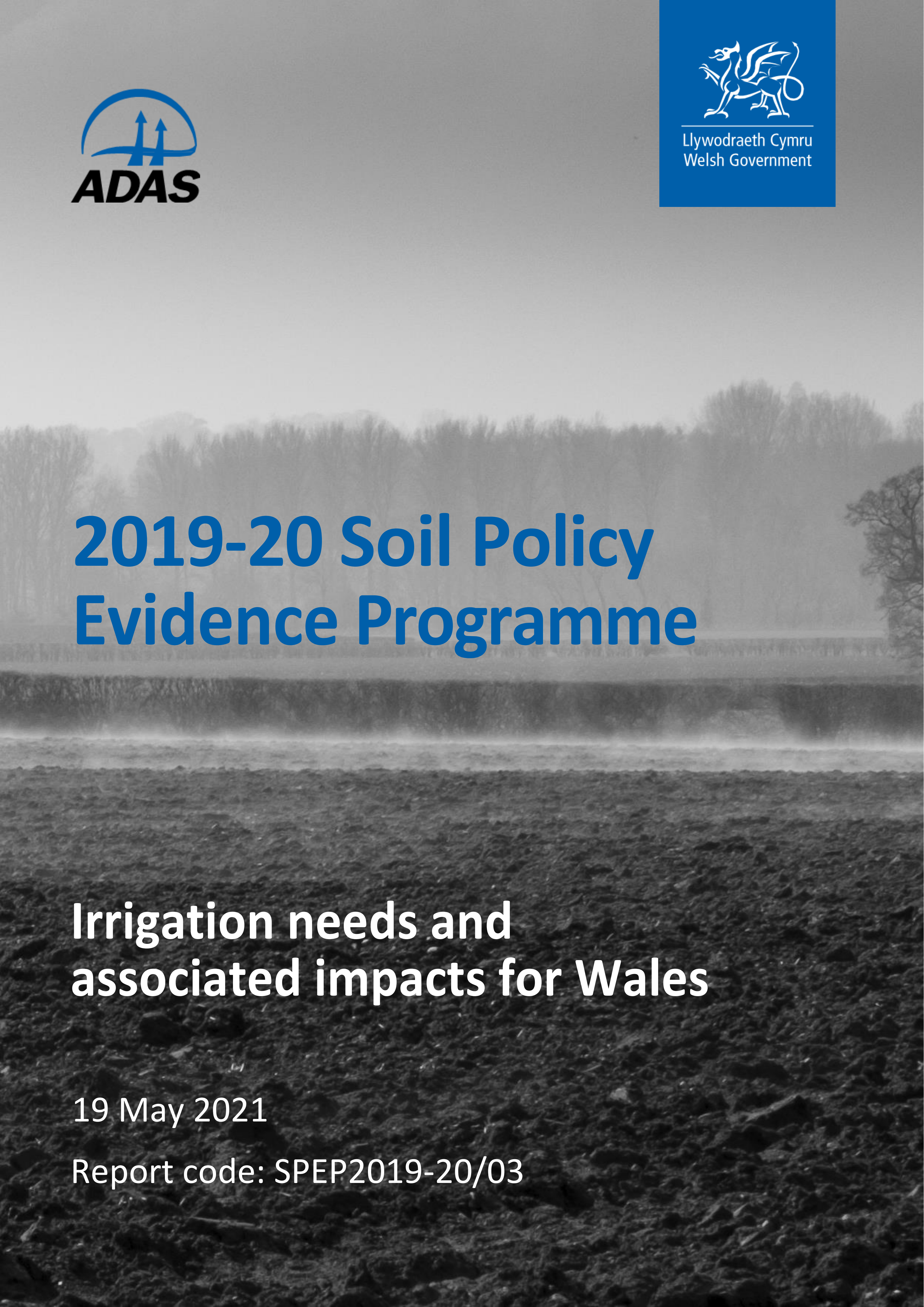

Llywodraeth Cymru
Welsh Government

2019-20 Soil Policy Evidence Programme

Irrigation needs and associated impacts for Wales

19 May 2021

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Mae'r ddogfen yma hefyd ar gael yn y Gymraeg. This document is also available in Welsh.

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Contents

1 Introduction

- The most recent UK Climate Projections (UKCP18) have produced new projections of how climate might change in the UK over coming decades (Lowe *et al*., 2018). The scenarios do not predict a change in total rainfall but suggest changes in seasonal distribution, with a decrease in summer precipitation and increase in winter precipitation for all scenarios. The greater annual variability of climate and frequency of extreme events (flooding, droughts, and heat waves) (Knox *et al*., 2010) is likely to affect the sustainability of crop production in certain areas.
- Outdoor crops are particularly sensitive to changes in climate, both directly from changes in rainfall and temperature, and indirectly since any changes in climate will also impact on the agricultural potential of soils by modifying soil water balances. This affects the availability of water to plants and impacts on other land management practices (Knox *et al*., 2010).
- Changes in temperature and rainfall pattern are likely to impact on crop yields and quality and may affect the viability of existing rain-fed crops. Water stress resulting from a lack of rainfall is currently less of a risk in Wales than in other drier regions of the UK (ASC, 2016). However, climate predictions suggest that the risk of water stress is likely to increase in the future and where summer droughtiness is a risk, irrigation could be used to maintain yields, both on existing irrigated crops (e.g. potatoes and field vegetables) and on other currently rain-fed crops such as wheat. Increased use of irrigation will require investment in on-farm storage of water (e.g. reservoirs and storage tanks) for water abstraction in peak periods or rainwater harvesting (ADAS and Cranfield University, 2014). Hence there is a need for Welsh Government to understand the future irrigation demand in Wales as well as the potential implications (positive and negative) of any increased requirement for water.

2 Objectives

- This project has reviewed the implications of future climate change for crop irrigation in Wales, specifically it has:
  - Investigated the impact of droughtiness on crop performance (e.g. growth, quality or yield).
  - Assessed the impact of current climate change predictions on crop available water supply in Wales and identified areas in Wales most likely to be affected.
  - Established current irrigation requirements in Wales and the impact of climate change scenarios on future irrigation needs for potatoes and wheat.
  - Identified best practice standards for construction of on-farm reservoirs and underground storage tanks.

3 Droughtiness

- Fresh water is a basic requirement for life, water is required for the germination of seeds and is the main component in plant cells. Water keeps plant turgid; it is used in photosynthesis, stomatal movements and transports nutrients throughout the plant. Many of the biochemical reactions that are part of growth occur in water and plants require water for growth and tissue expansion.
- Droughtiness is a normal, recurring feature of climate which occurs in virtually all climatic regimes. It is the tendency towards insufficient water being available for crop growth. This may be because of low rainfall or high evapotranspiration or where the soil holds only small reserves of soil moisture available to plant roots. The severity of the limitation will depend on the relationship between the soil properties and climatic factors as well as crop moisture demand. The relationship is complex, and the degree of moisture stress varies from year to year according to the weather. In comparison, drought is a short-term event that is characterised by changes in rainfall or temperature that means there is insufficient moisture to sustain plant growth. Soil droughtiness can be regarded as an important component of, if not synonymous with, agricultural drought (Zdruli *et al*., 2001).
- Agricultural water deficit arises from insufficient rainfall to supply sufficient crop available water during the growing season for optimum crop yields (Vadez *et al*., 2011; 2012; Wahid *et al*., 2007). Drought stress often occurs when the humidity of the soil and the relative air humidity are low, and the ambient temperature is high. These conditions result in an imbalance between potential evapotranspiration (demand) and water transport into the soil-root system. (Lipiec *et al*., 2013).
- Water deficit during drought spells is one of the most significant stress factors in crop production worldwide (e.g. Narasimhan and Srinivasan, 2005; Lobell and Field, 2007). It can lead to significant yield reduction or even crop failure. Beside the negative effects of water stress on yields, crop quality can also be affected (e.g., Jensen *et al*., 1996; Ozturk and Aydin, 2004).
- The influence of soil water supply on root growth and function is closely related to plant species and rooting depth (Vadez *et al*., 2012). In general, shallow-rooted crops such as potatoes are less drought tolerant than deep-rooted species such as alfalfa or maize. Plant response to drought and heat stress also differs in C_3 (e.g. wheat) and C_4 (e.g. maize) plants (C_3 and C_4 refers to different carbon fixation pathways; *c*.85% of plants use the C_3 pathway).
- In all plants CO_2 is fixed by the enzyme Rubisco producing a three-carbon compound phosphoglycerate (3-PGA), referred to as the C_3 cycle; plants utilising this cycle are C_3 species. A problem with the C_3 cycle is that Rubisco catalyses two competing reactions: carboxylation and oxygenation. Oxygenation directs the flow of carbon to the photorespiratory pathway which can lead to losses of 25-30% of the fixed carbon. High temperature and drought can increase the oxygenation reaction. The C_4 process is an adaption of the C_3 pathway that overcomes the limitations of photorespiration through biochemical and anatomical modifications that allow plants with this photosynthetic pathway to concentrate CO_2 at the site of Rubisco. C_4 plants can cope with higher temperatures and less water than C_3 plants. For example, Yan *et al*. (2016) reported that C_4 plants were better able to cope with drought conditions than C_3 plants; stomatal conductance decreased more in C_3 plants than C_4 plants under the same drought conditions.
- Plant variety or region of origin may also influence factors that will increase tolerance to droughtiness. For example, root length density has been reported to be shallower in modern UK winter wheat cultivars at 0.36 m than in older cultivars released in the 1970s and 1980s at

0.86 m (White *et al*., 2015). This suggests that modern varieties are potentially less efficient at accessing water at lower depths, albeit, it is likely that the effects of the soil environment (e.g. soil water content) on root length will be greater than any variety effect (Hodgkinson *et al*., 2017). Also, Narayanan *et al*. (2014) found that the region of origin had significant impact on the rooting depth of 297 genotypes of spring wheat. Genotypes that originated from dry regions (Australia, Mediterranean, and west Asia) had greater rooting depth than those from humid regions (south Asia, Latin America, Mexico, and Canada). The authors suggested that spring wheat genotypes that evolved in drier areas might have adapted by increasing rooting depth to capture water from the deeper layers of soil.

3.1 Evaporation, transpiration and evapotranspiration

- As crops grow, water is extracted from the soil by roots, and lost by transpiration from the leaves and evaporation from the soil and leaf surfaces. The combined effect is known as evapotranspiration.
- Where the soil supplies water to satisfy the evaporation demand, evaporation from the soil is determined only by meteorological conditions. However, when the water content in the topsoil drops and the soil surface dries out, the limited availability of water reduces the movement of water from depth to the soil surface. In the absence of any supply of water to the soil surface, evaporation decreases rapidly and may cease almost completely within a few days (Allen *et al*., 1988).
- Transpiration is defined as the vaporisation of liquid water contained in plant tissues and the vapour removal to the atmosphere (Allen *et al*., 1988). Crops predominately lose their water through stomata (small openings on the plant leaf through which gases and water vapour pass). Well over 90% of the water required by terrestrial plants is not 'used' in any biochemical way but lost through transpiration (Morison *et al*., 2008). Transpiration is essential for evaporative cooling, CO_2 acquisition (via stomata through which water loss is a continuous process), maintaining turgor and mineral nutrient uptake (Holding and Streich, 2013).
- Root growth under initial drought and high temperature conditions is generally enhanced to provide better access to water. However, prolonged drought results in root shrinkage, anatomical deformations, and weak root-soil contact that limits water and nutrient supply (Lipiec *et al*., 2013).
- When soils are wet, the water extracted by plants typically comes from shallow layers where the root density is highest (Canadell *et al*., 1996). However, as these layers dry there is a progressive shift towards deeper water, which allows plants to keep stomata open and extend growth into drier periods. Gregory *et al*. (1978) found that for winter wheat the 3% of roots (by weight) that were deeper than 1 m supplied 20% of the transpired water during dry periods. Where rooting depth is restricted plants may not be able to draw from deeper water reserves and yield potential can be reduced.

3.2 Soil moisture content

- The amount of water that soil can retain depends on its texture (sand, silt, clay etc.) and structure (how the particles are arranged). In a saturated soil, all the pore spaces between particles are filled with water (Figure 1). Following saturation, drainage progressively removes water, until the only water left is held in pores that do not drain under gravity (i.e. where the surface tension around the soil particles are in equilibrium with forces due to gravity). This state is called 'field capacity' (FC) and occurs on most soils when soil water tension is 5 kPa.

- As water is taken up by plant roots or evaporated from the topsoil soil moisture content will decrease and a soil moisture deficit (SMD) will develop. If no additional water is supplied the soil gradually dries out and any remaining water will become increasingly difficult for the plant roots to extract. Eventually, a point is reached when the plant cannot extract any more water (the permanent wilting point or PWP) and it will die. The permanent wilting point is defined as when soil water tension has reached 1500 kPa.
- The soil water available for the crop is therefore the amount held between field capacity and PWP and is described as the available soil moisture or available water capacity (AWC): thus AWC = FC minus PWP.

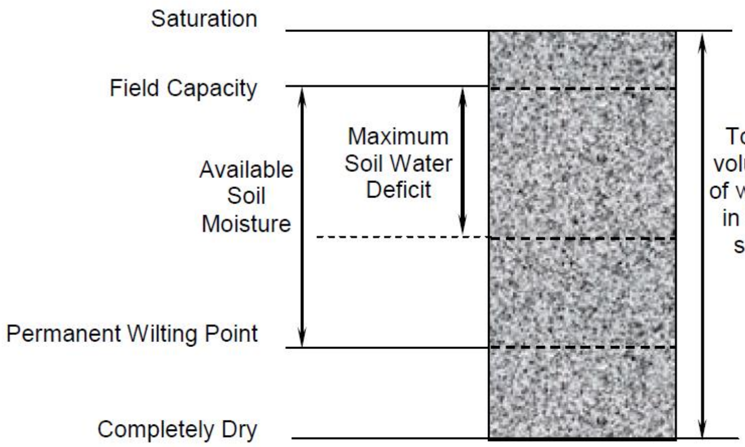

Figure 1. Soil water moisture terms

3.3 Available water capacity

- Crop available water supply is a function of the potential water holding capacity of the soil, the rainfall that the soil receives and the volume of soil that roots have access to. Soil texture, structure and organic matter content affect how much water the soil can hold at field capacity (BIO Intelligence Service, 2014). Sandy soils hold relatively little water, as their porous nature allows it to drain freely down the soil profile. In comparison, soils with a high clay content usually have a high water-holding capacity, but a relatively high proportion is not readily available because it is held in pores at tensions greater than 1500 kPa.
- As soil dries out, plants expend more energy to extract water and the point at which yields, and quality suffer is called the Critical SMD. For most crops the Critical SMD occurs when the soil moisture content is between 35 and 55% of the soil's available water capacity in the crop rooting zone (ADAS, 2003). Irrigation scheduling is managed to maintain soil water reserves above the Critical SMD at important phases (i.e. the response periods) - of the crop growth. For example, for potatoes it is important that water supply is adequate at tuber initiation (TI) so irrigation may begin shortly after full emergence to ensure the topsoil is close to field capacity when TI begins (ADAS, 2012).
- The total available water capacity of a soil is the average AWC (i.e. soil water content ≤1500 kPa) for each horizon based on texture, stoniness and thickness of horizon and the depth of rooting (Table 1). For example a shallow soil over consolidated or fragmented rock (other than chalk) is unlikely to hold sufficient water necessary to meet crop demand when transpiration

greatly exceeds precipitation e.g. during summer months and additional water from summer rainfall events or irrigation is required to support crop growth.

- The concept of easily available water capacity of soils (i.e. soil water content between 5 kPa and 200 kPa tension and 10 and 200 kPa for loamy sands) is used within ALC to account for the reduction in a roots ability to extract water as efficiently at depth in the soil (MAFF, 1988).

Table 1. Soil available water capacity (Source: ADAS *et al*., 2005).

Soil Texture	**Topsoil**		**Subsoil**	
	AWC %	easily available %	AWC %	easily available %
Silt Loam	23	15	22	14
Medium sandy silt loam	19	11	17	11
Clay loam	18	11	16	10
Medium sandy loam	17	11	15	11
Loamy medium sand	13	9	9	6
Loamy coarse sand	11	7	8	6

4 Effect of drought on yield and quality

- Drought, as an extreme weather phenomenon, is one of the major climatic constraints to crop yield (Lesk *et al*., 2016; Matiu *et al*., 2017; Zipper *et al*., 2016). Under drought conditions, crops close their stomata to limit evaporative water loss, leading to reduced carbon uptake by photosynthesis and consequent loss of yield.
- According to Earl and Davis (2003), drought stress reduces the yield of grain crops through three main mechanisms: (i) reducing canopy absorption of incident photosynthetically active radiation (PAR) (e.g., by limitation of leaf area expansion, leaf rolling or early leaf senescence), (ii) reducing radiation use efficiency, and (iii) reducing harvest index (i.e., the fraction of crop dry matter allocated to the grain).
- Hlavinka *et al.* (2009) noted that most crops are susceptible to drought within the April–June period, which is crucial for yield formation (Figure 2). Rape and winter rye were also sensitive to water stress before and during crop emergence in autumn. Drought severely decreased yields of spring barley, oilseed rape, oat and potatoes and to lesser degree winter wheat and winter rye whilst the yields of hay from meadows and grain maize were also reduced by extreme water stress (Figure 3). Spring cereals were found to be more vulnerable to drought than winter ones, and C_3 crops more vulnerable than C_4 crops (i.e. grain maize). The lower susceptibility of winter crops reflects their ability to establish deeper rooting systems than spring crops that lessen the impact of spring drought.

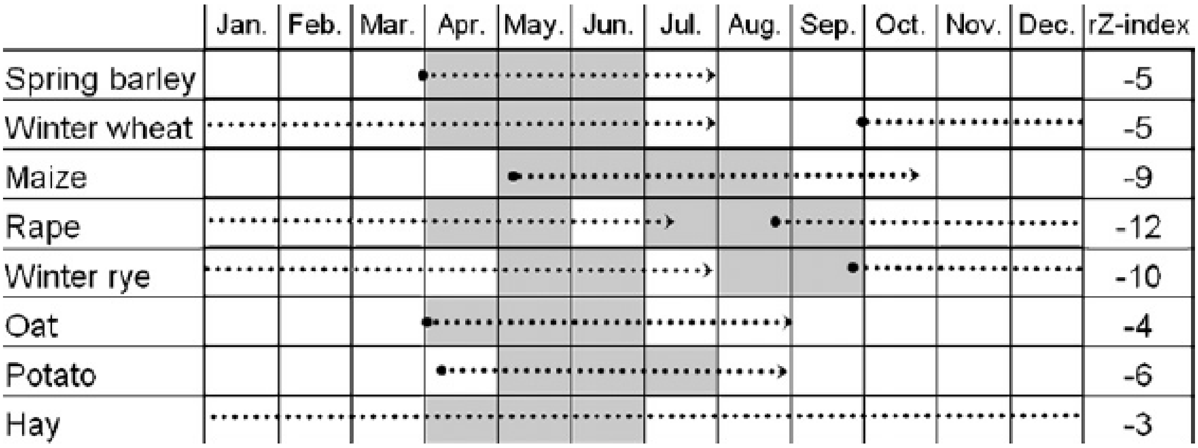

Figure 2. Periods of crop sensitivity to drought within the vegetative period of 8 selected crops (marked as shaded area). Approximate sowing date of crops within the Czech Republic is depicted by bold dots, duration of growth shown by dotted lines and harvest by arrows. The values of rZ-index indicate the level at which soil moisture deficit reduced crop yield. (Source: Hlavinka *et al.*, 2009).

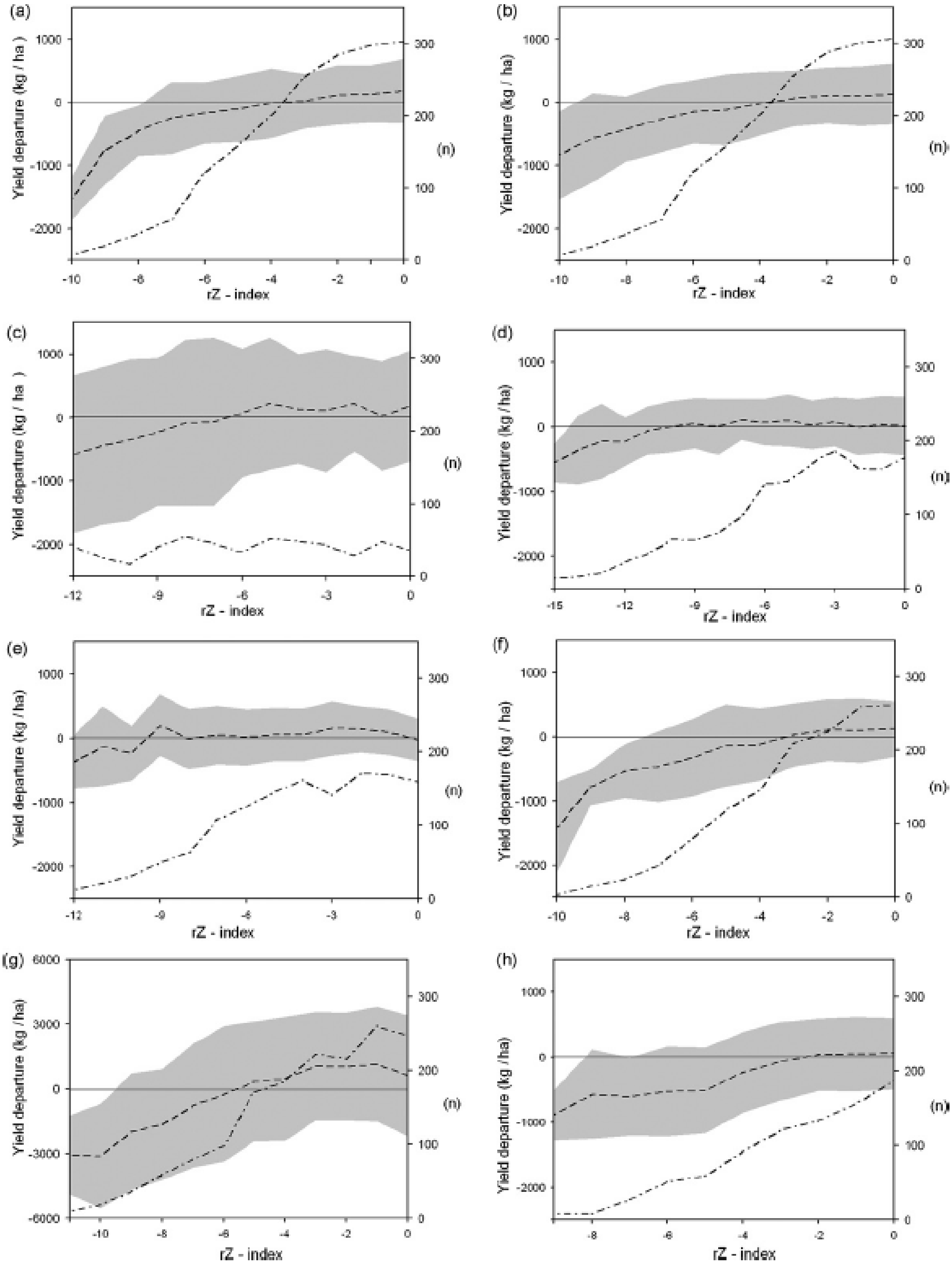

Figure 3. Effect of drought on spring barley (a), winter wheat (b), maize (c), rape (d), winter rye (e), oat (f), potato (g) and hay (h) yield (kg/ha). (Source: Hlavinka *et al*., 2009).

Notes: rZ-index 0 = no drought, rZ-index. -10 = severe drought. Yields are depicted by the broken line. Standard deviation (± from the average yield) is represented by the grey coloured surface. Number of district–seasons (n) for each drought category is shown by the dot-and-dash line.

