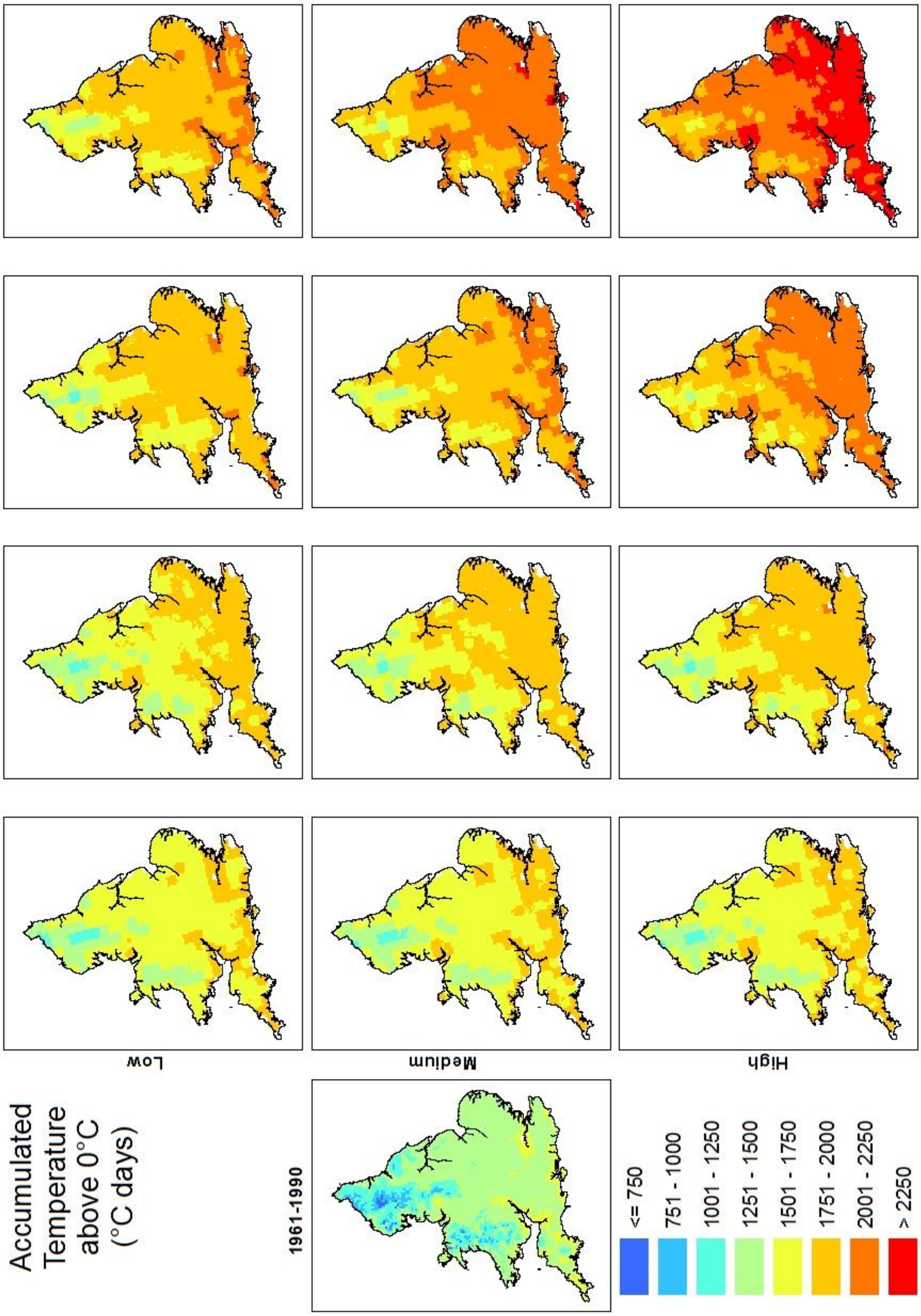



Figure 18 Accumulated Temperature above 0 °C interpolated for each of the NSI points from the UKCP09 projections © Crown 2011

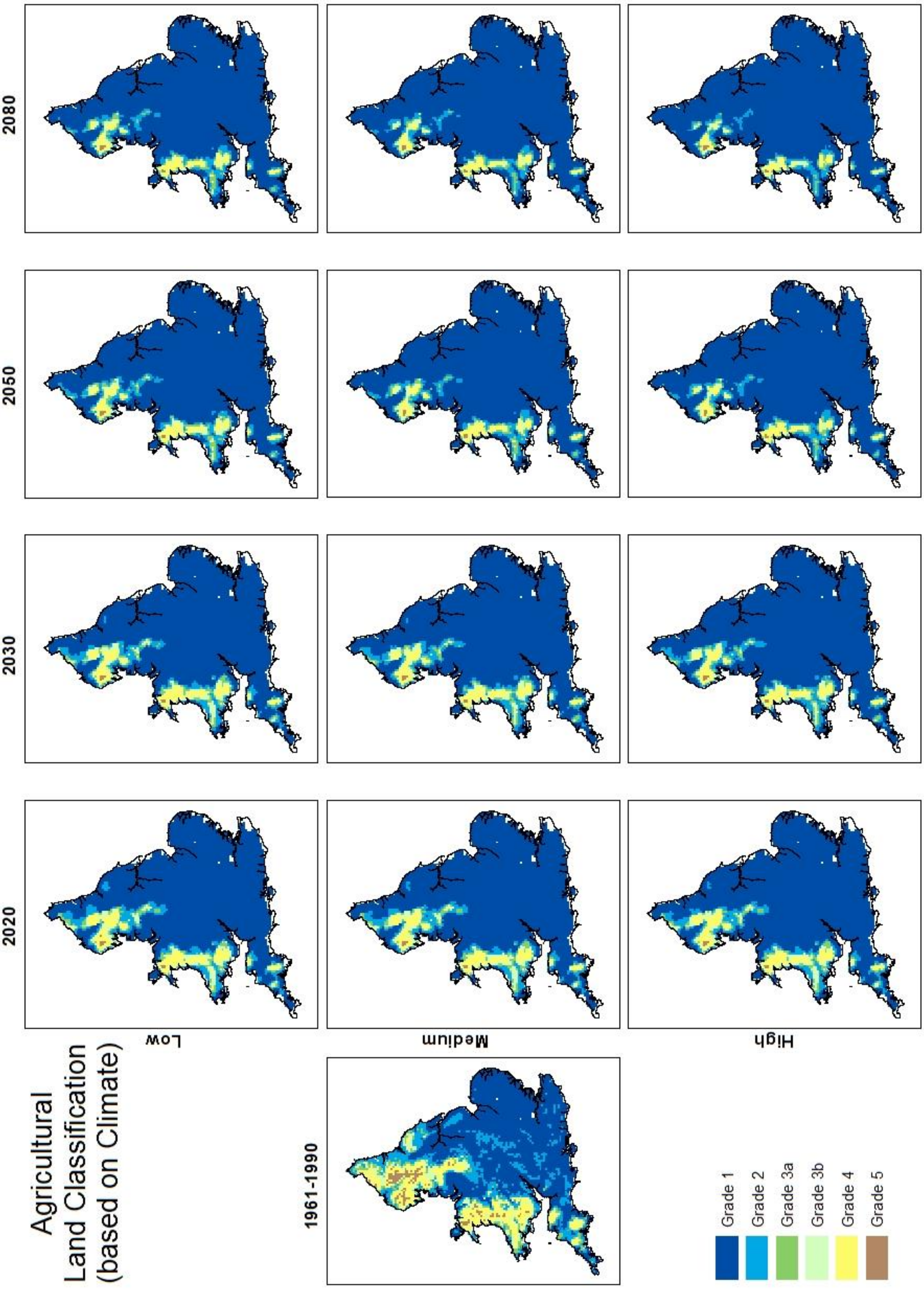



Figure 19 ALC Grade (based on climate criteria only) calculated from average annual rainfall and accumulated temperature above 0 °C at NSI sites for the UKCP09 projections © Crown and Cranfield University, 2011

### 6.3.2 ALC Grade by Soil Wetness

The predicted changes in FCD (Figure 20) result in quite subtle changes in ALC grade over the period 2020-2080. The bulk of the change in FCD occurs in the <126 and 126-150 ranges. Referring to Table 6 in Section 3.4 of MAFF 1988, it is clear that both these ranges return the same grade except in one instance (WC II, Texture: SC, ZC, C) where the grade changes from 3a(2) to 3b(3a), which explains why most of the grades based on soil wetness do not change over much of England and Wales (Figure 21). Even so there is a general trend towards drier soils, which results in more Grade 1 land by soil wetness by 2080. Table 19 shows how the grades vary between the two extremes of the original base data and the high scenario in 2080.

It is important to emphasise that the distributions portrayed in Figure 21, Figure 26, Figure 27, Figure 28 and Figure 29 use the soil properties from the NSI which are from single points in the landscape and do not necessarily represent the whole 5km square to which the climate data relate.

Table 19 Percentage of NSI sites in each ALC Grade by wetness excluding urban and non- agricultural land

| ALC | 61-90 | Scenario | 2020 | 2030 | 2050 | 2080 |
|---|---|---|---|---|---|---|
| 1 | 25.8% | low | 26.1% | 27.2% | 30.0% | 30.8% |
| | | medium | 26.2% | 27.2% | 30.3% | 31.5% |
| | | high | 26.2% | 27.3% | 30.6% | 32.2% |
| 2 | 15.0% | low | 14.7% | 14.6% | 15.1% | 15.3% |
| | | medium | 14.8% | 14.7% | 15.2% | 15.5% |
| | | high | 14.8% | 14.9% | 15.3% | 16.0% |
| 3a | 20.4% | low | 20.4% | 20.9% | 21.8% | 21.8% |
| | | medium | 20.4% | 20.9% | 21.8% | 22.1% |
| | | high | 20.5% | 20.8% | 21.8% | 21.9% |
| 3b | 24.7% | low | 24.4% | 23.6% | 20.9% | 20.1% |
| | | medium | 24.4% | 23.6% | 20.6% | 19.2% |
| | | high | 24.4% | 23.5% | 20.3% | 18.6% |
| 4 | 5.8% | low | 5.8% | 5.3% | 4.5% | 4.3% |
| | | medium | 5.8% | 5.2% | 4.3% | 4.1% |
| | | high | 5.8% | 5.2% | 4.3% | 3.8% |
| 5 | 8.3% | low | 8.5% | 8.3% | 7.8% | 7.8% |
| | | medium | 8.5% | 8.3% | 7.8% | 7.6% |
| | | high | 8.5% | 8.3% | 7.8% | 7.5% |

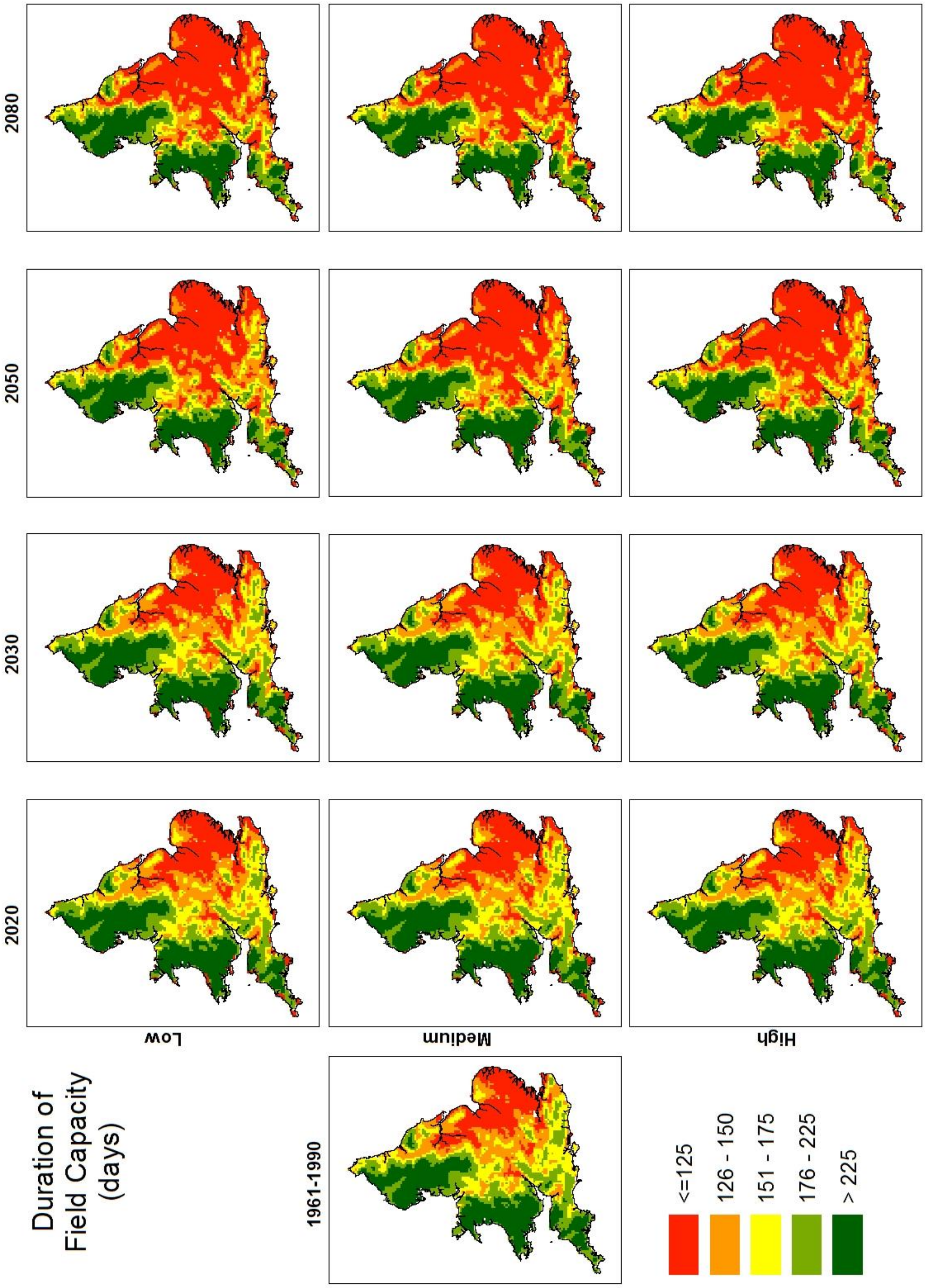



Figure 20 Field Capacity Days at the NSI sites for the UKCP09 projections © Crown 2011

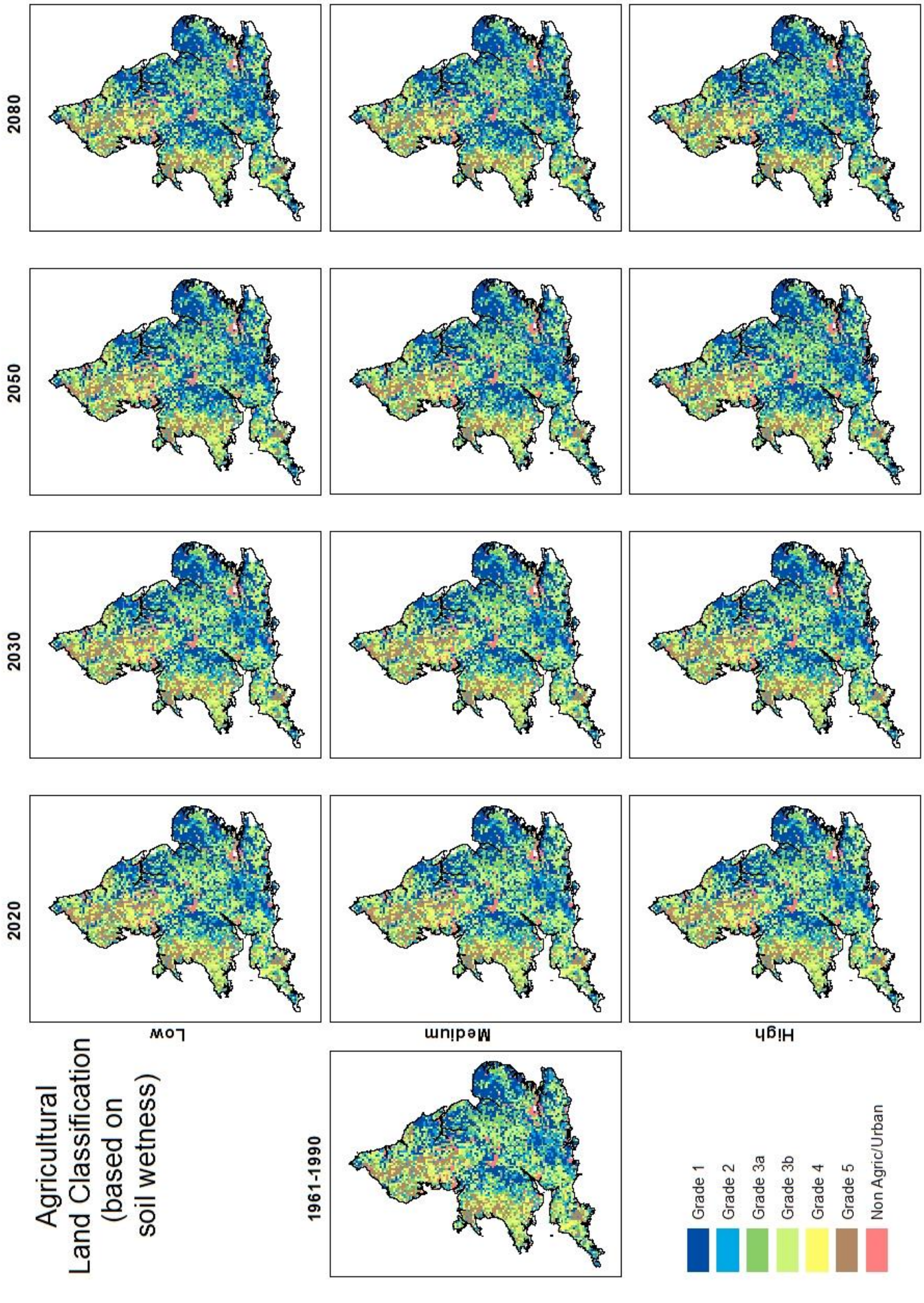



Figure 21 ALC Grade (based on wetness criteria only) at NSI sites for the UKCP09 projections © Crown and Cranfield University, 2011

### 6.3.3 ALC Grade by Droughtiness

Figure 22 and Figure 23 show the predicted changes in ASR and ATS respectively over the UKCP09 climate scenarios. Unlike AAR, which hardly changes, the ASR is predicted to get much lower in the south and east of the country. The ATS values are also predicted to increase considerably and by 2080 nearly the whole country is likely to be warmer than the hottest part is today. This combination of drier and warmer summers would compound to make droughtiness an issue for agriculture in the future.

Using the new MORECS equations (Table 15) to calculate the moisture deficit for main crop potatoes and winter wheat required for the assessment of droughtiness resulted in the distributions shown in Figure 24 and

Figure 25.The Moisture Deficit was then subtracted from the available water for each NSI site to calculate the droughtiness for winter wheat and main crop potatoes (Figure 26 and Figure 27). These were classified to give the ALC by droughtiness (Figure 28)

Table 20 Percentage of NSI sites in each ALC Grade by droughtiness (using MORECS based equation)

| ALC | 61-90 | Scenario | 2020 | 2030 | 2050 | 2080 |
|---|---|---|---|---|---|---|
| 1 | 37.0% | low | 22.4% | 19.2% | 13.3% | 11.0% |
| | | medium | 21.7% | 18.0% | 11.4% | 8.7% |
| | | high | 21.4% | 17.3% | 10.0% | 7.1% |
| 2 | 32.3% | low | 21.0% | 16.9% | 10.5% | 8.9% |
| | | medium | 20.1% | 15.4% | 9.2% | 6.7% |
| | | high | 19.2% | 14.6% | 8.0% | 4.4% |
| 3a | 18.9% | low | 29.5% | 28.4% | 18.8% | 14.0% |
| | | medium | 29.7% | 27.0% | 14.8% | 10.3% |
| | | high | 29.8% | 25.7% | 12.5% | 8.1% |
| 3b | 9.5% | low | 19.5% | 24.7% | 33.0% | 29.7% |
| | | medium | 20.5% | 27.1% | 30.5% | 21.4% |
| | | high | 21.2% | 28.7% | 26.9% | 14.7% |
| 4 | 2.2% | low | 7.5% | 10.7% | 24.5% | 36.4% |
| | | medium | 8.0% | 12.4% | 34.2% | 52.9% |
| | | high | 8.4% | 13.7% | 42.5% | 65.8% |
| 5 | 0.0% | low | 0.0% | 0.0% | 0.0% | 0.0% |
| | | medium | 0.0% | 0.0% | 0.0% | 0.0% |
| | | high | 0.0% | 0.0% | 0.0% | 0.0% |

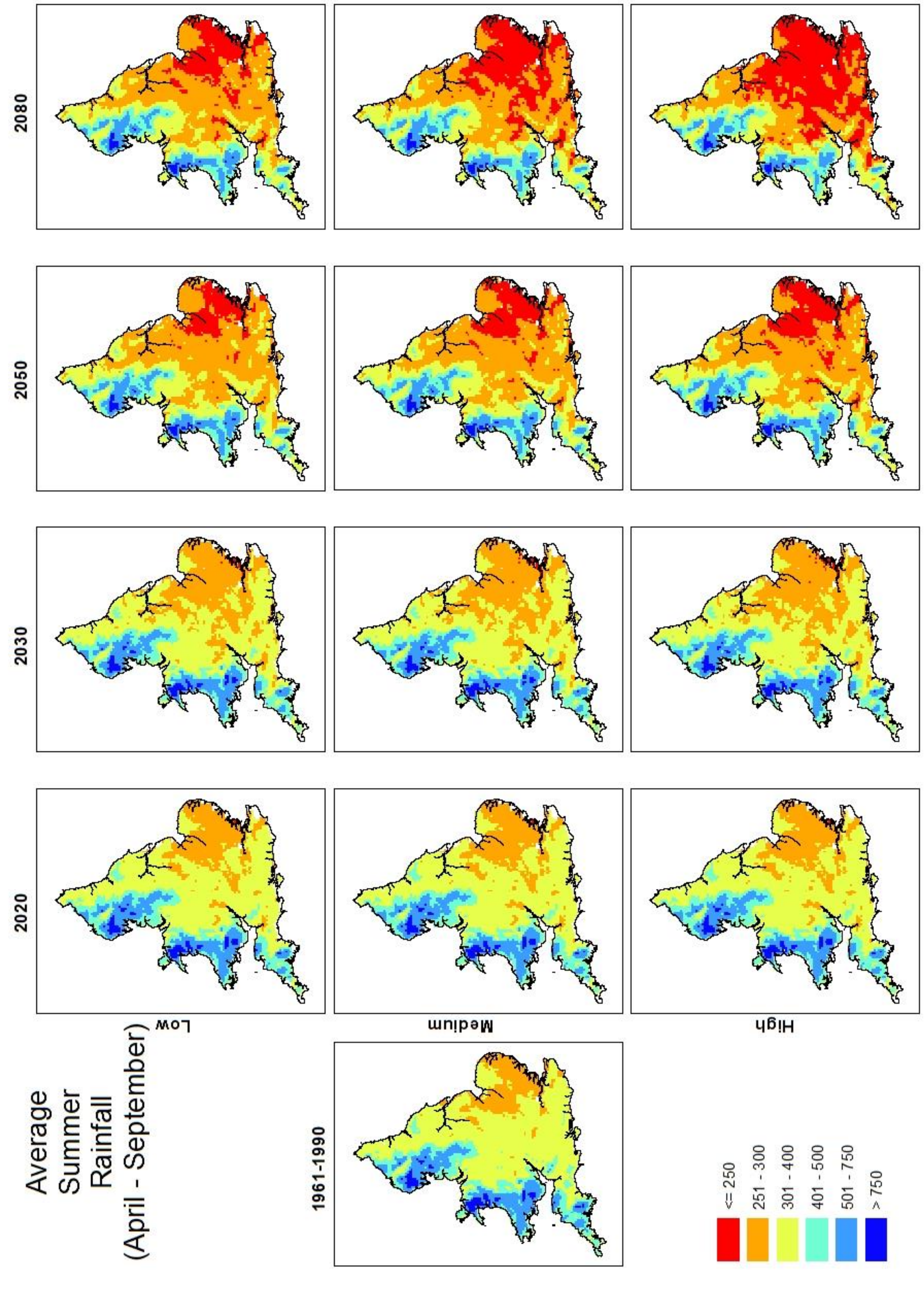



Figure 22 Average Summer Rainfall interpolated onto the NSI sites from the UKCP09 projections © Crown 2011