- Leng and Hall (2019) used a crop-country specific standardized precipitation index (SPI) and census yield data for 1961–2016 to build a probabilistic modelling framework for estimating yield loss risk (for wheat, maize, rice and soybeans) under a moderate (−1.2 < SPI < −0.8), severe (−1.5 < SPI < −1.3), extreme (−1.9 < SPI < −1.6) and exceptional (SPI < −2.0) drought (Figure 4, yield loss probability for rice and soybeans not shown). Globally, wheat was more vulnerable to droughts than maize, rice and soybeans, as indicated by the higher magnitude of yield loss probability under the four categories of droughts (i.e. moderate, severe, extreme and exceptional droughts). Results showed that there was >80% probability that wheat production would fall below its long-term average when experiencing an exceptional drought, especially in USA and Canada

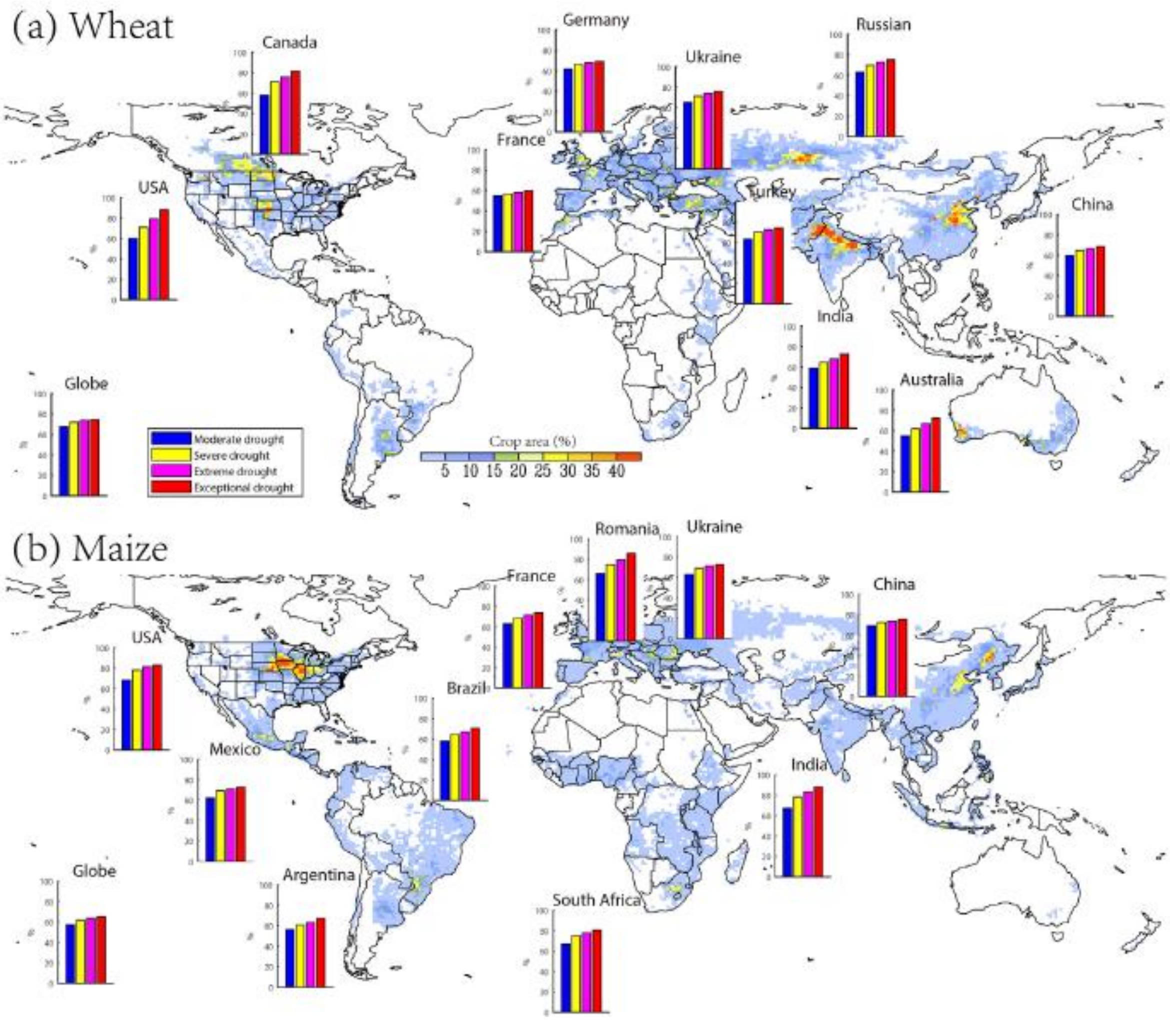

Figure 4. The probability (%) of yield loss (i.e. yield dropping below historical average) when experiencing a moderate (blue bar), extreme (yellow bar), severe (magenta bar) and exceptional drought (red bar) for (a) wheat and (b) maize. The top 10 producing countries for each crop are selected for illustration. (Source: Leng and Hall, 2019).

- Compared to present conditions, 11 crop models suggested an increase in yield loss risk by 9-12%, *c*.6%, 18-19% and 15-16% for wheat, maize, rice and soybeans by the end of 21st century, respectively, without considering the benefits of CO_2 fertilization and adaptations (Figure 5).

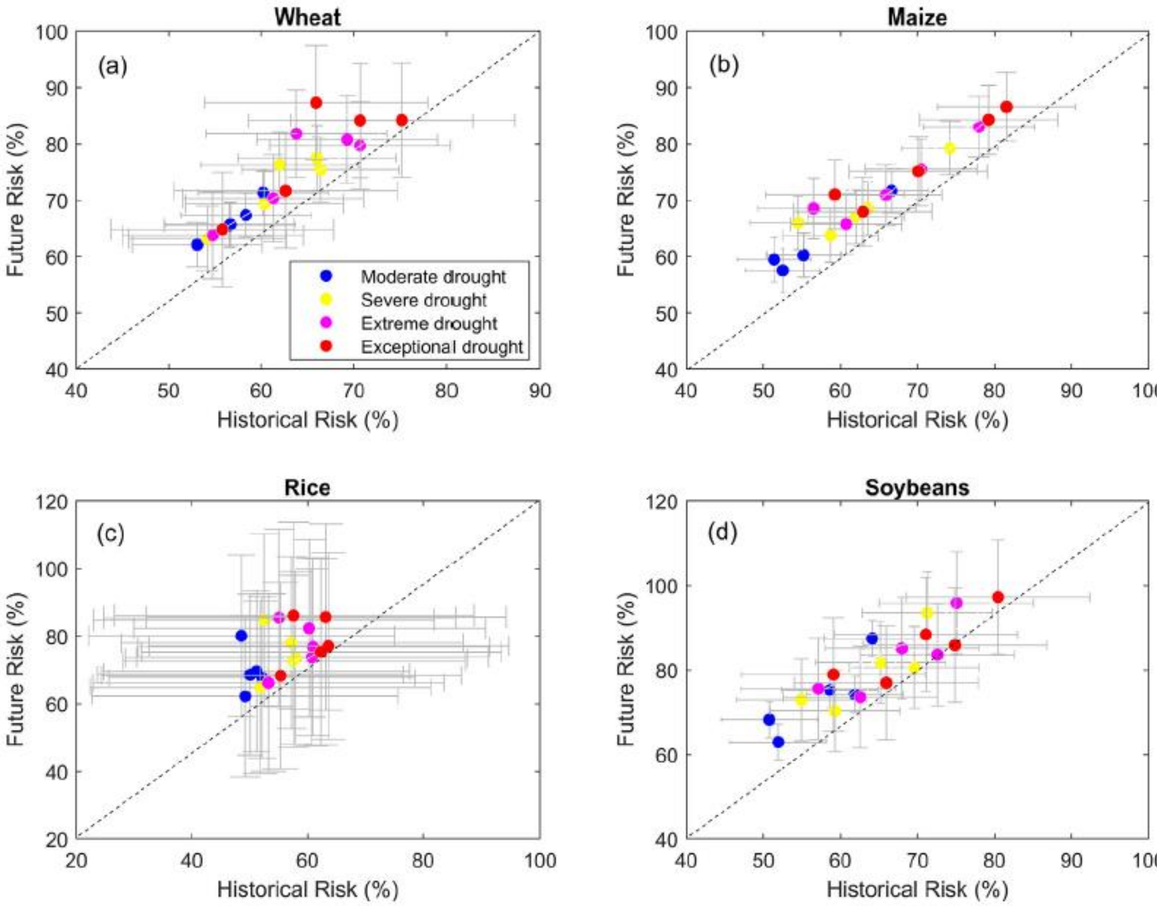

Figure 5. Projected changes in risk (%) of yield reduction in the future versus history as simulated by process-based crop models. Each dot represents the ensemble mean of risks simulated by 11 crop models under a given climate scenario, while the grey error lines indicate the corresponding uncertainties arising from crop models. The colours of dots represent the risk under various levels of drought severity. Here, five climate scenarios and four drought severity categories are considered, and there are 5 × 4 = 20 dots in each subplot. (Source: Leng and Hall, 2019).

5 Effects of drought on potato and cereals

- The effect of drought on potato growth and development at various stages is summarised in Table 2, below. Water deficit in the early stages of crop growth (i.e. during stolon formation, tuber initiation, and after tuber initiation) will have the greatest adverse effect on final yield. Although leaf growth is very sensitive to water deficit, if the deficit is moderate and short the plants can compensate, leading to minor impacts on yield (FAO, 2012). To optimize yield, generally the total available soil water should not be depleted by more than 30-50% (FAO, 2012).
- Similarly, cereals are dependent on water supply to produce healthy, high-yielding, good quality crops. The effect of drought on wheat growth and development at various stages is summarised in Table 3, below.

Table 2. Effect of drought on potatoes (Source: ADAS *et al*., 2005, Aliche *et al*., 2018 and Yara[1])

Crop stage	Under ideal soil and water conditions	Impact of too little water
Cultivations and drilling *March to April*	• An ideal potato soil is well structured, with good drainage to allow proper root aeration, tuber development with minimal root disease infestation.	• Drought at drilling in spring can make bed formation and ridging difficult.
Crop emergence, establishment and growth *April to May*	• The plant emerges about 7 days after planting under good conditions. • Root growth rate is rapid in the first 3-4 weeks after emergence. • Moisture conditions allow the shallow rooted potato plant to access sufficient nutrients for optimum leaf growth.	• Emergence may be delayed by limited soil moisture. • During canopy expansion the crop will not have reached its maximum rooting depth, and so the SMD at which a yield penalty occurs will be lower. Therefore, irrigation should take place at lower SMDs earlier in the season. • Dry soils restrict root growth so that capacity to take up water later in the growing season is reduced. • Moist soils encourage root growth (if soil structure is good). Therefore, in dry springs, early irrigation is desirable to encourage root growth
Tuber initiation and crop growth. *May-July*	• Moisture conditions allow the shallow rooted potato plant to access sufficient nutrients for optimum canopy growth, tuber initiation and subsequent tuber bulking.	• Drought around the critical times such as time of tuber initiation in potatoes can reduce the number of tubers formed and the longer the period of drought, the greater the reduction in tuber number. • Reduced quality blemish disease common scab occurs when soil moisture falls below field capacity after tuber initiation. The aim of irrigation scheduling and application for maximum common scab control is to maintain soil water reserves close to field capacity. • Fluctuations in soil moisture status within the ridge will lead to uneven tuber bulking, malformed tubers and growth cracks.

[1] https://www.yara.co.uk/crop-nutrition/potato/potato-agronomic-principles/

Harvest *July to October*		• Reduced yields, small tubers, tuber cracks, blemishes and greening (caused by sunlight on tubers where soil has cracked) • Tuber bruising may occur when potatoes are lifted from dry soil.

Table 3. Drought and cereals (Source: AHDB, 2013)

Crop stage	**Under ideal soil and water conditions**	**Impact of too little water**
Cultivations and drilling	• Soil structure is maintained during cultivations with seed in good contact with the soil, leading to rapid seed germination supported by soil water available to the seed	• Very dry soils are difficult to cultivate and require more energy to cultivate and can slow work rates. • Seedbeds are either hard or too fine, both leading to poor structure or future slumping when rain returns; seeds are left dry and fail to secure the moisture needed to germinate
Crop emergence, establishment and growth	• Crop establishes well, with good plant counts, and grows away quickly to provide rapid ground cover, which increases yield potential by intercepting more available sunlight	• Crop establishment can be poor, with crops struggling to grow due to restricted root development; as crops grow, a lack of water will lead to reduced nutrient uptake and stunted or weak crops
Grain and seed fill	• Water availability allows the crop to continue to grow vigorously throughout grain or seed fill, maximising yield potential	• A lack of water at this stage will lead to smaller shrivelled grain and seeds, crops will senesce early, reducing yield potential
Harvest	• Yield and quality potential fulfilled; crops harvested in good conditions, with no major damage to the soil	• Grain can become too hard and split, leading to loss of quality and more rejections; lack of moisture reduces yield if the grain is too dry and excessively over dry grain equals lost revenue.
Post-harvest	• Soil is easily workable to incorporate residues and generate seedbeds for the following crop	

6 Climate change and crop water supply

- For Wales, the 2008-2017 decade was 0.8°C warmer than the 1961-1990 average and most of the warmest years have been recorded since 1990 (Lowe *et al*., 2018). Annual rainfall in Wales has increased by 4% from the 1961-1990 average (Lowe *et al*., 2018). Also, of note is the run of recent wet summers; of the last ten summers from 2008 to 2017, only summer 2013 has seen a UK rainfall total below the 1981-2010 average. Thus, UK summers for the most recent decade (2008 to 2017) have been on average 20% wetter than 1961-1990 and 17% wetter than 1981-2010 (Lowe *et al*., 2018).
- UKCP18 has produced new projections of how climate might change in the UK over coming decades (Lowe *et al*., 2018). The regional climate projections are based on four 'Representative Concentration Pathways' (RCPs). RCPs are time-dependant projections of atmospheric GHG concentrations based on assumptions about economic activity, population growth, energy sources and other socio-economic factors. Each RCP is only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term pathway emphasises that not only the long-term concentration levels are of interest, but also the trajectory taken over time to reach that outcome. The four RCPs together span the range of year 2100 increases in radiative forcing values[2] (relative to pre-industrial conditions in 1750) found in the open literature, i.e. from 2.6 to 8.5 watts per square metre (W/m^2)[3]:
    - RCP2.6: low GHG concentration levels, radiative forcing peaks at 3 W/m^2 in around 2050, declining to 2.6 W/m^2 by about 2100.
    - RCP4.5: peak GHG by around 2100, followed by stabilisation. Radiative forcing peaks at 4.5 W/m^2.
    - RCP6: peak GHG by around 2100, followed by stabilisation. Radiative forcing peak at 6 W/m^2.
    - RCP8.5: increasing GHG over time. Radiative forcing peaks at 8.5 W/m^2.
- For each RCP scenario, the predicted changes have been modelled for the 5, 10, 50, 90 and 95th percentile. The 50% level is the median change, and the 5% and 95% levels provide lower and upper estimates of the associated uncertainty ranges. UKCP18 scenarios suggested an increase in both winter and summer temperature from the 2020s to the 2080s, with all areas of Wales experiencing similar relative increases in temperature. The projections for the 50th percentile suggest that by 2080-2099, depending on the scenario, annual mean temperatures will be 1-4°C higher than the baseline (1981-2000). Temperature increases of 1-3°C and 2-5°C, depending on the scenario, are predicted by 2080-2099 for winter and summer, respectively.
- RCP scenarios do not predict a change in total rainfall but instead suggested that there will be a difference in the seasonal distribution of rainfall, with a decrease in summer precipitation and increase in winter precipitation for all scenarios. For summer precipitation, the 50th percentile predicted reductions of 15-19% for 2040-2059 and 20-38% for 2080-2099 (in comparison with the 1981-2000 baseline). In comparison, for winter precipitation, the 50th percentile predicted

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[2] Radiative forcing is the change in the net, downward minus upward, radiative flux (expressed in Watts per square metre) at the tropopause or top of the atmosphere due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide (CO_2) or the output of the Sun. When forcing results in incoming energy being greater than outgoing energy, the planet will warm (positive RF). Conversely, if outgoing energy is greater than incoming energy, the planet will cool.

[3] The solar constant is 1,361 W/m^2. For the UK, the average daily solar radiation is 101 W/m^2 (ranging from 85 W/m^2 in northern Scotland to 114 W/m^2 in southern England). Daily values range from <50 to >200 W/m^2 (Burnett *et al*., 2014).

increases of 5-9% for 2040-2059 and 6-23% for 2080-2099 (in comparison with the 1981-2000 baseline).

6.1 Climate change and crop performance

- Changes in temperature and rainfall pattern are likely to impact on crop yields and quality and may affect the viability of existing rain-fed crops and create opportunities for new crop types (Knox *et al*., 2010).
- The warming climate allows for a potential expansion of land used for agriculture in Wales. Many areas that are currently marginal for cultivation due to climatic limitations could experience an improvement in land capability. However, there may also be limitations to future agricultural productivity due to increased soil aridity in some locations. For Wales, the area of ALC Grade 1-3a land is projected to decrease from 20% to 18%, 16% or 9% by 2080 under the low, medium and high RCP scenarios, respectively[4]. By 2080 the area of Grade 4 land in Wales is predicted to be similar to the baseline under the low and medium RCP scenario, but increases to 39% under the high RCP scenario (Keay and Hannam, 2020).
- A projected trend towards warmer drier summers would increase the risk of heat stress in sensitive crops (e.g. winter wheat) and reduce yield potentials for those crops with high water demands (e.g. potatoes). Warmer drier summers and increased mean winter temperatures may also be beneficial for some crops (e.g. maize which is sensitive to frost). Warmer temperatures would increase the probability of damage to vulnerable crops (for example wheat and salads) at extreme temperatures. Knox *et al*. (2010), suggest that a longer growing season may lead to increased cultivation of continental crops such as sunflowers, navy beans, soya, lupins and grapevines.
- The changing pattern of rainfall (i.e. wetter winters and drier summers) is likely to affect grassland productivity. Grass growth is restricted by drought and drier summers are likely to limit grass growth especially on soils with low soil available water in the summer months (St. Clair *et al*., 2009). Drought may also increase the risk of wildfires affecting extensive grazing areas.
- Grass growth begins above a minimum temperature (5.5°C) and is stimulated by warmer weather, provided there is sufficient soil moisture. Warmer temperatures will increase the length of the grazing season (IGER, 2003) with grass production starting earlier in the spring and continuing later in the autumn (Thomas *et al*., 2010). However, although grass yields improve with warmer conditions, they are also vulnerable to reduced soil moisture availability during drought (Brown *et al*., 2016).
- Studies have shown that grassland ecosystems can adapt to extreme events (Vicente-Serrano *et al.,* 2012) including physiological adaptations to overcome the challenges of drought stress (Craine *et al.,* 2013) and wildfire (Bond *et al*., 2005, Bond and Keeley 2005, Nano and Clarke, 2011). This may limit the effect of climate change on grasslands and several authors have noted that anticipated impacts of climate change on grassland dry matter yield are small. For example,

[4] The UKCP18 climate change predictions represent a 30-year average: the 2020 models for low, medium and high emissions represent the time period 2010-2039; the 2050 models represent 2040-2069; and 2080 represents the period 2070-2099. The low scenario predicts 1.8°C warming by 2100, modelled from Representative Concentration Pathway (RCP) 4.5, which represents a scenario of global greenhouse gas (GHG) emissions peaking around the year 2040, then declining. The medium scenario predicts 2.2°C warming by 2100, modelled from RCP 6.0, which represents GHG emissions peaking around the year 2080, then declining. The high scenario predicts 3.7°C warming by 2100, modelled from RCP 8.5, which represents GHG emissions continuing to rise throughout the 21st century (Lowe *et al*., 2018; IPCC, 2019).

the model used by Qi *et al*. (2018) predicted that by 2050, yield under the UKCP09 medium scenario would increase to 15.5 and 9.9 t/ha on temporary and permanent grassland, respectively (from 12.5 and 8.7 t/ha) and no significant change in the yield of rough grassland was predicted (2.8-2.7 t/ha). However, any dry matter yield increases will depend on other interacting factors such as soil N fertility (Daepp *et al*., 2001), water productivity and soil water stress (Deryng *et al*., 2016).

7 Climate change influences on the need for irrigation to support crop production in Wales

- In Wales, water stress resulting from a lack of rainfall is currently less of a risk than in other drier regions of the UK (ASC, 2016). However, where summer drought is a risk, irrigation is likely to become more important to maintain yields, both on existing irrigated crops and on other currently rain-fed crops such as wheat. Increased use of irrigation will require investment in on-farm storage of water (e.g. reservoirs and storage tanks) to harvest winter rainfall or water abstraction in peak periods (ADAS and Cranfield University, 2014).
- There is evidence that the biophysical capability of the land to support agricultural production has changed over recent decades as the climate has changed (ASC, 2016). The average length of the growing season has increased by around 60 degree-days over the 87-year period between 1914 and 2000 for England and Wales, with a substantial increase in the last decade of the 20th century. There is evidence that the trend to longer growing seasons and milder winters have provided opportunities for a shift to autumn-sown crops (ASC, 2016).

7.1 Climate change and ALC grade for 2020, 2050 and 2080[5].

- Keay and Hannam, (2020) applied the Agricultural Land Classification (ALC) climate interpolation routine to the UKCP18 scenarios to map the changes in ALC grade over time. The predicted changes suggest a reduction in the amount of ALC grades 1 and 2 land under all time period/RCP scenarios, with an initial downgrade to ALC grade 3a/3b in the 2050 scenario and in some areas a further downgrade to ALC 4 in the 2080 scenario (Figure 6). The medium and high RCP scenarios also suggest that some land that is currently ALC 3a/3b will be downgraded to ALC 4 in the 2080 scenario, particularly under the high RCP.
- Keay and Hannam, (2020) also produced maps for the individual climate parameters: average annual rainfall (AAR), average summer rainfall (ASR), median duration of field capacity days (FCD) and median accumulated temperature above 0°C January to June (AT0). For each parameter mapped data is shown for 2020 (representing 2010-2039), 2050 (representing 2040-2069) and 2080 (representing 2070-2099) for low, medium and high RCP scenarios.

7.2 Changes in temperature and rainfall

- For AAR, predictions suggest that there is little noticeable change in either the distribution or amount of rainfall for Wales for any of the time period/RCP scenario combinations (Figure 7). However, the distribution of rainfall changes between seasons. There is an increase in rainfall in the winter and less rainfall in the summer months from 2020 to 2080 for all RCP scenarios. In comparison, for summer rainfall (ASR) in Wales there is a noticeable reduction in rain between time periods but little difference between low, medium and high RCP scenarios (Figure 8). The

[5] The UKCP18 climate change predictions represent a 30-year average: the 2020 models represent the time period 2010-2039; the 2050 models represent 2040-2069; and 2080 represents the period 2070-2099. For brevity these are referred to at the 2020, 2050 and 2080 scenarios in this report.

reductions in summer rainfall are most marked in the south and east of Wales, for example in the medium scenario, ASR in Torfaen decreased by 77 mm from 527 mm in 2020 to 450 mm in 2050 and in Rhondda Cynon Taff by 85 mm from 687 mm in 2020 to 602 mm in 2050 (Figure 9).

- For the 2040-2069 period (2050), the prediction maps show a noticeable increase in the AT0 for the low, medium and high RCP scenarios, particularly in the south east of Wales (Figure 10). For example in the medium scenario, AT0 for Monmouthshire increases by 108°C, from 1,516°C in 2020 to 1,624°C in 2050 and for Torfaen by 108°C, from 1,353°C in 2020 to 1,461°C in 2050 (Figure 11). In line with the UKCP18 predictions, by 2080, accumulated temperature is predicted to increase further and there is a noticeable difference in the low, medium and high RCP scenarios, with the latter predicting the greatest increases in AT0 for Wales.

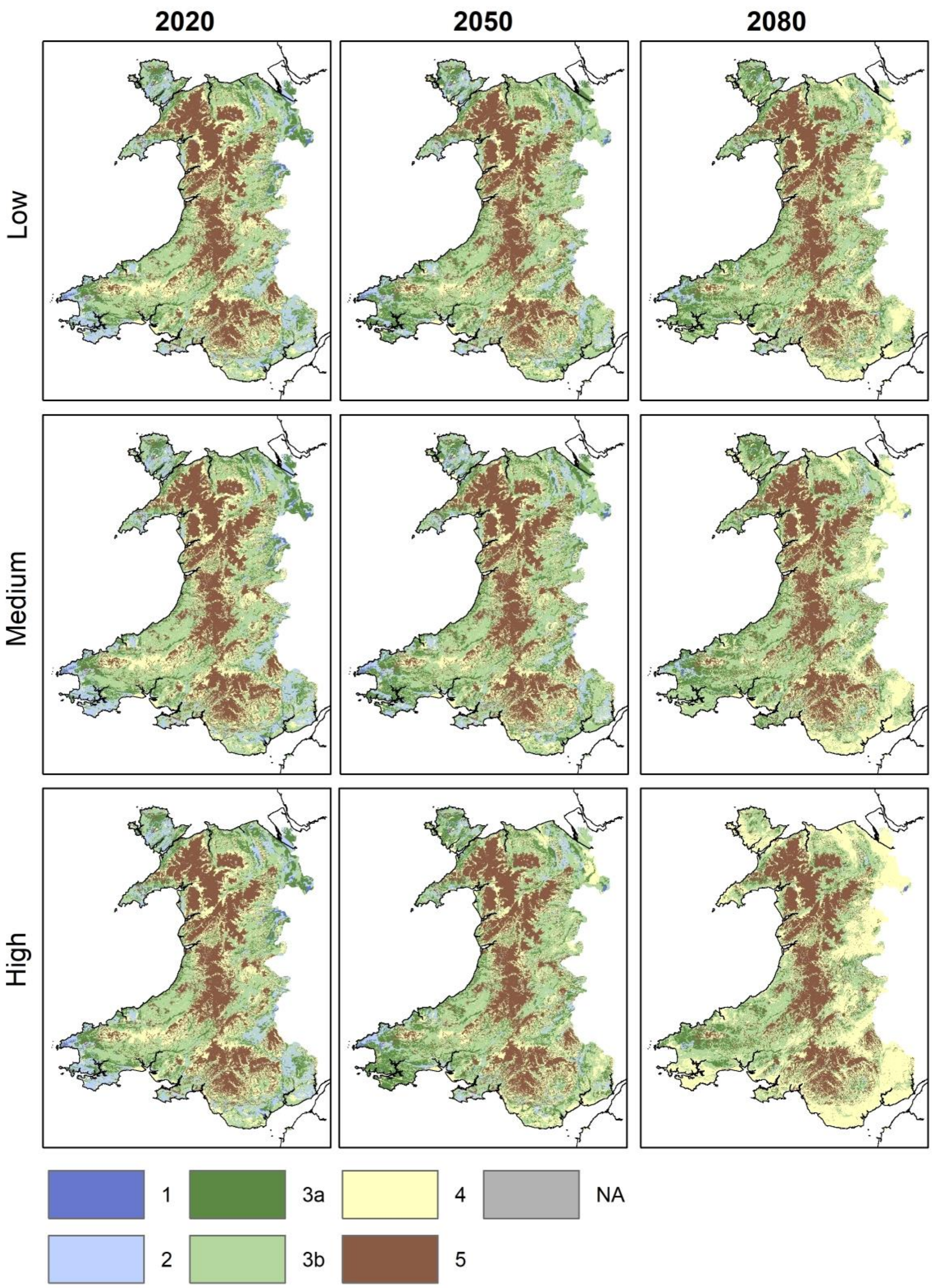

Figure 6. Agricultural Land Classification grade for 2020, 2050 and 2080 UKCP18 low, medium and high RCP scenarios (Source. Keay and Hannam, 2020).

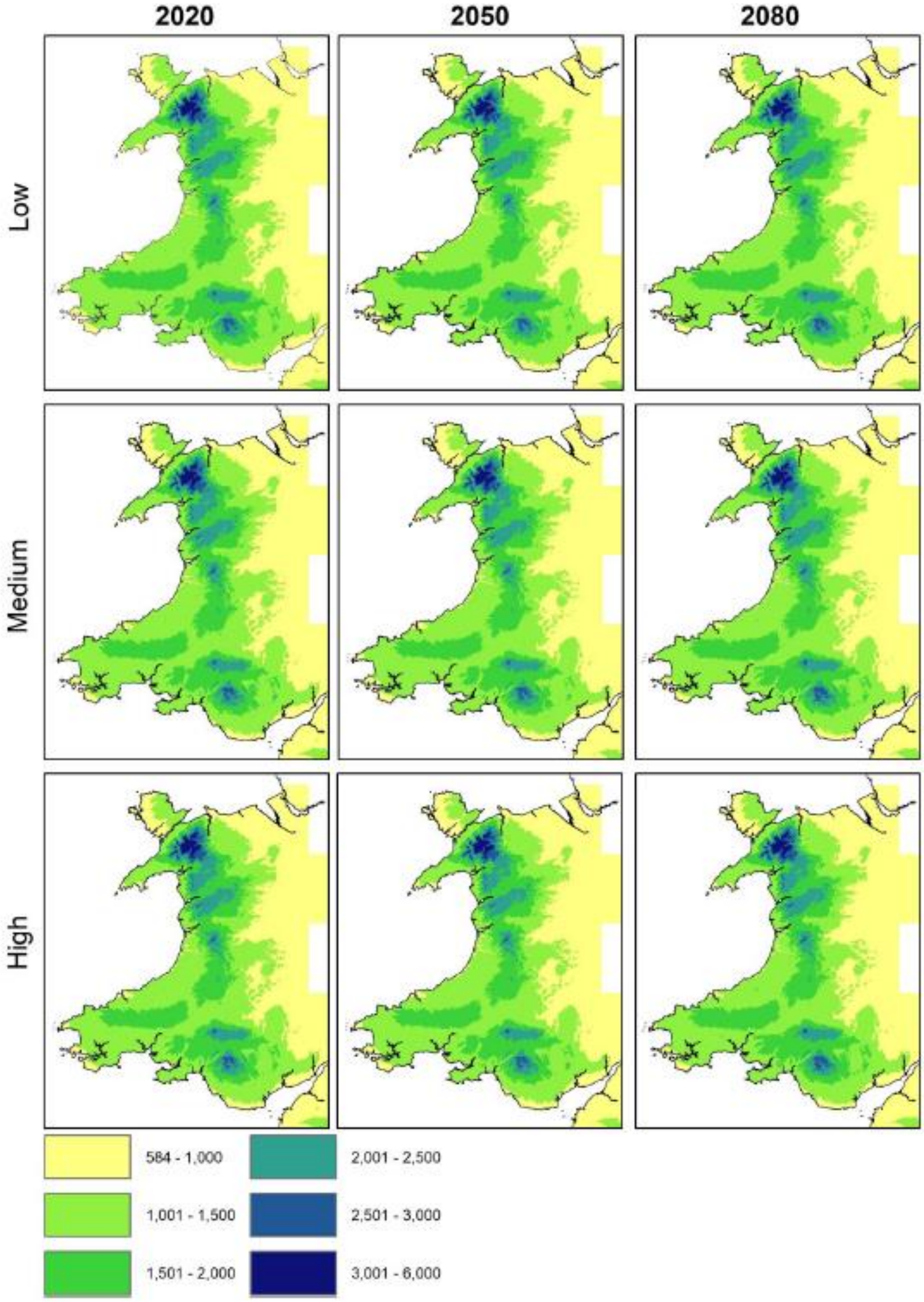

Figure 7. Average annual rainfall (mm) for 2020, 2050 and 2080 UKCP18 low, medium and high RCP scenarios for Wales (Source. Keay and Hannam, 2020).

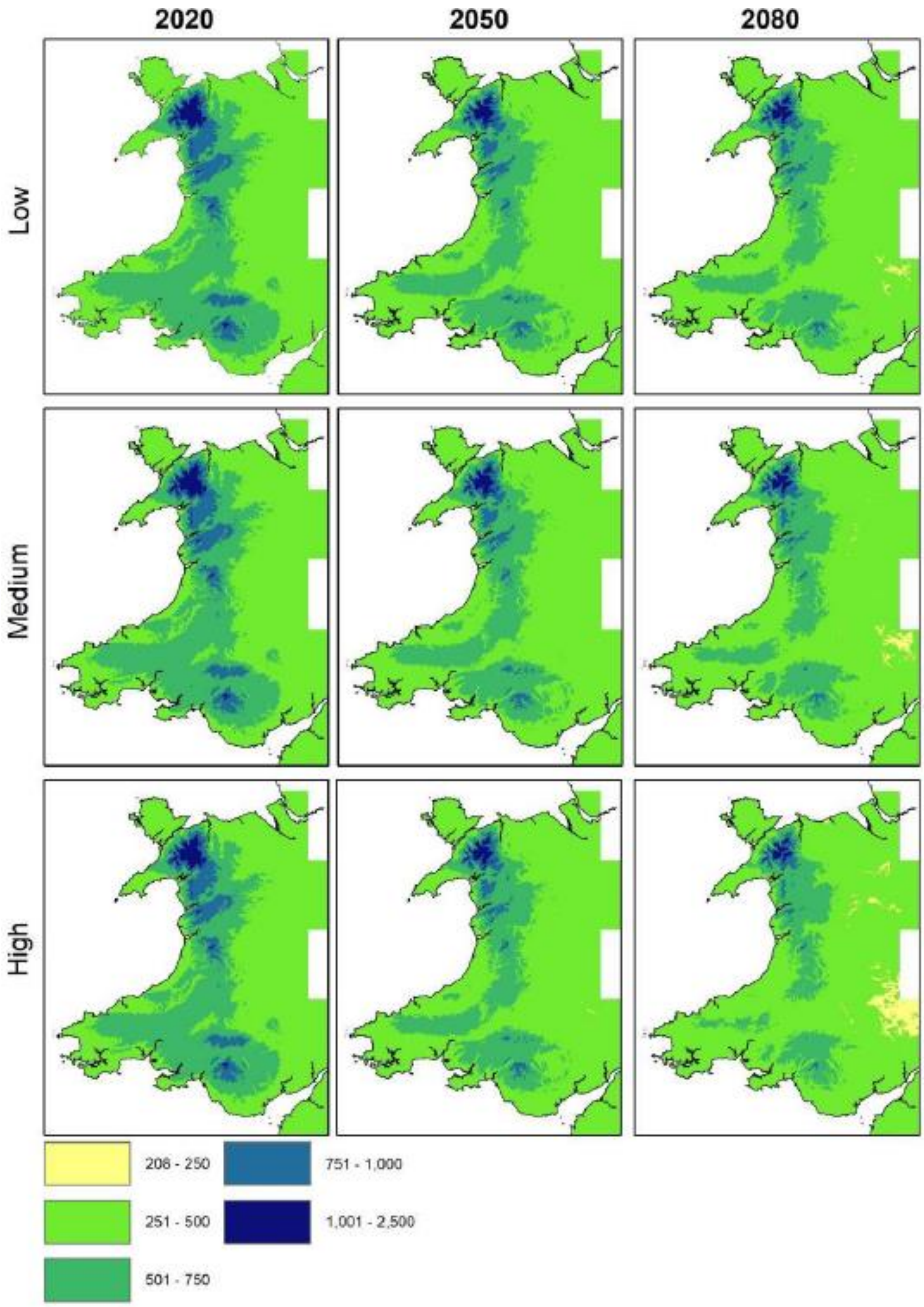

Figure 8. Average summer rainfall (mm) between April and September for 2020, 2050 and 2080 UKCP18 low, medium and high RCP scenarios for Wales (Source. Keay and Hannam, 2020).

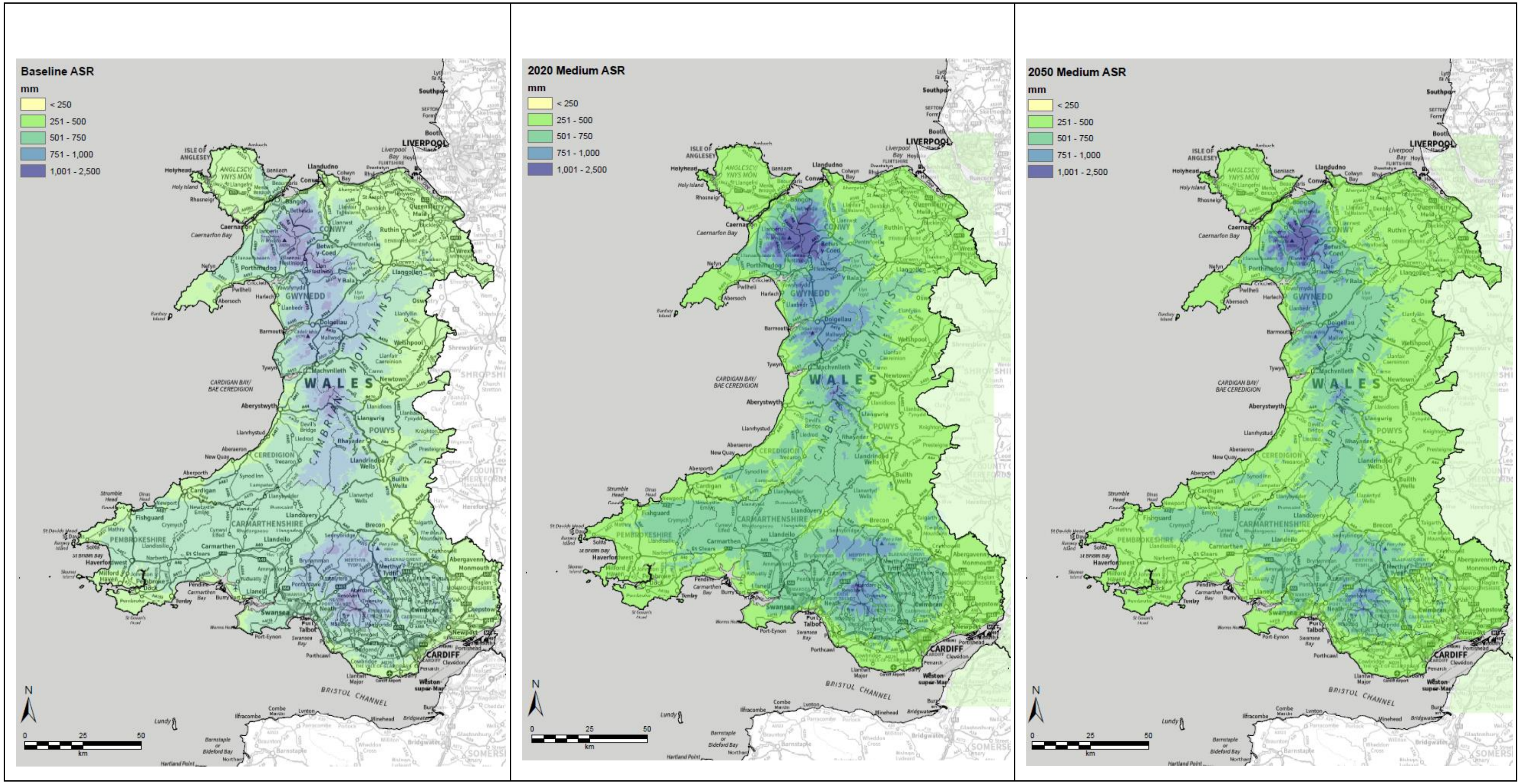

Figure 9. Average summer rainfall (mm) between April and September for the baseline (1961-1990), 2020 and 2050 UKCP18 medium RCP scenario for Wales.

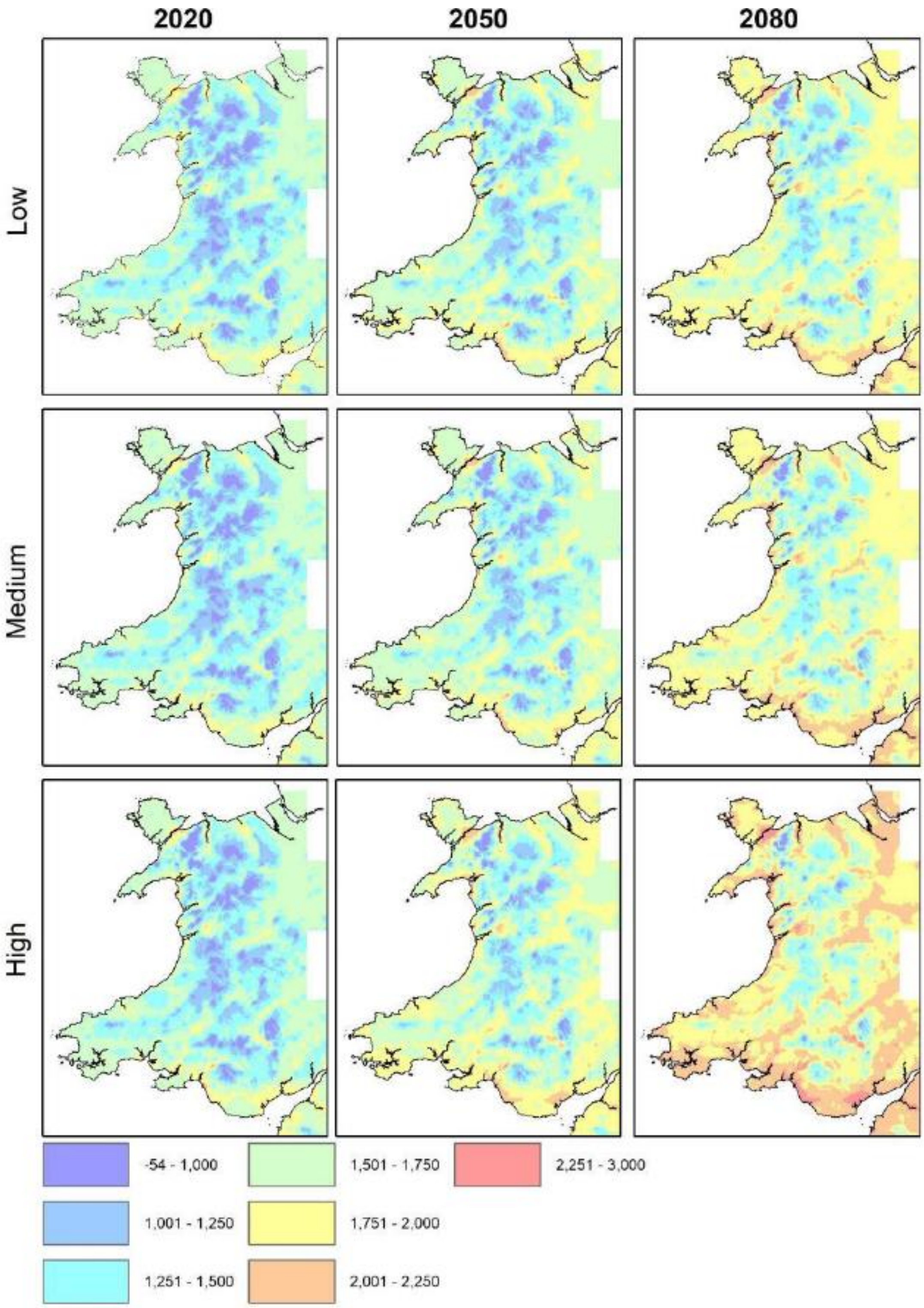

Figure 10. Median accumulated temperature above 0°C from January to June for 2020, 2050 and 2080 UKCP18 low, medium and high RCP scenarios for Wales (Source. Keay and Hannam, 2020).

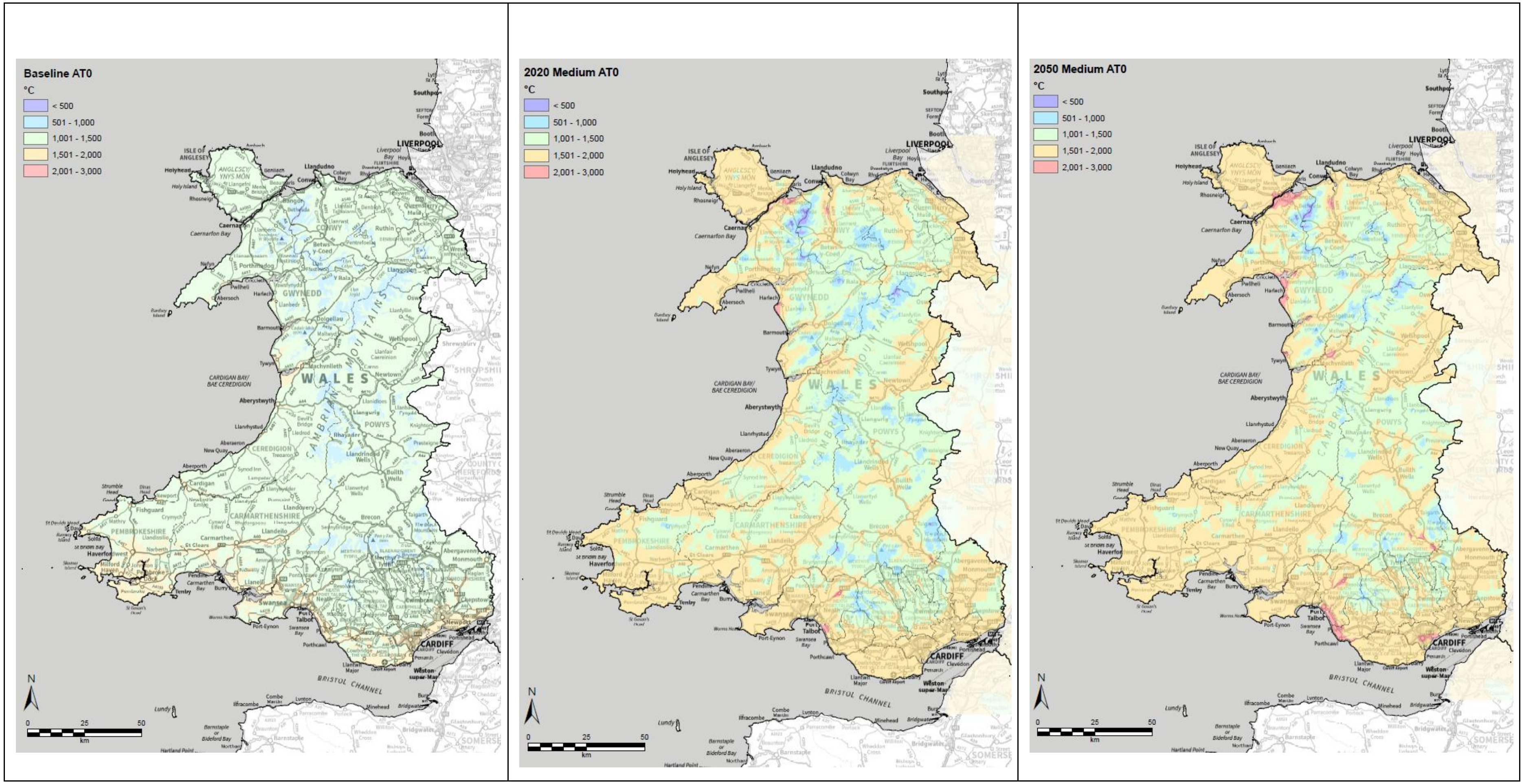

Figure 11. Median accumulated temperature above 0°C from January to June for baseline (1961-1990), 2020 and 2050 UKCP18 medium RCP scenario for Wales

7.3 Field capacity days

- Field capacity is defined as the point at which the soil moisture deficit is zero, i.e. when all soil pores other than those that drain under gravity are full of water. Soils usually return to field capacity during the autumn or early winter during periods when rainfall exceeds evapotranspiration. The field capacity period, measured in days, ends in the spring when evapotranspiration exceeds rainfall and a moisture deficit begins to accumulate.
- For the majority of Wales, the number of field capacity days is >250 days for all of the time period/RCP scenario combination (Figure 12). However, climate change scenarios suggest that for some areas of Wales (e.g. the south east) there could be a reduction in field capacity days in 2050 and 2080 compared to 2020, reflecting the reduction in summer rainfall noted above. For example, in Monmouthshire under the medium RCP scenario field capacity days are predicted to fall by 18 days between 2020 (209 days) to 2050 (191 days), Figure 13.
- As weather patterns become more volatile, risks introduced by weather variability will become more critical to agricultural production. The availability of days suitable for field work is driven by soil temperature and moisture, both of which may be altered by climate change (Tomasek *et al*., 2017).
- The availability of field working days is primarily driven by soil moisture, where soil moisture over a certain threshold is deemed too wet to work (Earl, 1997). Different soils are assumed to have the same threshold for workability if the volumetric soil moisture is measured as a percentage of either the field capacity (FC) or plastic limit (PL) of the soil (Rounsevell, 1993).
- Keay *et al*. (2014) reported that although AAR has remained fairly stable between 1921 and 2000 March and June rainfall has increased by 20-37% and July rainfall has decreased by >40%. The increased rainfall in March and June could result in a delay to the end of FC date, which would reduce the need for irrigation during the crucial spring growing period. In comparison, autumn rainfall patterns have remained stable but accumulated temperature AT0 has risen by 61 degrees days between 1914 and 2000. The higher temperatures suggest that the return of field capacity will be delayed until later in the year. Hence, although the overall duration of field capacity might not change much, it will start later (in autumn) and end later (in spring) which will favour autumn sown crops (Keay *et al*., 2014).