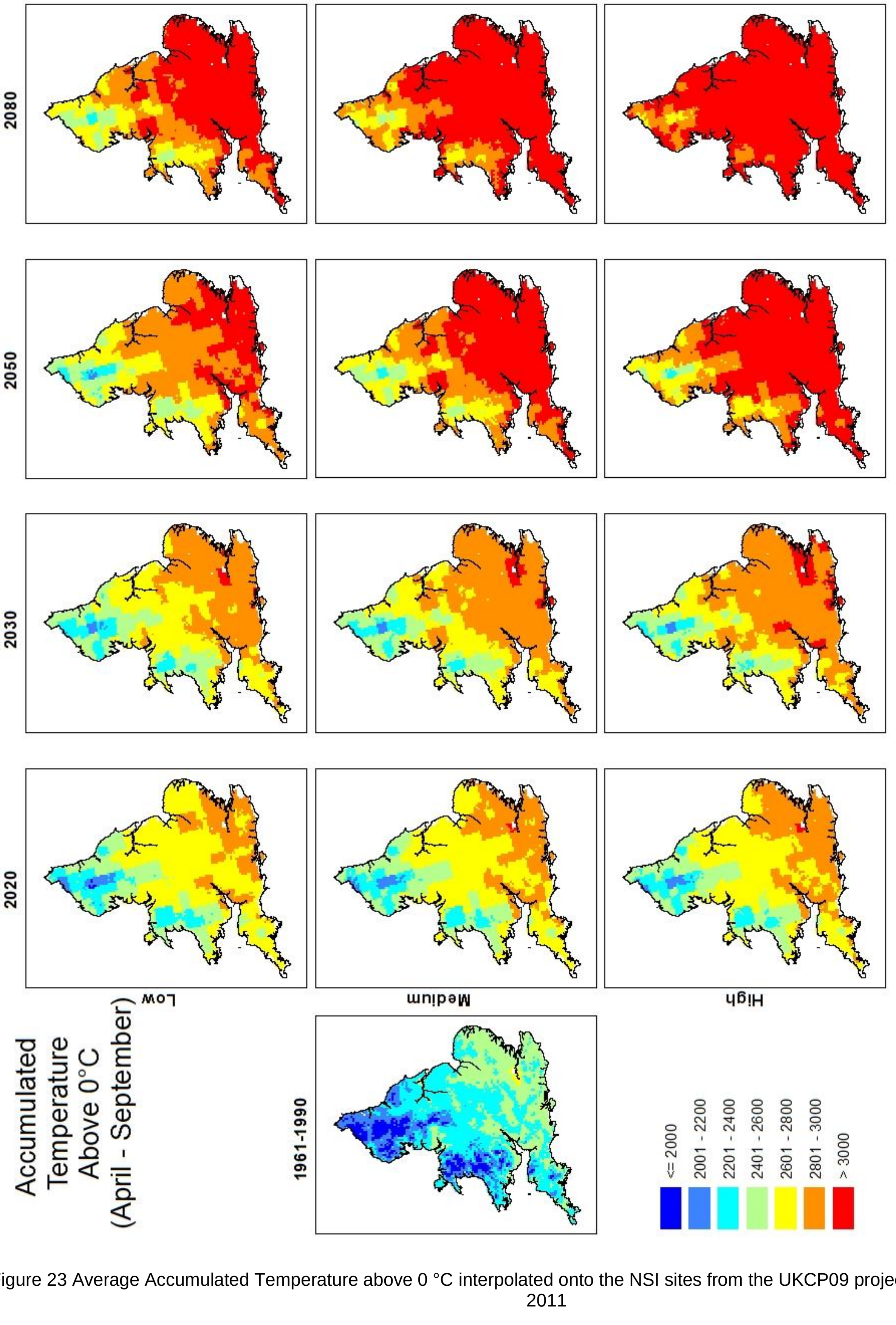



Figure 23 Average Accumulated Temperature above 0 °C interpolated onto the NSI sites from the UKCP09 projections © Crown 2011

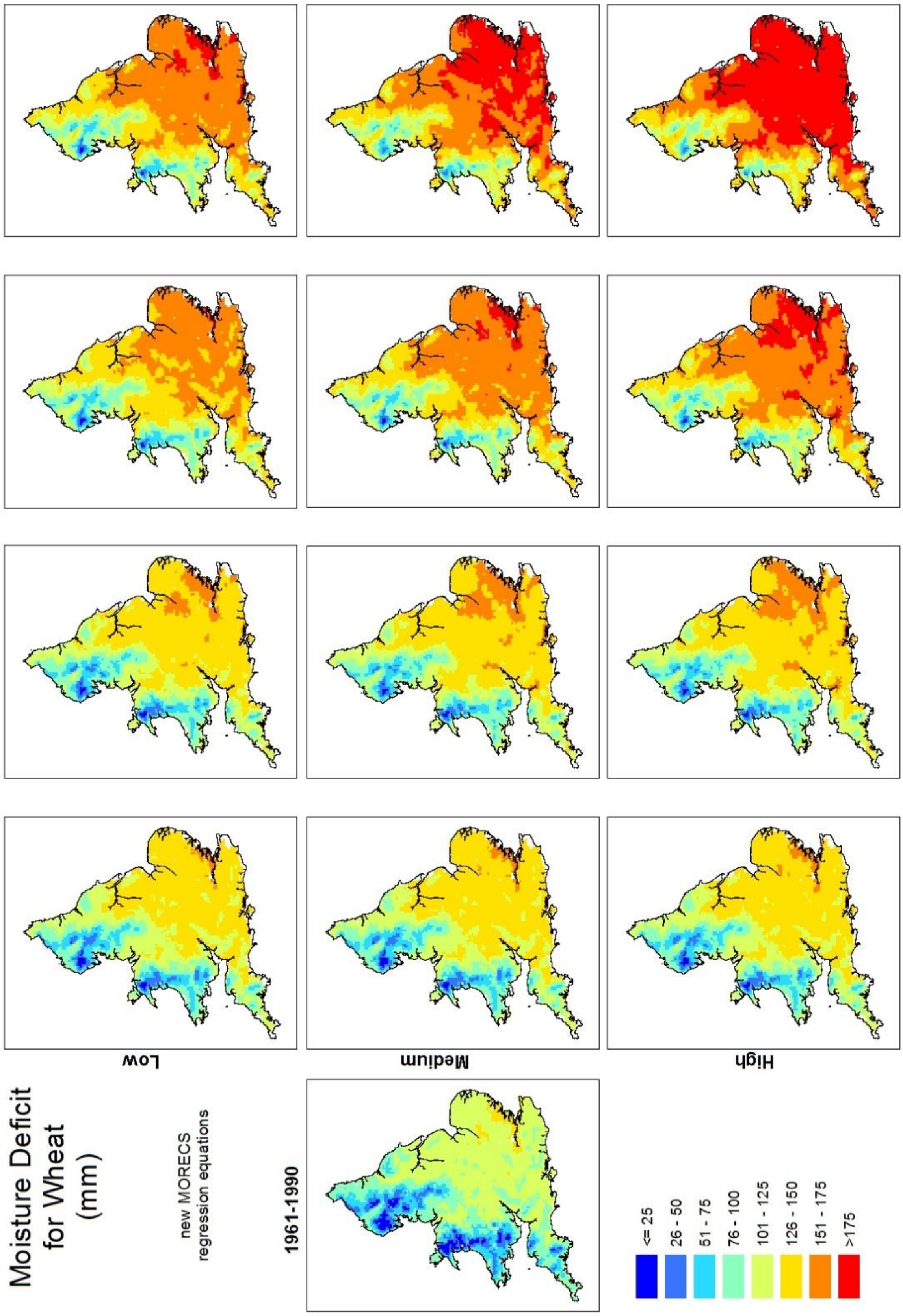



Figure 24 Moisture deficit for Wheat calculated using the New MORECS based regression equations at the NSI sites for the UKCP09 projections © Crown and Cranfield University, 2011

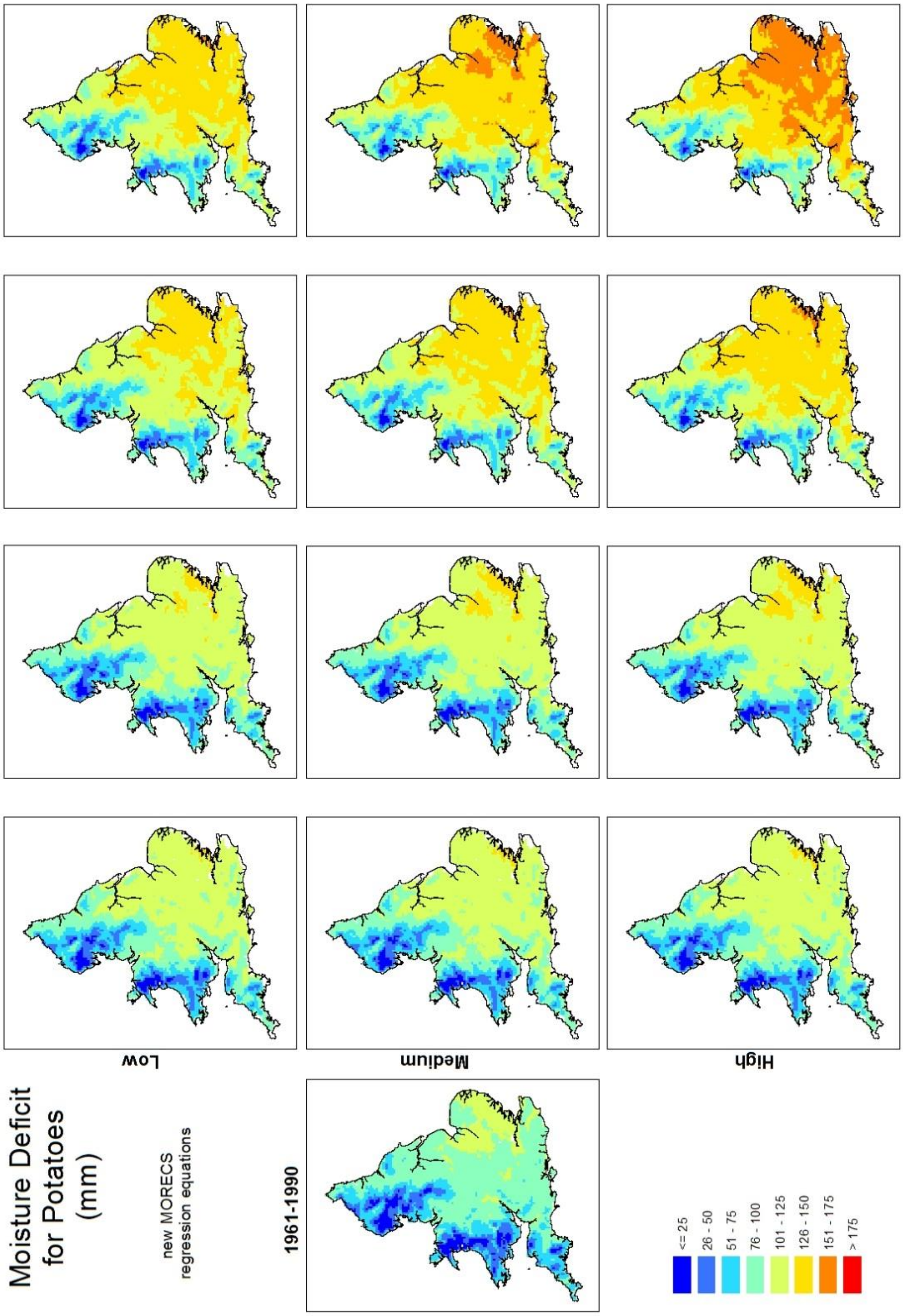



Figure 25 Moisture deficit for Potatoes calculated using the New MORECS regression at the NSI sites and the UKCP09 projections © Crown and Cranfield University, 2011

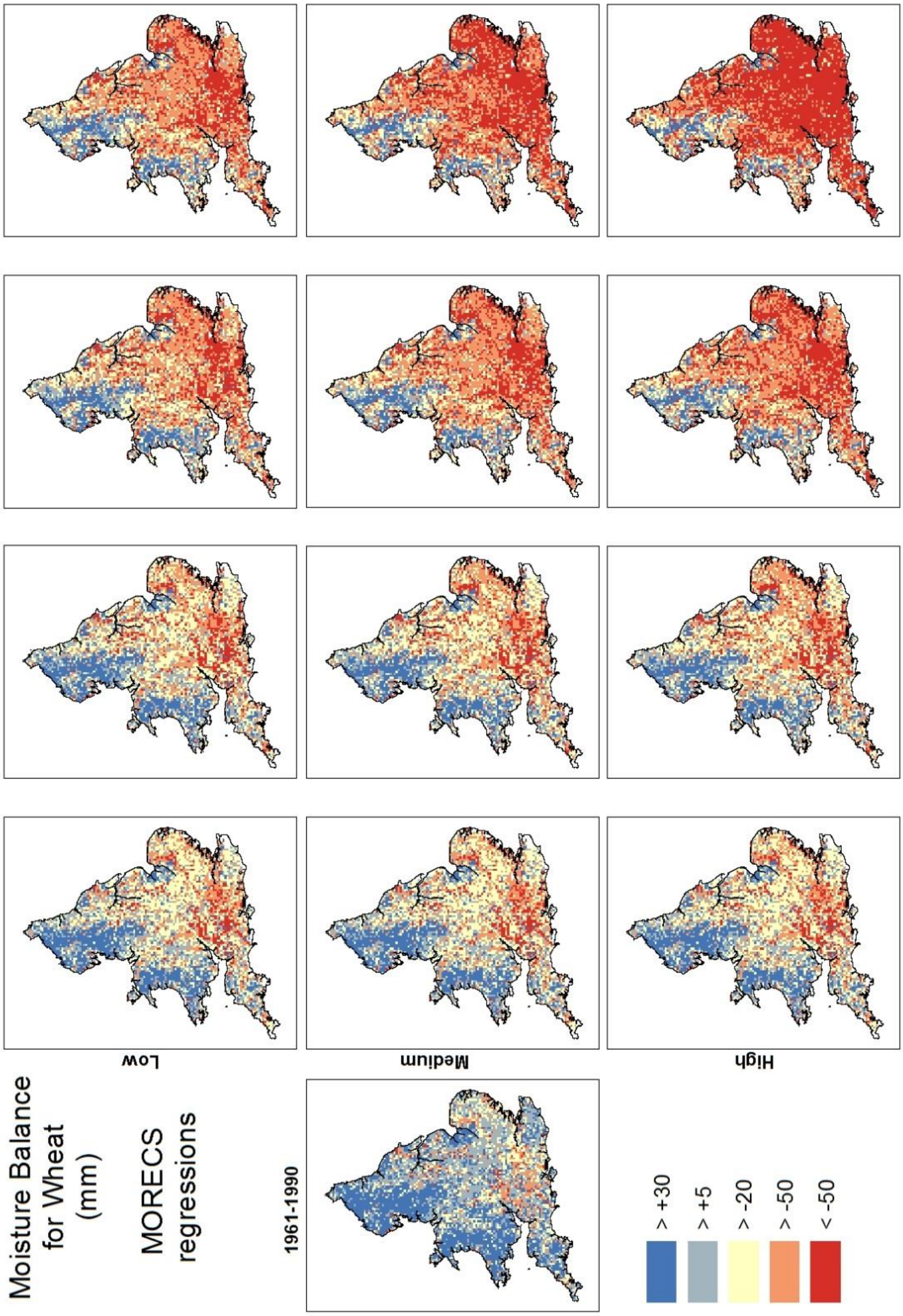



Figure 26 Droughtiness for Wheat using the new MORECS regression for moisture deficit at the NSI sites and the UKCP09 projections © Crown and Cranfield University, 2011

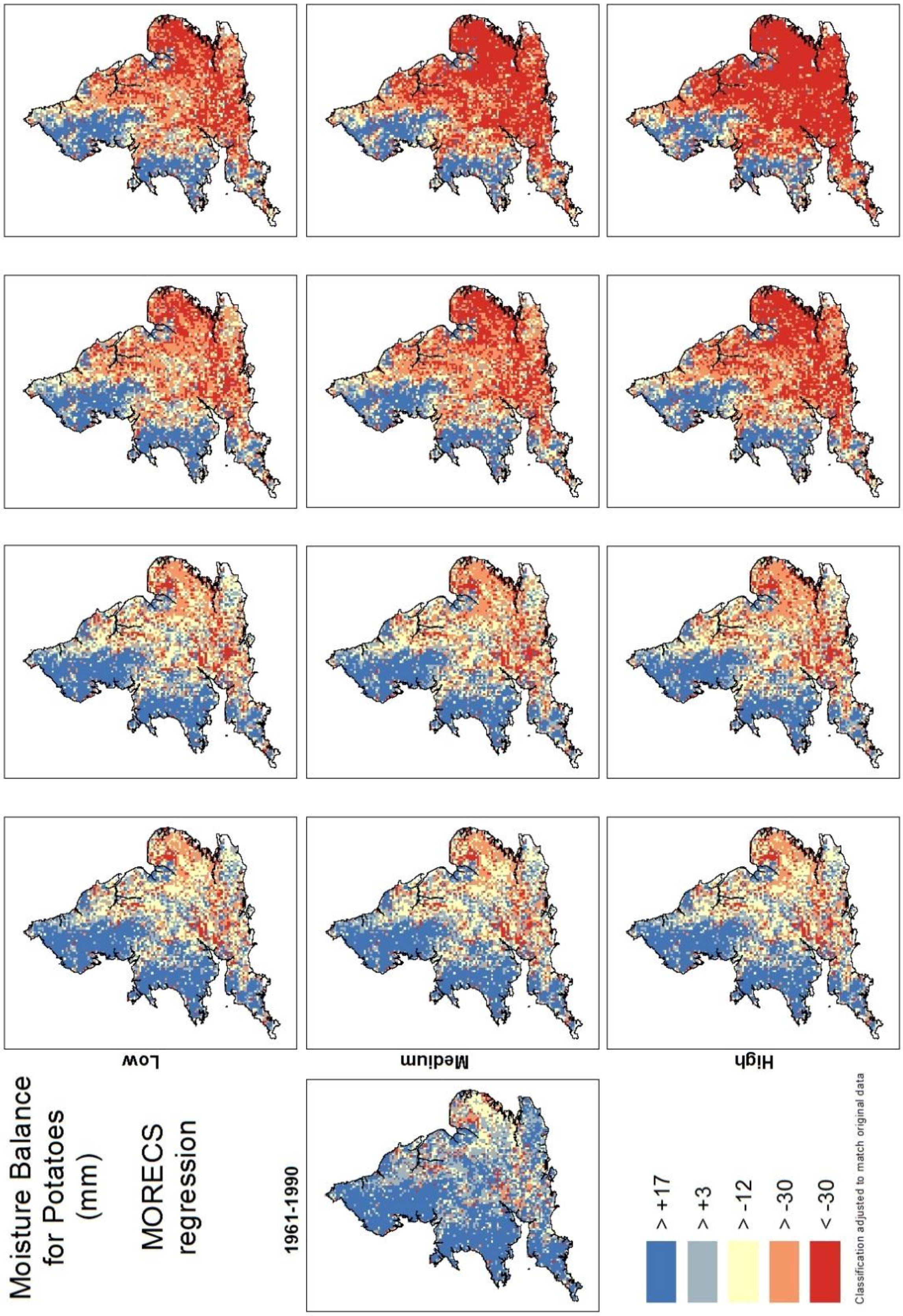



Figure 27 Droughtiness for Potatoes using the New MORECS regression with adjusted ALC cut-offs at the NSI sites and the UKCP09 projections © Crown and Cranfield University, 2011

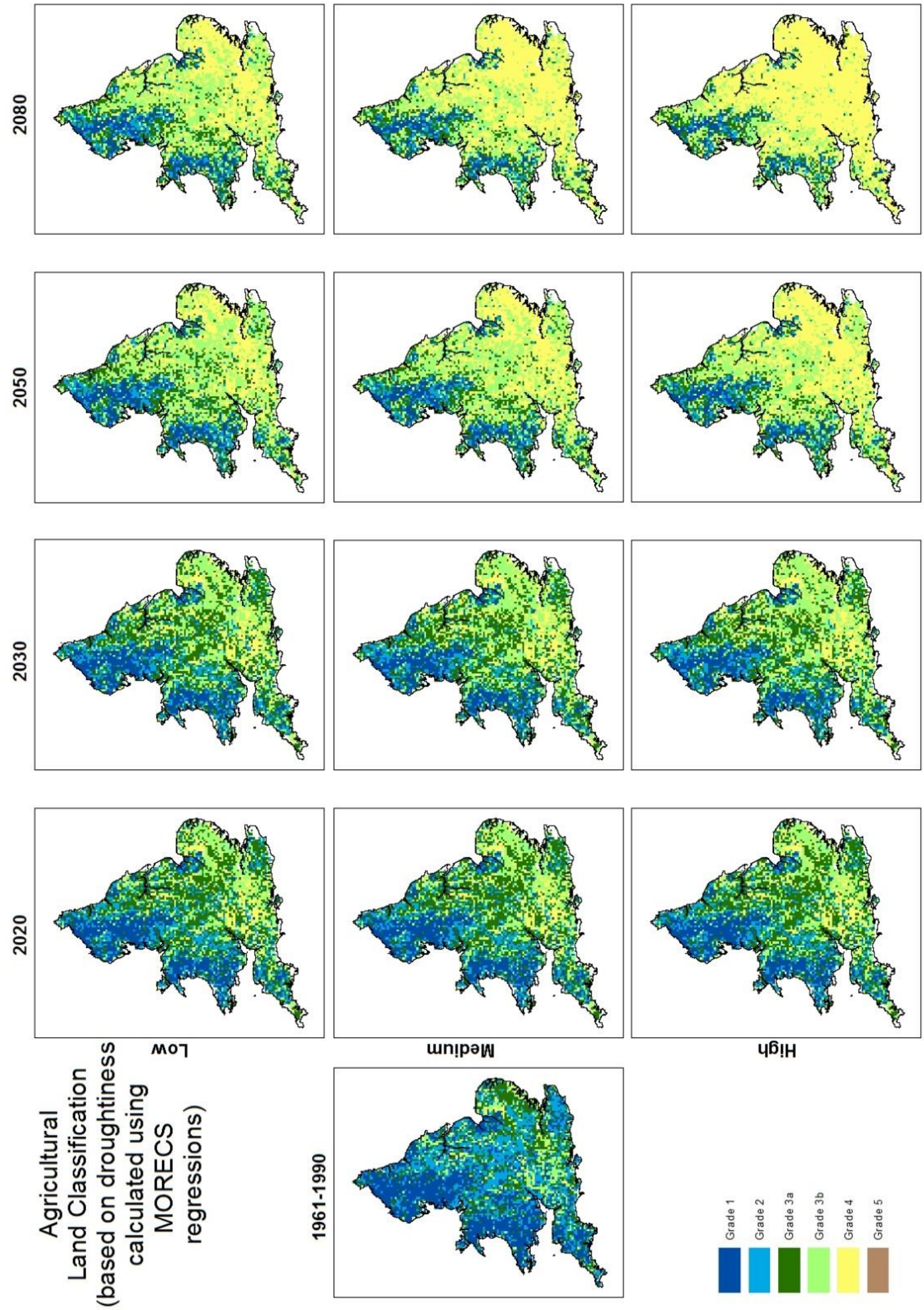



Figure 28 ALC Grade (based on droughtiness criteria only) using new MORECS regression and adjusted potato classification at the NSI sites and the UKCP09 projections © Crown and Cranfield University, 2011

#### 6.3.4 ALC Grade overall

Once the three ALC criteria that are affected by climate had been assessed (climate, soil wetness and drought), they were combined with the seven soil and site criteria (gradient, flooding, texture, depth, stoniness, chemical, and erosion) and the overall ALC grade was determined as the lowest grade from all 10 criteria. Figure 29 shows the distribution of resulting ALC grades for the NSI points with the original and adjusted droughtiness assessments respectively. Table 21 show the breakdown of the number of sites in each grade.

The droughtiness criterion dominates the resulting ALC grades, with over 69% of the NSI sites being classified as Grade 4 by 2080 under the high emission scenario conditions.

Table 21 Percentage of NSI Sites in each overall ALC grade (applying all 10 criteria) excluding urban and non-agricultural land

| ALC | 61-90 | Scenario | 2020 | 2030 | 2050 | 2080 |
|---|---|---|---|---|---|---|
| 1 | 2.2% | low | 1.0% | 0.7% | 0.5% | 0.4% |
| | | medium | 0.9% | 0.7% | 0.4% | 0.3% |
| | | high | 0.9% | 0.7% | 0.4% | 0.2% |
| 2 | 14.7% | low | 8.6% | 6.5% | 3.4% | 2.4% |
| | | medium | 8.1% | 5.8% | 2.6% | 1.5% |
| | | high | 7.7% | 5.3% | 2.0% | 0.9% |
| 3a | 21.2% | low | 20.4% | 18.7% | 11.8% | 8.0% |
| | | medium | 20.0% | 17.3% | 8.4% | 5.0% |
| | | high | 20.0% | 16.0% | 6.8% | 3.0% |
| 3b | 36.6% | low | 42.5% | 44.5% | 43.5% | 37.3% |
| | | medium | 43.1% | 45.4% | 38.6% | 26.0% |
| | | high | 43.3% | 46.3% | 33.3% | 16.6% |
| 4 | 14.3% | low | 16.9% | 19.1% | 30.8% | 42.0% |
| | | medium | 17.2% | 20.4% | 40.0% | 57.3% |
| | | high | 17.5% | 21.3% | 47.6% | 69.5% |
| 5 | 11.1% | low | 10.6% | 10.4% | 10.0% | 10.0% |
| | | medium | 10.6% | 10.4% | 10.0% | 9.8% |
| | | high | 10.6% | 10.4% | 10.0% | 9.7% |

It is important to emphasise that the distributions portrayed in Figure 21, Figure 26, Figure 27, Figure 28 and Figure 29 use the soil properties from the NSI which are from single points in the landscape and do not necessarily represent the whole 5km square to which the climate data relate.

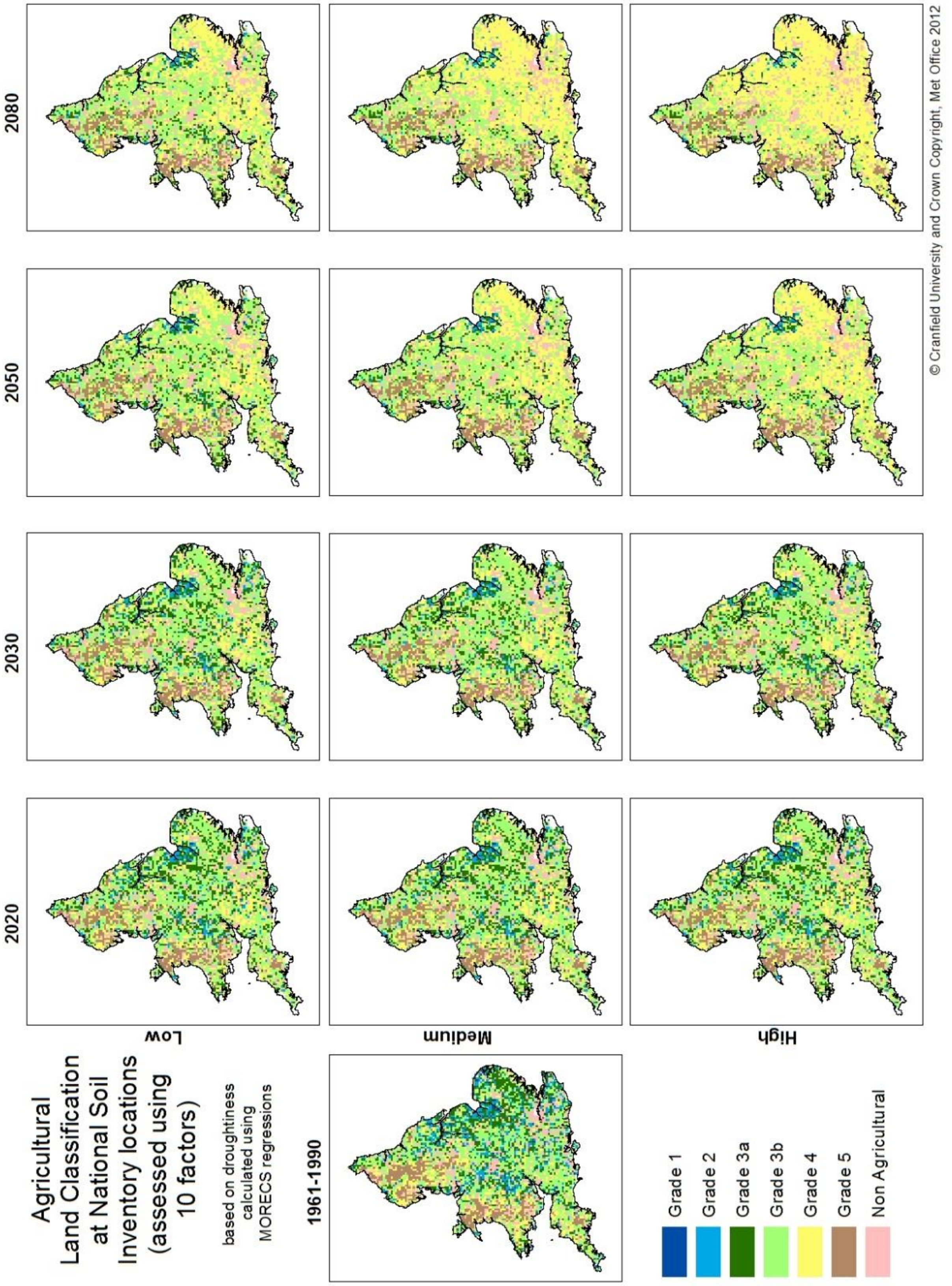



Figure 29 Projected ALC Grade (most limited of all 10 criteria) of the NSI sites with droughtiness using new MORECS regression and adjusted potato classification under different climate change scenarios.

## 6.4 Initial Conclusions

The results obtained thus far show that potentially significant changes to ALC grade are likely to occur as a result of climate change. These potential changes are, however, heavily driven by droughtiness and a number of issues must be considered before the findings of this work are either accepted or acted upon.

Revising the calculation of moisture deficit significantly reduces the impact of droughtiness and hence highlights the sensitivity of the parameter to this measure. Unfortunately neither the original method (MAFF, 1988) nor the revised calculation of this project have been peer reviewed and must therefore be considered a weak link in the science of the project.

In order to provide greater understanding of the results and to explore the sensitivity to the changes, the following additional research questions should be considered:

1. Will the predicted droughtiness be a real problem or is this an artefact of the classification? It is feasible that the droughtiness issue is manifested through the classification system used and does not represent real drought issues. It is recommended that further work is carried out to assess alternative classification methodologies to analyse the sensitivity of the system.

2. Are there more appropriate drought measures/indices that could be applied? The existing drought measure has been applied in a faithful fashion to the previous ALC methods. These methods may not represent the most appropriate approach for assessing drought under elevated temperatures in future climate scenarios. Further work is necessary to identify the most appropriate drought measure for the climate change scenarios. This work should involve a review of a wide range of measures and assessment of the best fit in terms of: the parameters required; the limitations of the approach; the applicability to the UK and importantly the validity of the methods under higher temperature scenarios.

3. What is water availability in areas that are subject to the most detrimental change? Will irrigation change the potential for land to produce crops? While the results of this project illustrate the potentially significant impacts of droughtiness on ALC grade, they do not quantify the volume of irrigation required to close the gap and return land to a higher grade, nor do they assess the likely availability of water in areas where irrigation would be required. It would be sensible to further research the water availability and irrigation need under climate change scenarios to fully understand the true impact of the predicted changes in ALC grade.

Some of these additional research questions are addressed under Objective 7.

# 7 Objective 6: To take consideration of the effects of potential sea level rise

## 7.1 Background to the Predicted Sea Level Rise

This objective addresses the influence that future sea level rise may have on the available agricultural land under each ALC grade as predicted by Objective 5 of the project.

The UKCP09 sea level projections provide information on how sea levels might change in the UK over the coming century, based on regional projections of sea level rise from global climate models. They do not attempt to show the detailed consequences of how the rise in sea level will affect coastal areas as a result of inundation. The coastal landscape is complicated by local topography and sea defences and therefore it is not considered possible to predict how the UK coast might look at a future certain time.

The graphs in Figure 30 show the predicted sea level rise around the UK for each of the 3 emission scenarios. Even with the high scenario at 95%, the predicted rise is only 0.8m by 2100.

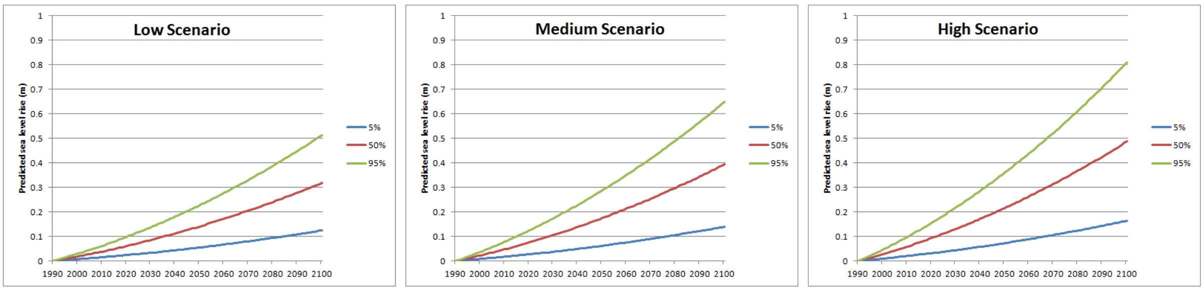



Figure 30 Graphs showing the predicted sea level rise under the three Climate Scenarios



## 7.2 Methods

NSI points that have an altitude of 2m or less were identified as being potentially vulnerable to inundation, assuming no sea defence measures exist. This includes areas reasonably far inland in the Fens, where sea level rises could broach the drains. However much of the Fens is already below sea level and measures are in place to keep the sea water out using a series of pumps, though they will become more difficult to drain as sea water rises. As long as these defences are not overwhelmed by a combination of high tides and storm conditions in the North Sea, then the area ALC grading might not be at risk until the end of the century. The ALC grade at each of these vulnerable sites under the 3 climatic scenarios for the 2020s, 2030s, 2050s and 2080s was calculated in Objective 5 of this project.

## 7.3 Results and Discussion

Table 22 shows the distribution of NSI points in each ALC class by period and climate scenario. Assuming no defence of the encroachment was planned, of the current 96 Grade 1 sites, 13 could be potentially at risk from inundation as the sea level rises. By the 2080 period, there would only be 9 NSI sites remaining in Grade 1 (mostly as a result of downgrading through drought) and of these 3 could be lost to flooding. It must be emphasised that the results from this analysis indicate the likely effects of an average sea level rise of 80cm on management of and access to land. The effect of high tides combined with storm conditions are not catered for, especially the impact of the east coast sea defences being overwhelmed by an extreme storm surge in the North Sea. This happened in 1953, when the sea walls were breached inundating $1000km^2$ (Stratton, 1969), and experience suggests that large areas of the Fen lands would be flooded with sea water if this happened again in the future. However, the probability and subsequent effects of such an occurrence would need to be the subject of an additional study in collaboration with those organisations responsible for coastal defences.

Table 22 NSI Points classified by ALC grade identifying those vulnerable to sea level rise

| ALC | 6190 | | Scenario | 2020 | | 2030 | | 2050 | | 2080 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | all points | at risk points | | all points | at risk points | all points | at risk points | all points | at risk points | all points | at risk points |
| 1 | 96 | 13 | low | 35 | 10 | 30 | 9 | 21 | 6 | 16 | 6 |
| | | | medium | 32 | 10 | 27 | 8 | 18 | 6 | 13 | 6 |
| | | | high | 31 | 10 | 25 | 7 | 15 | 6 | 9 | 3 |
| 2 | 694 | 49 | low | 335 | 35 | 249 | 24 | 125 | 22 | 91 | 12 |
| | | | medium | 307 | 28 | 220 | 25 | 95 | 13 | 63 | 6 |
| | | | high | 297 | 28 | 202 | 25 | 74 | 8 | 37 | 6 |
| 3a | 1053 | 38 | low | 897 | 31 | 752 | 36 | 439 | 14 | 319 | 19 |
| | | | medium | 878 | 37 | 699 | 32 | 341 | 18 | 192 | 15 |
| | | | high | 863 | 36 | 659 | 32 | 261 | 19 | 131 | 6 |
| 3b | 1834 | 19 | low | 2211 | 40 | 2313 | 43 | 1948 | 44 | 1564 | 37 |
| | | | medium | 2231 | 38 | 2293 | 44 | 1646 | 38 | 1039 | 23 |
| | | | high | 2245 | 39 | 2270 | 44 | 1385 | 37 | 693 | 20 |
| 4 | 723 | 1 | low | 946 | 4 | 1088 | 8 | 1918 | 34 | 2463 | 46 |
| | | | medium | 976 | 7 | 1193 | 11 | 2351 | 45 | 3153 | 70 |
| | | | high | 988 | 7 | 1277 | 12 | 2717 | 50 | 3595 | 85 |
| 5 | 547 | 0 | low | 523 | 0 | 515 | 0 | 496 | 0 | 494 | 0 |
| | | | medium | 523 | 0 | 515 | 0 | 496 | 0 | 487 | 0 |
| | | | high | 523 | 0 | 514 | 0 | 495 | 0 | 482 | 0 |
| Non Agric. | 621 | 4 | all | 621 | 4 | 621 | 4 | 621 | 4 | 621 | 4 |
| Urban | 259 | 8 | all | 259 | 8 | 259 | 8 | 259 | 8 | 259 | 8 |

# 8 Objective 7: Further Investigation of drought under different climate scenarios, and potential cropping outcomes for England and Wales

## 8.1 Summary

The results of objectives 4 and 5 of the current project highlighted a particular problem when the classification of droughtiness was applied to the ALC. This part of the project was undertaken to review other independant ways of assessing drought in order to establish whether the predicted effects of future drought are likely to occur. Additionally it aimed to determine whether the particular method used to measure droughtiness, as developed for the ALC system, was returning realistic values when extrapolated to the more extreme temperature and modified rainfall patterns that UKCP09 predicts.

The first phase of work under this objective was to review various indices used around the world to classify different climatic zones and to determine how the UK is currently classified and whether the predicted change in climate is sufficient to shift England and Wales into different climatic zones. Where the required data are readily available for these indices, maps have been produced to compare the current baseline data (1961-90), the 2020 low emission scenario and the 2080 high emission scenario to give an idea of the potential range of change. The purpose of this exercise was thus to determine whether these indices agree with the predicted change in drought severity.

The second stage of work under this objective was to consider how the change in climate could impact cropping outcomes in the UK; in particular, to review the potential effects of flood risk, pests, disease, aridity and drought on crop yield. Adaptation to mitigate the effect of drought may be required to sustain crop yield in future, for example consideration was given to drought resistant crops and varieties as well as different approaches to water and soil management.

Regions across Europe with similar climates to the predicted future climate of England and Wales were identified to see how agricultural land use might react to various different climate scenarios in the 2050s and 2080s.

A simple analysis was undertaken to determine the drought limitation on Maincrop Potatoes in real terms as measured by the predicted future irrigation water requirements.

Lastly a brief look at the variability of the predicted future climates in the UKCP09 data sets was undertaken to determine how the predicted drought could vary with the likely range of possible future climates.

## 8.2 Review of Aridity Indices

Aridity indices are a useful way to compare how droughtiness varies spatially and temporally. Over the last century, numerous indices have been developed utilising different drivers of drought over varying time scales and for different regions. In this study, several indices were applied to give an indication of the change in aridity across England and Wales that might result from future climate change.

Precipitation alone provides only a partial indication as to how much moisture is in an ecosystem. The loss of moisture from the system, through evaporation and transpiration, is also important. Therefore, many indices are based on the water balance; or the ratio between precipitation and potential evapotranspiration (PET). As PET is not easy to measure directly, a number of different methods of calculating it have been developed.

A range of aridity indices were identified from the literature and their potential for application evaluated. However, firstly, the different methods for calculating PET were summarised.

### 8.2.1 Data Preparation for comparing Indices

Where the data requirements for the indices are straightforward, maps of the UK were produced to illustrate the distribution of the classes. The UKCP09 absolute map data were used for this purpose. The 2020 Low emission scenario and the 2080 High emission scenario were selected to highlight the range of results and the 50% probability value used in each case.

Variables provided in each map were delineated as follows:

| | |
|---|---|
| ADP | average daily precipitation mm/day |
| AAT | average daily temperature over the year (°C) |
| JanT…DecT | average daily temperature over each month (°C) |
| JanP…DecP | average monthly precipitation (average daily precipitation multiplied by the number of days in each month) |
| JanET…DecET | monthly potential evapotranspiration, calculated using the Thornthwaite method from the latitude and monthly temperature. |
| AAR | average annual rainfall (sum of JanP…DecP) |
| PET | annual potential evapotranspiration, calculated using the Thornthwaite method (sum of JanET…DecET) |
| JanMD…DecMD | Monthly moisture deficit from balance of JanP..DecP and JanET..DecET |
| PSMD | Maximum of JanMD..DecMD |

### 8.2.2 Potential evapotranspiration

Potential evapotranspiration is the ‘evaporation (and/or transpiration) from an extended surface of a short green crop which fully shades the ground, exerts little or negligible resistance to flow of water, and is always well supplied with water’ (Rosenberg *et al.,* 1983, p211). Evapotranspiration is dependent on a number of environmental factors, including solar radiation, wind speed, humidity, vegetation and soil properties (Heim, 2002).

#### *8.2.2.1 Thornthwaite Method*

Thornthwaite (1948) argues that solar radiation is the dominant factor affecting evapotranspiration. However, measurements of solar radiation are not widely available (Heim, 2002). Therefore, Thornthwaite (1948) derived a simple empirical relationship between temperature, latitude and hours of daylight in order to calculate PET:

$PET = 1.6*(L/12)*(N/30)*(10T/I)^{a}$

Where:

$L$ is the average day length of the month being calculated (hours)

$N$ is the number of days in the month being calculated

$T$ is the mean monthly temperature (°C).

$I$ is a heat index for a given location, which is the sum of 12 monthly index values, i:

$i = (T/5)1.514$

$a$ is an empirically derived exponent which is a function of I:

$a = 6.75*10-7I3 – 7.71*10-5I2 + 1.79*10-2I + 0.49$

Hulme *et al.* (1992) evaluated the Thornthwaite method for calculating PET globally. One of the main limitations of this method is that it is based on an empirical relationship and therefore has limited effectiveness outside of the humid region of the southern USA in which it was developed. It has been found to underestimate PET in arid months or regions and overestimate PET in cold climates.

On short timescales, temperature is not an appropriate measure of solar radiation. However, on the timescales of interest to this study, both temperature and evapotranspiration are similar functions of radiation, resulting in autocorrelation between them (Rosenberg *et al*., 1983).

The Thornthwaite method for calculating PET is the most widely used method, and it is applied to many different indices including Thornthwaite’s own moisture index.

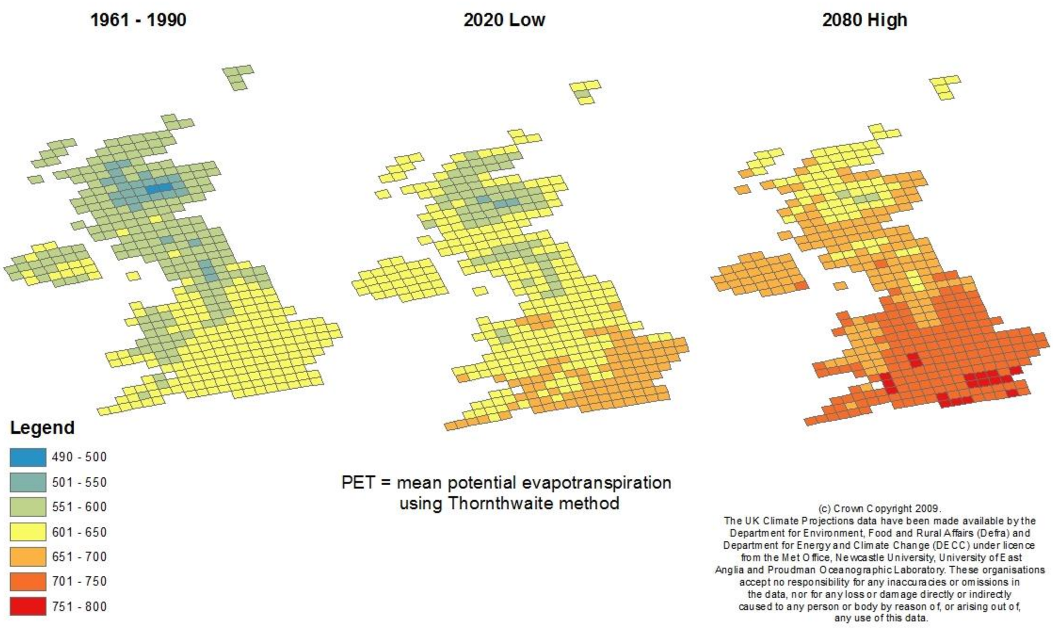



Figure 31 Mean Potential evapotranspiration calculated from the UKCP09 projection data (2020s high scenario and the 2080s high scenario), using Thornthwaite method

#### *8.2.2.2 Hargreaves Method*

Hargreaves (1974) developed this method with the aim of calculating PET with minimal climatic data. This method can be represented by the following equation (Yates and Strzepek, 1994):

$$PET = 0.0022 * (RA) * (T + 17.8) * (Tmax - Tmin)^{1/2}$$

Where:

RA is the mean extra-terrestrial radiation (mm/day), which is a function of latitude and is available from reference tables.

T is the mean air temperature (°C).

Tmax and Tmin are the mean monthly maximum and minimum air temperatures (°C).

#### *8.2.2.3 Penman Method*

The original Penman equation was developed in 1948 and describes evaporation from an open water surface (Penman, 1948). In simplified terms it reads:

$$R_p = H + \lambda E + G$$

Where:

Rp = energy flux density of net incoming radiation ($W/m^2$)

H = flux density of sensible heat into the air ($W/m^2$)

$\lambda E$ = flux density of latent heat into the air ($W/m^2$)

G = heat flux density into the water body ($W/m^2$)

#### *8.2.2.4 Penman-Monteith Method*

The Penman-Monteith equation (Allen et al, 1998) was a variation on the original Penman-Monteith equation used to predict net evapotranspiration. It requires as input of variables including daily mean temperature, wind speed, relative humidity and solar radiation and is described below:

$$ETo = \left[\frac{\Delta}{\Delta+\gamma^*} \cdot \frac{(R_n - G)}{\lambda}\right] + \left[\frac{86.4}{\lambda} \cdot \frac{1}{\Delta+\gamma^*} \cdot \frac{\rho cp}{ra}(ea - ed)\right]$$

Where:

ETo reference crop evapotranspiration (mm d-1)

Δ slope of vapour pressure curve (MJ kg-1)

γ* modified psychrometric constant (kPa °C-1)

Rn net solar radiation (MJ m-2 d-1)

G Soil heat flux (MJ m-2 d-1)

λ latent heat of vaporisation

ρ atmospheric density (kg m-3)

cp specific heat of moist air (1.013 kJ kg-1 °C-1)

ra aerodynamic resistance (s m-1)

ea mean saturation vapour pressure (kPa)

ed actual vapour pressure (kPa)

To highlight the variation that these different methods produce, the following graph (Figure 32) illustrates the differences over a single year (1969) for a selected point from the UKCP09 historic climate data.

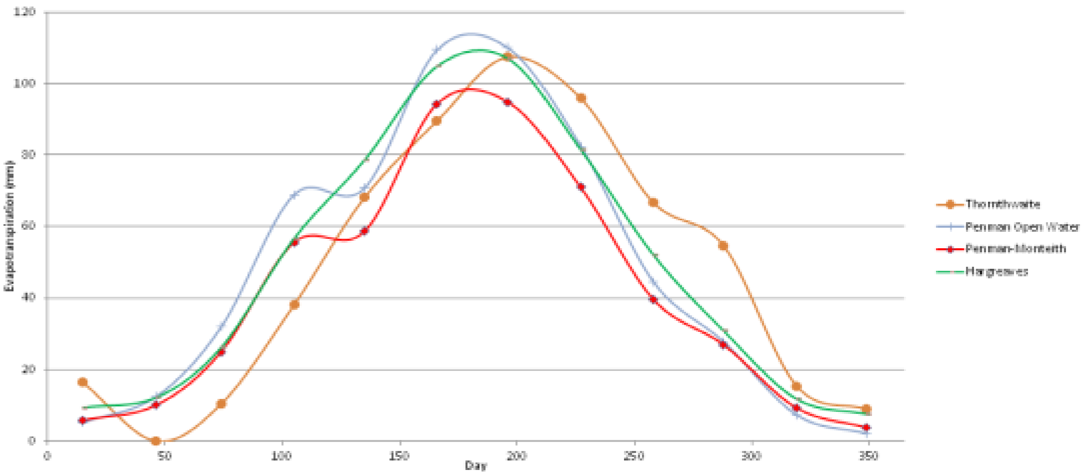



Figure 32 Comparison of different methods for calculating Potential evapotranspiration for a selected location in a single year (1969).

### 8.2.3 Lang Factor

#### *8.2.3.1 Background*

Created by Lang in 1915, the pluviometric factor was the first attempt to use temperature and rainfall to demarcate soil zones with a recognised geographical distribution (Lang, 1915).

#### *8.2.3.2 Parameterisation*

Parameterisation is derived by the simple ratio between mean precipitation and mean temperature:

$$\frac{AAR}{AAT}$$

where:

AAR = Annual average rainfall in mm.

AAT = Average daily temperature over the year °C.

Using this index as limit for the major soils distribution, Lang formulated the following global classification of soil climatic zones (Table 24).

Table 24 The classification of the Lang Factor into soil climatic zones.

| Lang Factor | Class |
|---|---|
| > 160 | soils of cold regions (podzols) |
| 160 – 100 | soils of steppe (chernozem, black earths) |
| 100 – 60 | soils of temperate regions (brown earths) |
| 60 – 40 | soils of tropical and subtropical regions (yellow and red earths) |
| < 40 | desert and semi-desert soils |

#### *8.2.3.3 Limitations*

This factor causes a division by zero error when the temperature value is equal to 0. In polar regions, an average daily temperature of zero or less is possible and thus an exception has to be introduced to avoid the error.