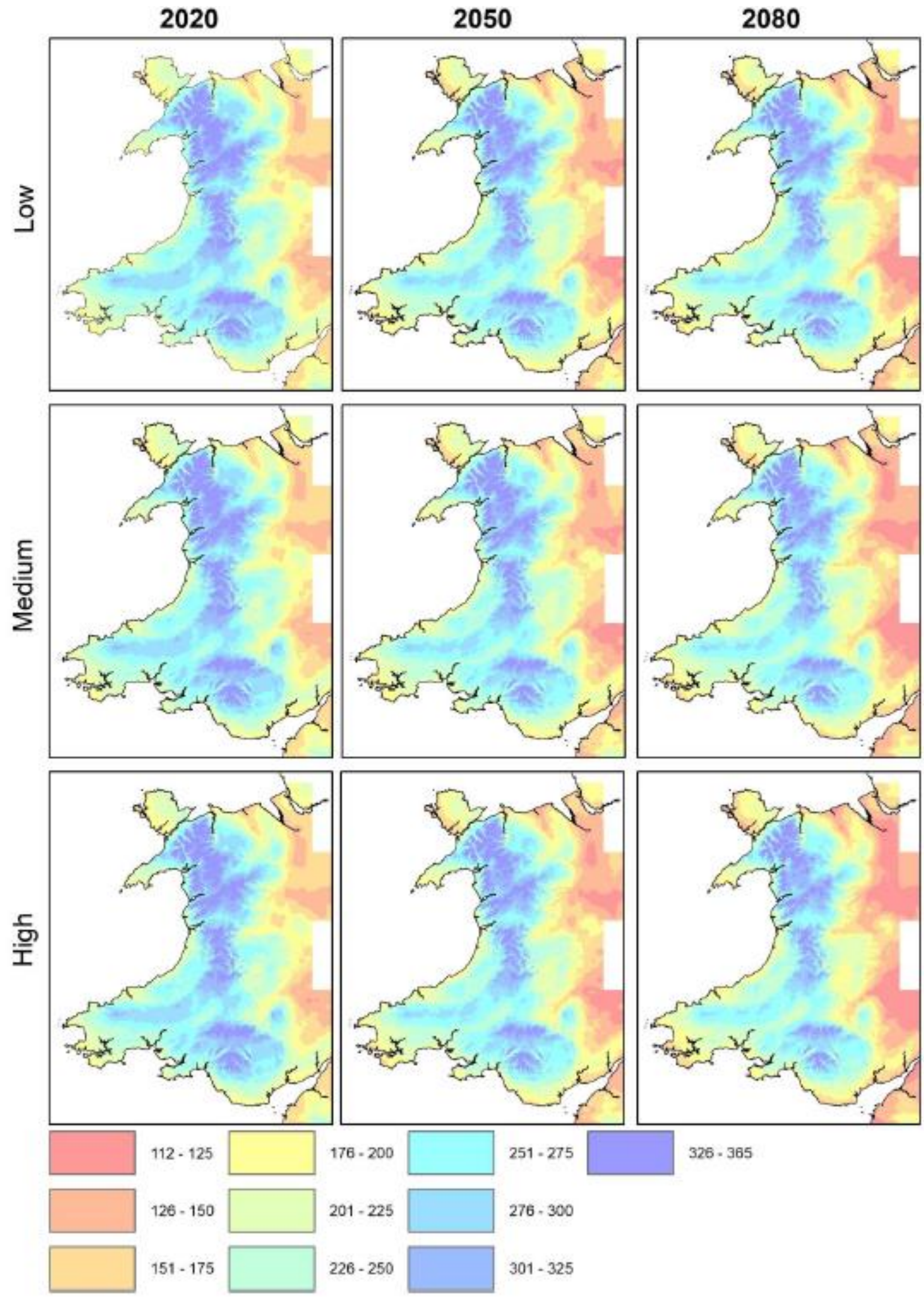

Figure 12. Median duration of field capacity (days) for 2020, 2050 and 2080 UKCP18 low, medium and high RCP scenarios for Wales (Source. Keay and Hannam, 2020).

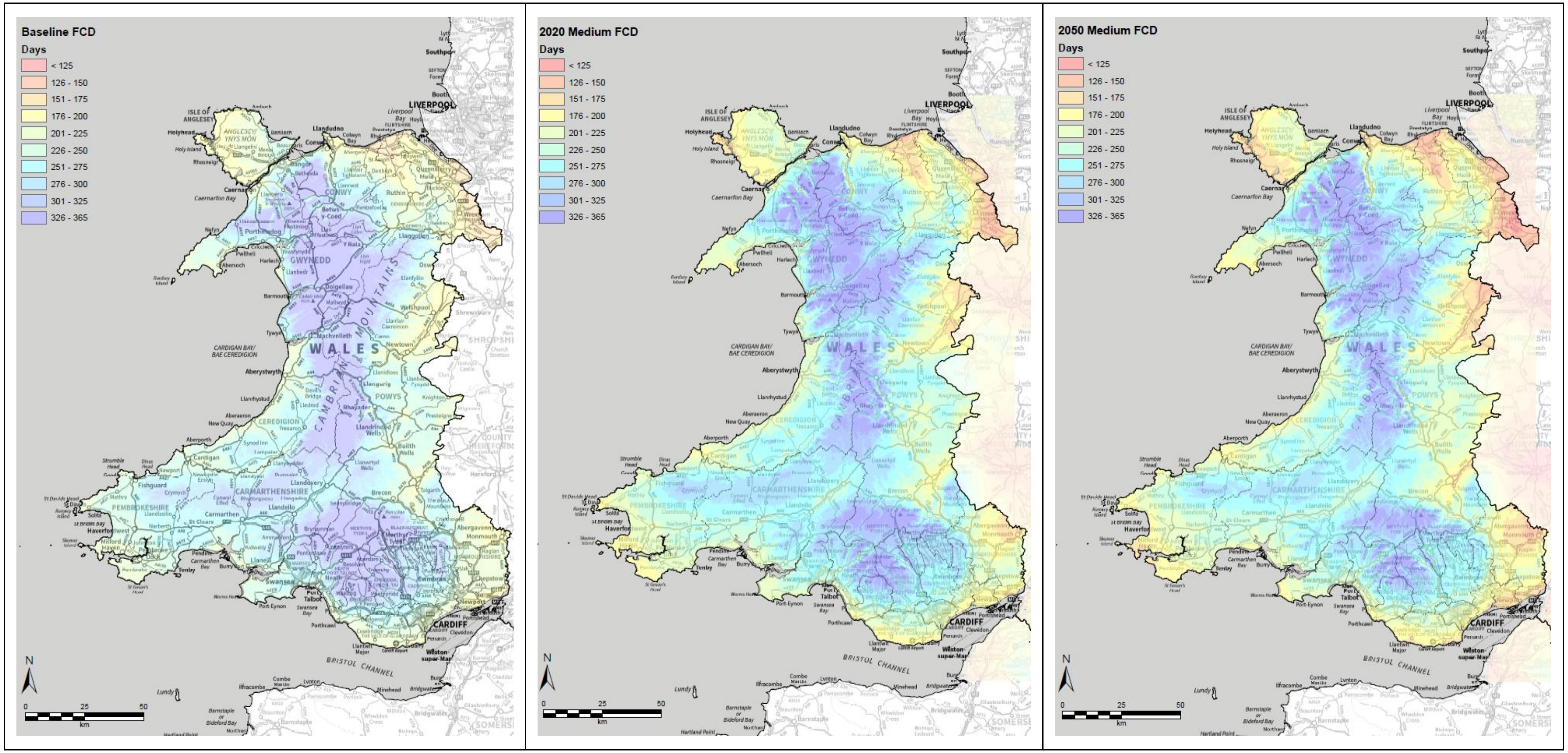

Figure 13. Median duration of field capacity (days) for baseline (1961-1990), 2020 and 2050 UKCP18 medium RCP scenario for Wales

8 Climate change and soil moisture deficit

8.1 ALC and soil moisture deficit: UKCP09 scenarios

- Keay *et al*. (2014) investigated how future changes in climate may affect agriculture in England and Wales using the ALC system as a surrogate measure. The study focused on the time period 1961-1990 to generate a baseline from which relationships were derived to apply to the future climate change scenarios. Twelve UK Climate Projections for 2009 (UKCP09) climate change scenarios were investigated namely the low, medium, high and emission scenarios for 2020 (2010-2039), 2030 (2020-2049), 2050 (2040-2069) and 2080 (2070-2099) time periods. 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 UK Climate Projections UKCP09 reflected scientists' best understanding at the time of how the climate system operates and how it might change in future. UKCP09 should be seen as providing possible projections rather than absolute predictions or forecasts of future climate. No one scenario is any more likely than the other.
- The ALC droughtiness criteria method is based on an estimation of the average soil moisture balance for two reference crops (potatoes and wheat) at a given location. Moisture balance is calculated from two parameters: 1, the crop-adjusted available water capacity of the soil profile (AP) and 2, moisture deficit (MD). As the climate gets warmer and drier in the summer the drought factor becomes more limiting to crop productivity.
- The percentage of National Soil Inventory (NSI) sites in each ALC grade by droughtiness was assessed for four time periods (i.e. 2020, 2030, 2050 and 2080) in comparison to the baseline (1961-1990), for the UKCP09 low, medium and high emission scenarios. The percentage of sites classed as ALC Grade 1 fell from 37% (baseline value) to 21-22% in 2020, 17-19% in 2030, 10-13% in 2050 and 7-11% in 2080 (range: low to high emission scenarios). In comparison, the percentage of sites classed as ALC Grade 4 increased from 2% (baseline value) to 7-8% in 2020, 11-14% in 2030, 25-43% in 2050 and 36-66% in 2080 (range: low to high emission scenarios). As the overall ALC grade is defined by the most limiting factor, very large areas of England and Wales were predicted to be downgraded to Grade 4 as a result of increased risk of droughtiness. However, note that the work of Keay *et al*. (2014) can only be used to identify trends not absolute magnitudes or exact locations of any change and the results should not be interpreted at a local scale. Grades for the whole of England and Wales were not determined.

8.2 Soil moisture deficit calculation

- The calculation of the soil moisture deficit is a key component of assessing soil droughtiness in the ALC (MAFF, 1988). Moisture deficit (MD) represents the balance between rainfall and potential evapotranspiration (PE) during a critical portion of the growing season and is a crop related variable. MD (winter wheat) and MD (potatoes) is calculated based on relationships between annual summer rainfall (ASR, April to September) and accumulated summer temperature (AST, April to September) from *c*.90 weather stations between 1960 and 1980. The relationship explained *c*.90% of the variation in crop adjusted MD.
  - MD (winter wheat) = 325.4 - 162.3 $\log_{10}$ ASR = 0.08022 ATS
  - MD (potatoes) = 326.4- 196.5 $\log_{10}$ ASR = 0.1127 ATS
- Keay *et al*., (2014) initially used the regression equations above to calculate the moisture balance for the climate change scenarios. However, when the equations were used to predict future MDs the results were extreme and by the 2080s the whole country would have been assessed as Grade 4. As a result, the authors used the Met Office rainfall and evaporation

calculation system (MORECS) to establish modified regression equations which were used in the assessment of future ALC grades.

  - MD (winter wheat) = 271.4754 + (-168.802. x $\log_{10}$ ASR) +(10.00217 x ATS)
  - MD (potatoes) = 337.8238 + (-185.614. x $\log_{10}$ ASR) +(5.849057 x ATS)

- The new MORECS equations were used to predict the MD for potatoes and wheat (Figure 14 and Figure 15) for the baseline, 2020, 2030, 2050 and 2080 low, medium and high UKCP09 scenarios. For potatoes, the initial MD (1961-1990) for Wales was between 0 and 50 mm, except for some areas along the English/Welsh border where the deficit was greater (50-75 mm). Similarly, by 2020 and 2030 most areas of Wales were predicted to have a MD of between 0 and 50 mm although, MDs in the Welsh borders were beginning to increase; there was little difference in the predicted MD for the low, medium and high scenarios. By 2050, the predictions suggested a further increase in the MD to >100 mm in the Welsh borders, which was greatest in the high RCP scenario. Finally, by 2080, although large areas of the west and central uplands of Wales still had low MD (i.e. 0-50 mm), especially in the low and medium scenarios, the predicted MDs were significantly greater than the baseline predictions. For example, for areas in south east Wales, such as Monmouthshire and Newport MDs of 126-150 or 151-175 mm, were predicted depending on the scenario, suggesting a high risk of drought conditions. In comparison, baseline MDs for Monmouthshire and Newport were <100 mm (Figure 14).
- The predicted MD increases in all the main potato growing areas (Anglesey, Pembrokeshire, Monmouthshire and Powys) over time, indicating an increasing need for irrigation.

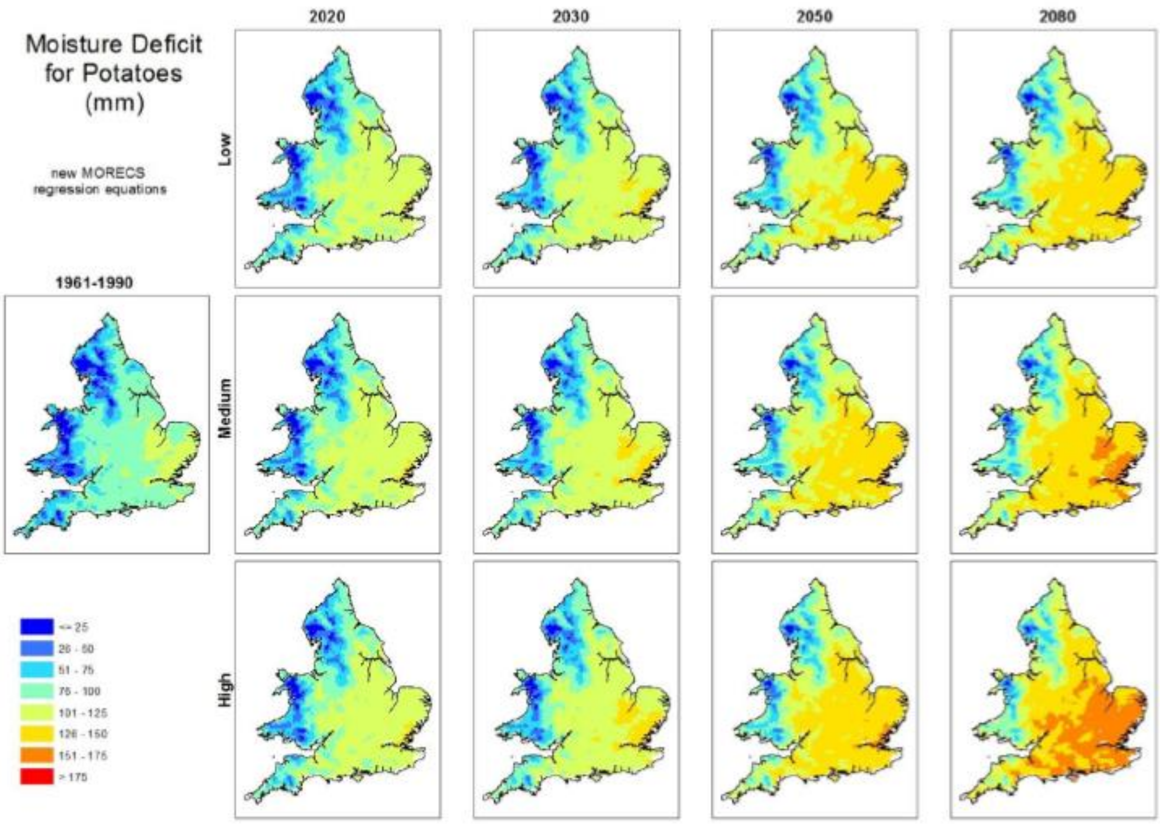

Figure 14. Moisture deficit for potatoes for the baseline (1961-1990) and UKCP09 projections for 2020, 2030, 2050 and 2080. Source: Keay *et al*., 2014.

- For wheat, the initial MD (1961-1990) was between 0 and 50 mm, except for some areas along the English/Welsh border where the deficit was greater (50-75 mm), Figure 15. By 2020 and 2030 most areas of Wales were predicted to have a MD of 0 to 75 mm although, the MD in the Welsh borders increased to >100 mm for the high scenarios. By 2050, the predictions suggested a further increase in the MD for most of Wales; many areas had a predicted MD of >100 mm. Finally, by 2080, only small areas of north west Wales and the uplands of Wales were predicted to have low MD (i.e. 0-50 mm) and in large areas the MD was >126 mm. Also, some areas in the south east of Wales, such as Monmouthshire and Newport had MDs of 151-175 mm, suggesting a high risk of drought conditions. Many of the traditional wheat growing areas (Vale of Glamorgan, Powys, Pembrokeshire and Monmouthshire) are situated in those areas where the increase in MD was predicted to be greatest.

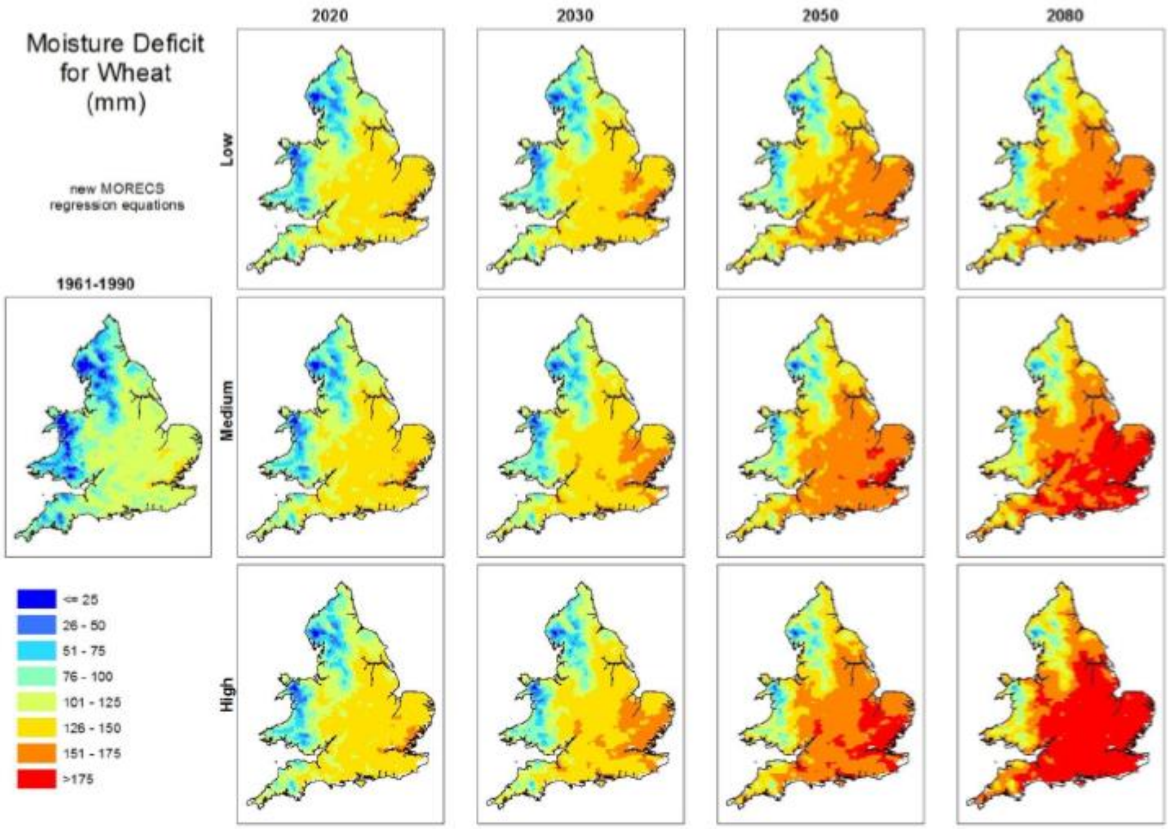

Figure 15. Moisture deficit for wheat for the baseline (1961-1990) and UKCP09 projections for 2020, 2030, 2050 and 2080. Source: Keay *et al*., 2014.

8.3 ALC and soil moisture deficit: UKCP18 scenarios

- More recently, Keay and Hannam (2020) investigated the effect of climate change on ALC in Wales using the UKCP18 scenarios. The methodology used to calculate the MD for potatoes and wheat was the same as described earlier and used by Keay *et al*. (2014). The UK Climate Projections (UKCP18) are the fourth generation of climate change information for the UK, and its projections are based on a methodology designed by the Met Office. UKCP18 reflects scientists' best understanding at the time of how the climate system operates and how it might change in future. UKCP18 should be seen as providing possible projections rather than absolute predictions or forecasts of future climate. No one scenario is any more likely than the other.

- Most of Wales is not limited by drought in the baseline (>90% of the area is classified as Grade 1 for droughtiness). This is also the case for 2020 (73% is Grade 1) although some areas are starting to downgrade for the drought criteria. By 2050 and 2080 many areas in Wales (Welsh border, Pembrokeshire, Anglesey and north Wales) are significantly downgraded due to drought constraints. This assumes crops are not irrigated.
- Similarly, to the soil moisture deficits calculated by Keay *et al*. (2014) from the UKCP09 scenarios there is a significant increase in MD between 2020 and 2080. The largest deficits are evident in the border areas of Wales, South Wales, Pembrokeshire and Anglesey, Figure 16.