#### *8.2.3.4 Application to the UK*

By applying classifications derived from the Lang Factor and calculated for both the 2020 low scenario (ranging from 46 to 397) and the 2080 high scenario (ranging from 35 to 328), it is possible to delimit all five of the soil climatic zones. Under the high emissions scenario (Figure 33), the UK's climate may shift increasingly towards both the tropical/subtropical and semi-desert designations by 2080.

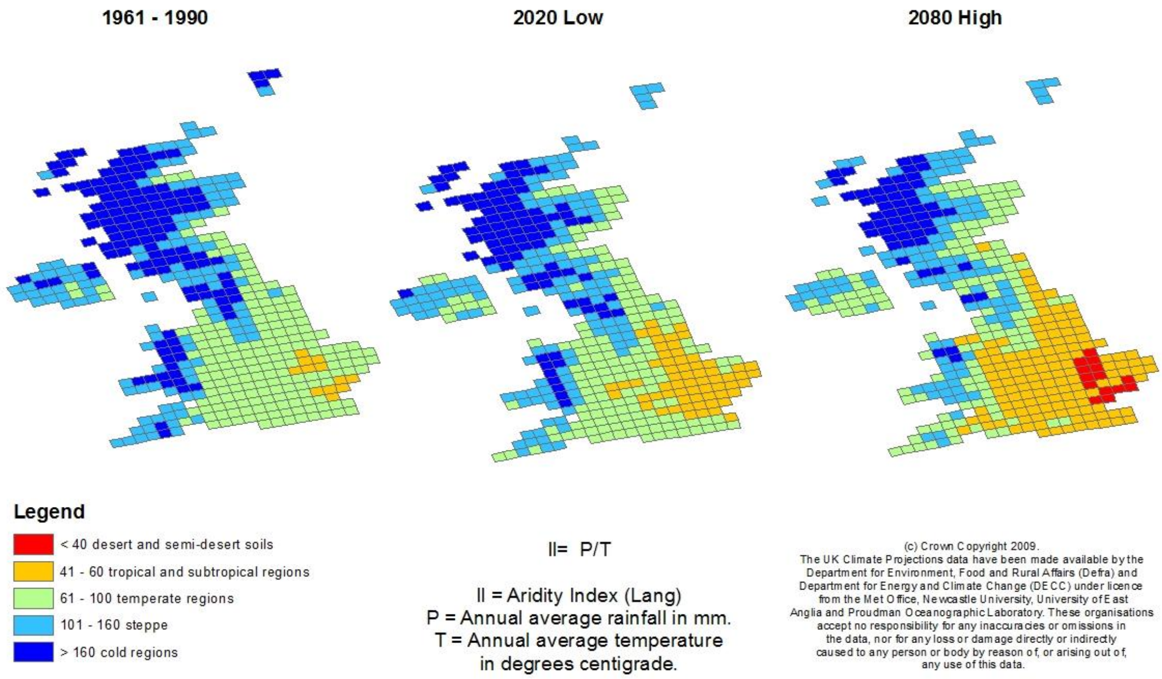



Figure 33 Classification of the UK climate (UKCP09 projections) according to the Lang Factor

### 8.2.4 Aridity index of De Martonne

#### *8.2.4.1 Background*

The aridity index of De Martonne was generated in 1926 to avoid the problematic zero point of the Lang factor (De Martonne, 1926). The index has inherent similarities to that of the Lang Factor but accounts for a temperature increase of 10°C in order to overcome potential disparities with colder regions, where the average annual temperature may be as low as 0 °C. The aridity index of De Martonne (Im) is therefore defined as the ratio of the annual precipitation sum P in mm and the annual mean temperature in °C +10. This index serves to show general trends from one region to another.

#### *8.2.4.2 Parameterisation*

$$Im = \frac{AAR}{AAT + 10}$$

Im = Aridity Index (De Martonne)

AAR = Annual average rainfall in mm.

AAT = Average daily temperature over the year °C

Table 25 Classification of climate zones according to the aridity Index of De Martonne

| Aridity Index | Climate Type |
|---|---|
| 0 to10 | Arid |
| 10 to 20 | Semi-arid |
| 20 to 24 | Mediterranean |
| 24 to 28 | Semi-humid |
| 28 to 35 | Humid |
| 35 to 55 | Very Humid |
| Greater than 55 | Extremely Humid |

#### *8.2.4.3 Limitations*

One of the main advantages of the De Martonne index is its simplicity, as records of mean annual precipitation and temperature are usually relatively easy to source. This factor has contributed to the index's prevalence over the last 80 years; however, it is not without deficiencies. In particular, the annual figures of rainfall and temperature neglect regional seasonality, which could have a very high influence on aridity. Some countries, for example, may have very localised and intense rainfall over a short period of time (one or two months of the year). This may result in a higher average rainfall which would make the drought situation look less severe than it actually is.

#### *8.2.4.4 Application to the UK*

The UKCP09 scenarios provide the annual average rainfall and mean temperature for each of the twelve future climate scenarios of interest in this project. It is therefore possible to map this index and see how it may vary for the UK. The following maps show the variation in De Martonne index for the two extreme scenarios 2020L and 2080H (calculated using the absolute climate variables for the 50$^{th}$ percentile). This classification scheme is detailed enough to allow up to five distinct classes across the British Isles. It shows the increased area of the semi-humid area and the development of a more Mediterranean climate by the 2080s in areas of East Anglia. The change in aridity showing over the UK from this index however is only being influenced by the increase in mean annual temperature as the annual average rainfall hardly changes across the scenarios. However, drier summers will result in increased drought conditions over the important growing season and this is not being assessed by this index.

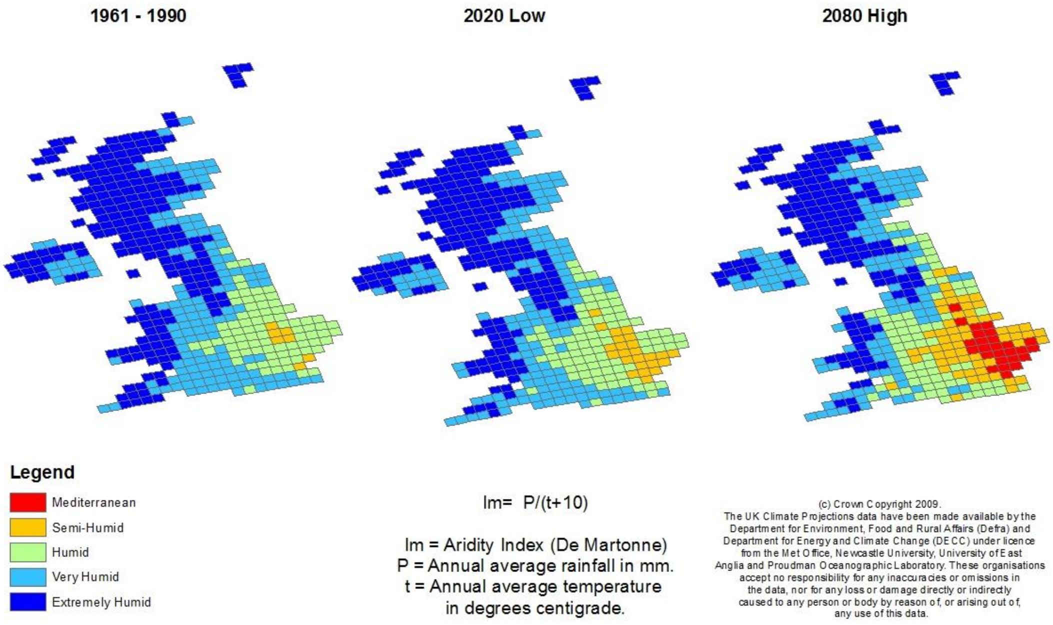



Figure 34 Classification of the UK climate (UKCP09 projections) according to the De Martonne Aridity Index

### 8.2.5 FAO-UNEP (Aridity Index)

#### *8.2.5.1 Background*

The atmospheric conditions that characterise 'dry land' are those that create large water deficits, because potential evapotranspiration (PET) is much greater than precipitation (AAR). The FAO-UNESCO (1977) bioclimatic index AAR/PET is used to evaluate these conditions. The calculation of evapotranspiration (PET) is always the complicating factor in this classification. The recommended method is to use the Penman-Monteith approach as described in FAO56, however this requires a number of environmental variables which are not always easily obtainable. As a result, the Thornthwaite method is a commonly used technique of approximating the ETP; however, in this case the class cutoffs require subtle adjustment.

#### *8.2.5.2 Parameterisation*

$$Iu = \frac{AAR}{ETP}$$

Iu = Aridity Index (UNEP)

ETP = Mean Evapotranspiration (Thornthwaite method)

Table 26 Classification of climate zones according to the FAO-UNEP aridity index

| Index | Class |
|---|---|
| < 0.03 | Hyper-arid zone |
| 0.03 - 0.2 | Arid zone |
| 0.2 - 0.5 | Semi-arid zone |
| 0.5 - 0.65 | Dry sub-humid zone |
| 0.65 - 0.75 | Sub-humid zone |
| 0.75 - 1.25 | Humid |
| 1.25 - 2.50 | Very humid |
| 2.5 - 6.0 | Wet |

#### *8.2.5.3 Limitations*

As with De Martonne, this index considers annual figures without consideration for seasonality. The method used to calculate PET can have a significant effect on the results.

#### *8.2.5.4 Application to the UK*

The UKCP09 dataset has monthly temperature data and it is therefore possible to calculate the PET using the Thornthwaite method and classify the UK accordingly. Using this index the climate in the UK only just reaches the Sub-humid zone in a few 25km squares by 2080 (high emissions). Figure 35 shows the change in aridity in the UK using the FAO-UNEP index which can be compared to Figure 36 which shows the distribution of Aridity zones across Europe in the present day. Currently, the sub-humid zone is only in the drier areas of southern France.

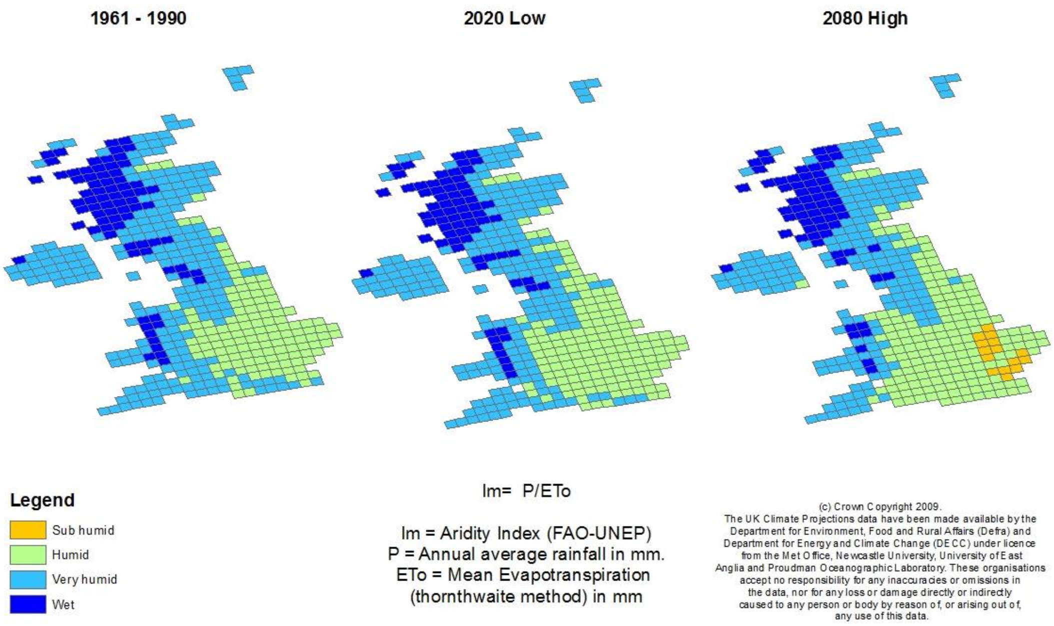



Figure 35 Classification of the UK climate (UKCP09 projections) according to the FAO-UNEP Aridity Index

### 8.2.6 Other Indices

There is a vast range of drought indices in the literature, many of which are modifications of existing indices. A number of additional indices were researched and subsequently dismissed as part of this review. Often this was due to a dearth of literature which tended to indicate a lack of relevant application, but also resulted from the age of the original research.

#### *8.2.6.1 Global Humidity Index (Thornthwaite)*

The Global Humidity Index is a basic ratio between mean precipitation (P) and mean potential evapotranspiration (PET). This index was developed by Thornthwaite (1948) with the aim of creating a classification for climate. Over the last 60 years this index has been modified and different aspects have been applied to a range of different studies. While the original method applied a scaling coefficient of 0.6 to the moisture deficiency parameter, for example this was dropped by Thornthwaite and Mather (1955) in later iterations.

#### *8.2.6.2 Emberger Index*

The Emberger index is a pluviothermal aridity index that represents the relationship between precipitation and thermal continentality. While the relationship between AAR/PET and precipitation and thermal continentality are closely correlated (Le Houerou, 2004), the Emberger index differs from other indices in that it is represented by the latter relationship. This index was developed for Mediterranean climates (Emberger, 1930) and while it has been widely used in these regions, it may be unsuitable for UK applications at present. Furthermore, there are no available examples of its use in the UK to date. The use of the Emberger index is unusual when making spatial comparisons as it does not use values for PET.

#### *8.2.6.3 Palmer Drought Severity Index*

The Palmer Drought Severity Index (PDSI) is a measure of the departure from the normal moisture supply (Palmer, 1965) and is the most widely used drought index in the USA, where it forms the basis of England and Wales' drought monitoring system (Alley, 1984).. It is a relatively complex index with multiple stages to its computation, although at its core it uses temperature and rainfall to calculate the degree of dryness (Motha, 2011). The PDSI does not suit the applications required in this study. The PDSI provides a method for analysing the temporal aspects of drought events, such as duration; however, this study is primarily concerned with long-term trends in the spatial distribution of aridity.

#### *8.2.6.4 Crowther (Leaching index)*

This factor, generated by E.M. Crowther in 1930 was used for the first time in the USA to delimit major soil climatic zones; it is still used widely as a "Leaching Factor" in pedology. Its application provides information on the soil leaching process. Values of this index around zero indicate an absence of leaching, positive values and negative values indicate the presence of active leaching process and capillarity ascension, with intensity proportional to the increasing or decreasing absolute value of the index respectively. Other than distinguishing three general classes above, below and near 0, no further sub categorisation of this index is recognised

#### *8.2.6.5 Prescott Index*

This simple index gives an indication of the intensity of leaching and provides a measure of potential biological productivity; it provides an estimate of the water balance and was defined by Prescott in 1948. This index was largely adopted in Australia where it was recently used as component of a soil microbial activity index in a model for the identification of natural regions with the potential to enhance soil carbon content. No standard classification of this index exists which makes it difficult to assess the extent of the changes. This index was created for use in Australia to distinguish desert areas from areas with a lack of drainage and similarly identify where rainfall is balanced against evapotranspiration. As a result, the index's three classes correspond to 1) less than 0.5 (denoting desert not present in the UK), 2) between 1.1 and 1.5 (indicating areas between nil drainage and balanced rainfall) and 3) areas above 1.7 (indicating a division between pedocal soils, which are formed under arid/semi-arid conditions, and pedalfer soils, which form under humid conditions).

#### *8.2.6.6 Modified de Martonne index*

The original de Martonne index takes the annual averages of rainfall and temperature; however, this was modified in 1998 by Botzan *et al*. in order to capture seasonal variations in the water budget. Botzan *et al.* (1998) applied their modified index to the Napa Basin, California. However, no further applications of this index are available.

#### *8.2.6.7 Soil Climatic Index (Canada)*

This index was first developed by Mitchell et al. (1944) in order to classify climate for crop production in Saskatchewan, Canada. It requires mean annual precipitation and temperature as parameters in an empirical equation. However, the resulting climate classifications, defined by Henry (1990), are very specific to the Canadian prairies. There has been no application of this index outside of Canada.

#### *8.2.6.8 SPEI Modified Palmer*

The Standardized Precipitation Evapotranspiration Index (SPEI), developed by Vicente-Serrano et al. (2010), is based on a water balance similar to the PDSI. However, it also has multi-scalar aspect, which allows distinction between different types of drought, on different temporal scales. Therefore, potentially it has wider applications than PDSI for assessing the effects of climate change (Vincente-Serrano *et al*., 2010). However, similar to the PDSI, the emphasis of this index is on the monitoring of drought and analysis of specific events in time, whereas this study is interested in longer term changes to aridity.

This index is under development (2010), and as a result the range of the possible applications has not been explored.

### 8.2.7 Discussion

#### *8.2.7.1 Effect of changes in Aridity Index*

Reviewing the aridity indexes suggests that there will be a significant increase in drought conditions in the south and east of England with many areas shifting to a much drier climate type. However, these indices are mostly based on annual figures and do not account for seasonality. The annual rainfall for the UK is not predicted to change significantly and therefore aridity indices do not reflect a significant change. The change to warmer/wetter winters and hotter/drier summers is not reflected in the indices but will have a significant effect on the growth pattern of our current crops. This change is most obvious in potatoes, which will no longer be able to be grown in most of England and Wales unless they are grown under irrigation (Daccache et al, 2011).

The FAO-UNEP Aridity Index is probably the most universally applied aridity index. Figure 36 shows the current distribution of the Aridity Index Zones across Europe (Trabacco and Zomer, 2009). By 2080, the aridity index in England and Wales suggests that some areas of the UK in the south east will move into the sub-humid zone - this is equivalent to climatic areas of the south of France as well as the central belt of Poland, where rainfall is currently less than 500mm per year. Figure 37 shows the distribution of potato production across Europe, which shows extensive potato production in Poland, even in the central area where climate is drier (Huaccho and Hijmans, 1999). This indicates that it is still possible to grow potatoes in this climate zone with appropriate irrigation. However, the comparison with Poland ends when seasonal distribution of rainfall is considered.

Although the central belt of Poland has similar annual rainfall to the predicted annual rainfall in 2080 in the south east of the UK, the rainfall in Poland falls mainly in the summer months during potato crop growth. Conversely, it is predicted that the summer months will be the driest months in the UK (Figure 38). In the rest of Europe the distribution of potato production largely avoids the sub-humid zones. Figure 38 also illustrates a comparison of the seasonal rainfall and temperature from three sites around Europe which are currently in the sub-humid zone: Warsaw in Poland, Montpellier in the south of France and Ravenna in Italy.

The Languedoc-Roussillon region of France has a more similar temperature range to that predicted in the east of England by 2080H with a more comparable rainfall pattern (wetter in Winter and drier in Summer). Currently this area of France is dominated by the production of Wine particularly in the deep clay soils. There is some potato production in this area but very little. In all the sub-humid zones potato production is only possible with irrigation.

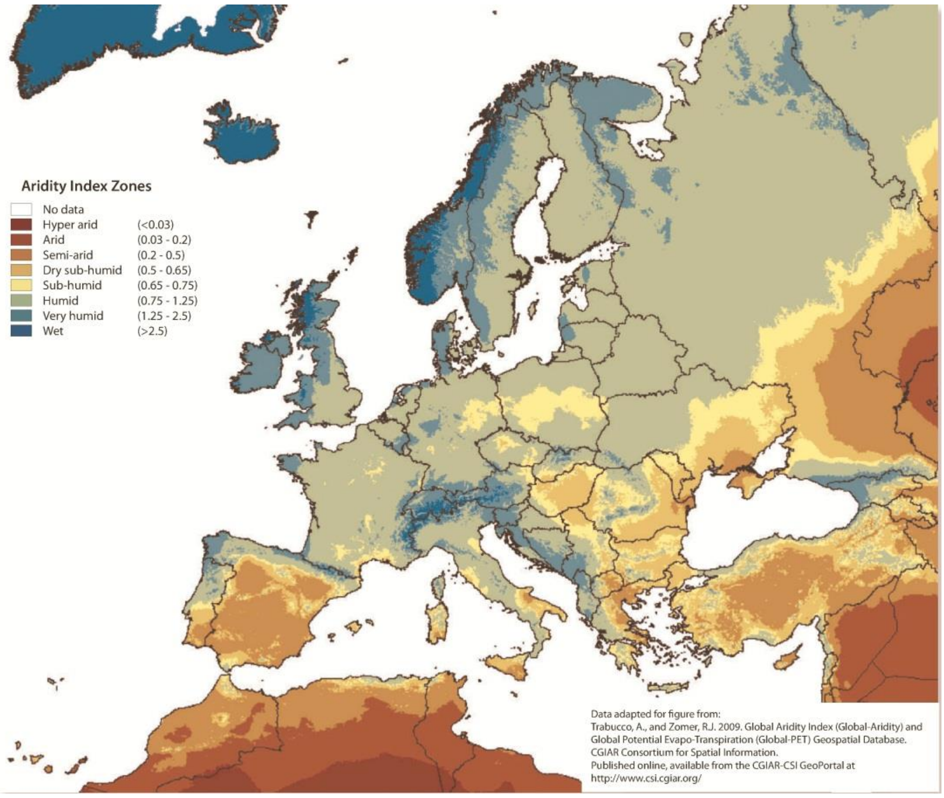



Figure 36 FAO-UNEP Aridity Index Zones in Europe in present day (map published online, available from the CGIAR-CSI Geoportal at [http://www.cgiar-csi.org/](http://www.cgiar-csi.org/))

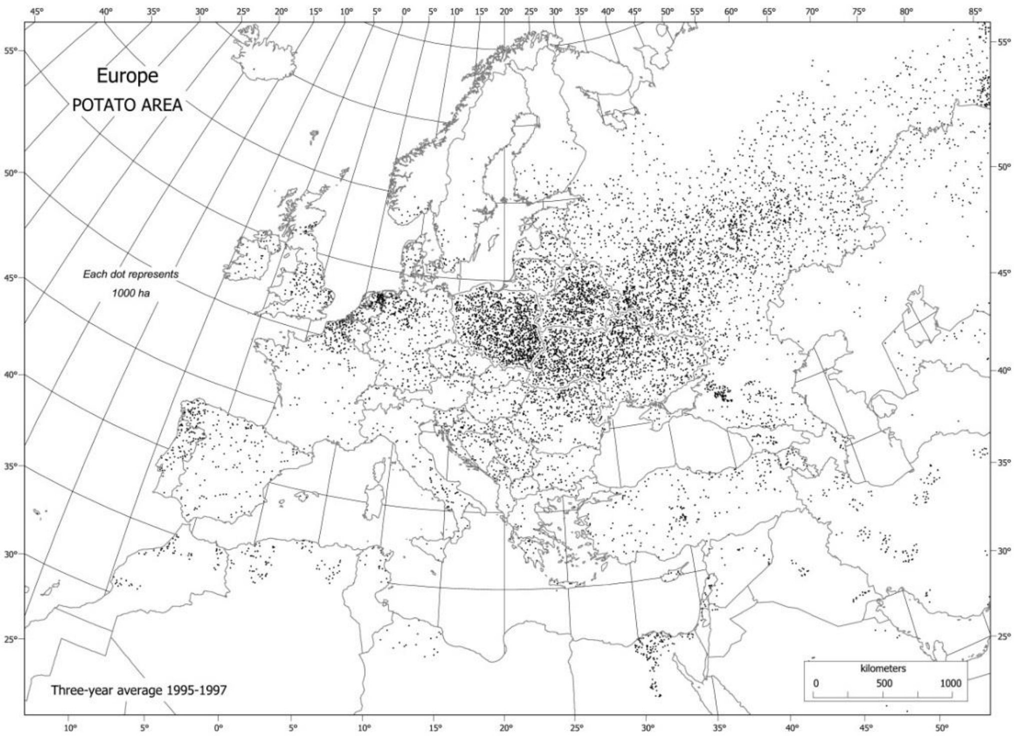



Figure 37 Potato distribution in Europe (1995-1997) (Huaccho and Hijmans, 1999)

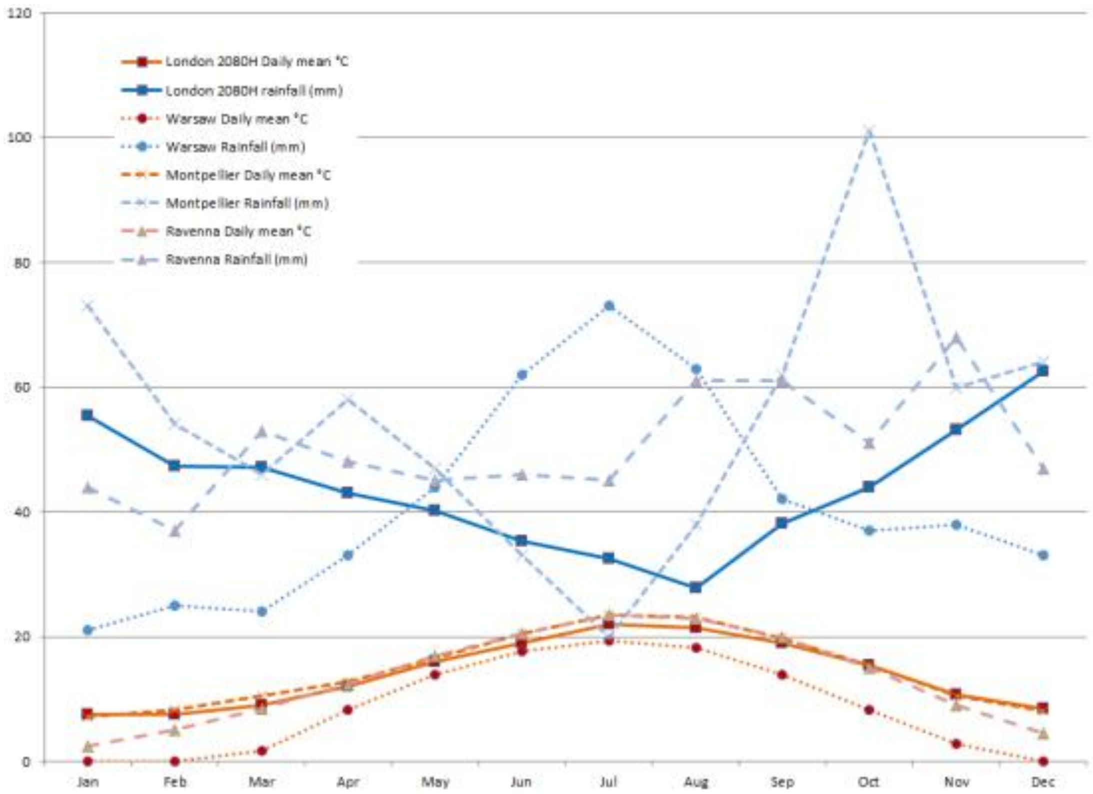



Figure 38 Comparison of monthly rainfall and temperature for selected European cities in Sub-humid zone

#### *8.2.7.2 ALC grade for droughtiness in Wales and the North of England*

It is clear from the application of the various aridity indices that the south and east of England may become significantly drier and more arid by the 2080s, especially under a high emission scenario; however, it is less clear whether or not the northern and western areas of England and Wales will change to any great extent. The application of aridity indices to these areas indicate that they are still within the humid/wet zones, so the ALC's prediction of drought in these regions (downgraded to Grade 4 by 2080) remains a key question. However, this question can be answered by looking at the predicted changes in moisture deficit. Unlike the other aridity indices, which use annual figures, moisture deficit is calculated by combining the monthly rainfall and evapotranspiration to illustrate how the water deficit builds up through the year. The combined effect of less summer rainfall and higher temperatures thus increase the potential for droughty conditions.