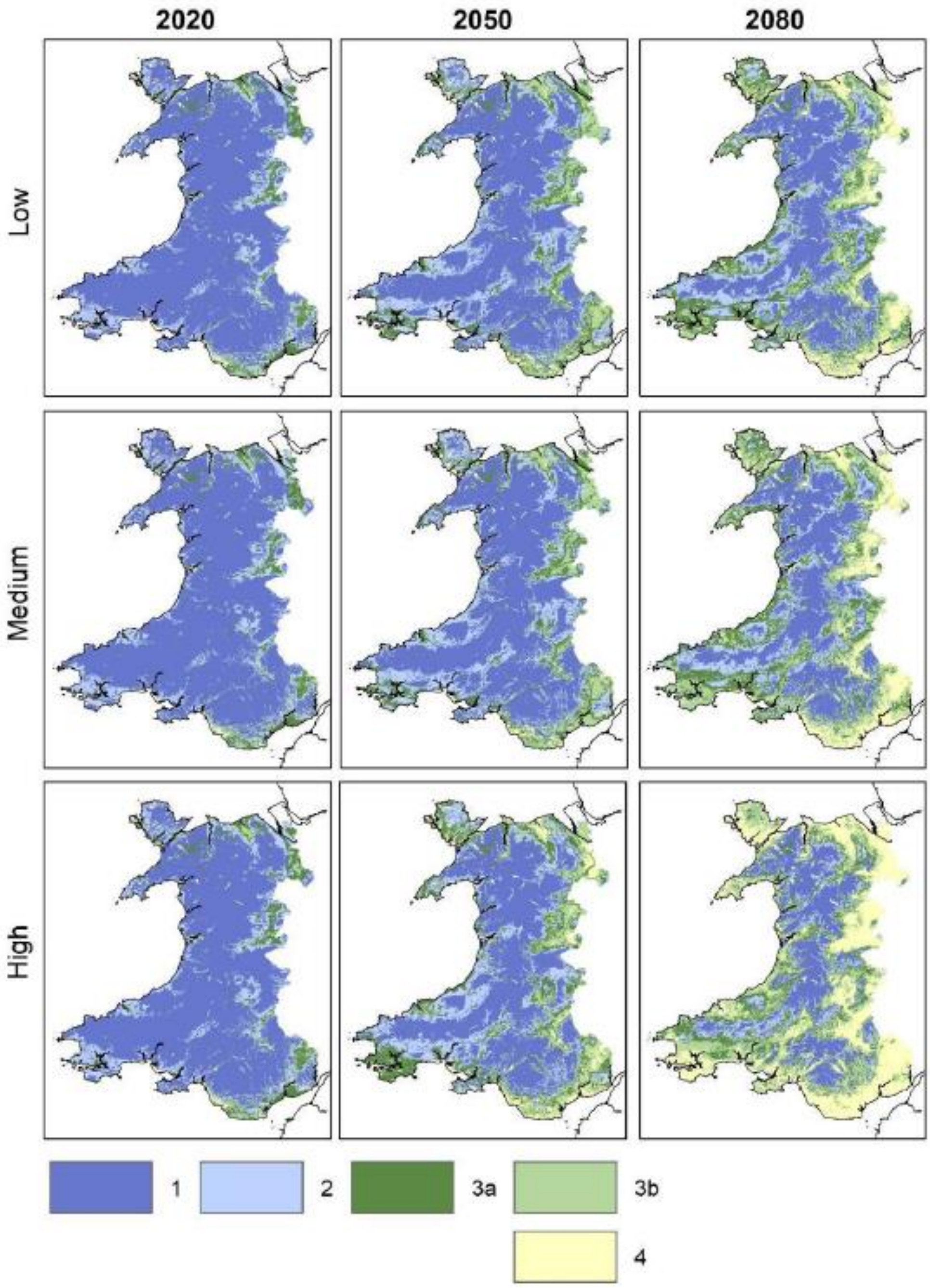

Figure 16. ALC Grade by droughtiness under UKCP18 RCP scenarios (Source. Keay and Hannam, 2020).

- For potatoes, there is little difference in the predicted MD for the 2020 scenarios with predictions suggesting most of Wales has a MD between 0-75 mm (Figure 17). Likewise, the predictions for 2050 are not greatly different for the low, medium or high scenarios. However, by 2050, there are increasingly areas of Wales where the MD is predicted to be between 126 and 175 mm, particularly in Monmouthshire, the Vale of Glamorgan and Powys. By 2080, the difference between the low, medium and high scenarios is more apparent, in the high RCP scenario, MD are predicted to be >200 mm for many areas in the Welsh borders.
- In line with the predictions based on UKCP09 (Keay *et al*., 2014), the MD increases in the main potato growing areas (Anglesey, Pembrokeshire, Monmouthshire and Powys) over time, indicating an increasing need for irrigation. For example, the MD in Anglesey was <100 mm in 2020 (low, medium and high scenarios) increasing to >150 mm by 2080 in the high RCP scenario.

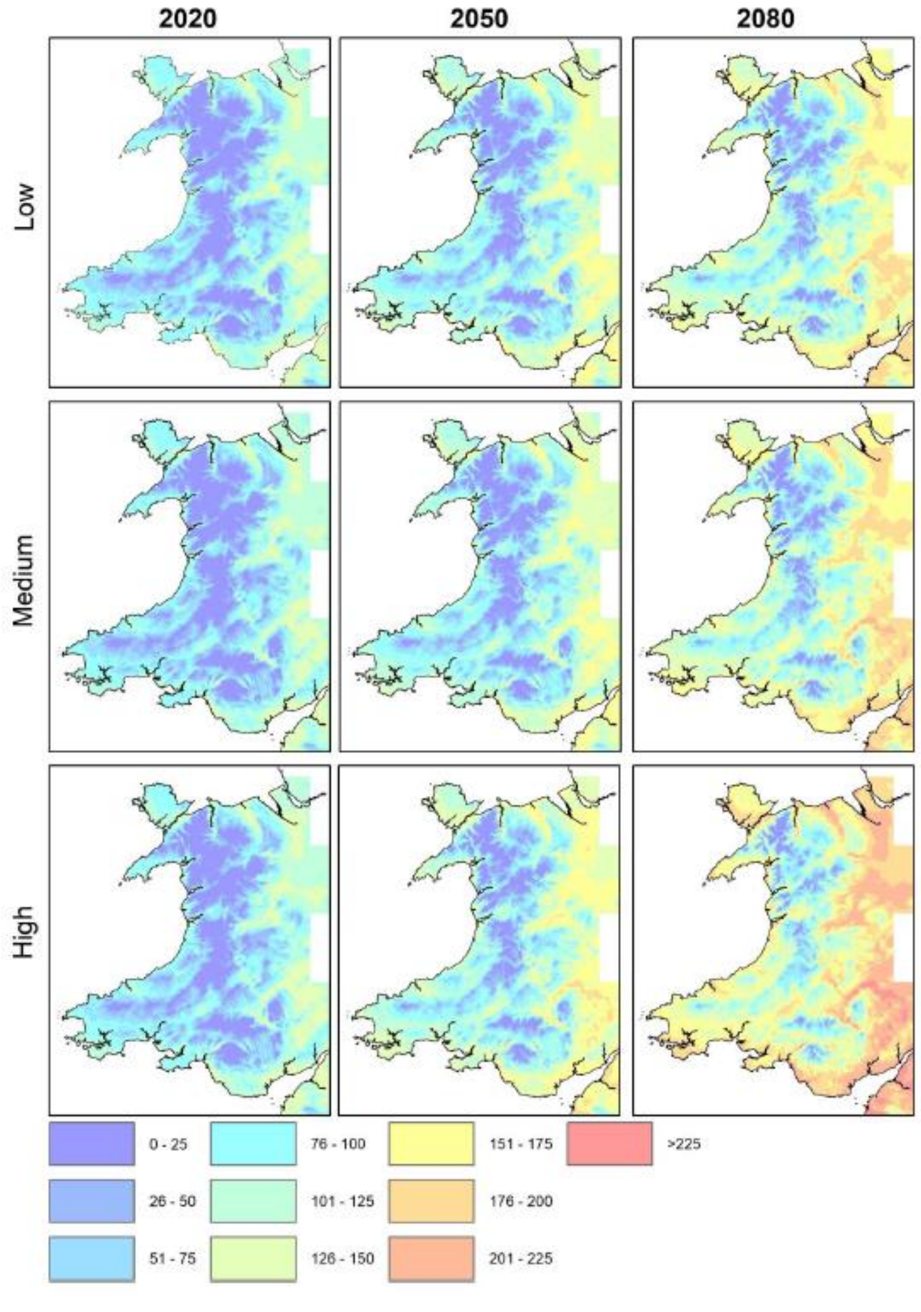

Figure 17. Crop adjusted moisture deficit potatoes (mm) under UKCP18 RCP scenarios (Source. Keay and Hannam, 2020).

- For wheat, predictions suggest that there is little difference in MD between the low, medium and high scenarios in 2020 with most of Wales having an MD of between 0 and 75 mm (Figure 18). In addition, the predictions for 2050 are not greatly different for the low, medium or high scenarios. However, by 2050, increasing areas of Wales are predicted to have MDs under wheat of between 126 and 150 mm, particularly in Monmouthshire, the Vale of Glamorgan and Powys. By 2080, the difference between the low, medium and high scenarios is more apparent. In the high RCP scenario, MDs of >150 mm are predicted for many of the traditional wheat growing areas in the Welsh borders, Anglesey, Pembrokeshire and the Vale of Glamorgan, suggesting a high risk of drought conditions.

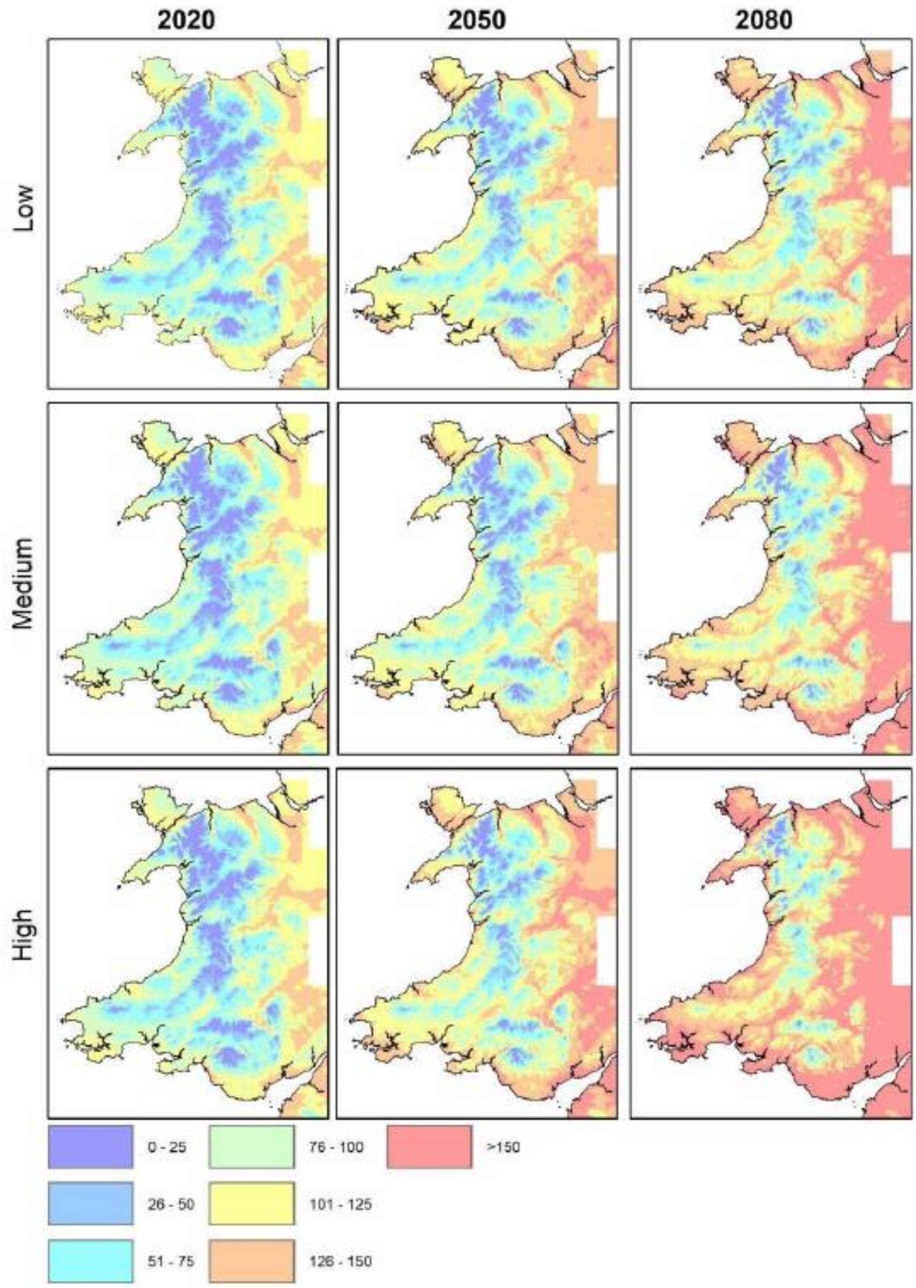

Figure 18. Crop adjusted moisture deficit wheat (mm) under UKCP18 RCP scenarios (Source. Keay and Hannam, 2020).

9 Irrigation

- Irrigation regulates the quantity and seasonal availability of rainfall to ensure water supply matches agricultural needs. Over the last 25 years there has been a marked increase in the irrigation of high value crops, particularly potatoes and field vegetables, driven by the supermarket demands for quality, consistency and continuity of supply (Knox *et al*., 2013).
- The most common irrigation methods used in the UK (Figure 19) are hose reels with rain guns or booms (used for 95% of water applied to UK arable crops); trickle, sprinkle or drip irrigation is much less common (ADAS, 2007). Wheat is not typically irrigated.

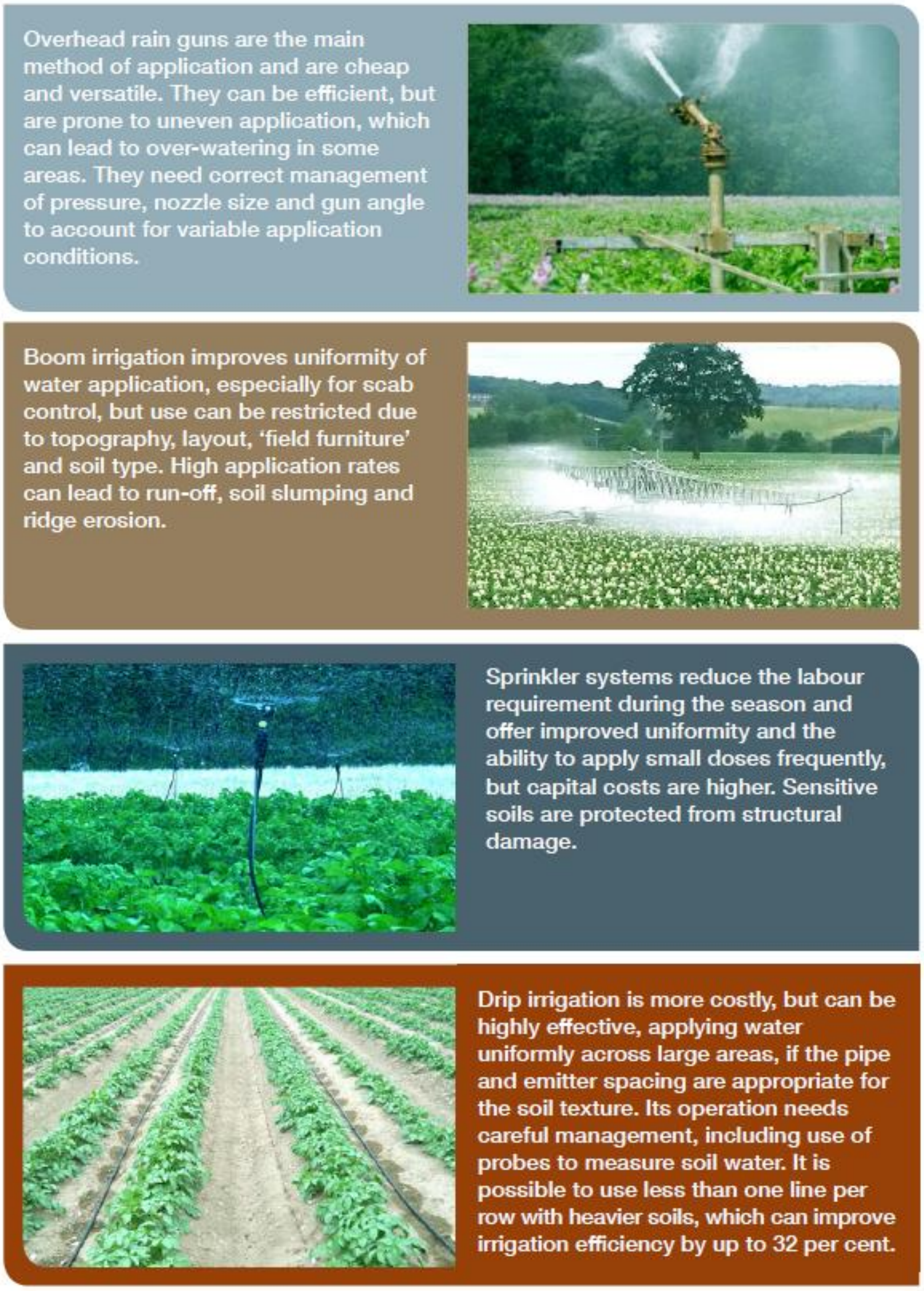

Figure 19. Irrigation methods for potatoes (Source: AHDB, 2018).

- Irrigation can be used to ‘correct’ any moisture deficit and enhance the potential of agricultural land especially in drier areas. The demand for irrigation varies significantly from year to year depending on soil water content which is mainly controlled by rainfall, temperature, soil texture and structure. The amount of summer rainfall is particularly important in controlling irrigation needs. Irrigation in England and Wales uses between 1 to 2% of total water use, although it can be the largest abstractor from some catchments in dry summers (Knox *et al*., 2013). Irrigation abstractions are highest in East Anglia and Lincolnshire (Knox *et al.,* 2020).
- Irrigation demand is generally low in Wales because rainfall amounts during the growing season are usually adequate to meet most crop requirements. However, some areas of Wales have no or little scope for further summer surface water abstractions as water is already ‘over-licensed’ or ‘over abstracted’ (Knox *et al*., 2013), for example the Wye catchment.
- Future government policy may implement major legislative reforms to the abstraction licensing regime to reduce levels of over-abstraction and restore environmental flows. This will introduce additional costs associated with licensing and may make it more difficult to obtain permission to irrigate land. However, because the cost of the irrigated water accounts for only 5-7% of total irrigation costs, demand for water is currently not responsive to price (Morris *et al.* 2004).
- Irrigation is a consumptive use (i.e. the water is not returned to the environment in the short term) and is concentrated in the driest areas in the driest years and driest months when resources are most constrained (Knox *et al*., 2010). Consequently, irrigation can be the largest abstractor in some catchments in dry summers (Watts *et al*., 2015). This creates conflict with other water demands, most notably those for public water supply and environmental protection.
- Where irrigation is currently practised in the UK, summer abstraction is increasingly unreliable for many existing abstraction licence holders, and new summer licences are unobtainable in many catchments (Weatherhead *et al*., 2014). However, abstraction during the winter and/or at high flows into reservoirs is usually possible and can provide a more reliable resource. Reservoir construction requires planning permission and compliance with the Reservoirs Act 1975 and large raised reservoirs (≥25,000 m^3) must be designed by a qualified engineer and registered with the environmental regulator. Due to the substantial capital investment required, on-farm reservoirs are most suited to the irrigation of high value crops and/or where reliability of supply is important (e.g. supermarket contracts).
- Knox *et al*. (2013) calculated a volumetric irrigation water demand for England and Wales for a ‘design’ dry year of 85 million m^3 based on the 2010 pattern of land use. The statistically defined ‘design’ dry year is equivalent to the 5th driest year in 20. Almost, 70% of the demand for water was for irrigation of potatoes, 12% for sugar beet, 11% for grass, 6% for vegetables; small areas of cereals, soft fruit and orchards were also irrigated. For Wales, Knox *et al.* (2013) calculated a volumetric irrigation demand of 3.5 million m^3, of which over 90% was for potatoes. Note, however, that this demand was calculated for the Environment Agency region defined as Wales, rather than the country as a whole (Figure 20), so the irrigation demand is likely to be higher.
- Knox *et al*. (2013) modelled future demand for irrigation in the 2050s under four scenarios which predicted increases in the demand for irrigation water of between 40 and 167%, i.e. 1. Innovation (+157%), 2. Uncontrolled demand (+167%), 3. Sustainable behaviour (+56%) and 4. Local resilience (+40%).

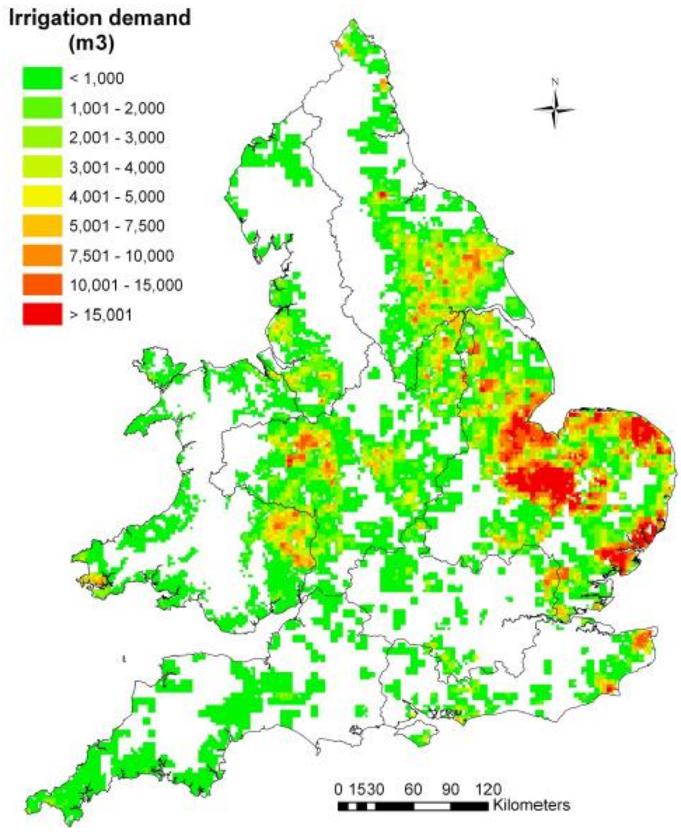

Figure 20. Design dry year modelled volumetric irrigation water demand (m^3) for potatoes in England and Wales (Source: Knox *et al*., 2013).

9.1 Irrigation scheduling

- Irrigation demand reflects the soil water storage (SWS) capacity which is defined as the total amount of water that is stored in the soil within the plant's root zone which is determined by soil type and crop rooting depth. A deeper rooting zone provides a larger reservoir of water for the crop to draw upon between irrigations. The soil water storage capacity is used to quantify the volume and frequency of irrigation events. For example, the amount of water applied at one time on a sandy soil, which has a low soil water storage capacity, would be less than for a loam soil, which has a higher soil water storage capacity. An availability coefficient is used to calculate the percentage of irrigation water supplied that is readily available to the plant.
- Irrigation scheduling has at its core a method of measuring SMD, which can be based on manual or computerised balance sheets or direct measurements of soil moisture. Soil moisture deficits that trigger irrigation range from 15 mm to 75 mm and are dependent on rooting depth, soil type, crop and accuracy of the equipment used (ADAS, 2003). Generally, the trigger point is defined as AWC x 0.5 (i.e. 50% of AWC). However, on soils with a low AWC, the trigger point may need to be reduced when evapotranspiration rates are high. To assess suitable irrigation regimes, soils can be divided into 3 classes, each having different levels of water availability for a given depth (Table 4); most soils are in class B (ADAS, 2007). Table 5, illustrates some irrigation schedules for a range of potato types grown on soils with a variety of AWCs.