Figure 39 shows how the maximum soil moisture deficit in an average year will vary for the three climate scenarios. Figure 40 and Figure 41 illustrate a comparison of the rainfall, evapotranspiration and moisture deficit for two 25x25km squares selected from the UKCP09 datasets; these represent a wet site in Wales and a dry site near London. They show how the moisture balance builds through the summer months and how this will increase in each of the two future scenarios compared to the current baseline data. The PSMD for the Welsh site reaches similar levels (150mm) in 2080 to the PSMD for the site in London in the present day (200mm), which suggests that even in Wales the sites will be becoming more droughty, though less so than present day London.

It should also be noted that the soils in London are still in deficit by the end of the year and may not reach field capacity before the spring of the following year, when the soils again begin to dry out. The calculation of MD for ALC purposes assumes that the previous year's deficit is eliminated by the end of February. If this doesn't happen in later years, the droughtiness in these areas will be more severe than originally predicted.

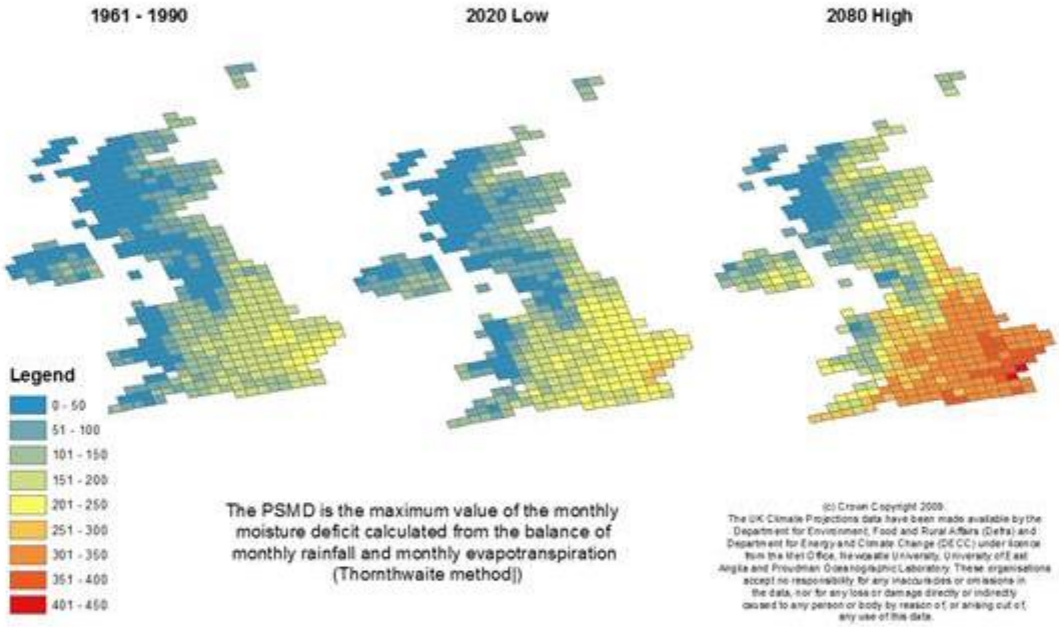



Figure 39 Potential Soil Moisture Deficit (PSMD) calculated from monthly balance of Rainfall and Evapotranspiration, using the UKCP09 projection data.

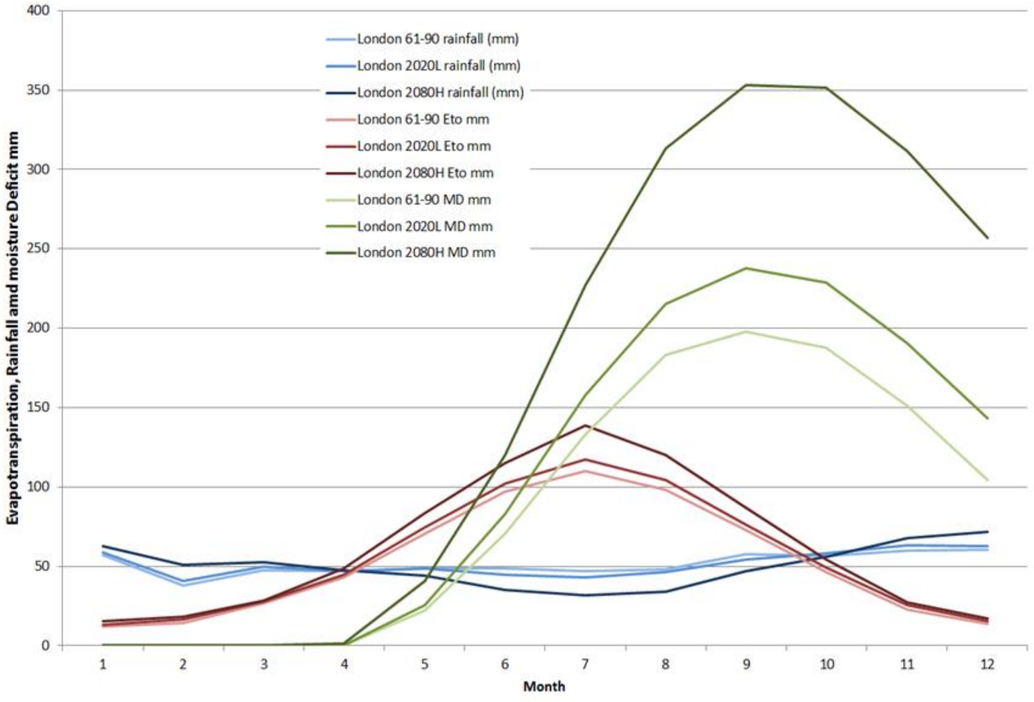



Figure 40 Comparison of monthly Rainfall, Evapotranspiration and Moisture Deficit in London from 1961-90, 2020L and 2080H

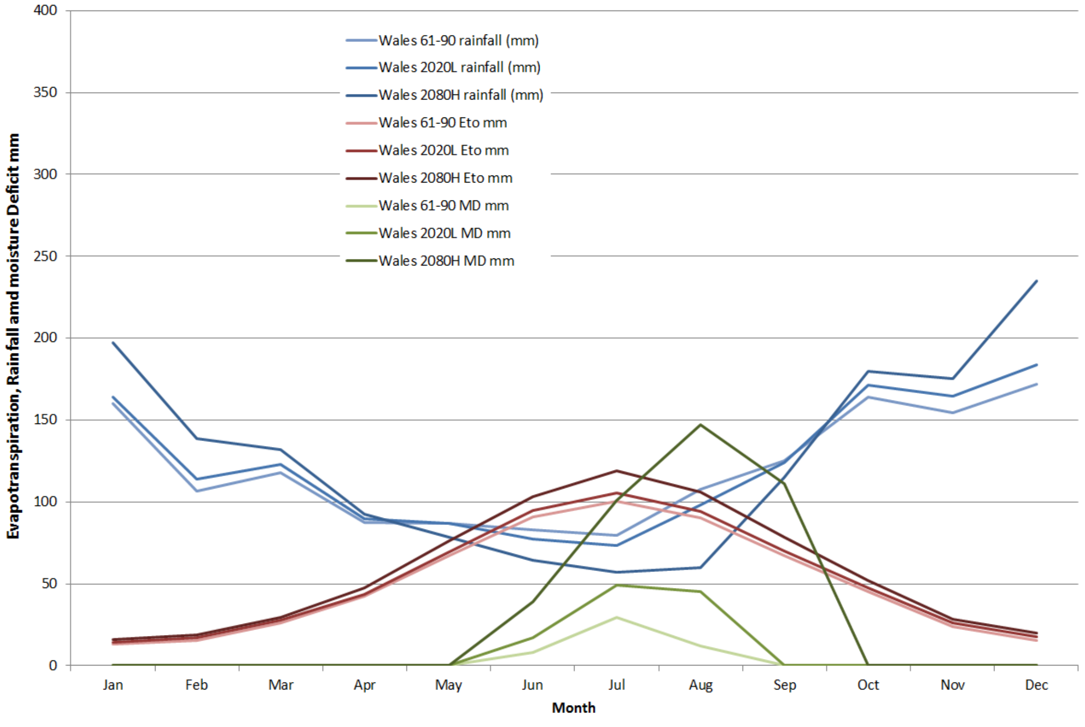



Figure 41 Comparison of monthly Rainfall, Evapotranspiration and Moisture Deficit in Wales from 1961-90, 2020L and 2080H

## 8.3 Impact of climate change on cropping outcomes

### 8.3.1 Introduction

Agricultural production is very sensitive to atmospheric and climatic conditions and production will likely undergo significant alteration under future environmental change. However, these changes are complex, with a number of interrelated positive and negative effects. A recent Defra led report – which acts as part of the UK 2012 Climate Change Risk Assessment (CCRA) – provides an assessment of the current and future risks and opportunities to the UK agricultural industry as a result of a changing climate (Knox *et al*., 2012). There are several directions the industry could take depending on the extent to which adaptations to climate change are adopted by farmers and implemented by policy makers. The CCRA has evaluated how this may influence UK cropping outcomes.

This chapter summarises the impact a changing climate may have on crop yields in the UK, with particular emphasis on winter wheat and maincrop potatoes as they are the reference crops used by the ALC droughtiness model. The various environmental stresses and extreme events, which are likely to become more prevalent in warming climates, are evaluated in terms of the problems they may pose for yields. Table 27 provides a summary of the potential changes that may occur in the UK due to global climate change. Some of the negative impacts on crop yields may be reduced or prevented if the agricultural industry adapts to change and exploits the opportunities that it provides. Adaptation can happen on many different scales, from nationwide geographical shifts in cropping regions (including the introduction of new crops) and large scale water management projects all the way to farm scale solutions focusing on soil management. Some adaptation measures are summarised here and their potential to help mitigate the effects of climate change assessed.

| Variable | UKCP09 projected change |
|---|---|
| Mean temperature | All areas of UK warm, more so in summer than in winter. Changes in summer mean temperatures are greatest in parts of southern England (up to 4.2ºC (2.2 to 6.8ºC) and least in the Scottish islands (just over 2.5ºC). |
| Mean daily Maximum temperature | Increase everywhere. Increases in summer average are up to 5.4ºC (2.2 to 9.5ºC) in parts of southern England and 2.8ºC (1 to 5ºC) in parts of northern Britain. Increases in winter are 1.5ºC (0.7 to 2.7ºC) to 2.5ºC (1.3 to 4.4ºC) across the country. |
| Mean daily Minimum temperature | Increases on average in winter by about 2.1ºC (0.6 to 3.7ºC) to 3.5ºC (1.5 to 5.9ºC) depending on location. In summer, increases by 2.7ºC (1.3 to 4.5ºC) to 4.1ºC (2.0 to 7.1ºC), with the biggest increases in southern Britain and the smallest in northern Scotland. |
| Annual precipitation | Central estimates show very little change over UK at the 50% probability. The biggest change ranges from –16% (10% probability) to +14% (90% probability) in the West of Scotland. |
| Winter precipitation | Biggest changes in winter are increases of up to +33% (+9 to +70%) along western UK. Small decreases (–11 to +7%) over parts of Scottish highlands. |
| Summer precipitation | Biggest changes in summer are down to about –40% (–65 to –6%), for parts of the far south of England. Changes close to zero (–8 to +10%) for parts of northern Scotland. |
| Sea level | The range of absolute sea level rise around the UK (before land movements are included) is projected to be between 12 and 76 cm for 1990–2095. |

Notes: Data presented are for the 2080s medium emissions scenario, and for the summer, winter and annual mean changes relative to a 1961–1990 baseline) using 'central estimates' (50% probability). Uncertainty expressed as 'very likely' and 'very unlikely (10 and 90% probability levels shown in brackets. Derived from Jenkins *et al.* (2009b).

Table 27 Summary of projected climate change in the UK (from Knox *et al*., 2012)

### 8.3.2 Crop yields

#### *8.3.2.1 Positive impacts*

There are a number of benefits that warmer climates will bring to crop growth. Biological processes that result in plant growth occur at increasing rates as temperature rises, up to an optimal point. Consequentially, warmer climates could result in increased crop yields. Increased atmospheric $CO_2$ may also lead to higher yields due to increased photosynthesis. The amount that $CO_2$ fertilisation affects crop productivity depends on the species in question. For some species, increased $CO_2$ uptake can result in a larger root density and more efficient use of water (Defra, 2012).

Some biophysical models have indicated that, despite some scenarios that predict a drop in yields, the quality of the crop may improve. However, this effect has not been assessed fully (Defra, 2012). However, positive temperature and $CO_2$ effects on yields do not tell the whole story. The potential increases in yield may be hampered by other restrictions to plant growth, most notably, water. Heat stress around flowering is also a potentially significant issue (Semenov, 2009).

#### *8.3.2.2 Increased aridity and drought risk*

The availability of water is likely to be the main constraint on crop yields under future climate scenarios. Although average annual rainfall is likely to see only a modest decline, the increased seasonality will have serious implications for crop production. A decrease in the average summer rainfall, as well as increased potential evapotranspiration due to warmer temperatures, may result in higher soil moisture deficits during the summer months. Without adequate irrigation, this increase in aridity over the next century will put increased stress on crop yields. The picture is not a consistent one across the UK; with the south of England experiencing the highest increase in aridity.

Agricultural droughts are likely to become more prevalent in the coming decades. Drought can have devastating effects on expected yields, with large yield compared to the norm and in some cases, total crop failure. Again, it is likely that there will be great variation between different species, with some species and varieties experiencing greater yield losses than others. This has already been demonstrated during droughts and heat waves over the last few decades, although the effect of droughts on yields is dependent on the level of adaptation in a particular crop's production system (Mechler *et al*., 2010).

#### *8.3.2.3 Flood risk*

Increased flood risk poses another threat to crop production under future climates. An increase in frequency of extreme rainfall events, as well as the effects of sea level rise, will both result in the degradation and loss of agricultural land. In England and Wales the amount of good quality agricultural land (ALC grades 1 to 3) that is flooded by sea or rivers once every three years is projected to increase from 31,000 ha, currently, to 36,000 in the 2020s (medium emissions scenario, central estimate). However by 2050s this area may have more than doubled, with 75,000 ha being flooded once every three years for the medium emissions scenario; and by 2080s the increase may be four-fold (Knox *et al*., 2012). Furthermore, agricultural land generally has a lower level of flood protection compared to built-up areas. Increasingly frequent floods may result in land becoming unviable for high-value crops and unsuitable/difficult for the use of machinery at key points in the agricultural calendar. Therefore flooding may cause indirect effects on crop yield, as well as directly damaging crop stands.

Increased risk of heavy rainfall in winter may also lead to increased soil erosion, with implications for soil structure and reduced fertility resulting in long term soil degradation and reduction of yields. Surface flooding and water logging can also have devastating effects on crop production, as well as resulting in anaerobic soil conditions leading to reduced plant growth (Gornall *et al*., 2010).

Currently the regions with the greatest areas of good quality agricultural land at risk of 1 in 3 year flooding are the Midlands, Wales and East Anglia. However, under future UKCP09 scenarios, the risk across all of England and Wales will increase, with particularly large areas in the South West being affected (Defra, 2012).

#### *8.3.2.4 Pests and diseases*

Warmer climates, especially milder winters, are likely to be exploited by a range of pests and pathogens, due to their great capacity for generating, recombining, and selecting traits which will increase their prevalence. However, understanding of past trends is limited due to the dampened effect of climate variability on the disease signature, due to improvements in treatment and crop agronomy over the last few decades. Therefore, without discernible understanding of the relationship with past climate variability, the interactions between crops, pests and pathogens are currently poorly understood in the context of climate change (Knox *et al.*, 2012).

#### *8.3.2.5 The impact on wheat yields*

There have been a number of studies that use biophysical crop models to assess the impact of future climates. Semenov (2009) used the UKCIP02 data in a stochastic weather generator as an input into the Sirius wheat simulation model, in order to assess the probability of heat stress at flowering and the severity of the drought stress, as these two indices can pose significant risks to wheat yields. With warmer temperatures it is likely that wheat will mature earlier, and therefore it may avoid the most severe of the summer droughts. Indeed, Semenov (2009) found that due to earlier maturity, drought may pose less of a stress on wheat than it does in the present climate. However, while there may not be yield loss due to increased drought stress in warmer, drier summers, they found that an increased risk of heat stress during flowering will have a serious adverse effect on yields (Semenov, 2009).

Semenov (2009) found that increased heat and drought stress may affect different winter wheat cultivars to different extents. It was found that both cv. Avalon and cv. Mercia are projected to flower about two weeks earlier than the baseline period by 2050s (high scenario). However, cv. Mercia is a later flowering variety and so the maximum temperature during flowering is expected to rise by 1.06 °C, despite the earlier average flowering date; compared to 0.35 °C for cv. Avalon. As a result the risk of heat stress during flowering may increase by over two-fold between the baseline period and 2050 for cv. Mercia, whereas the risk for cv. Avalon changes very little.

Overall the adverse effects of heat stress during flowering on yields, for both cultivars, may be overcome by earlier maturity resulting in the worsening summer droughts being avoided, as well as the effects of $CO_2$ fertilisation. Semenov (2009) found that under the UKCP09 2050s high scenario cv. Avalon yields would increase by as much as 17.5 – 20% in the south east of England. For the same region and scenario cv. Mercia may see yields increase by 7.5 – 10%.

#### *8.3.2.6 The impact on potato yields*

For potatoes, empirical analysis of yield and mean summer rainfall variability indicate that potential main crop potato yields will decrease. By the 2050s yields are projected to have fallen by 5% (central estimate, with a range of -12% to +3% change) for the medium emission scenario (Knox *et al*., 2012).

However, biophysical crop models, which also consider the effects of increased $CO_2$, have produced a different outcome. Daccache *et al.* (2011) used the SUBSTOR-Potato model for the 2050s to assess future potato yields and irrigation requirements. They found that the potential yield may increase by 13-16% by the 2050s (UKCP09 climatology), principally due to increased solar radiation, temperature and $CO_2$ levels. However, this increase may actually be limited to 3-6% because of limitations in the availability of water and nitrogen. In order to achieve the higher potential yields, irrigation would need to increase by an average of 14 – 30%, depending on emission scenario. Generally the response of potato yields to climate change is less well constrained compared to wheat; depending on the method of prediction used, it is unclear which will be the dominant factor influencing yields: increased solar radiation and $CO_2$ concentrations, or reduced water and nitrogen availability (Defra, 2012).

### 8.3.3 Adaptation

Despite the potential negative impacts on crop yields due to climate change, there is large scope for adaptation in the agricultural industry in order to mitigate the impact. Adaption can take one of two forms: autonomous adaption or planned adaption, defined by the IPCC AR4 (2007):

- Autonomous adaptation does not constitute a conscious response to climatic stimuli but is triggered by ecological changes in natural systems and by market or welfare changes in human systems. [The CCRA definition differs slightly as also including anticipated adaptation that is not part of a planned adaptation programme, and therefore may include behavioural changes by people who are fully aware of climate change issues].

- Planned adaptation is the result of a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state.

In the agricultural industry much of the adaptation will require long term investment and development of infrastructure and technology, particularly involving water resources issues. However, there will also be smaller scale autonomous adaptation by individual farm businesses, for example improving soil management practices to prevent worsening soil conditions. The uptake of certain adaptation options may depend on the level of funding and other support available, especially for smaller farm businesses. For example, larger agribusinesses are more likely to invest in adaptation measures, such as farm storage reservoirs, before their potential necessity or benefit becomes apparent, whereas smaller farms are at risk of falling behind and suffering greater yield losses as a result.

#### *8.3.3.1 Crops*

Constraints on crop yield may be overcome by the opportunities a warmer, drier climate provides for changing and expanding the range of crops grown in the UK. This adaptation has the potential to change the UK's agricultural landscape and economy. New food crops could include blueberries, table grapes, maize, sunflowers and soya. In addition to food crops, there could be a move towards new energy crops for biogas, biomass or bioethanol production. New pharmaceutical crops and industrial crops could also emerge (Knox *et al*., 2012). Suitable cropping areas are likely to shift northwards with warming climates.

There may also be a geographical shift in traditional crops, for example potato-growing areas may move towards the west, in order to reduce irrigation needs. Temporally, there may also be a change in cropping practice, with the timing of growing seasons for particular crops changing, in order to maximise optimal conditions and reduce the impact of seasonal stresses, such as summer droughts. For example, potatoes may be sown earlier due to less risk of frost during the milder winter and springs.

These changes in crops are likely to fall under the autonomous adaptation category. Farmers are likely to change their cropping regime gradually, with more land being designated to new crops, as the climate changes and new markets emerge. However, some changes may be due to planned adaptation if new policy is introduced to encourage diversification. As well as new crops there may be advances in breeding of more climatically robust crops.

#### *8.3.3.2 Water management*

The increased risk of drought and heat stress may be overcome by increasing the amount of water abstracted by farmers for irrigation. On a grander scale, advances in technology and investment in infrastructure could address some the geographical disparities in water supply, with the transport of water from the wet north to the dry south. The seasonal differences in water supply from precipitation could also be solved with improvements in water storage. Rain from the wetter winters could be used to replenish soil moisture deficits over the drier summers. Large scale investment in winter storage reservoir construction is being considered and planned by the major water companies as the most viable solution to future water resource issues across all sectors (Norton *et al*., 2011). Locally, on individual farms or groups of farms, small scale storage of winter excess could potentially contribute greatly towards relieving summer deficits, allowing farmers to plan cropping activity with greater effectiveness (Norton *et al*., 2011).

#### *8.3.3.3 Soil management*

Soil management may prove to have an important role in mitigating the effects of climate change. Soil structure may be compromised due to drier summers and wetter winters, resulting in increased susceptibility to soil compaction and erosion; which, in turn, leads to increased nutrient loss. There are a number of soil management methods which could help reduce the impact of climate change on soil structure and nutrients; for example, minimum tillage and buffer strips could help reduce erosion and runoff.

### 8.3.4 Summary

Climate change is likely to have an impact on arable production in the UK in the coming decades. While warmer temperatures and increased $CO_2$ concentrations may result in improvements in wheat and potato yields; it is likely crops will suffer from adverse effects of climate change, especially related to water stress. It is currently unclear what the combined effect of environmental change will have on crops. The impact of climate change is not just dependent on climatology and plant physiology; a main driver in determining the impact of climate change on agriculture is the extent to which the industry responds and adapts.

There is great potential for adaptation in the agricultural sector, some of which is likely to be planned as part of policy adaption. However, much of the adaptation is likely to be autonomous, as individual farmers respond to their locally changing environment. Improvements in soils and water management may be necessary in order to maintain yields, but there may be some more fundamental changes in cropping in the UK also. For example, there may be a geographical shift in the crops grown, including the introduction of crops not currently grown in the UK. The fifth section of this report provides a basic assessment of the future land capability in the UK compared to present conditions in Europe.

## 8.4 Future climatic conditions in UK compared with current conditions in Europe.

### 8.4.1 Introduction

A simple analysis of climate, soils and cropping was carried out, comparing current European conditions with predicted climate in the UK in the 2050s and 2080s. The analysis was focused on wheat and potato cropping regions in the UK. This comparison provided empirical evidence as to whether land under future climates in the UK will be able to support crops currently grown, in particular winter wheat and maincrop potatoes. It also gave an indication of other crops that are already grown in comparable areas in Europe.

This section aims to make an overall comparison between climate in the UK under the 2050s and 2080s climate projections and current European climate. In addition to this, specific areas within the UK are compared to areas within Europe with matching soil types, land use and climate; in order to make more specific comparisons. This will give an indication of the future land capabilities of predominantly arable areas in the UK by assessing current land capabilities in Europe.

### 8.4.2 Methods

In order to assess future UK climate in relation to land capability in other European countries, a number of datasets were used:

- The Soil Geographical Database of Eurasia (SGDBE)[2]: Raster data for European soils – in particular the texture was used:
    - 0 No information
    - 9 No mineral texture (Peat soils)
    - 1 Coarse (18% < clay and > 65% sand)
    - 2 Medium (18% < clay < 35% and >= 15% sand, or 18% < clay and 15% < sand < 65%)
    - 3 Medium fine (< 35% clay and < 15% sand)
    - 4 Fine (35% < clay < 60%)
    - 5 Very fine (clay > 60%)
- Corine Land Cover 2006 raster data[3]: European land use data – the land use class used in this comparison was non-irrigated arable land.
- Climatic Research Unit long term means (1961-1990) for Europe[4]: A 0.5° latitude/longitude land cell dataset of mean monthly surface climate. From the monthly means average summer climatic conditions were calculated as this is representative of the growing season (April to September). A raster dataset was created for each of the following:
    - Average summer precipitation (ASR)
    - Maximum summer temperatures (ASTmx)
    - Minimum summer temperatures (ASTmn)
- UK climate projection (UKCP09) data for the 2050s and 2080s low and high emissions scenarios, downscaled to 5 km x 5 km resolution[5]: The same seasonal climatic variables were calculated for these future climates, as the baseline period (ASR, ASTmx and ASTmn).
- England and Wales cropping data[6] on a 1km grid for winter wheat and maincrop potatoes.

Summer climatic averages were used in the comparison because annual average climates are likely to dampen seasonal variation. Therefore, annual climatic comparisons between different locations would be less meaningful, especially for the purpose of investigating arable crops.

Initially, cropping data were used to assess where winter wheat and maincrop potatoes are currently grown in England and Wales. The 1km grid cells in which winter wheat and maincrop potatoes accounted for >10ha and >1ha of the area respectively were spatially joined to the UKCP09 climate data, allowing projected future climatic conditions in these areas to be summarised; i.e. for both the winter wheat and maincrop potato growing areas. For each UKCP09 scenario, a range of values (mean ± 1 standard deviation) were found for average summer rainfall and average maximum and minimum summer temperatures within these areas. For each climatic variable and UKCP09 scenario, this range of values was used to create grids for which a value of 1 represents the cells that fall within the range of each climate variable suitable for the growing of winter wheat and maincrop potatoes and 0 represented cells that did not. Thus areas in Europe that currently fall within the range of all three variables could be

[2] The European Soil Database (distribution version v2.0) (http://eusoils.jrc.ec.europa.eu/esdb_archive/ESDBv2/)

[3] European Environment Agency (http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-1

[4] Data as per *Hulme et al*., (1995a, b).

[5] Data as per Chapman *et al*. (2012).

[6] ADAS land-use database 2010 June agricultural census update as per Comber *et al*. (2008)

found. This was used to give an indication of the current areas in Europe that reflect the potential UK climate conditions in the future.

In addition to this, four predominantly agricultural areas within the UK, each with a particular dominant soil type (coarse, medium, medium fine and fine), were selected in order to make comparisons with other European areas. For each sample area, the summer climate was assessed for each of the UKCP09 projections. The range of climatic conditions used to make a comparison with the European climate data was calculated from the mean ±3 standard deviations. GIS analysis was used to determine the areas within Europe that currently have climates that fall within these ranges, as well as being non-irrigated arable areas with the relevant soil texture. This was accomplished by selecting grid cells from the European baseline climate that were within the ranges for each of the scenarios and areas. The land use and soils data were also manipulated so that grid cells with the relevant land use and soil type had values of 1. This allowed for the identification of grid cells across Europe that were within the appropriate range for all three climate variables, as well as of the same land use type and soil type as the sample areas. This provides an indication of how future climate scenarios will impact the four sample areas.

### 8.4.3 Results

#### *8.4.3.1 Winter Wheat*

Winter wheat is a common arable crop in England and some parts of Wales. Grid cells with an average winter wheat area of above 10 ha per $km^2$ were used in the climate analysis (Figure 42), from this area, the average climatic conditions were derived (Table 28).

Table 28 Climatic conditions across the current winter wheat growing areas in England and Wales, for the relevant UKCP09 scenarios: average summer rainfall (ASR); and average maximum (ASTmx) and minimum (ASTmn) summer temperature.

| UKCP09 scenario | ASR (mm) | | ASTmx (°C) | | ASTmn (°C) | |
|---|---|---|---|---|---|---|
| | Mean - 1SD | Mean +1SD | Mean - 1SD | Mean +1SD | Mean - 1SD | Mean +1SD |
| 2080H | 219.9 | 273.4 | 22.8 | 24.8 | 13.4 | 14.5 |
| 2080L | 239.4 | 291.4 | 20.6 | 22.4 | 11.4 | 12.5 |
| 2050H | 239.9 | 292.9 | 21.2 | 23.0 | 11.9 | 13.0 |
| 2050L | 247.7 | 300.5 | 20.0 | 21.7 | 10.8 | 11.9 |

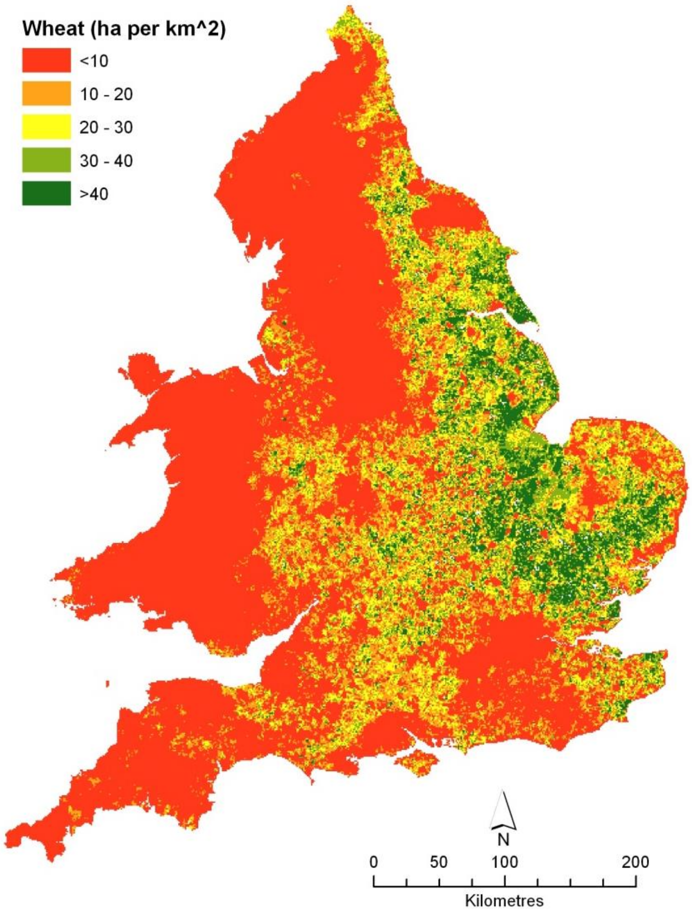



Figure 42 Distribution of winter wheat across England and Wales.

Figure 43 shows the areas within Europe that, for the baseline period, have a similar climate as the winter wheat area under climate change in England and Wales. There is a general southwards shift in the areas with matching climates from the 2050s to the 2080s and between the low and high emissions scenarios.

Figure 43a shows that in the 2050s under the low emissions scenario, the land in England and Wales that currently grows winter wheat will have a similar climate to that found in areas of western France and the east and south of Ukraine, as well as smaller areas in south Spain and Italy, and north Turkey. These areas in France and the Ukraine support wheat production, although the yields in Ukraine tend to be significantly lower than the UK and France (~1.5 tonnes ha-1 in 2004 versus 7.9 and 7.0 tonnes ha-1 (2010), respectively). However, the locations in southern Spain and Italy, and northern Turkey, marked in Figure 43a, are not wheat growing areas.

The 2050s high emissions scenario projection comparison (Figure 43b) shows the southwards shift in comparable areas. The main areas with a climate that matches the projection are to the north and west of the Black Sea, which are wheat growing areas. There are also isolated locations around the west Mediterranean, including North Africa. However, the Corine land cover data show there is no non-irrigated arable land in this area.

Figure 43c shows that for the 2080s low emissions scenario the areas with a comparable baseline climate are in similar locations to the 2050s projections; although the dominant comparable area is in Ukraine. In the high emissions scenario the comparable area spreads into Russia as well as locations all around the Mediterranean coast (Figure 43d). Compared to the previous UKCP09 scenarios, this scenario matches the climate in the region around the Aegean Sea (i.e. Greece and western Turkey). Greece's agricultural production suffers from a dry climate and poor soils, however the region marked out in Figure 43d in the north of England and Wales is the main arable centre of the country, with crops including wheat (as well as beans, olives, and fruit).

The southwards shift in the analogous locations between the 2050s and 2080s is an indication of how the wheat growing areas in England and Wales may change over the coming decades. Many of the areas in Europe that match the future UK climates have some wheat production. A few of the locations that have emerged in this investigation are dominated by the production of wheat and grains in general (i.e. parts of France and Ukraine). However, as future climate scenarios become more extreme (e.g. 2080s high emissions), the matching areas shift southwards into areas where non-irrigated wheat production is less successful.

Wheat production is not restricted to specific combinations of summer rainfall and temperatures, and therefore this provides a general comparison and analogy with present conditions.

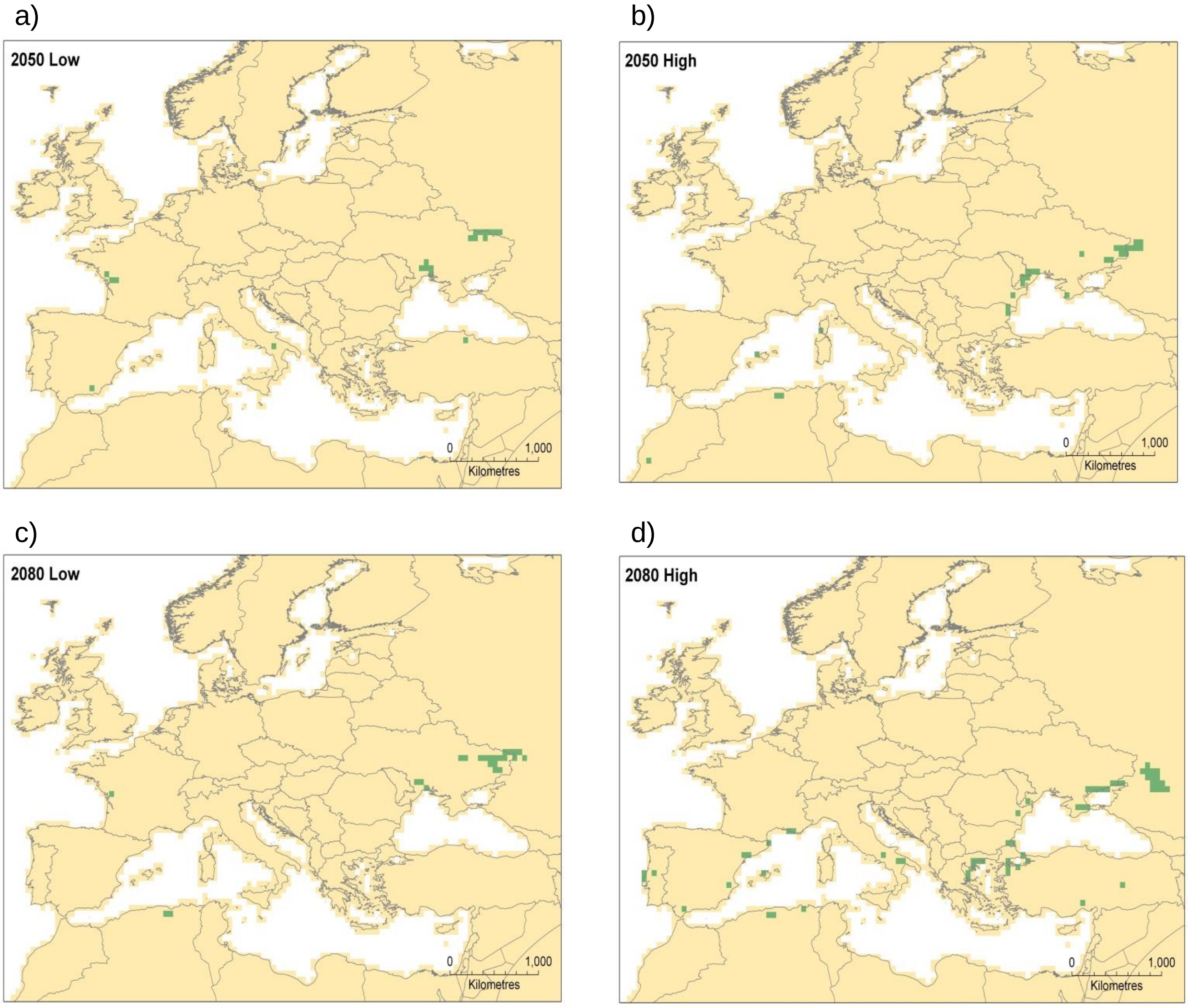



Figure 43 Green shading represents areas that have similar climatic conditions during the baseline period (1961 to 1990) to the UKCP09 projected climatic conditions in winter wheat growing areas in England and Wales.

#### *8.4.3.2 Maincrop Potatoes*

For the maincrop potatoes a threshold of 1 ha per km$^2$ was applied across England and Wales in order to create the area needed for analysis, as shown in Figure 44. From this area, the average climatic conditions were derived (Table 29).

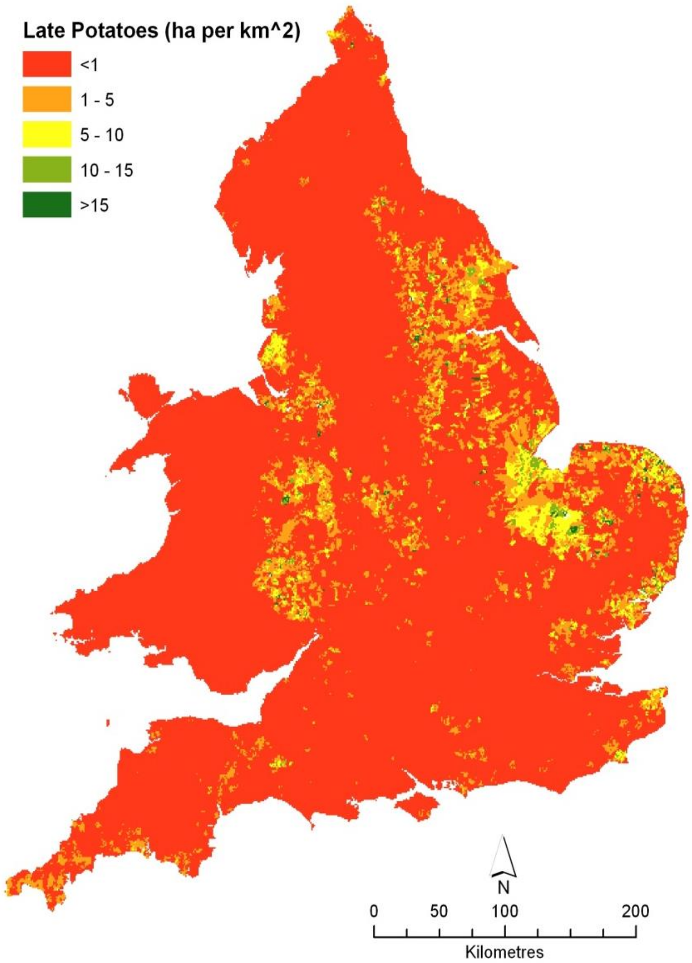



Figure 44 Distribution of maincrop potato area in England and Wales

Table 29 Climatic conditions across the current maincrop potato growing areas in England and Wales, for the relevant UKCP09 scenarios: average summer rainfall (ASR); and average maximum (ASTmx) and minimum (ASTmn) summer temperature.

| UKCP09 scenario | ASR (mm) | | ASTmx (°C) | | ASTmn (°C) | |
|---|---|---|---|---|---|---|
| | Mean - 1SD | Mean +1SD | Mean - 1SD | Mean +1SD | Mean - 1SD | Mean +1SD |
| 2080H | 220.7 | 286.1 | 22.5 | 24.3 | 13.4 | 14.4 |
| 2080L | 238.5 | 303.1 | 20.4 | 22.0 | 11.4 | 12.4 |
| 2050H | 238.6 | 304.3 | 21.0 | 22.7 | 11.9 | 13.0 |
| 2050L | 245.7 | 311.3 | 19.8 | 21.4 | 10.8 | 11.9 |

The potato area comparisons are similar to the wheat comparisons because there is a southwards shift in the comparable European locations as the climate scenarios progress from 2050s to 2080s and from low to high emissions scenarios. This is shown in Figure 45. The range of climatic conditions is similar between the wheat and potato areas, because both wheat and potatoes are grown in broadly similar regions in the UK. Therefore, the analogous locations around Europe are similar between wheat and potatoes.

Similarly to the wheat analogous areas, there is a southwards shift in the European locations comparable to the England and Wales potato growing area, between the 2050s and 2080s. The specific comparable areas are also very similar between the wheat and potato analysis. Areas such as western France, southern Spain and Italy and areas in Ukraine and around the Black Sea are all areas with similar climates to future climates for the potato growing area in England and Wales. While potatoes are grown in Ukraine, they are generally found in the north west of the country. However, Figure 45 shows that it is the southern and eastern regions of Ukraine that may match future UK climates.

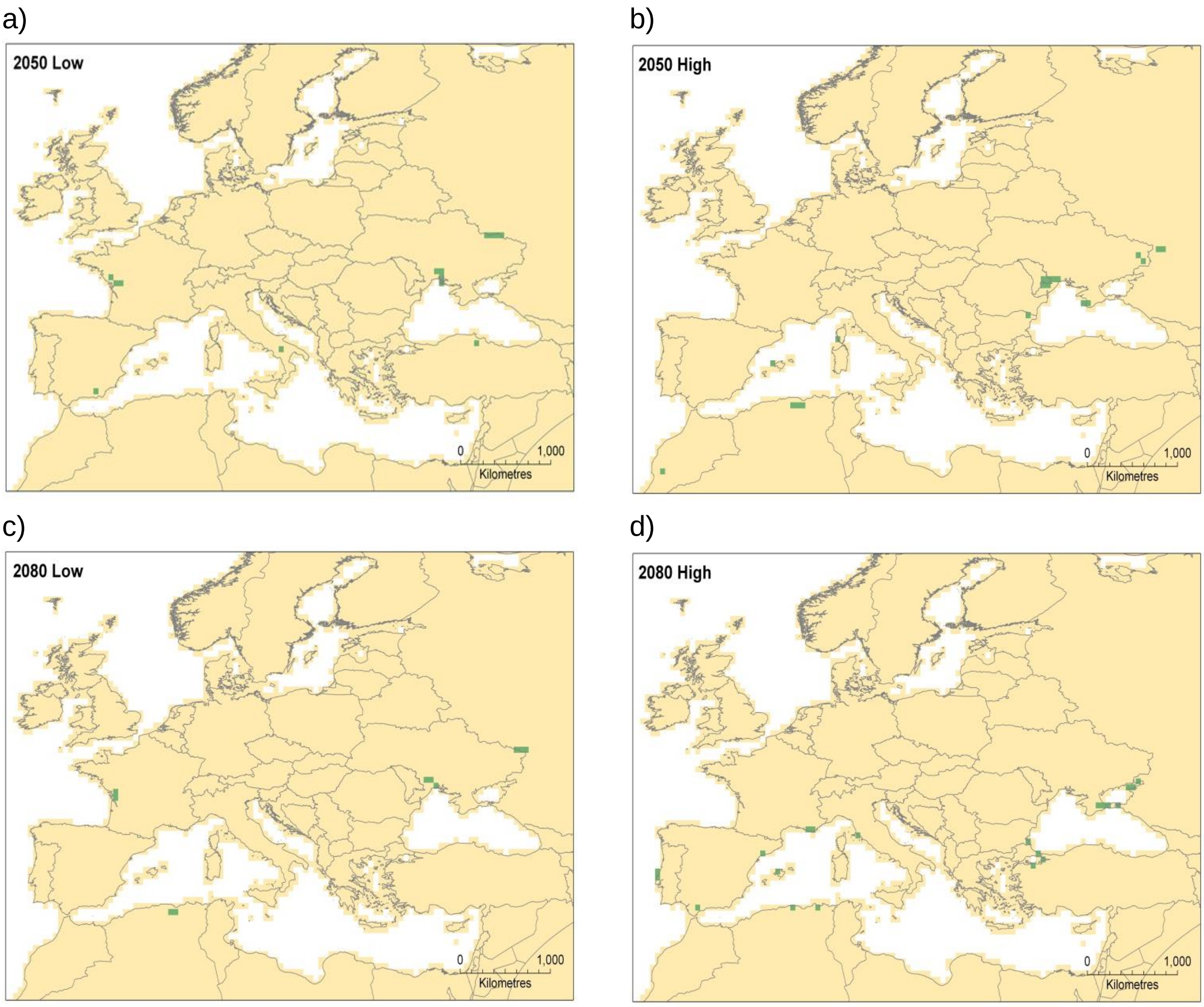



Figure 45 Green shading represents areas that have similar climatic conditions during the baseline period (1961 to 1990) to the UKCP09 projected climatic conditions in maincrop potato growing areas in England and Wales.

### 8.4.3.3 Soil and land use comparison

#### 8.4.3.3.1 Study Area 1: East of England (medium soils)

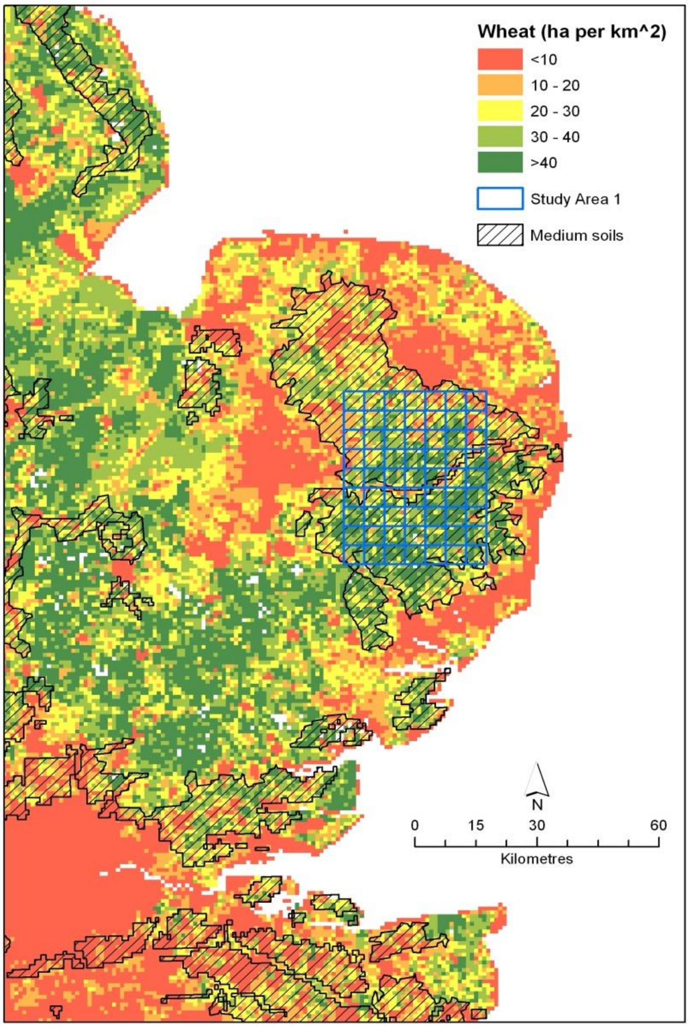



Figure 46 Location of study area 1

A large area of East Anglia is dominated by a medium textured soil. This corresponds with an area of intense agriculture, with typically over 30 ha of wheat per km$^2$ (Figure 46). The average summer rainfall over the baseline period is ~292 mm and the average summer temperature ranges from approximately 8.9 to 17.6 °C. The UKCP09 projections indicate that, by 2080 (under the high emissions projection), the area may have an average summer rainfall of ~228 mm and an average summer temperature range of 14.0 to 24.0 °C. A non-irrigated arable area currently comparable to the 2080s high emissions scenario for the region in East Anglia, in terms of climate and soil, is the southernmost region of Spain. Another area with a similar climate and soil at present is the westernmost point of Portugal. However, there is limited non-irrigated arable farming in this region; most of the agriculture around the Tagus River is irrigated – with crops including wheat, corn, oilseeds and rice.