Table 4. Water availability classes (Source: ADAS, 2003; 2007).

Class	Water availability	Example soil types
Class A	Low soil water availability ≤60 mm of water/500 mm soil depth AWC ≤12.5%	Coarse sand, loamy coarse sand, loamy sand
Class B	Low soil water availability 60-100 mm of water/500 mm soil depth AWC 12.5-20%	Loamy sand, loam, silty clay loam
Class C	Low soil water availability >100 mm of water/500 mm soil depth AWC >20%	Very fine sand, peat, peaty loam

Table 5. Example irrigation schedules for potatoes (Source: ADAS *et al*. 2005).

Variety and soil type	**10% crop cover to 6 weeks after TI***	**6 weeks after TI to mid-August**	**Mid-August to desiccation**
Estima variety for pre-pack history of common scab (silt loam soil)	10 mm @ 12 mm SMD	25 mm@ 40 mm SMD	20 mm @ 50 mm SMD
	20% crop cover to 4-5 weeks after TI	**4-5 weeks after TI to late harvest**	
Lady Rosetta crisping (loamy sand)	20 mm @ 25 mm SMD	25 mm@ 35 mm SMD	
	15% crop cover to 4-5 weeks after TI	**4-5 weeks after TI to late August**	**Late August to desiccation**
Maris Piper for chipping (sandy loam)	15 mm @ 15-18 mm SMD	25-30 mm@ 35-40 mm SMD	18 mm @ 35 mm SMD

*Tuber initiation

9.2 Efficiency of irrigation strategies

- Current irrigation efficiencies are often below 50 %, as much of the diverted water is lost in the conveyance system or through inefficient application to the plants (Jägermeyr *et al*., 2015), Figure 21. In comparison, Irmak *et al*. (2011) noted that potential irrigation efficiency of well-designed sprinkler and micro-irrigation systems was 65-95% (Table 6). The magnitude of irrigation system loss is determined not only by the irrigation system (e.g., sprinkler, surface, drip) but also by meteorological and other environmental conditions.

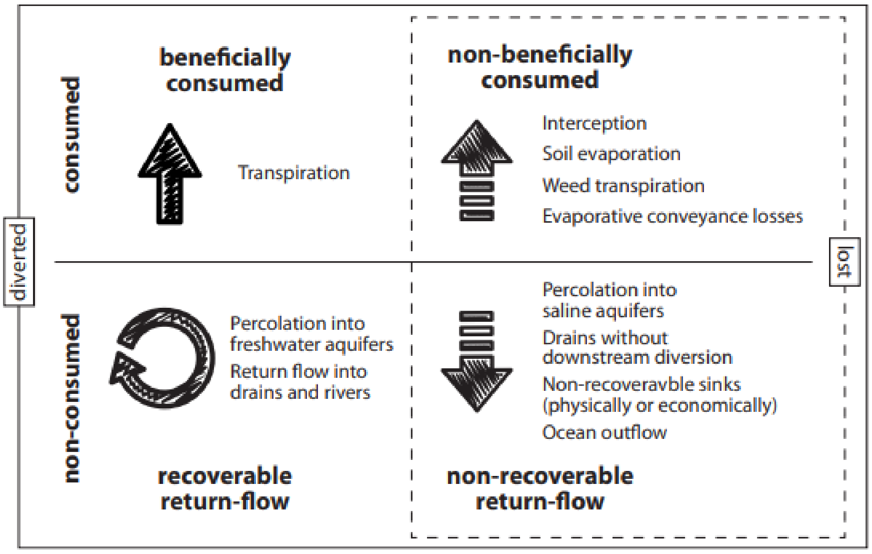

Figure 21. Pathways of irrigation water fluxes. Water is either consumed (non-) beneficially, or re-enters rivers, aquifers etc. making it recoverable through return flow. Non-beneficial consumption and non-recoverable return flow can be considered losses (Jägermeyr *et al.*, 2015).

- Jägermeyr *et al*. (2015) used the global bio-agrosphere model LPJmL to calculate the irrigation water requirement of three major irrigation systems (surface, sprinkler, and drip) for various crop functional types (CFT). The model accounted for the daily surface and soil water balance (potentially limiting water withdrawal) and partitioned irrigation water fluxes into transpiration, soil evaporation, interception loss, surface and subsurface runoff, and deep percolation. Using this approach, Jägermeyr *et al*. (2015) estimated a global irrigation water withdrawal of 2469 km^3 (2004–2009 average); irrigation water consumption was calculated to be 1257 km^3 (51%), of which 649 km^3 was beneficially consumed (i.e. transpired by crops) and 608 km^3 was non-beneficially consumed, i.e., lost through evaporation, interception, and conveyance. The authors calculated a beneficial efficiency of 33%, with the lowest values in south Asia and sub-Saharan Africa and the highest in Europe and North America (determined by both the irrigation system in use and the local biophysical conditions). In comparison, when the model assumed all sprinkler irrigation or all-drip irrigation, the beneficial efficiency was increased to 51% and 70%, respectively.
- Figure 22 illustrates the modelled breakdown of irrigation water fluxes for each crop and all three irrigation systems. Jägermeyr *et al*. (2015) noted that modelled, transpiration was relatively constant across irrigation systems. For surface irrigation return flow formed the major part of the non-beneficial fluxes, whereas sprinkler systems and drip systems had considerably lower return flow fraction (34% and 13% of withdrawal, respectively). Modelled conveyance losses were significantly lower with sprinkler or drip systems due to pressurized conveyance. Evaporation losses were relatively similar between surface and sprinkler systems, while drip systems showed lower losses due to their system design. Interception losses from sprinkler systems (surface and drip apply water below canopy) made only a minor contribution to non-beneficial fluxes (Figure 22).

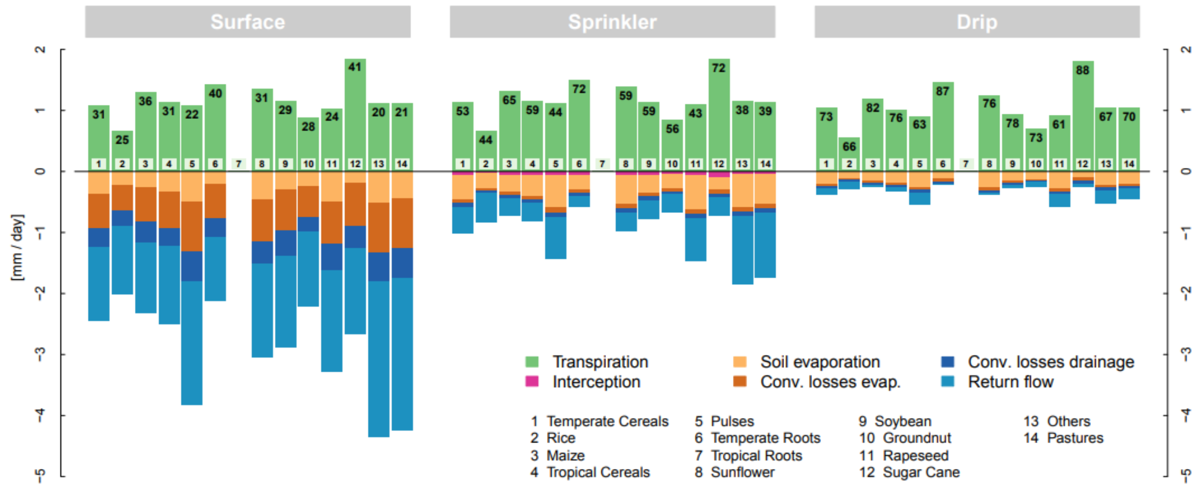

Figure 22. Breakdown of beneficial and non-beneficial water fluxes for each simulated crop and irrigation system (mm/day) averaged over the growing season and cultivated area. Each system was applied on all irrigated areas, assuming the same optimal management. The number at the top of the bar represents the crop specific beneficial irrigation efficiency (%).

Table 6. Potential application efficiencies for well-designed and well-managed irrigation systems (Source: Irmak *et al.*, 2011).

Irrigation system	**'Potential' application efficiency (%)**
Sprinkler systems	
LEPA	80-90
Linear move	75-85
Centre pivot	75-85
Travelling gun	65-75
Side roll	65-85
Hand move	65-85
Solid set	70-85
Micro-irrigation systems	
Bubbler (low head)	80-90
Micro-spray	85-90
Micro-point source	85-90
Micro-line source	85-90
Subsurface drip	>95
Surface drip	85-95

10 Future irrigation needs in Wales

- In 2017, there were around 3,350 ha of potatoes grown in Wales, of which 75% were main crop potatoes with the remainder early varieties which are usually harvested by 31 July (Table 7). Around half of the potato crop is grown in Pembrokeshire; other areas that grow more than 200 ha of potatoes are Anglesey, Monmouthshire and Powys. Most potatoes grown in Wales are rainfed and do not receive irrigation water. In the same year, wheat production in Wales covered around 21,500 ha of which 19% is grown in Pembrokeshire, 19% in Monmouthshire, 18% in Powys, 12% in the Vale of Glamorgan and 20% in North East Wales (Table 7). It is unlikely that irrigation water is currently used on any of the Welsh wheat crop.

Table 7. 2017 area growing wheat and potatoes (ha) in Wales

Region	Unitary Authority	Wheat	Potatoes (Earlies)	Potatoes (main crop)
North West Wales	Isle of Anglesey	451	91	137
	Gwynedd	94	2	48
North East Wales	Conwy	184	2	43
	Denbighshire	1,346	<0.5	74
	Flintshire	741	1	98
	Wrexham	1,943	<0.5	11
South Wales	Swansea	40	23	51
	Neath Port Talbot	24	~	18
	Bridgend	83	~	<0.5
	Vale of Glamorgan	2,606	<0.5	84
	Rhondda Cynon Taf	12	~	~
	Merthyr Tydfil	~	~	~
	Caerphilly	509	~	14
	Blaenau Gwent	22	~	~
	Torfaen	~	~	3
	Monmouthshire	4,018	6	324
	Newport	597	~	4
	Cardiff	20	~	0.43
Powys	Powys	3,938	4	322
Ceredigion	Ceredigion	524	21	64
Pembrokeshire	Pembrokeshire	4,156	671	1,116
Carmarthenshire	Carmarthenshire	163	7	118
Total		**21,468**	**828**	**2,530**

10.1 Quantifying the irrigation requirement of potatoes

- Main crop potatoes will typically use around 350 mm of water in an average growing season (ADAS *et al*., 2005). Depletion of the AWC by more than 50% is associated with a severe yield penalty for potatoes and irrigation is used to reduce the SMD when rainfall is not sufficient to maintain yield (ADAS *et al*., 2005). Maximum control of the blemish disease common scab is achieved by maintaining soil water reserves close to field capacity consequently where scab is a risk irrigation is applied before 50% AWC depletion is reached.

- The predicted abstraction water volumes to irrigate potatoes in 2020, 2050 and 2080 were calculated for a number of scenarios, assuming that the potato growing area of Wales remained at current levels, i.e. there was no change in the geographic spread, area (hectares) and crop type (earlies and main crop) over the period.
- For each of the scenarios the water volumes were calculated on a regional basis based on a) ensuring that the soil was maintained at half of the crop adjusted water capacity or b) ensuring the SMD did not exceed 25 mm (scab control).
- The crop adjusted available water capacity was calculated, based on soil textural class, using the values in Table 14 of the ALC guidelines (MAFF, 1988). In the ALC guidance it is assumed that under favourable conditions potatoes will root to 700 mm.
- Example calculations of crop adjusted soil available water capacity (AP) for potatoes for a clay loam and medium sandy loam soil is shown in Table 8.

Table 8. Crop adjusted soil available water capacity (AP) for potatoes in clay loam soil

Soil	Depth	Total available water (TA_v)[1]	Easily Available water (EA_v)[2]	Calculation	Total AP
Clay loam (to 700 mm depth. Subsoil condition moderate)					
Topsoil	0-330	18%		330 x 18% = 59 mm	118 mm
Subsoil 1	330-700	16%	10%	370 x 16% = 59 mm	
Soil moisture deficit irrigation trigger value					59 mm
Medium sandy loam (to 700 mm depth. Subsoil condition moderate)					
Topsoil	0-330	17%		330 x 17% = 56 mm	112 mm
Subsoil 1	330-700	15%	11%	370 x 16% = 56 mm	
Soil moisture deficit irrigation trigger value					56 mm

[1]TA_v the volumetric soil water content between 0.05 and 15 bar tension (or 0.10 and 15 bar tension for sands and loamy sands). Note: For potatoes the TA_v is used for the full rooting depth of 700 mm.

[2]EAv the volumetric soil water content between 0.05 and 2.0 bar tension.

- Projected climate data for monthly 50th percentile precipitation rate (mm), and minimum and maximum air temperature (°C) were sourced from the UK Climate Projections (UKCP18) for a total of twelve climate change scenarios, including high, medium and low RCPs for the time periods 2020's, 2030's, 2050's, and 2080's. Data from the 50th percentile were used to identify the median projected changes in the climate parameters for all dates.
- The 25 x 25 km UKCP18 data was downscaled to 5 x 5 km for comparison with the 1961-1990 ALC baseline data. An average of the climate value for each 25 x 25 km grid cell was calculated. The original 5 x 5 km values were then divided by the baseline 25 x 25 km average to determine the proportion of the baseline climate value that makes up the average. These proportions were then used on the UKCP18 climate variable values to provide an estimate of the climate projections data at a 5 x 5 km grid cell resolution.
- Soil moisture deficits were calculated for the low, medium and high RCP pathways for each time period (i.e. 2020, 2050 and 2080) for each 5 km x 5 km grid cell. Grid cells were assigned to each

of the 22 unitary authorities in Wales and the MD value was averaged to calculate the mean value for each region.

- The MD was calculated as follows, where ASR is summer rainfall (precipitation rate for each month was multiplied by the number of days in the month, and the months April-September totalled) and ATS is accumulated summer temperature (AT was calculated for each month as: ((0.4476+ (0.4854*max temp for month)+ (0.4804*min temp for the month))* days in the month), which was summed for the months April-September):
  - **MD potatoes:** 326.4-196.5 x Log10 ASR + 0.1127 x ATS
- The amount of irrigation water that was required was calculated as follows:
  - **Irrigation at half AP**: ((SMD potatoes mm– (0.5 x crop adjusted AP mm))/1000) x (crop area (ha) x 10,000) adjusted for application losses of 50%[6].
  - **Irrigation at SMD of 25 mm**: ((SMD potatoes mm – 25 mm)/1000) x (crop area (ha) x 10,000) adjusted for application losses of 50%.

10.2 Moisture deficit: potatoes

- The predicted moisture deficit for each combination of climate and RCP scenarios is reported for 22 Welsh unitary authorities in Table 9. Areas with the lowest MD are shaded green and those with the highest MD are shaded red. For 2020, there is little difference in the MD values for the low, medium and high RCP scenarios. The average MD across the whole of Wales in 2020 was *c*.65 mm, ranging from <20 mm in Conwy to >100 mm in the Vale of Glamorgan, Newport and Cardiff. By 2080, the average MD was predicted to increase by 20 mm to *c.*85 mm for the low/medium RCP scenarios and by 35 mm to *c.*100 mm for the high RCP scenario. For the 2080 low and medium scenarios the predicted MD values ranged from <40 mm in Gwynedd and Conwy to >120 mm in Flintshire, the Vale of Glamorgan, Newport and Cardiff. In comparison, for the 2080 high RCP scenario predicted MD values were around 20 mm higher than for the other RCP scenarios ranging from <60 mm in Gwynedd and Conwy to >140 mm in Newport and Cardiff.
- Overall the scenarios predict an increase of 30-40 mm in the MD by 2080 in all of the main potato growing areas of Pembrokeshire, Monmouthshire, Powys and Anglesey (Table 9).

[6] In line with Jägermeyr *et al.* (2015) irrigation efficiency was assumed to be 50% for overhead systems typically used in potato production.

Table 9. Moisture deficit (potatoes) for the UKCP18 low, medium and high scenarios for 2020, 2050 and 2080.

Region	2020			2050			2080		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Isle of Anglesey	95	95	96	115	114	126	111	115	127
Gwynedd	21	21	23	41	40	53	40	45	58
Conwy	15	15	17	35	34	47	36	41	55
Denbighshire	61	61	63	84	82	96	85	89	103
Flintshire	93	93	95	118	116	130	116	120	133
Wrexham	83	82	84	108	107	121	105	109	122
Swansea	80	80	82	103	102	116	95	100	113
Neath Port Talbot	53	53	55	76	75	89	71	75	88
Bridgend	59	59	61	82	81	96	76	80	93
Vale of Glamorgan	103	103	105	128	127	142	118	123	135
Rhondda Cynon Taf	33	33	35	57	56	70	51	56	69
Merthyr Tydfil	33	32	34	57	56	70	52	56	70
Caerphilly	58	58	60	83	82	97	76	80	93
Blaenau Gwent	38	38	40	62	61	76	58	62	75
Torfaen	53	52	54	80	79	94	71	75	87
Monmouthshire	88	87	89	116	115	130	105	109	121
Newport	114	113	115	142	141	156	130	135	147
Cardiff	109	108	110	134	133	148	125	130	142
Powys	47	47	49	70	69	84	69	73	87
Ceredigion	39	38	40	60	59	73	57	61	74
Pembrokeshire	69	69	71	94	93	106	83	87	99
Carmarthenshire	51	51	53	75	73	87	68	73	86

10.3 Irrigation demand: potatoes

- The MD predictions were used to estimate irrigation demand for UKCP18 low RCP scenario in 2020 (baseline) and high RCP scenarios in 2050 and 2080. The irrigation requirements assumed medium sandy loam soil with 33 cm of topsoil and 37 cm of subsoil and an available water capacity of 112 mm.
- The predictions assessed abstraction requirements for (i) the whole potato growing area in Wales and (ii) main crop only. In addition, two irrigation regimes were assessed (i) when MD reached 50% crop adjusted available water requirement (for optimum yield) and (ii) maintaining soil at ≤25 mm MD (for scab control).

10.3.1 UKCP18 2020 low RCP scenario (baseline)

- The 2020 abstraction water requirement for optimum main crop potatoes yield was 610,000 m^3 (Table 10). Pembrokeshire (360,000 m^3), Monmouthshire (160,000 m^3) and Anglesey (73,000 m^3) accounted for *c.*75% of the demand for water for main crop potatoes reflecting the high proportion of the potato growing area in these districts.

- The abstraction requirement for all potato crops was *c*.812,000 m^3 (Table 10). Most of the additional water required would be in Pembrokeshire (+101,000 m^3) and Anglesey (+49,000 m^3), reflecting the high proportion of early potatoes grown in these districts.
- The 2020 abstraction water requirement to control scab (i.e. maintaining MD ≤25mm) was estimated at 2.2 million m^3, Table 11.

10.3.2 UKCP18 2050 and 2080 high RCP scenario

- The predicted irrigation water requirement to maintain optimum potato yields under the high RCP scenario for 2050 and 2080 were similar at *c*.2.5 million m^3 - an increase of *c*.1.7 million m^3 compared with the 2020 low RCP scenario (Table 10).
- Of the main potato growing areas Pembrokeshire was predicted to have the highest increase in irrigation water demand (300% increase); followed by Monmouthshire (120% increase) and Anglesey (90% increase).
- Predicted water requirements to minimise the risk of scab were also similar under 2050 and 2080 high RCP scenarios at *c*.4 million m^3 an increase of *c*.1.75 million m^3 compared with the 2020 low RCP scenario, Table 11.

Table 10. Predicted abstraction requirements for irrigation water for three climate scenarios based on UKCP18. Modelled requirements are based on maintaining a sandy loam soil at half crop adjusted available water capacity (AP) assuming a) all potatoes are irrigated and b) only main crop potatoes are irrigated.

Region	Sandy loam: half AP scenario (all potatoes)				Sandy loam: half AP scenario (main crop only)		
	Low 2020	***High 2050***	***High 2080***		***Low 2020***	***High 2050***	***High 2080***
Isle of Anglesey	133,989	239,431	243,802		80,630	144,081	146,712
Gwynedd	0	0	1,848		0	0	1,779
Conwy	0	0	0		0	0	0
Denbighshire	6,295	45,226	52,700		6,281	45,129	52,586
Flintshire	55,898	110,652	115,318		55,334	109,534	114,154
Wrexham	4,729	11,320	11,582		4,570	10,940	11,193
Swansea	27,248	67,626	63,576		18,818	46,704	43,907
Neath Port Talbot	0	8,765	8,589		0	8,765	8,589
Bridgend	22	275	259		22	275	259
Vale of Glamorgan	59,868	109,270	100,804		59,662	108,895	100,458
Rhondda Cynon Taf	0	0	0		0	0	0
Merthyr Tydfil	0	0	0		0	0	0
Caerphilly	487	8,714	7,944		487	8,714	7,944
Blaenau Gwent	0	0	0		0	0	0
Torfaen	0	1,734	1,434		0	1,734	1,434
Monmouthshire	157,496	369,296	325,000		154,732	362,813	319,295
Newport	3,504	6,070	5,506		3,504	6,070	5,506
Cardiff	342	595	558		342	595	558
Powys	0	135,907	150,966		0	134,097	148,956
Ceredigion	0	21,615	23,788		0	16,313	17,952
Pembrokeshire	362,499	1,354,040	1,160,603		226,431	845,787	724,959
Carmarthenshire	0	58,361	55,836		0	55,306	52,914
Total	**812,377**	**2,548,897**	**2,330,112**		**610,813**	**1,905,753**	**1,759,152**

Note: Abstraction calculations account for irrigation losses (i.e. 30% on application and 20% evaporation) so modelled requirements are 1.5 times greater than the water required for irrigation.

Table 11. Predicted abstraction requirements for irrigation water for three climate scenarios based on UKCP18. Modelled requirements are based on maintaining a soil moisture deficit ≤25 mm and assumes that all potatoes requiring water are irrigated.

Region	≤25 mm soil moisture deficit: quality scenario		
	Low 2020	*High 2050*	*High 2080*
Isle of Anglesey	239,177	344,619	348,990
Gwynedd	0	20,664	24,824
Conwy	0	14,739	20,142
Denbighshire	40,681	79,613	87,086
Flintshire	101,641	156,394	161,061
Wrexham	10,097	16,688	16,950
Swansea	61,639	102,017	97,967
Neath Port Talbot	7,412	16,891	16,715
Bridgend	235	487	472
Vale of Glamorgan	98,925	148,328	139,862
Rhondda Cynon Taf	0	0	0
Merthyr Tydfil	0	0	0
Caerphilly	7,015	15,242	14,472
Blaenau Gwent	0	0	0
Torfaen	1,272	3,138	2,838
Monmouthshire	309,882	521,682	477,386
Newport	5,366	7,932	7,368
Cardiff	540	794	756
Powys	109,803	286,496	301,555
Ceredigion	17,609	60,918	63,090
Pembrokeshire	1,187,959	2,179,500	1,986,063
Carmarthenshire	49,328	115,732	113,207
Total	**2,248,584**	**4,091,875**	**3,880,804**

Note: Abstraction calculations account for irrigation losses (i.e. 30% on application and 20% evaporation) so modelled requirements are 1.5 times greater than the water required for irrigation.

10.4 Quantifying the irrigation demand for winter wheat

- El Chami *et al*. (2015) investigated the economics of irrigation of cereals in the East of England; the authors concluded that irrigation was only financially viable under certain limited combinations of soil type, existing irrigation systems, available water and weather. As a result, future investments in new irrigation systems for cereals would require substantial increases in wheat prices or cost reductions (for irrigation equipment) to be justified. However, although the effects of climate change are likely to reduce water availability and potentially make the financial benefits stronger El Chami *et al.* (2015) suggest that the irrigation of other crops is likely to take precedence.
- Under typical UK climate conditions, irrigation is not generally needed on wheat before April, and it is recommended to stop before the beginning of June with the initiation of flowering (Tester and Bacic, 2005). Furthermore, experimental studies in the East of England showed that irrigation on cereals after flowering increased the risk of lodging (Bailey, 1990). El Chami *et al*.