Under the UKCP09 2050s low emissions scenario, the region in East Anglia will have a climate and soil texture similar to the upland areas in the Basilicata region in Southern Italy. The area is heavily cultivated, with 46% of the land area covered by arable crops. Wheat is the main crop across the Basilicata region, although potatoes and maize are produced in the mountainous areas.

#### 8.4.3.3.2 Study Area 2: East Midlands (fine soils)

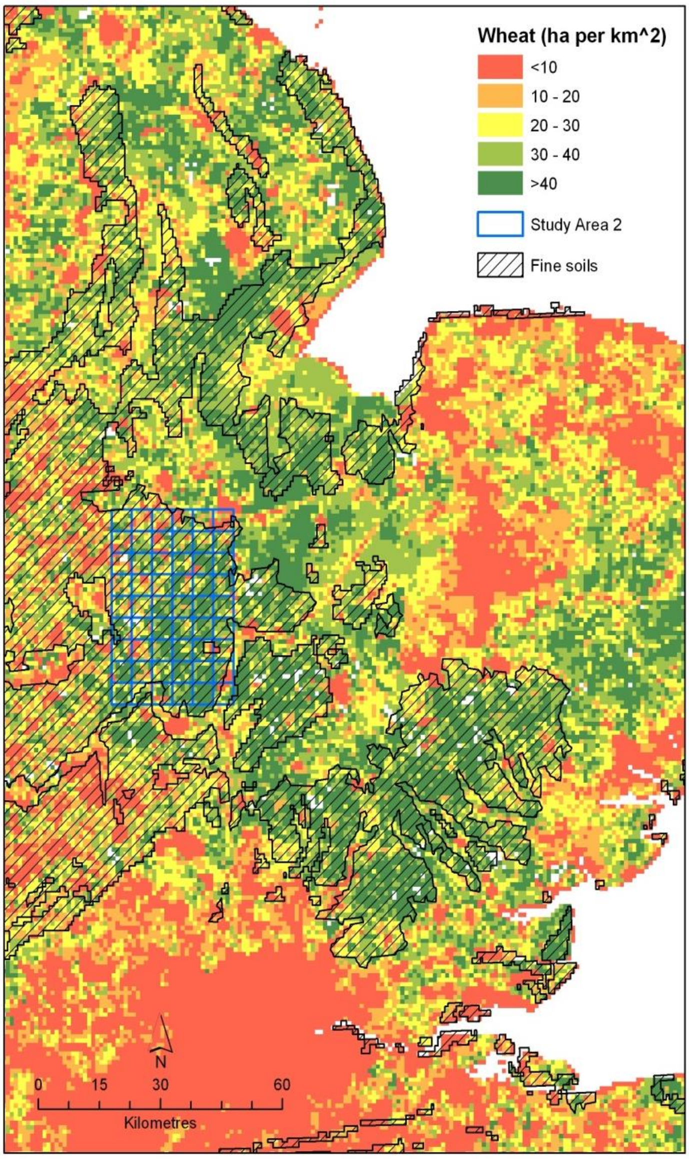



Figure 47 Location of study area 2

The second area of comparison is on the border between the East of England and the East Midlands, which covers an area with predominantly fine soils (Figure 47). This area is also a major wheat growing region. The average climatic conditions are very similar to the area in East Anglia, although with a slightly greater temperature range (8.1 to 17.8 °C) due to its location further inland. Therefore, similarly to the previous comparison for the 2080s high emissions scenario, this arable area can be compared to the Portugal, near the mouth of the Tagus River.

The projected climate in this area in the 2050s (high emissions) is similar to the climate in eastern Romania, which has some areas of fine soils (although predominantly medium fine soils are found in this region, especially towards the Danube Delta). This area of Romania is dominated by non-irrigated arable land; in particular the cultivation of cereals.

#### 8.4.3.3.3 Study Area 3: Yorkshire and the Humber (medium fine soils)

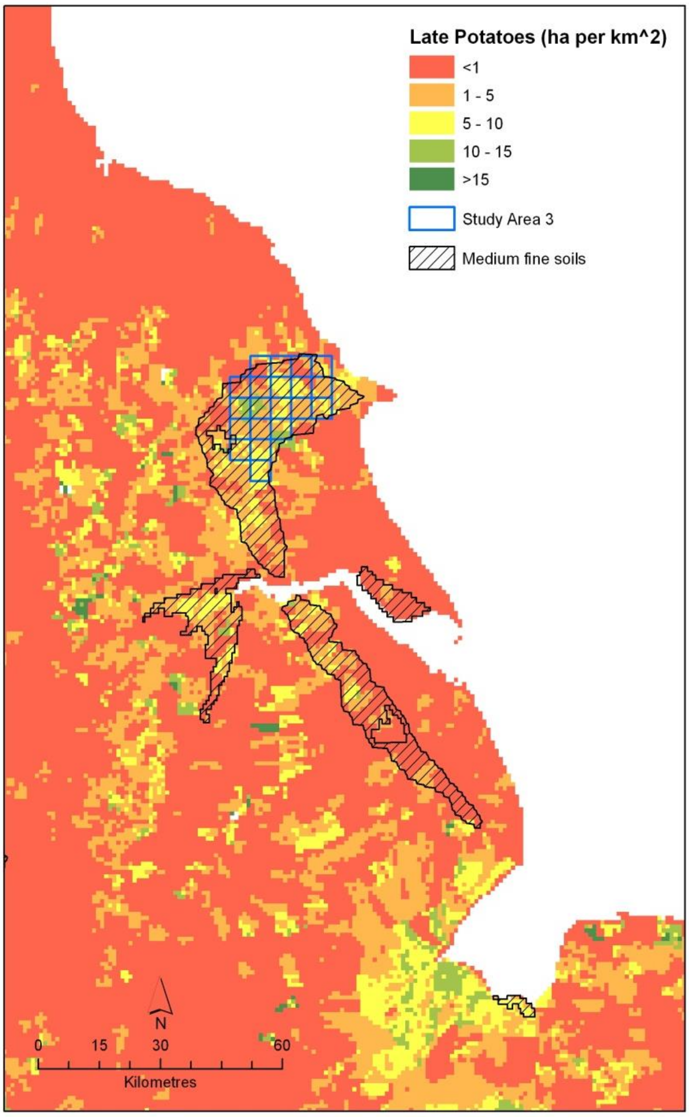



Figure 48 Location of study area 3

Currently wheat and potatoes are grown in Yorkshire and the Humber, in an area dominated by medium fine soils (Figure 48). The average summer climate is colder and wetter here compared to the previous two areas, with average summer rainfall of ~336 mm and temperature range of ~7.8 to 16.0 °C (baseline period).

By the 2050s this area in Yorkshire and the Humber will have a similar climate to areas in Northern France (for the low emissions scenario especially), where medium fine soils are widespread. France is a world leading agricultural producer and exporter. Northern France is characterised by large arable farms, particularly grains. The climate of the study area under 2050s low emissions scenario matches areas with medium fine soils in Picardy, Northern France. Picardy is dominated by highly productive large-scale arable farms (with an average size of 80 ha), the majority of which is used for growing grain, including wheat. Sugar beet and potato production is also important in this region of France.

Under the 2050s high and 2080s low emissions scenarios, the area of France that matches the warmer, drier climate of the study area, shifts southwards towards Nantes and the Bay of Biscay. However, medium soils become dominant here over medium fine soils and therefore the area is generally less comparable to the Yorkshire study area. Livestock production is more important here than in Picardy; however, it also produces a wide variety of crops including fruit, market garden crops and horticultural products. Wheat, maize and oilseed are also produced.

#### 8.4.3.3.4 Study Area 4: East of England (coarse soils)

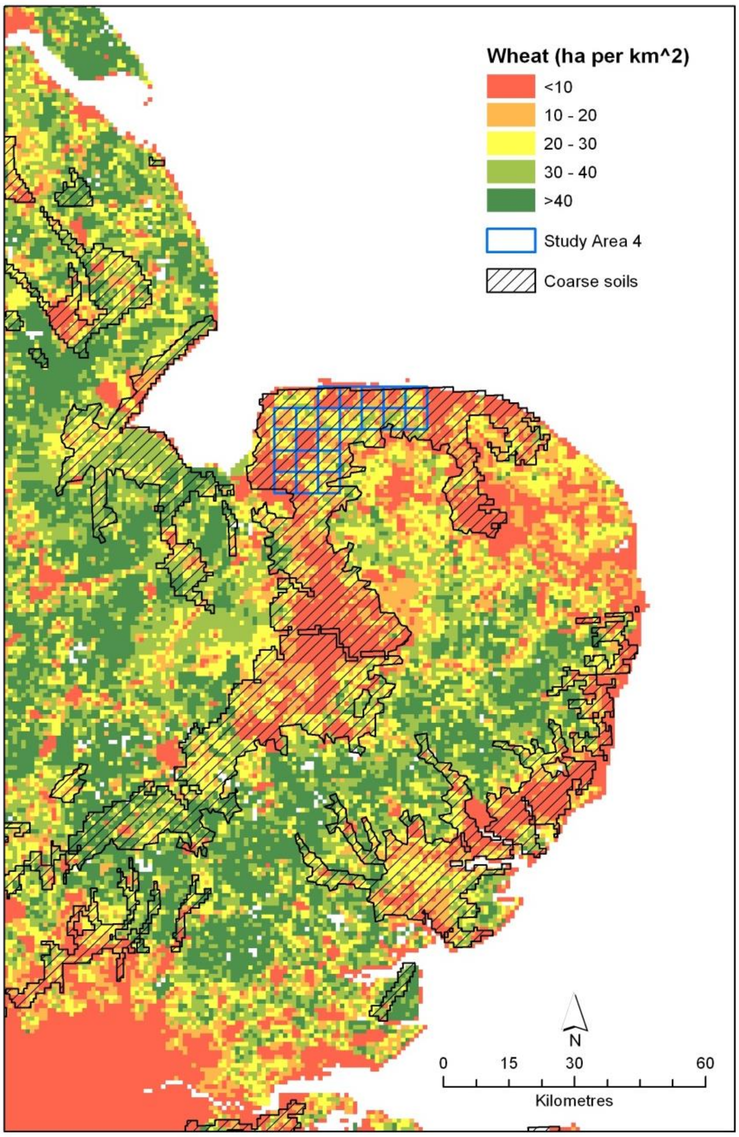



Figure 49 Location of study area 4

Coarse soils are less common in England and Wales compared to fine and medium textured soils; however, there is an area within the mostly arable land in the East of England that is dominated by coarse soils (Figure 49). Both wheat and potatoes are grown in this area. This study area has a similar climate to the previous study area in East Anglia (medium soils), although with a higher average summer rainfall of 345 mm.

Similarly to the 2050s low emissions scenario for study area 1, a similar climate can be found in southern Italy. However, the comparable area is much smaller because coarse soils are less widespread in the area compared to medium textured soils. There are also areas on the western coast of France with a comparable climate and land use to study area 4. As discussed for the third study area comparison, the non-irrigated arable land in this region is diverse, with crops ranging from grains to fruit.

For the 2080s low emissions scenario, the study area can also be compared to the current conditions on the west coast of France, although further south than the 2050s scenario. Oilseed and maize are important agricultural outputs in this region. The shift southwards continues for the 2080 high estimate scenario, with areas in the south of France having a similar climate to the study area. However, non-irrigated arable farming is very limited in this region. The study area under the 2080 high scenario can also be compared to the current conditions on the west coast of Portugal, similar to the study area 1 under the 2080 high climate.

### 8.4.4 Discussion

This piece of work has made a comparison between projected future conditions in the UK and current conditions in Europe. There is some evidence to suggest that under future climate scenarios, the conditions in arable areas in England and Wales will become similar to current climate conditions in some areas in Europe that currently grow similar arable crops, for example in Ukraine, Romania, and north and west France. However in many of these European areas, cropping is less intensive with yields generally lower than in the UK, and includes crops that are not currently widespread in the UK.

By the 2050s grain maize may become an important crop in the UK. Currently France is the largest grain maize producer in the EU and the western regions in particular contribute significantly to this production. Currently grain maize is not widely produced in the UK, although production may increase as the climate becomes warmer, similar to the climate in western France.

By the 2080s, according to the high emissions scenario in particular, areas of England and Wales that grow wheat and potatoes currently are projected to have climates similar to the south coast of Spain, as well as other areas surrounding the Mediterranean. Olives are an important crop in these regions, along with other warm-weather crops such as grapes, cotton and sugarcane. This indicates that there may be opportunity to grow these Mediterranean crops in areas of the UK in future climates.

The comparisons derived here are empirical, and wheat and potato cropping is not necessarily limited to the climatic conditions summarised here. Yields may change with future climates, but direct comparisons with other countries should not be made because farming methods and economic conditions are different.

Without adaptation (for example irrigation) it is likely that cropping areas will shift within the UK. Potato growing regions may become better suited to growing cereals and the highly intensive wheat production in the East of England may produce more oilseed and maize, as well as starting to produce more Mediterranean crops. Potential changes in crop phenology may necessitate modifications in the drought model used in the ALC process, as the current model assumes certains cropping patterns through the year with particular starts and end dates of full crop cover, flowering and senescence and consequently harvesting.

## 8.5 Analysis of Irrigation Gap

This section provides a simple evaluation of the likely irrigation requirement under the future climate scenarios. For this exercise it is assumed that the area of potatoes currently grown will continue to be used for potatoes in the future, with the necessary adjustment to irrigation.

The measurement of droughtiness used in the ALC study describes the depth of water a soil is in deficit or surplus by taking the amount of water that is available in the soil to the crop (depending on texture and rooting depth) and subtracting the moisture deficit calculated from the crop adjusted balance between rainfall and evapotranspiration. For potatoes it is possible to overcome this deficit and return the soil to a condition suitable for growth by irrigating the soil. The volume of water required to overcome the predicted deficit was calculated for the area of potatoes grown in each 5km grid square as provided by the ADAS land-use data for 2004 (covering a total of 109,256 ha) (see Figure 44). The volume of irrigation water was then calculated from the depth of water (m) required to raise the droughtiness to +10 mm (the point at which the soil is no longer considered to be limiting the crop by drought), multiplied by the area of potatoes in $m^2$ to give the volume of water in $m^3$ (Table 30)

Table 30 Volume of Irrigation Water Required in England and Wales (x $10^6$ $m^3$)

| | 1961-1990 | 2020 | 2030 | 2050 | 2080 |
|---|---|---|---|---|---|
| Low | | 46.4 | 56.4 | 79.4 | 93.8 |
| Medium | 15.2 | 48.9 | 61.9 | 92.9 | 116.5 |
| High | | 50.5 | 65.4 | 105.0 | 142.6 |

These levels of annual irrigation can be compared to the estimated water levels in Knox et al (1995) where the net volumetric irrigation water requirement for England and Wales in a 'design' dry year such as 1990 was estimated to be 61 x $10^6$ $m^3$ for all maincrop potatoes currently irrigated. This compared with previous estimates of 40 x $10^6$ $m^3$ and government agricultural census returns suggesting 51 x $10^6$ $m^3$ were actually applied in 1990, when some restrictions were in force (Knox et al, 1995).

The method used to calculate the volume of irrigation required also enables identification of areas where potatoes are being grown where irrigation should not be required (

Table 31). The Potato Council returns for 2009, for example, show that of the 88,572 ha of potatoes grown 43% were rainfed and 57% irrigated. This is similar to the proportion of rainfed to irrigated sites indicated by the results for the 1961-90 period, which estimates 42% rainfed to 58% irrigated (45,170 ha / 109,256 ha).

Table 31 Area of Potato Crops not requiring irrigation in England and Wales (ha)

| | 1961-1990 | 2020 | 2030 | 2050 | 2080 |
|---|---|---|---|---|---|
| Low | | 9,058 | 6,981 | 4,283 | 3,227 |
| Medium | 45,170 | 8,550 | 5,653 | 3,239 | 1,208 |
| High | | 7,614 | 5,252 | 1,434 | 610 |

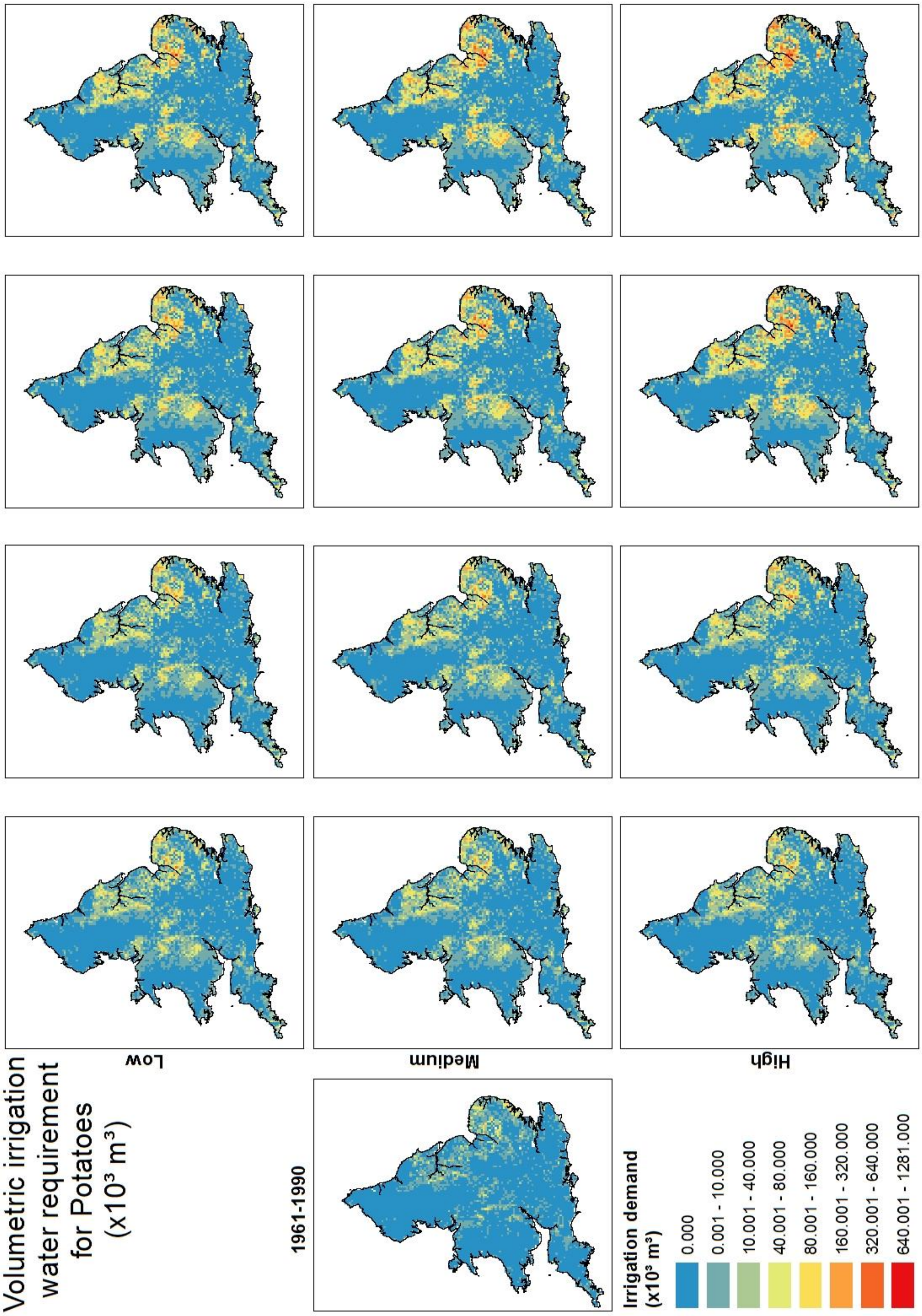



Figure 50 Volumetric irrigation water requirements for Potatoes © Cranfield University

## 8.6 Sensitivity analysis of climate change scenarios

The UKCP09 climate data is probabilistic and thus provides a widening range of potential climate values into the future. It should be possible to calculate the best and worst case scenarios using the range of data provided. The best case scenario for drought would be where the temperature is the lowest and the rainfall is the highest. Thus to develop the best case map for the 2080 period would require the low emission scenario with the temperature data from the 10th percentile and the rainfall data taken from the 90th percentile. The worst case scenario would be where the temperature is highest as in the 2080 period high scenario 90th percentile and the rainfall is the lowest which is displayed in the 10th percentile of the 2080 period high scenario.

To highlight the potential variation in climate, Figure 51 and Figure 52 show how the daily temperature and rainfall in July are predicted to vary with the different UKCP09 scenarios for the 2020 and 2080 time periods and the 10th, 50th and 90th percentiles. From 2020 to 2080 however the picture is clear that the July temperature will get hotter and the July rainfall will be less. Only the 90th percentile of the low emission scenario has the possibility of the conditions getting wetter.

The low emission scenario has only a very slight rise in temperature at the 10th percentile end of its range but it is still getting ever so slightly warmer, if this outcome were to manifest then the change in drought conditions would be very slight.

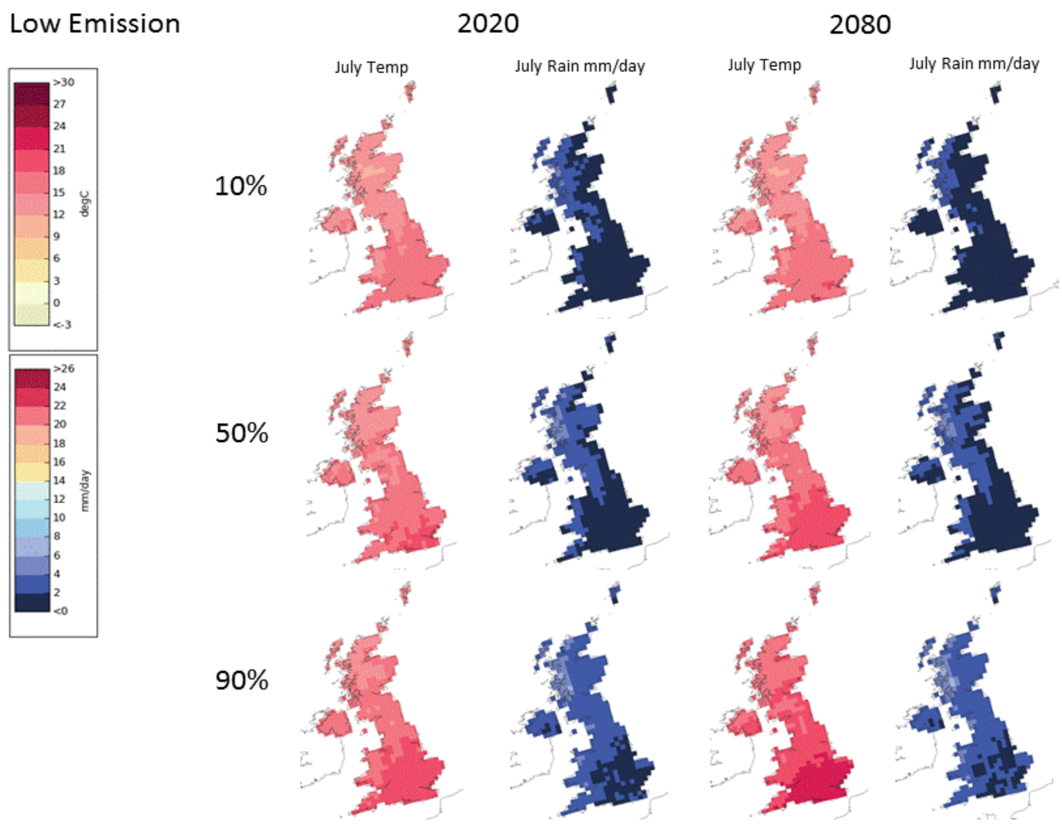



Figure 51 Variation in Daily Temperature and Rainfall in July between the 2020s and 2080s with the low emission scenario

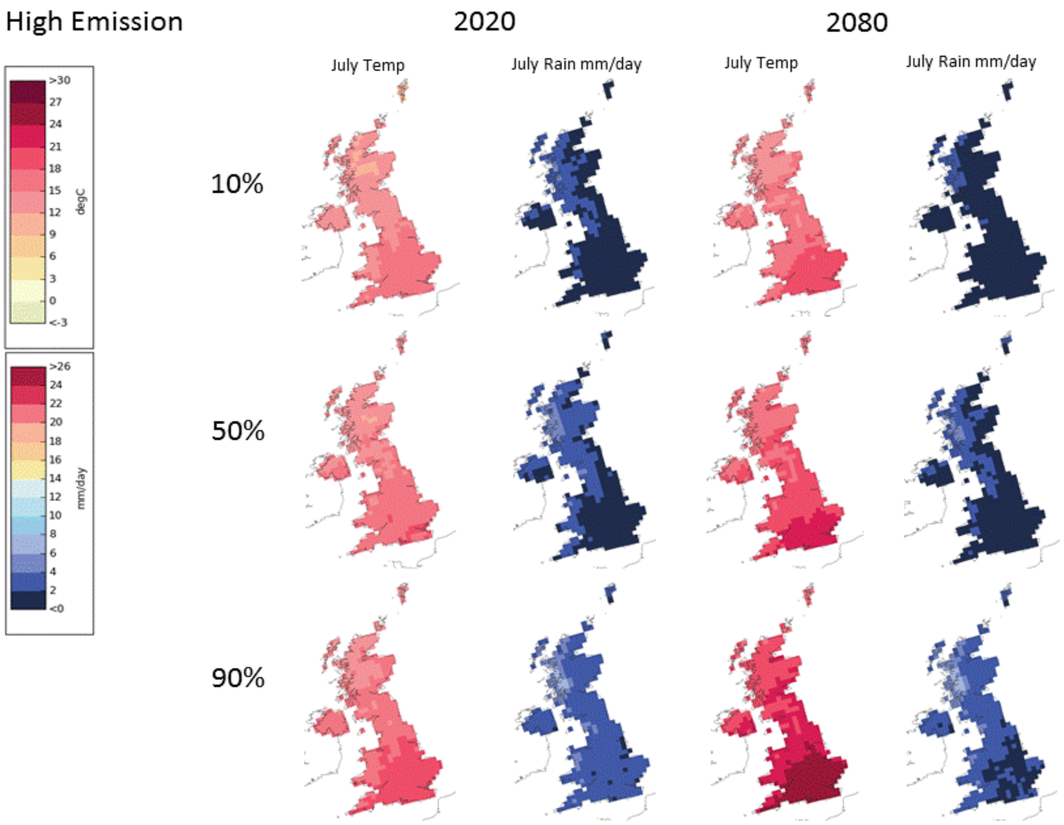



Figure 52 Variation in Daily Temperature and Rainfall in July between the 2020s and 2080s with the high emission scenario

# 9 Conclusions

The grading of ALC by climatic factors alone is built on the premise that the warmer and drier the climate the better the grade. Although the AAR remains steady throughout the future scenarios there is an increase in AT0 which results in the ALC grade (by climate) improving with the proportion of England and Wales potentially in grade 1 increasing from 58% in 1961-90 to over 90% in 2070-99. The soil wetness is a much more soil dependant variable and therefore isn't predicted to change as significantly as the grade by climate. However, there is an overall drying of the soils resulting in fewer sites being downgraded by being too wet with the proportion of England and Wales potentially in Grade 1 increasing from 24% in 1961-90 to over 30% in 2070-99.