(2015) suggest that a small SMD should be maintained in the root zone to maximise the effective use for rainfall and suggest that irrigation should begin at a 50 mm SMD.

10.5 Moisture deficit: wheat

- The model predicted moisture deficit under wheat for each of the 22 Welsh unitary authorities is detailed in Table 12, below; regions with the lowest MD are shaded green and those with the highest MD are shaded red. For 2020, there is little difference in the MD values for the low, medium and high scenarios. The average MD in 2020 is 78 mm, ranging from *c*.40 mm in Conwy to >100 mm in Anglesey, Flintshire, Vale of Glamorgan, Newport and Cardiff. By 2080, the average MD is predicted to increase by *c*.10 mm to *c*.90 mm for the low and medium RCP scenarios and by 20 mm to c.100 mm for the high RCP scenario For the 2080 low and medium scenarios predicted MD values range from *c*.60 mm in Gwynedd and Conwy to >120 mm in Flintshire, Newport and Cardiff. In comparison, for the 2080 high scenario predicted MD values ranged from *c.*70 mm in Gwynedd and Conwy to >130 mm in Flintshire, Newport and Cardiff.
- The UKCP18 scenarios predict an increase of 19-26 mm in the MD (i.e. it becomes more negative) in all of the main wheat growing areas of Pembrokeshire, Monmouthshire, Powys, the Vale of Glamorgan and Wrexham (Table 12).

Table 12. Moisture deficit (wheat) for the UKCP18 low, medium and high scenarios for 2020, 2050 and 2080.

Region	2020			2050			2080		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Isle of Anglesey	102	102	103	117	116	125	113	116	124
Gwynedd	45	44	46	59	58	67	58	61	70
Conwy	41	41	42	56	55	64	56	59	69
Denbighshire	78	78	79	95	93	103	95	98	107
Flintshire	102	101	103	120	119	129	118	121	130
Wrexham	94	94	95	113	112	122	110	113	121
Swansea	88	88	89	105	105	115	98	101	110
Neath Port Talbot	68	67	69	84	83	94	79	82	91
Bridgend	73	72	74	90	89	99	84	87	96
Vale of Glamorgan	106	106	107	125	124	135	116	119	128
Rhondda Cynon Taf	53	53	54	71	70	80	65	68	77
Merthyr Tydfil	54	53	55	71	70	81	67	70	79
Caerphilly	73	73	74	91	91	101	85	88	97
Blaenau Gwent	59	58	60	76	76	86	72	75	84
Torfaen	70	69	71	90	89	100	81	84	93
Monmouthshire	97	96	98	118	117	128	108	111	119
Newport	115	115	116	136	135	146	126	129	137
Cardiff	110	110	111	129	128	139	121	124	133
Powys	66	66	67	83	82	93	81	84	94
Ceredigion	59	59	60	75	74	84	71	74	83
Pembrokeshire	82	82	83	100	99	109	90	93	102
Carmarthenshire	68	68	69	85	84	94	79	82	91

10.6 Irrigation demand wheat

- The MD predictions were used to estimate irrigation demand for UKCP18 low RCP scenario in 2020 (baseline) and high RCP scenarios in 2050 and 2080. The abstraction requirements were calculated for two soil types (i) clay loam and (ii) medium sandy loam and assumed 30 cm of topsoil and 90 cm of subsoil to give a rooting depth of 120 cm
- For each of the scenarios the abstraction water required was calculated on a regional basis based on maintaining the soil at half of the crop adjusted water capacity.
- The crop adjusted available water capacity was calculated based on soil textural class using the values in Table 14 of the ALC guidelines (MAFF, 1988), Table 13. In the ALC guidance it is assumed that under favourable conditions cereals will root to about 120 cm. However, the root systems of cereals are less well developed below 50 cm and so are less able to extract water beyond that depth. Below 50 cm, it is assumed that only the volume of easily available water (held in the soil between 50 and 200 kPa tension) is extracted.

Table 13. Crop adjusted soil available water capacity (AP) for wheat

Soil	**Depth**	**Total available water (TA_v)[1]**	**Easily Available water (EA_v)[2]**	**Calculation**	**Total AWC**
Clay loam (to 1200 mm depth. Subsoil condition moderate)					
Topsoil	0-300	18%		300 x 18% = 54 mm	156 mm
Subsoil 1	300-500	16%		200 x 16% = 32 mm	
Subsoil 2	500-1200		10%	700 x 10% = 70 mm	
Soil moisture deficit trigger value					78 mm
Medium sandy loam (to 1200 mm depth. Subsoil condition moderate)					
Topsoil	0-300	17%		300 x 17% = 51 mm	158 mm
Subsoil 1	300-500	15%		200 x 15% = 30 mm	
Subsoil 1	500-1200		11%	700 x 11% = 77 mm	
Soil moisture deficit irrigation trigger value					79 mm

[1]TA_v the volumetric soil water content between 0.05 and 15 bar tension (or 0.10 and 15 bar tension for sands and loamy sands). Note: For potatoes the TA_v is used for the full rooting depth of 700 mm.

[2]EAv the volumetric soil water content between 0.05 and 2.0 bar tension.

- The methodology used to calculate the MD for wheat and subsequent irrigation requirements were as described in Section 10.1. However the specific MD for wheat was calculated as follows, where ASR is summer rainfall (precipitation rate for each month was multiplied by the number of days in the month, and the months April-September totalled) and ATS is accumulated summer temperature (AT was calculated for each month as: ((0.4476+ (0.4854*max temp for month)+ (0.4804*min temp for the month))* days in the month), which was summed for the months April-September):
    - **MD wheat:** 325.4-162.3 x Log10 ASR + 0.08022 x ATS
- The amount of irrigation water that was required was calculated as follows:
    - **Irrigation at half AP**: ((MD wheat mm– (0.5 x crop adjusted AP mm))/1000) x (crop area (ha) x 10,000) adjusted for irrigation losses of 50%.

10.6.1 UKCP18 2020 low RCP scenarios

- Predicted irrigation requirement was similar for both soil types, which is unsurprising given the similar AWC calculated in Table 13, above. The requirement for abstraction water for 2020 low RCP scenario was 3.5 million m^3, Table 14. Monmouthshire (1.1 million m^3) and the Vale of Glamorgan (1.1 million m^3) accounted for 61% of the total demand for irrigation. Of the main wheat growing areas, only Powys did not require irrigation in 2020 in this scenario.

Table 14. Predicted abstraction requirements for irrigation water for three climate scenarios based on UKCP18. Modelled requirements are based on maintaining a) a clay loam soil and b) a sandy loam soil at half crop adjusted available water capacity (AP) assuming all wheat that requires water is irrigated.

Region	Clay loam: half AP scenario				Sandy loam: half AP scenario		
	Low 2020	***High 2050***	***High 2080***		***Low 2020***	***High 2050***	***High 2080***
Isle of Anglesey	162,873	315,606	310,630		156,105	308,838	303,862
Gwynedd	0	0	0		0	0	0
Conwy	0	0	0		0	0	0
Denbighshire	0	514,247	588,928		0	494,060	568,741
Flintshire	264,393	566,511	575,709		253,271	555,390	564,588
Wrexham	467,497	1,278,680	1,264,112		438,356	1,249,539	1,234,971
Swansea	6,146	21,798	19,062		5,551	21,203	18,467
Neath Port Talbot	0	5,510	4,764		0	5,156	4,411
Bridgend	0	26,288	22,058		0	25,043	20,813
Vale of Glamorgan	1,107,066	2,218,373	1,945,713		1,067,978	2,179,285	1,906,625
Rhondda Cynon Taf	0	389	0		0	214	0
Merthyr Tydfil	0	0	0		0	0	0
Caerphilly	0	176,779	142,641		0	169,147	135,009
Blaenau Gwent	0	2,658	1,993		0	2,325	1,660
Torfaen	0	0	0		0	0	0
Monmouthshire	1,126,517	3,029,525	2,496,645		1,066,247	2,969,255	2,436,375
Newport	332,341	612,076	530,485		323,384	603,118	521,528
Cardiff	9,572	18,069	16,214		9,276	17,773	15,918
Powys	0	864,650	918,077		0	805,584	859,012
Ceredigion	0	44,438	42,317		0	36,584	34,462
Pembrokeshire	249,898	1,944,859	1,472,487		187,560	1,882,521	1,410,149
Carmarthenshire	0	38,428	31,724		0	35,990	29,285
Total	**3,726,304**	**11,678,885**	**10,383,560**		**3,507,729**	**11,361,024**	**10,065,875**

Note: Abstraction calculations account for irrigation losses (i.e. 30% on application and 20% evaporation) so modelled requirements are 1.5 times greater than the water required for irrigation.

10.6.2 UKCP18 2050 and 2080 high RCP scenarios

- The requirement for abstraction water for 2050 and 2080 high RCP scenarios was 10-11 million m^3, a 3-fold increase compared to the baseline requirement. Monmouthshire, the Vale of the Glamorgan, Pembrokeshire and Wrexham accounted for 70% of the water requirement. The greatest increases in water requirement (between 2020 and 2080) was predicted for Monmouthshire (+1.4 million m^3) and Pembrokeshire (+1.2 million m^3).

10.7 Irrigation conclusions

- Knox *et al*. (2013) calculated a volumetric irrigation water demand for England and Wales for a 'design' dry year of 85 million m^3 based on the 2010 pattern of land use; this included an irrigation demand for Wales of 3.5 million m^3, of which over 90% was for potatoes. Note, however, that this demand was calculated for the Environment Agency region defined as Wales, rather than the whole country so the actual irrigation demand is likely to be higher. For Wales, our calculations suggest an abstraction demand for 2020 (i.e. the period 2010-2039) of up to 2.2 million m^3 for potatoes and 3.7 million m^3 for wheat (based on irrigation at 25 and 50 mm SMD, respectively). For comparison, the Environment Agency (2020) noted that the direct consumptive abstraction for agricultural water use in 'Water Resources East'[7] (includes East Anglia and the East Midlands) totalled 74 million m^3 per year, of which 94% (69.6 million m^3) was for spray irrigation. Total agricultural water use in other regions was between 12 and 21 million m^3 per year (split between spray irrigation, aquaculture, horticulture, general (livestock) and other (forestry, orchards etc). In comparison, in the West Country Water Resources area (the Southwest area of England), consumptive water use is dominated by livestock water demand. The report also notes that a significant component of livestock water demand is met from mains supplies and therefore excluded from the totals.
- The Environment Agency predict that the demand for spray irrigation will increase in the future, particularly in Water Resources East. Nationally the demand could range from the baseline of around 100 million m^3 to almost 200 million m^3 (with a best estimate of 140 million m^3) in 2050. However, it is noted that there is significant uncertainty around these figures as demand will be affected by several factors including irrigation efficiency, food quality standards, diet trends etc. In comparison, by 2080 (i.e. the period 2070-2099) abstraction demand in Wales for irrigation is predicted to increase to 14.3 million m^3 of which c.70% (10.4 million m^3) would be applied to wheat.

[7] One of the five regional water resources planning groups (i.e. North, West, East, South East and West Country) set up by the Environment Agency to produce regional plans for water use by September 2023.

11 Cattle water demand

- To estimate cattle water demand agricultural census data was coupled with estimates of livestock drinking water demand (by age category) based on literature data.
- The number of cattle and calves in Wales was taken from the most recent edition of the Welsh Agricultural Statistics 2016 (Welsh Government, 2018), which splits cattle into three broad groupings, aged two or more years, aged 1-2 years and under 1 year (Table 15). The broad groupings are further sub-divided into females: dairy breeds, females: non-dairy breeds and males. In total, for 2016 there was 1.1 million cattle in Wales of which around 40% were dairy cattle. Of the dairy cattle aged two or more it was assumed that 85% were 'in milk', i.e. 253,351 cattle.

Table 15. Number of cattle (by age group) in Wales in 2016 (Source: Welsh Government, 2018)

Cattle	Total	Dairy females
Cattle ≥2 years	544,525	298,060
Cattle 1-2 years	262,929	88,787
Cattle <1 year	326,887	77,830
Total	1,134,341	464,677

- Literature data on drinking water consumption from DAERA[8], AHDB[9], Defra[10] and ADAS (2012) was combined to estimate the daily water consumption for cattle of different age groups or management. For cattle ≥2 years, daily water consumption for dairy cattle (81 l/day) is almost twice that of non-dairy cattle (37 l/day) of the same age. The calculated figures are in line with those reported by Knox *et al*. (2013) who noted a water consumption of 91 l/day for dairy cattle, 20 l/day for beef cows and heifers and 12.5 l/day for calves.
- Daily drinking water demand was multiplied by 365 to calculate the annual water demand for each group of cattle (Table 16). Overall, the annual drinking water demand for cattle was calculated as 15,592,167,510 l (or 15.6 million m^3). In addition, to the demand for drinking water, Knox *et al*. (2013) reported a daily demand of 29 l for 'wash water' for dairy cattle, this equates to an additional annual demand for water of 2,681,720,135 l.
- Adding together the demand for drinking water and wash water gives a total annual water demand for cattle in Wales of 18,273,887,845 litres or 18.3 million m^3. Similarly, Knox *et al*. (2013) calculated the annual water demand for cattle for the EA Wales region to be 16.7 million m^3. Note also that Knox *et al.* (2013), calculated a total water demand for livestock for the EA Wales region of 30.6 million m^3. For comparison, based on a population of 3.15 million[11] and a daily consumption of 150 litres of water for washing, drinking, cooking etc. (Welsh Government, 2015) human water consumption in Wales is estimated at 173 million m^3.

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[8] https://www.daera-ni.gov.uk/articles/water-advice-livestock-farmers

[9] https://media.ahdb.org.uk/media/Default/Imported%20Publication%20Docs/Water-use-reduction-and-rainwater-harversting-on-beef-and-sheep-farms.pdf

[10] http://adlib.everysite.co.uk/adlib/defra/content.aspx?doc=246307&id=246337

[11] https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/bulletins/annualmidyearpopulationestimates/mid2019estimates

Table 16. Cattle daily and annual drinking water consumption (litres)

Cattle type	Total (number)	Litres per day	Annual total (litres)
Dairy cows in milk	253,351	81	7,513,440,594
Cattle ≥2 years	291,174	37	3,889,793,466
Cattle 1-2 years	262,929	25	2,399,227,125
Cattle <1 year	326,887	15	1,789,706,325
Total (drinking)	***1,134,341***		***15,592,167,510***
Wash water	253,351	***29***	***2,681,720,335***
Total (cattle)			**18,273,887,845**

- It is outside of the remit of this project to estimate future water demand for livestock, which will depend on several factors including livestock numbers, temperature related changes in livestock drinking water demand etc. Knox *et al*. (2013) suggest increases of 5-10% for cattle based purely on relationships between temperature and drinking water demand. However, they acknowledge that this is likely to be an underestimate due to the many other indirect impacts of climate change.

11.1 Conclusions

- The current demand for water by cattle in Wales is *c*.18.3 million m^3 (taking other livestock into account this increases to around 30 million m^3). In comparison, the calculated irrigation water demand for 2020 for potatoes is <1 to 2.3 million m^3 (i.e. <15% of the cattle water demand based on the higher figure) and 3.5-3.7 million m^3 for wheat (i.e. 20% of the cattle water demand). Although the future demand for irrigation water will grow, even the highest predicted demand of *c*.12 million m^3 for wheat is less than the water currently consumed by cattle.

12 Impacts and compliance

12.1 Abstraction

- Water can be abstracted from rivers, streams, ponds, wells, boreholes and drains. The cost of abstraction water is cheaper in the winter period (November to March) than the summer period (April to October).

12.1.1 Applications

- Natural Resources Wales (NRW) is responsible for managing water resources in Wales to ensure abstractions do not damage the environment and to protect existing water supplies. Under the Water Resources Act 1991 most surface and groundwater abstractions over 20 m^3 per day will require a licence. Discussions with NRW should be held early in the reservoirs design phase to ensure water is available for abstraction in the proposed area, if not other water sources/locations will have to be assessed as an alternative.
- Applications require information on the location of the proposal, where the water will come from and whether the water can be accessed legally. The most common licence used for on farm reservoirs and irrigation is a full abstraction licence which allows abstraction of water over a period of 28 days or more, these are usually targeted at winter abstraction times to take advantage of a lower water demand elsewhere as well as higher flows.
- Temporary abstraction licences may be used if water needs to be abstracted over a period of less than 28 days. Other permits that may be required in designated areas or certain situations could include: Fish pass installation or a flood risk activity permit as well as the potential for a protected species licence or an environmental permit for discharge to surface or groundwater, which are all dependent on individual situations.

12.1.2 Reforms

- Current summer abstraction depletes water resources from the environment and other users. The UKCP prediction of 56% less summer rainfall in the high RCP scenario renders the current levels of summer abstraction unsustainable. To address water competition between habitats, households, industrial, main rivers, recreation; on different soil types; agricultural practices; and, crop varieties the UK Government has formulated the Water Abstraction Plan.
- Reform of abstraction will amend abstraction licences to protect the environment and will prioritise changes to licences having the greatest impact. The aim of the reform is to ensure around 90% of surface water bodies and 77% of groundwater bodies meet the required standards by 2021. The reforms will affect the way agriculture can use water and include:
    - A review of time limited licences by 2021 adjusting them as necessary to make sure they do not allow environmental damage now or in the future
    - Adjust all permanent licences shown to be seriously damaging.
    - Revoke an estimated 600 unused licences that are no longer needed, and work with abstractors to reduce under-used licences. This will prevent increased abstraction.
- As part of the reforms it is proposed that water abstraction and impoundment licensing is moved into the Environmental Permitting Regulations (EPR) regime. This gives regulators the opportunity to update legislation to ensure it is fit for the future and supports a more flexible approach to licensing that allows improved access to water while protecting the environment.

12.2 On farm storage

- At present most irrigation water is abstracted from surface water (52%) and ground water (41%) sources with the remainder from public water supply, ponds, and harvested rainwater (7%). Abstraction is seasonal, with 68% typically occurring between June and August. A third (32%) is abstracted during the winter months and when river flows are high and stored in farm reservoirs ready for use in the summer (Knox *et al*., 2020).
- Reservoirs can greatly improve business water supply resilience throughout the irrigation season. Taking water daily and storing it requires little energy and can accommodate a low source flow (AHDB, 2019). Larger reservoirs also offer the capacity to store water abstracted or harvested through the winter at peak flow or rainfall periods. If suitable available land restricts the potential for a reservoir, then the short-term water supply resilience of a business can be improved via the installation and use of water storage tanks. Water storage tanks should be sized to allow for enough water to be available for a minimum of 48 hours during peak irrigation demand in the event of a mains failure (AHDB, 2019).
- Predictions of climate change suggest that winters are expected to become slightly wetter and summers drier meaning that the requirement for irrigation is likely to increase. As a result, reservoir capacity should allow headroom to deal with potentially more extreme drought in the future.

12.3 Social and economic benefits of water abstraction

12.3.1 Resilience and services

- Agricultural land can provide a reservoir for the reduction of flood risk and is integral to flood management. The provision of water abstraction and storage from high intensity rainfall events is a potential benefit. The availability of water storage capacity may provide a means to mitigate the damaging effects of flood water from Welsh rivers.

12.4 Planning permissions

- The necessary planning requirements will be dependent upon the size, location and farm specific situation. Information concerning planning issues can be obtained from the local authority planning offices.

12.4.1 Planning permission

- **Permitted development order 1995**. Construction of some farm reservoirs may be permitted under the Town and Country Planning (General Permitted Development) Order 1995/2015. It is more likely that this will apply for smaller sized reservoirs (<25,000 m^3). Application will still be needed to the local planning authority to confirm the permitted development rights are acceptable. If the construction does not meet the requirements, then full planning will be required.
- **Full permission.** If full planning permission is required, applications for farm reservoirs are also generally viewed positively by planners, due to the sustainability benefits offered by the development. A full application requires full plans; the reservoir design, site map, land owned/controlled by the applicant, plans showing the layout of nearby buildings, access points to the site, trees, roads and anything else relevant to the application to be supplied. Guidance on the information required will be set out by the local planning authority. Assessments that may be needed could include details of any special landscape or natural value of the site as well as any environmental impact assessment deemed necessary.

- Local archaeological interests will be determined by local authority and assessments will be required dependent on location. If investigations are required, they may consist of either examination during excavations or more detailed studies which may include trench excavations prior to construction which can be lengthy and expensive.
- The environmental impact of the construction and use of the reservoir will be judged and mitigation measures should be included where possible. Local authorities may ask for environmental impact assessments to be carried out to help quantify the environmental impact.
- Consideration should also be given to the impact of the construction on the surrounding area. Consideration of the impact of the construction/use of the reservoir on the surrounding community is essential. Factors to be consider should include, whether public rights of way are to be affected, how construction traffic will affect and integrate with local communities and infrastructure, if the development of the reservoir will affect any other water abstractions. Where notable impacts are likely on the local area then mitigation measures should be put into place where possible. Previous community impact mitigation measures have included the use of the reservoirs for bird watching or fishing.

12.5 Key legislation

12.5.1 Registration of the reservoir

- Reservoirs with a capacity of more than 10,000 m^3 (above the natural level of the ground) will require formal registration with the NRW.

12.5.2 The Reservoirs Act 1975

- The Reservoirs Act 1975 is enforced by NRW and is aimed at maintaining the safety of constructions that hold water above the natural ground level. Reservoirs that hold 25,000 cubic meters or more are included, and the design and construction must be supervised by an independent panel engineer. Once completed it must also be regularly inspected by a panel engineer and records must be kept about the reservoir's use (water intake/outtake amounts and dates etc.).

12.5.3 The Flood and Water Management Act 2010

- The Flood And Water Management Act 2010 amends the Reservoir Act 1975 regarding management of flood risk from reservoirs that are deemed "High Risk" based on factors other than reservoir size, such as location and if a breech occurred the impact that could have on human life. The NRW are the classifiers and reservoirs noted as high risk are required to employ civil engineers to supervise and inspect the reservoirs.

12.5.4 The Land Drainage Act 1991 (amended in 1994)

- The Land Drainage Act 1991 is the legislation involved in ensuring free flow of water is not impeded.

13 Reservoir projects good practice

- Reservoirs require correct planning, construction and maintenance in order to function efficiently and continue to do so for as many years as possible.

13.1 Project plan

- A reservoir needs to be planned and constructed using the correct, qualified professionals as well as adhering to legislation governing reservoir construction and use. Use of a panel or reservoir engineer that is correctly certified is advised.

13.1.1 Location

- Reservoir site location is critical to the successful construction use and maintenance of the reservoir. Best suited locations are a flat site with good access with a low land productivity and/or value, with a suitable soil type (i.e. slowly permeable) allowing for efficient use and lower construction costs. Sloping sites with a large gradient will increase the size of the embankment required to contain the outgoing water pressure, resulting in a larger reservoir, which will increase cost. Generally, cost effective reservoirs have a slope of less than 5°. Slopes greater than 1:25 will require a structural engineer to be consulted. There are also benefits of siting reservoirs at higher sites to allow either gravity feed or reduced pumping of water.
- Practical placement close to the irrigated areas and initial water source are advised and if pumping is required proximity to a power source (electricity) can lower construction, running and maintenance costs as well as increase efficiency.
- When choosing the site great effort should be made to site it with minimal disturbance to the surrounding landscape. Sites should not be placed on or close to environmentally sensitive areas or SSSIs as well as avoiding historic zones or archaeological features.
- Reservoirs should not be sited on land known for lying wet/heavily saturated or springs (frequently running or not). 'Wet' areas increase permeability of clay lined reservoirs as well as significantly increase the risk of bank slippage from either increasing the saturation of the bank soil or undermining the structural strength of the bank.
- Flood plains should not be considered for construction as a reservoir will lower the flood plains capacity to hold flood water (possibly increasing flooding elsewhere). There is also potential for flood water to destabilise the reservoir banks.
- Sites close to infrastructure or services, e.g. roads, houses, electric or gas lines above and below ground need also be avoided. Locations should be away from routes of public access or close to dwellings due to safety concerns from people/children in proximity. Vandalism or damage can also be a risk regarding the reservoirs liner if people can easily access the site.

13.2 Standard best practice

13.2.1 Design

- The type and design of reservoir will be influenced by many factors, for example the amount of water it is required to store, financial capacity, available water, site locations (geology, topography etc.) and planning regulations.
- For large volume storage of winter abstracted water for field crop irrigation the first option is an earth banked reservoir, although constructed reservoirs and tanks all have a place in the catchment and utilisation of rainfall. The most common ways to store volumes of water on farm include bunded reservoirs (lined and unlined), below ground storage or above ground storage tanks constructed from masonry or steel.

13.2.2 Open reservoirs

- Open reservoirs can hold water solely below the level of the surrounding ground or can be built with embankments that can retain water above the surrounding ground. Holding water below the surrounding ground levels enables gravity filling. Reservoirs that store water completely below the ground level are called pits. However, these are uncommon as the excavated soil from the pit will have to be removed from the site incurring higher cost. In addition, deeper digging is required to achieve the same storage capacity as a part below/part above ground reservoir.

- The most common and cheapest construction design is where the reservoir is excavated and the soil that is excavated is used to form the embankment that provides capacity above the surrounding land. There is no need then for movement of the earth from the site. Impacts on the surrounding landscape designs can be minimised by ensuring that a suitable location and appropriate mitigation measures are used. These reservoirs usually take up the largest area of land.

13.2.3 Above/below ground tanks

- Above or below ground storage tanks are more suited to rainwater harvesting than abstracted water storage due to their high cost and lower capacity than a conventional reservoir. Although it is highly unlikely rainwater harvesting will supply as much water as full reservoir abstraction, it is still a useful option to reduce abstraction requirements and utilise water that would otherwise be lost, therefore increasing farm water efficiency.
- The rainwater can be collected off farm building (planning permissions may be required if large alterations to buildings are made) and piped to a storage area to be used at a time of high demand. Collected water may be stored in a separate rain harvested tank or if practical may be piped directly to the main irrigation reservoir. Water may also be collected and used for other on farm tasks such as machinery wash down or crop processing if not required for irrigation purposes.
- Above ground tanks are usually constructed either out of concrete or steel. They offer good long-term storage potential. They may require pumping to fill but can offer gravitational feed in the correct location. They generally have a lower surface area than other open storage reservoirs, giving a low evapotranspiration rate and can be covered where necessary. Compared with other storage types they do not erode or suffer pest damage etc. but are of high risk of impact damage from machinery in certain locations (e.g. farmyard) as well as taking space on the yard. These tank systems often high cost for the storage capacity they provide and can be complex in design as well as being difficult to expand if needed. They can also negatively impact on the landscape.
- Below ground tanks are like above ground tanks but they are less vulnerable to impact damage, take up less space and are more aesthetically pleasing to the surrounding landscape. However, they are more costly than above ground storage and are less accessible for repair/maintenance.
- Both above and below ground tanked storage do not offer the volume of water storage required for field irrigation, they are often too costly for water storage compared to an open reservoir and are not currently commonly seen.

13.3 Site Selection and Construction

13.3.1 Soil type

- Permeability of the structure is determined by soil type. For successful water storage a soil will have to be sufficiently impermeable to stop water escaping from it. Soils with a no less than 20% clay content are suitable otherwise a liner will be required. Soils with more than 30% clay should not be used as they are difficult to form and can be prone to slumping. Stoney soils are also not suitable and those with more than 30% stones larger than 20 mm are not suitable, due to the imperfections that will be caused in the construction.

- Trial pits should be dug by a qualified engineer prior to any work starting. These will determine the soil type, suitability for use and any underlying limitations in the geology/soil that may arise from construction (e.g. springs, stony and permeable layers etc.). They should be dug in accordance to BS 5930: 2015; the code of practice for site investigations. Pits should be dug at equal spacing around the edge of the proposed area and one dug in the centre of the reservoir.

13.3.2 Embankment

- Reservoir embankments should be designed by qualified and experienced contractors, adhering to the requirements in BS EN 1997-1:2004. The structure must both resist the hydrostatic forces exerted by the water and be sufficiently impermeable to the contained water. Embankments constructed need to withstand the load put on them, ensuring suitable width and slopes with no slumping, calculated from BS 5502, part 50 using a qualified engineer.
- The embankments should be built with a slight dome on top to ensure rainwater runs off and does not puddle, as this can infiltrate the bank and cause bank failure (Figure 23). If machinery is to be used on top the bank then the widths will have to be suitably adjusted, any damage caused needs to be reinstated as soon as possible. Where machines are used regularly such as for pumping or filling activities then a concrete pad should be built to stop bank damage and erosion. During the construction of the embankments at least 10% increase in height should be allocated to allow for soil settlement following construction.
- If a reservoir is constructed entirely below the original ground level, then a steeper bank angle can be used as the soil has not been disturbed. But the above regulations still apply.

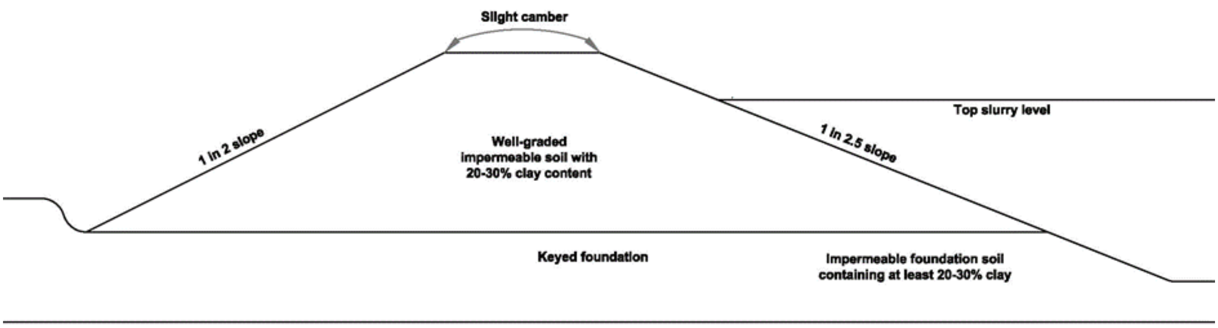

Figure 23. Typical embankment construction on impermeable soil

13.3.3 Shape

- The reservoir shape will be dependent on planning permissions, site/landscape and reservoir budget. It is largely understood that rectangular reservoirs are cheapest to construct, however a circular shape gives a better ratio of water stored/bank area. The aim should be to incorporate the shape of the reservoir into the surrounding landscape to lessen its environmental impact. Where possible irregular shapes following the landscape should be used to naturalise the design.

13.3.4 Lined/unlined

- A reservoir would have to be lined if the soil used does not confirm to specific permeability specifications as stated above. If clay can be accessed and is suitable for construction, then the reservoir can be lined with a layer of clay around 3-4 metres thick.
- If clay is not available or suitable then a manufactured liner should be used, such as butyl or polypropylene. Guidance should be used from liner manufactures to allow for best choice in the specific situation and information on the installation requirements and lifespans, which can be guaranteed for up to 20 years.
- Leak detection systems may be of relevance in some lined reservoirs. Construction of a perforated pipe system installed underneath the liner, draining to a central point should catch water leaking through the liner. Draining to a single point allows for inspection (interpretation of this should allow for some natural land drainage water).
- On sites where soil may emit high levels of gas it will be necessary to install vents below the liner to allow for gas removal. It is possible if this is not completed then gas may form a pocket under the liner lifting it and creating a bubble in the reservoir.

13.3.5 Health and safety

- Health and Safety is the responsibility of the reservoir owner. Danger signs marking deep water should be present (Health and Safety – Safety Signs and Signals- Regulations 1996). The area should be fenced to limit exposure to people and livestock ensuring fences offer no accessible hand or foothold with suitable deterrents to prevent access. It is also necessary to provide a means of escape for people to exit the reservoir should they fall in. It is recommended escape routes are permanently fixed around the embankment at a minimum interval of 15 m.
- Implementing and following correct health and safety procedures from the construction phase through to the general use and maintenance of the reservoir is essential. The construction phase should follow The Construction Design and Management (CDM) Regulations 2015, which is sub sectioned and guidance given by the Health and Safety Executive.
- Guidance from the NRW and qualified reservoir engineers should be followed throughout all the planning and construction phases to ensure successful, safe and compliant installation.

13.4 Management/maintenance

- Once the reservoir is in use it will require regular maintenance and inspection. There should be regular routine, inspections and after heavy rainfall and at times of maximum and minimum water levels.
- A freeboard (from the water level to the top of the embankment) of at least 750 mm should be always maintained to ensure the water level does not exceed the reservoir design capacity and overflow and avoid bank erosion and potential failure.
- Preventing trees growing on reservoir banks is important as roots can substantially reduce bund strength.
- Animals should also be managed to reduce the risk of damage to the liner or the bunds. Moles, rats, foxes, badgers and rabbits can burrow into the banks, whilst cattle drinking/travelling over banks can cause significant damage.
- Good agricultural management of land around the reservoir/water source should be adopted. Avoidance of over application of nutrients to land and heavy stocking as well as ensuring correct pesticide buffer strips and timings (reduce drift etc.) to ensure no water is contaminated,

possibly resulting in algal blooms or excessive weed growth around the reservoir as well as pollution from chemicals, sediment etc.

- Regular monitoring of the reservoir for leaks and damage should be undertaken when full. Looking for wet areas on banks, perceived springs or surface water in the field area around the reservoir and studying the internal and external banks for signs of weakness/damage is essential. Focus closely at the original ground level (bottom of embankment), where pipework enters/exits the reservoir and areas under greatest pressure. If present, monitoring of leak detection systems will aid examination of lined reservoirs.

13.5 Landscaping and wildlife enrichment

- Reservoirs should be designed to mitigate any wildlife disturbance caused by construction and to enrich the environment for wildlife. Many of these environmental measures can also increase the reservoir lifespan and water storage efficiency.
- Planting of trees and shrubs around the reservoir is encouraged to reduce windspeeds and reduce the risk of waves eroding the bank. Trees provide weather protection to the reservoir banks and can shade stored water lowering evapotranspiration potential. Trees can also offer good naturalisation of the landscape around the reservoir reducing its aesthetic impact.
- Embankments should be covered with grasses and or wildflower mixes to stabilise the soil surface and minimise erosion risks. Wildflower mixes encourage biodiversity and vegetative cover should be managed to limit growth of aggressive weeds.
- The design should allow access and exit for animals and humans at times of reduced water levels by the inclusion of shallow slopes for reservoir edges. Where this is not possible ramps or steps may be a way of granting easy access. Shallow slopes also allow for easier vegetation coverage to develop.

13.6 Water quality and use

- The quality of the water stored in the reservoir should be considered dependent on the crop type it will be used on and the risks associated with this. High salinity levels in water will impact potato growing potential, therefore areas at risk of this will require monitoring. Sediment quantities, nutrient concentrations and chemical levels in the reservoir may also require examination, dependent on location and final crop use of the water. Pathogen loading in water may need to be considered in certain situations, such as fresh produce crops or some water sources that may be contaminated before entering the reservoir.
- Where circumstances dictate a filtration system may have to be installed within the irrigation chain to remove the desired impurities. These can be installed either prior to the reservoir or once the water has left the reservoir dependent on situation and aim.

13.7 Further guidance and more information

- UK Irrigation Association
- BS 8002:2015 – Code of practice for earth retaining structures
- BS 5930: 2015 – The code of practice for site investigations
- National Resources Wales (NRW)
- Farm reservoir design guide – Suffolk Coast and heaths
- The British Dam Society

- CIRIA C759b Chapter 7 Lagoon embankments
- Thinking about an irrigation reservoir? – A guide to planning, designing, constructing and commissioning a water storage reservoir. Cranfield University.
- Farm Reservoir Design Guide. 2010. A guide to good planning and design of farm reservoirs in the Suffolk coast and heaths area of outstanding natural beauty. Suffolk Coast and Heaths AONB unit.
- On-farm reservoir storage. ADAS UK Ltd and Cranfield University.

14 Summary

14.1 Future changes in the Welsh climate

- UKCP18 regional climate projections are based on four 'Representative Concentration Pathways' (RCPs), i.e. RCP2.6, RCP4.5, RCP6 and RCP8.5, representing the range of increases in radiative forcing (relative to pre-industrial conditions) to 2100 found in literature. Each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The UKCP18 climate change predictions represent 30-year averages: the 2020 model represents the time period 2010-2039; the 2050 model represents 2040-2069; and the 2080 model represents the period 2070-2099. In this report, changes in the demand for water abstraction for irrigation relating to three scenarios have been explored; low refers to RCP4.5 (GHG emissions peak in 2040 then decline), medium to RCP6 (GHG emissions peak around 2080 then decline) and high to RCP8.5 (GHG emission continue to increase).
- UKCP18 projections of how climate might change in the Wales over coming decades do not predict a change in total annual rainfall but suggest changes in seasonal distribution; there is an increase in rainfall in the winter and less rainfall in the summer months from 2020 to 2080 for all RCP scenarios. In comparison, for summer rainfall in Wales there is a noticeable reduction in rain between the 2020 to 2080 time periods but little difference between low, medium and high RCP scenarios. The reductions in summer rainfall are most marked in the south and east of Wales, for example in the medium scenario, ASR in Torfaen decreased by 77 mm from 527 mm in 2020 to 450 mm in 2050 and in Rhondda Cynon Taff by 85 mm from 687 mm in 2020 to 602 mm in 2050.
- Changes in temperature and rainfall pattern are likely to impact on crop yields and quality and may affect the viability of existing rain-fed crops. Water stress resulting from a lack of rainfall is currently less of a risk in Wales than in other drier regions of the UK. However, climate predictions suggest that the risk of water stress is likely to increase in the future and where summer droughtiness is a risk, irrigation could be used to maintain yields, both on existing irrigated crops (e.g. potatoes and field vegetables) and on other currently rain-fed crops such as wheat.

14.2 Future changes in soil moisture deficit

- Soil moisture deficit represents the balance between rainfall and potential evapotranspiration. Based on the method described in the ALC, crop specific soil moisture deficit (MD) values can be calculated for potatoes and wheat (to represent a range of shallow and deeper-rooted crops). The ALC method was used to calculate MD for both crops in 2020, 2050 and 2080 for the low, medium and high RCP scenarios.
- For potatoes, there was little difference in the predicted SMD for the low, medium and high scenarios for 2020 or 2050. The average MD (potatoes) across the whole of Wales in 2020 was c.65 mm, ranging from <20 mm in Conwy to >100 mm in the Vale of Glamorgan, Newport and Cardiff. By 2050, the MD (potatoes) was also predicted to be >100 mm in Anglesey, Flintshire, Wrexham, Swansea and Monmouthshire. By 2080, the average MD (potatoes) was predicted to increase to *c*.85 mm for the low/medium RCP scenarios (range: <40 mm in Gwynedd and Conwy to >120 mm in Flintshire, the Vale of Glamorgan, Newport and Cardiff) and to *c*.100 mm for the high RCP scenario (ranging from <60 mm in Gwynedd and Conwy to >140 mm in Newport and Cardiff). Of note are the predicted MD increases of 30-40 mm in all the main potato growing areas (Anglesey, Pembrokeshire, Monmouthshire and Powys) over time, indicating an increasing need for irrigation.

- For wheat, 2020, predicted MD (wheat) values for the low, medium and high scenarios were similar. The average predicted MD (wheat) in 2020 was 78 mm, ranging from *c*.40 mm in Conwy to >100 mm in Anglesey, Flintshire, Vale of Glamorgan, Newport and Cardiff. By 2080, the average predicted MD (wheat) increased by *c.*10 mm to *c*.90 mm (range: *c*.60 mm in Gwynedd and Conwy to >120 mm in Flintshire, Newport and Cardiff) for the low and medium RCP scenarios and by 20 mm to *c.*100 mm (range: *c.*70 mm in Gwynedd and Conwy to >130 mm in Flintshire, Newport and Cardiff) for the high RCP scenario. Notably, the UKCP18 scenarios predict an increase of 19-26 mm in the MD in all the main wheat growing areas (Pembrokeshire, Monmouthshire, Powys, the Vale of Glamorgan and Wrexham) over time.

14.3 Irrigation

- Irrigation regulates the quantity and seasonal availability of rainfall to ensure water supply matches agricultural needs. It can be used to 'correct' any moisture deficit and enhance the potential of agricultural land especially in drier areas. The demand for irrigation varies significantly from year to year depending on soil water content which is mainly controlled by rainfall, temperature, soil texture and structure. The amount of summer rainfall is particularly important in controlling irrigation needs. For Wales, Knox *et al.* (2013) calculated a volumetric irrigation demand for a 'design' dry year (the statistically defined 'design' dry year is equivalent to the 5^{th} driest year in 20) of 3.5 million m^3, of which over 90% was for potatoes. Wheat is not typically irrigated in Wales under the current climatic conditions.
- Over the last 25 years there has been a marked increase in the irrigation of high value crops, particularly potatoes and field vegetables, driven by the supermarket demands for quality, consistency and continuity of supply (Knox *et al.,* 2013). However, future government policy may implement major legislative reforms to the abstraction licensing regime to reduce levels of over-abstraction and restore environmental flows. This will introduce additional costs associated with licensing and may make it more difficult to obtain permission to irrigate land. At present, water accounts for only 5-7% of total irrigation costs and demand for water is currently not responsive to price (Morris *et al*. 2004).
- Irrigation is a consumptive use (i.e. the water is not returned to the environment in the short term) and is concentrated in the driest areas in the driest years and driest months when resources are most constrained (Knox *et al*., 2010). Consequently, irrigation can be the largest abstractor in some catchments in dry summers (Watts *et al*., 2015). This creates conflict with other water demands, most notably those for public water supply and environmental protection.
- Where irrigation is currently practised in the UK, summer abstraction is increasingly unreliable for many existing abstraction licence holders, and new summer licences are unobtainable in many catchments (Weatherhead *et al*., 2014). However, abstraction during the winter and/or at high flows into reservoirs is usually possible and can provide a more reliable resource.
- Climate predictions suggest that the risk of water stress is likely to increase in the future and where summer droughtiness is a risk, irrigation could be used to maintain yields, both on existing irrigated crops (e.g. potatoes and field vegetables) and on other currently rain-fed crops such as wheat.

14.4 Irrigation scenarios

- In 2017, there were around 3,350 ha of potatoes grown in Wales, of which 75% were main crop potatoes with the remainder early varieties which are usually harvested by 31 July. Around half of the potato crop is grown in Pembrokeshire; other areas that grow more than 200 ha of potatoes are Anglesey, Monmouthshire and Powys. Most potatoes grown in Wales are rainfed and do not receive irrigation water. In the same year wheat production in Wales covered around 21,500 ha of which 19% was in Pembrokeshire, 19% in Monmouthshire, 18% in Powys, 12% in the Vale of Glamorgan and 20% in North East Wales. It is unlikely that irrigation water is currently used on any of the Welsh wheat crop.
- The predicted water abstraction volumes to irrigate potatoes and wheat in 2020, 2050 and 2080 for Wales were calculated, assuming that the cropped areas remained at current levels, i.e. there was no change in the geographic spread, area (hectares) and crop type (earlies and main crop potatoes) over the period.

14.4.1 Abstraction water for potatoes

- The amount of water that would be required to be abstracted was calculated for three time periods/RCP scenarios, i.e. 2020 (low), 2050 (high) and 2080 (high). Modelled abstraction requirements were based on maintaining a sandy loam soil at 1) half crop adjusted available water capacity (a typical trigger point for irrigation scheduling) and 2) maintaining a soil moisture deficit of ≤25 mm. For the first scenario, abstraction requirement was calculated assuming a) all potatoes received irrigation water and b) only main crop potatoes were irrigated. For the second scenario, it was assumed that all potatoes were irrigated. In line with literature values, abstraction calculations accounted for irrigation losses (i.e. 30% on application and 20% evaporation) so modelled requirements are 1.5 times greater than the water required for irrigation.
- The 2020 abstraction water requirement for optimum main crop potatoes yield was 610,000 m^3. Pembrokeshire (360,000 m^3), Monmouthshire (160,000 m^3) and Anglesey (73,000 m^3) accounted for *c*.75% of the demand for main crop potato irrigation reflecting the high proportion of the potato growing area in these districts.
- In comparison, the 2020 abstraction requirement for all potato crops was c.812,000 m^3. Most of the additional water required would be in Pembrokeshire (+101,000 m^3) and Anglesey (+49,000 m^3), reflecting the high proportion of early potatoes grown in these districts.
- The 2020 abstraction water requirement to control scab (i.e. maintaining SMD ≤25 mm) was estimated at 2.2 million m^3.
- The predicted abstraction water requirements to maintain optimum potato yields under the high RCP scenario for 2050 and 2080 were similar at *c*.2.5 million m^3 - an increase of *c.*1.7 million m^3 compared with the 2020 low RCP scenario. Of the main potato growing areas Pembrokeshire was predicted to have the highest increase in irrigation water demand (300% increase); followed by Monmouthshire (120% increase) and Anglesey (90% increase).
- Predicted water requirements to minimise the risk of scab were also similar under 2050 and 2080 high RCP scenarios at *c*.4 million m^3 an increase of *c*.1.75 million m^3 compared with the 2020 low RCP scenario.

14.4.2 Abstraction water for wheat

- The amount of water that would be required to be abstracted was calculated for three time periods/RCP scenarios, i.e. 2020 (low), 2050 (high) and 2080 (high). Modelled abstraction requirements were based on maintaining 1) a sandy loam soil and 2) a clay loam soil at half crop adjusted available water capacity.

- The requirement for abstraction water for 2020 low RCP scenario was *c*.3.5 million m^3 for both soil types. Monmouthshire (1.1 million m^3) and the Vale of Glamorgan (1.1 million m^3) accounted for 61% of the total demand for irrigation. Of the main wheat growing areas, only Powys did not require irrigation in 2020 in this scenario.
- The requirement for abstraction water for 2050 and 2080 high RCP scenarios was 10-11 million m^3, a 3-fold increase compared to the 2020 requirement. Monmouthshire, the Vale of the Glamorgan, Pembrokeshire and Wrexham accounted for 70% of the water requirement. The greatest increases in water requirement (between 2020 and 2080) was predicted for Monmouthshire (+1.4 million m^3) and Pembrokeshire (+1.2 million m^3).

14.4.3 Overall

- In 2020, based on the scenarios with the highest demand for water, total water abstraction is 6 million m^3. In comparison, the current demand for water by cattle in Wales is *c.*18.3 million m^3 (increasing to around 30 million m^3 if other livestock are also included). Therefore in 2020, water abstraction demand for irrigation is 33% of that used for cattle, or 20% of the total water used for livestock. Although the future demand for irrigation water will grow, even the highest predicted demand of *c*.15.5 million m^3 for wheat and potatoes is less than the water currently consumed by cattle. Also note that, based on a population of 3.15 million, and a daily consumption of 150 litres of water for washing, drinking, cooking etc. (Welsh Government, 2015) human water consumption in Wales is estimated at 173 million m^3.

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