The implications of the potential seasonal changes in rainfall pattern is not being accounted for in the method used for ALC depends on soil wetness class which varies according to the duration of field capacity (FCD) for the different climate periods. This is because the FCD periods are defined in part by the AAR, which was found not to change significantly until after the 2040-69 period.

However, looking at the general trends in seasonal rainfall and temperature, two conclusions can be drawn. Firstly, the increased rainfall in March and June could result in a delay in the end of FC date, which would have a significant effect on the workability of the land in that crucial spring window. Secondly, in the autumn the rainfall pattern is not changing significantly from October to December but there is a considerable rise in accumulated temperature over this time. This will result in the return date of field capacity being delayed until later in the year. Although the overall duration of field capacity might not change much, it will start later (in autumn) and end later (in spring) meaning that cropping patterns may need to change to more autumn sown crops.

The potential impact of the predicted change in climate only becomes significant when the effect of the droughtiness is considered. For ALC purposes the assessment of drought is currently performed for two representative crops: winter wheat and main-crop potatoes. The amount of water available in the soil (which is affected by the depth, texture and structure of the soil) is offset by the Moisture Deficit (MD) calculated as the balance between the rainfall in and the evaporation from the soil, together with the transpiration from crop plants. The general prediction indicates that the annual total rainfall is unlikely to change significantly but there will be a likelihood of a shift to wetter winters and drier summers. The air temperature will increase throughout the year but particularly in the summer months.

The excess rainfall in the winter is usually lost through runoff to surface drainage systems or percolation to ground water once field capacity has been reached. Once the soils begin to dry out in April, the reduction in summer rainfall combined with the increased temperature will cause a significant reduction in the water available to crops during key growth periods. The current method for measuring and classifying drought results in grade 1 sites (no drought limitation on the basis of a drought limitation alone) being reduced from 37% of sites in England and Wales in 1961-90 down to only 7.1% by the 2070-99 (high emission scenario) whereas the amount of sites in grade 4 increases from 2.2% to nearly 66% of England and Wales. As the overall ALC grade is set as the lowest grade from the assessed criteria this would result in a very large area of the England and Wales being downgraded to Grade 4.

A further study was performed to specifically look at the way droughtiness has been calculated and ways of assessment have been reinvestigated. It was shown that using a number of alternative scales (indices of aridity) an increase in drought conditions is likely to lead to a more Mediterranean like climate in the South and East of England. As most of these indices use annual average climatic data they don't necessarily highlight the specific drought problems likely to occur in England and Wales as a result of the seasonal changes, which appear destined to increase the magnitude of the average summer droughts.

Comparisons between the various aridity indices suggest that the climate in England and Wales is very likely to become increasingly droughty during the rest of the 21st century, possibly enough to reclassify some regions in the south and east of England into a more arid zone. The exact degree of this change is difficult to estimate accurately as there are many variables to consider, the interaction between which may lead to a wide range of potential outcomes. These findings confirm the results produced using the adopted procedure of the ALC system as it addresses droughtiness.

There are many different methods used to calculate Potential Evapotranspiration (PE), which is an important factor in the calculation of drought. The method chosen can have significant effect on the resulting PE value. The current ALC procedure calculates MD using the relationship with the average summer rainfall (ASR) and accumulated temperature over the summer months (ATS). For future scenarios these two parameters are sufficient for estimating the MD and there is no longer a need to calculate the actual PE from the limited meteorological variables available. However the original regression equations developed for the revised ALC in 1988 were calculated using a limited number of Meteorological stations that measured all the required parameters. The MORECS data, which represents a larger and more up-to-date dataset, were used to determine new relationships between the available future climate variables and moisture deficit. Using these new regression equations improved the predicted effect of drought but even so considerable areas (66%) of England and Wales would still be downgraded to Grade 4 under the High emission scenario by 2070-99.

Areas across Europe comparable to current wheat and potato growing areas of England and Wales were identified. These areas were selected on the basis of having similar a) annual summer rainfall and, b) annual summer minimum/maximum temperatures to that which is projected for England and Wales in the 2050 and 2080 periods. Regions identified as having similar climatic characteristics as England and Wales under the 2050 period low emission scenario include parts of the Ukraine and the east of France. Both these areas are arable regions which have lower wheat and potato yields compared to England and Wales whether this is due solely to climatic factors is uncertain.

Under the 2050 period high emission scenario and 2080 period low emission scenario, climate characteristics for England and Wales undergo a southern shift to reflect areas in Europe near the Black Sea and Corsica. Crucially, neither of these areas have any non-irrigated arable land at present. The 2080 period high emission scenario identifies areas around the Mediterranean coast and the eastern plains of Russia as having a climate which is similar to the predicted climate for England and Wales. These regions currently have a markedly dry climate and generally poor soils.

This comparison suggests that arable production in England and Wales may need to be adapted to changing conditions, with the introduction of crops currently found on mainland

Europe or changing the management of existing crops. For example, three to four times more irrigation water than is currently applied would be required to maintain production on land currently growing main-crop potatoes in England and Wales

Climate change is likely to have an impact on arable production in the UK in the coming decades. While warmer temperatures and increased $CO_2$ concentrations may result in improvements in wheat and potato yields; it is likely crops will suffer from adverse effects of climate change, especially related to water stress and crop heat stress. It is likely that the agricultural sector will have to adapt to the changing conditions, in order to stay profitable. It is currently unclear what the combined effect of environmental change, as well as any adaptations, will have on crop production.

ALC is one of the few (possibly only) land classification systems that could be used for climate change predictions in this level of detail. Some of the underlying equations in ALC have been used subsequently by the JRC for the recent re-designation of Less Favoured Areas (Areas facing Natural Constraint) as no other classification has really superseded them.

The overall conclusion from this project is that what could happen if the climate of England and Wales becomes warmer with wetter winters and drier summers as predicted by the 50$^{th}$ percentile of the UKCP09 scenarios. The percentile variation within these scenarios suggests that the climate is unlikely to become cooler in the coming century under all emission scenarios but, according to the 90$^{th}$ percentile of the low emission scenario there is a small chance that summer rainfall could increase.

If the UKCP09 scenarios are accurate then summer droughts will become a normal occurrence in England and Wales and adaptations will be required such as by increasing irrigation levels, selecting more drought tolerant crop varieties and transferring some important staple crops to regions where conditions have become more suitable.

# 10 Potential future work

- Specific agronomic issues are not covered within the scope of this study. Further work would benefit the understanding of UK cropping outcomes under future climates.
- The scope of the European climate analysis was limited. It would be prudent to carry out a more robust assessment to include elements such as solar degree days and average climatology, rather than max/min temperature.
- Some aridity indices (e.g. the PDSI) require time series climatology. Further work could be carried out using time series data for climate change scenarios, in order to investigate severity and duration of drought
- The ALC system should be reviewed using contemporary weather and crop yield statistics to determine the significance of the droughtiness factor in the grading of agricultural land in England and Wales. The analyses presented in this report do suggest that some arable areas in lowland England are likely to suffer from increased droughtiness which would significantly reduce the yields of cereal crops. Under current conditions this deficiency could not be alleviated by management techniques (e.g. the areas are in regions where water supply is limited for irrigation). This is an important issue which needs to be addressed in the near future.
- Future work should focus on possible impact of rising temperatures on the oxidation rates of peat soils, particularly the drained lowland peats that are presently graded ALC grade 1 and 2. Oxidation of these soils, graded as grade 1 in the 1960s, has led to significant reduction in depths of organic surface horizons reducing sites so affected from grade 1 to grades 2 or 3, depending on the depth to fine textured, often acidic sub soil.
- The present study uses point data to examine the impact of climate change on ALC. A future study could usefully rerun this analysis using the 1:250,000 scale National Soil Map of England and Wales coupled with the appropriate climate and topographic data, land use information and other relevant sources.
- The study of sea level rise is a significant challenge in the context of agricultural land classification. The effects on land grade of potential sea level rises would require a great deal of further research including the potential effects of river flooding as a result of both sea level rise, high rainfall events and river flow back-ups caused by raised sea levels and high tides.
- A future study of the effect on soil organic matter levels in the soil in a warming climate is required – will turnover be quicker? - What are the implications that might have for soil structure and water holding capacity?

# 11 References

ADAS (1994), Second revision of the Agricultural Land Classification. Report on the work carried out by ADAS under the 1993/94 Land Use Memorandum of Understanding. Main Report with Figures, ADAS.

Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. (1998). Crop Evapotranspiration—Guidelines for Computing Crop Water Requirements. FAO Irrigation and drainage paper 56. Rome, Italy: Food and Agriculture Organization of the United Nations. ISBN 92-5-104219-5].

Alley, W.M. (1984) The Palmer Drought Severity Index: Limitations and assumptions. Journal of Climate and Applied Meteorology, 23, 1100-1109.

Anon (1985). Degree days. Fuel efficiency booklet 7. Energy Efficiency Office.

Barrie, I. 2004. A Revision of the Climate Database for the Agricultural Land Classification System (2004), Met Office Rural Environment Team Technical Note 36.

Botzan, T.M., Marino, M.A. and Necula, A.I. (1998) Modified de Martonne aridity index: Application to the Napa Basin, California. *Physical Geography*, 19(1), 55-70.

CEC (1986), "Directive of June 1986 on the protection of the environment and in particular of the soil, when sewage sludge is used in agriculture.", Official Journal of the European Communities, vol. No. L181, no. /6-12.

Chapman, V.; Barrie, I.; Procter, C.; Astbury, S. (2012). SP1104 Project: the Impact of climate change on the capability of soils for agriculture as defined by the Agricultural Land Classification – Objective 2 Climate data and Methods, DEFRA 35pp.

Cloppet, E. (2011) Agricultural Drought Indices in France and Europe: Strengths, weaknesses, and limitations. *In*: Sivakumar, M.V.K., R.P. Motha, D.A. Wilhite and D.A. Wood (Eds.). 2011. Agricultural Drought Indices. Proceedings of the WMO/UNISDR Expert Group Meeting on Agricultural Drought Indices, 2-4 June 2010, Murcia, Spain: Geneva, Switzerland: World Meteorological Organization. AGM-11, WMO/TD No. 1572; WAOB-2011.

Comber, A. Procter, C. Anthony, S. (2008) The Creation of a National Agricultural Land Use Dataset: Combining Pycnophylactic Interpolation with Dasymetric Mapping Techniques. Transactions in GIS. 12(6) 775–791

Crowther, E.M. (1930) Proc. Roy. Soc., B, 107, 1.

Daccache, A., Weatherhead, E.K., Stalham, M.A. and Knox, J.W. (2011) Impacts of climate change on irrigated potato production in a humid climate. Agricultural and Forest Meteorology, 151, 1641-1653.

Dai, A., Trenberth, K.E. and Qian, T. (2004) A Global dataset of Palmer drought severity index for 1870-2002: Relationship with soil moisture and effects of surface warming. *Journal of Hydrometeorology*, 5, 1117-1130.

Dai, A., (2011) Characteristics and trends in various forms of the Palmer Drought Severity Index during 1900-2008. Journal of Geophysical Research, 116, D12115.

De Martonne E., 1926. Une nouvelle fonction climatologique: L'indice d'aridité. La Meteorologie, 449-458.

Defra (2010), UK Climate projections, available at: http://ukclimateprojections.defra.gov.uk/ (accessed 31/08/2010).

Defra (2012) Evidence Report. The UK Climate Change Risk Assessment 2012, Defra, London.

Emberger, L. (1930) "La Vegetation de la region Mediterraneenne. Essai d'une classification des groupements vegetaux," [Vegetation of the Mediterranean region. Contribution to a classification of vegetation groups]. Revue Générale de Botanique, 504, 704-721.

FAO - UNESCO. 1977. World of desertification. United Nations Conference on desertification, 1977.

Field, M. (1983), Creating the 'Complete' Agromet Dataset, Agricultural Memorandum No 983, Meteorological Office, Bracknell.

Francis, P.E. 1981. The climate of the agricultural areas of Scotland. Climatological Memorandum No 108., Meteorological Office.

Gornall, J., Betts, R., Burke, E., Clark, R., Camp, J., Willet, K. and Wiltshire, A. (2010) Implications of climate change for agricultural productivity in the early twenty-first century. Philosophical Transactions of the Royal Society B, Biological Sciences, 365, 2973-2989.

Hallett, S. H. and Jones, R. J. A. (1993), "Compilation of an accumulated temperature database for use in an environmental information system", Agriculture and forest Meteorology, vol. 63, pp. 21-34.

Hargreaves, G. H., 1974: Estimation of potential and crop evaporation. - Trans. ASAE. 17, 701-704.

Harvey, L. (1983), Extending the 'Complete' Agromet Data-set, Agricultural Memorandum No 983A, Meteorological Office, Bracknell.

Haverkort, A.J. and MacKerron, D.K.L. (eds) (2006) management of nitrogen and water in potato production. Wageningen Academic Publishers, The Netherlands.

Heim, R.R. (2002) A review of Twentieth-Century drought indices used in the United States. Bulletin of the American Meteorological Society, 83, 1149-1165.

Henry, J.L. (1990) Development of crop water production functions for wheat, barley and canola to revise nitrogen fertilizer recommendations in Saskatchewan. Department of Soil Science, University of Saskatchewan, Saskatoon, SK, Mimeo Report.

Hess, T. (2000). Reference Evapotranspiration Program, Cranfield University, Silsoe.

Hodgson, J. M. (1976), Soil Survey Field Handbook, Technical Monograph No. 5, Soil Survey, Harpenden.

Huaccho, L. and Hijmans, R.J. (1999). A Global Geo-Referenced Database of Potato Distribution for 1995-1997 (GPOT97). Production Systems and Natural Resources Management Department Working Paper No. 1. International Potato Center, Lima, Peru.

Hulme, M., Marsh, R. and Jones, P.D. (1992) Global changes in a humidity index between 1931-60 and 1960-90. *Clim. Res*., 2, 1-22.

Hulme, M., Conway, D., Jones, P.D., Jiang, T., Zhou, X., Barrow, E.M. and Turney, C. (1995a) 1961-90 Gridded Surface Climatology for Europe. Climatic Research Unit, Norwich, 51pp. (plus maps).

Hulme, M., Conway, D., Jones, P.D., Jiang, T., Barrow, E.M. and Turney, C. (1995b) Construction of a 1961-90 European climatology for climate modelling and impacts applications Int. J. Climatol., 15, 1333-1364

IPCC (2007) Climate Change 2007: The Physical Science Basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (Eds.). Cambridge University Press, Cambridge, UK and New York, NY, USA.

Jensen, M.E. and Haise, H.R., 1963. Estimating evapotranspiration from solar radiation. J. Irrig. Drainage Div. ASCE, 89: 15-41.

Jones, R.J.A. (1985). The Soil Survey's field capacity dataset – an aid to assessing soil wetness. Soil Survey and Land Evaluation 5 (1), 1-12.

Jones, R.J.A. and Thomasson, A.J. (1985). An agroclimatic databank for England and Wales. Soil Survey Technical Monograph No.16, Harpenden, UK. 45 pp.

Jones, R. J. A., Proctor, M. E. and Hollis, J. M. (1994), Data Extraction from the National Soil Inventory: for Agricultural Land Classification, Document CIS 105 version 1.3, Cranfield University, Silsoe.

Knox, J.W., Weatherhead, E.K., Bradley, R.I., (1997). Mapping the total volumetric irrigation water requirements in England and Wales. Agric. Water Manage. 33, 1-18.

Knox, J.W., Hurford, A., Hargreaves, L. and Wall, E. (2012) Climate Change Risk Assessment for the Agricultural Sector. The UK 2012 Climate Change Risk Assessment, Defra, London.

Lang, R. (1915) Int. Mitt. Bodenk. 5, 312.

Le Houerou, H.N. (2004) An agro-bioclimatic classification of arid and semiarid lands in the isoclimatic Mediterranean zones. *Arid Land Research and Management*, 18, 301-346.

MAFF (1966), Agricultural Land Classification, Technical Report No. 11, Ministry of Agriculture, Fisheries and Food, London: Agricultural Land Service.

MAFF, 1967. Technical Bulletin 16 Potential Transpiration

MAFF, 1971. Technical Bulletin 24. The Significance of Winter Rainfall Over Farmland in England and Wales

MAFF (1976), Agricultural Land Classification of England and Wales. The definition and identification of Sub-grades within Grade 3, Technical Report 11/1, Ministry of Agriculture, Fisheries and Food, London.

MAFF (1988). Agricultural Land Classification for England and Wales: Revised guidelines and criteria for grading the quality of agricultural land. MAFF Publications Alnwick, UK, 52pp.

McGrath, S.P. and Loveland, P.J. (1992). The Soil Geochemical Atlas of England and Wales. Blackie Academic & Professional, London, pp101.

Mechler, R., Hochrainer, S., Aaheim, A., Salen, H. and Wreford, A. (2010) Modelling economic impacts and adaptation to extreme events: Insights from European case studies. *Mitigation and Adaptation Strategies for Global Change*, 15(7), 737-762.

Meteorological Office (1969), Tables for the Evaluation of Daily values of Accumulated Temperature Above and Below 42 degrees F From Daily Values of Maximum and Minimum Temperature. MO Leaflet No. 10, HMSO.

Meteorological Office (1989). Climatological data for Agricultural Land Classification. HMSO, ISBN-0-86180-249-7.

Meteorological Office (2006), UKCP09: Monthly data sets, available at: http://www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09/available/monthly.html (accessed 31/08/2010).

Mitchell, J., Moss, H.C. and Clayton, J.S. (1994) Soil Survey of Southern Saskatchewan from Township 1 to 48 inclusive. Soil Survey Report no. 12. University of Agriculture, Saskatoon.

Motha, R.P. (2011) Agricultural Drought: USDA perspectives. *In*: Sivakumar, M.V.K., R.P. Motha, D.A. Wilhite and D.A. Wood (Eds.). 2011. Agricultural Drought Indices. Proceedings of the WMO/UNISDR Expert Group Meeting on Agricultural Drought Indices, 2-4 June 2010, Murcia, Spain: Geneva, Switzerland: World Meteorological Organization. AGM-11, WMO/TD No. 1572; WAOB-2011.

Nakicenovic et al. (2000) Special Report on Emissions Scenarios http://www.grida.no/publications/other/ipcc_sr/?src=/climate/ipcc/emission/

Natural England (2012) TIN049 edition 2 - Agricultural Land Classification: protecting the best and most versatile agricultural land, Natural England Technical Information Note.

Norton, M., Harpin, R. and Lane, A. (2011) Adaptation to climate change in the UK: a water infrastructure solution? Halcrow, Swindon, UK.

ODPM (2004), Planning Policy Statement 7: Sustainable Development in Rural Areas, , HMSO, United Kingdom.

Palmer, W. (1965) Meteorological drought. *US Weather Bureau*, Res. Pap. No. 45, 58.

Penman, H. C., 1948: Natural evapotranspiration from open water, bare soil and grass. - Proc. R. Soc. Lond., Vol A193, 120-145

Perry, M. and Hollis, D. (2005a), "The development of a new set of long-term climate averages for the UK", International Journal of Climatology, vol. 25, no. 8, pp. 1023-1039.

Perry, M. and Hollis, D. (2005b), "The generation of monthly gridded datasets for a range of climatic variables over the UK", International Journal of Climatology, vol. 25, no. 8, pp. 1041-1054.

Perry, M. (2006), A Spatial analysis of trends in the UK climate since 1914 using gridded datasets (Version 1.1), Climate Memorandum No 21, National Climate Information Centre, MetOffice, MetOffice, Devon.

Prescott, J.A. (1950) A Climatic index for the leaching factor in soil formation. Waite Agricultural Research Institute, University of Adelaide, South Australia)

Ragg, J. M., Jones, R. J. A. and Proctor, M. E. (1988), "The refinement and representation of spatial data in an information system using statistical and DBMS procedures, and trend surface analysis.", Geol. Jb., vol. A104, pp. 295-308.

Robson, J. D. and Thomasson, A. J. (1977), Soil Water Regimes. A study of seasonal waterlogging in English lowland soils, Technical Monograph No. 11, Soil Survey, Harpenden.

Rosenberg, N.J., Blad, B.L. and Verma, S.B. (eds.) (1983) *Microclimate: The biological environment*. 2nd ed. USA: Wiley-interscience.

Semenov, M.A. (2009) Impacts of climate change on wheat in England and Wales. Journal of the Royal Society Interface, 6(33), 343-350.

Smith, L. P. (1967), Potential Transpiration, Technical Bulletin No. 16, Ministry of Agriculture, Fisheries and Food, London: Her Majesty's Stationery Office.

Smith, L. P. (1971), The Significance of Winter Rainfall over Farmland in England and Wales, Technical Bulletin 24, Ministry of Agriculture, Fisheries and Food, London: Her Majesty's Stationery Office.

Smith, L. P. (1976), The Agricultural Climate of England and Wales. Areal Averages 1941-70, Technical Bulletin 35, Ministry of Agriculture, Fisheries and Food, London: Her Majesty's Stationery Office.

Smith, L.P. and Trafford, B.D. (1976). Climate and Drainage. Technical Bulletin No. 34, Ministry of Agriculture, Fisheries and Food, London, 119pp.

Stratton, J.M. (1969). Agricultural Records. John Baker. ISBN 0-212-97022-4.

Thomasson, A. J. (1979), "Assessment of Soil Droughtiness", in Jarvis, M. G. and Mackney, M. (eds.) Soil Survey Applications, Technical Monograph No.13 ed, Soil Survey, Harpenden, pp. 43-197.

Thompson, N., Barrie, I. and Ayles, M. (1981) The Meteorological Office Rainfall and Evaporation Calculation System MORECS, Hydrological Memo No 45, Met Office Bracknell.

Thornthwaite (1948) An approach to a rational classification of climate. Geographical Review, 38(1), 55-94.

Thornthwaite, C.W. and Mather, J.R. (1955) The Water-Balance, Pub. In Clim. Of the Laboratory of Climatology (Centerton, N.J., U.S.A.) 8 (1), 1-104.

Trabucco, A. and Zomer, R.J. 2009. Global Aridity index (Global-Aridity) and Global Potential Evapo-Transpiration (Global-PET) Geospatial Database. CGIAR Consortium for Spatial information. Published online, available from CGIAR-CSI GeoPortal at http://www.csi.cgiar.org/.

UKCP 2009: http://ukclimateprojections.defra.gov.

Van der Schrier, G., Briffa, K.R., Jones, P.D. and Osborn, T.J. (2006) Summer Moisture Variability across Europe. *Journal of Climate*, 19, 2818-2834.

Vicente-Serrano, S.M., Beguería, S. and López-Moreno, J.I. (2010) A multi-scalar drought index sensitive to global warming: the Standardized Precipitation Evapotranspiration Index. *Journal of Climate*, 23, 1696-1718.

Wells, N., Goddard, S. and Hayes, M.J. (2004) A Self-Calibrating Palmer Drought Severity Index. *Journal of Climate*, 17, 2335-2351.

Yates, D. and Strzepek, K. (1994) Potential evapotranspiration methods and their impact on the assessment of river basin runoff under climate change. *Working Papers, 46, International Institute of Applied Systems Analysis*.