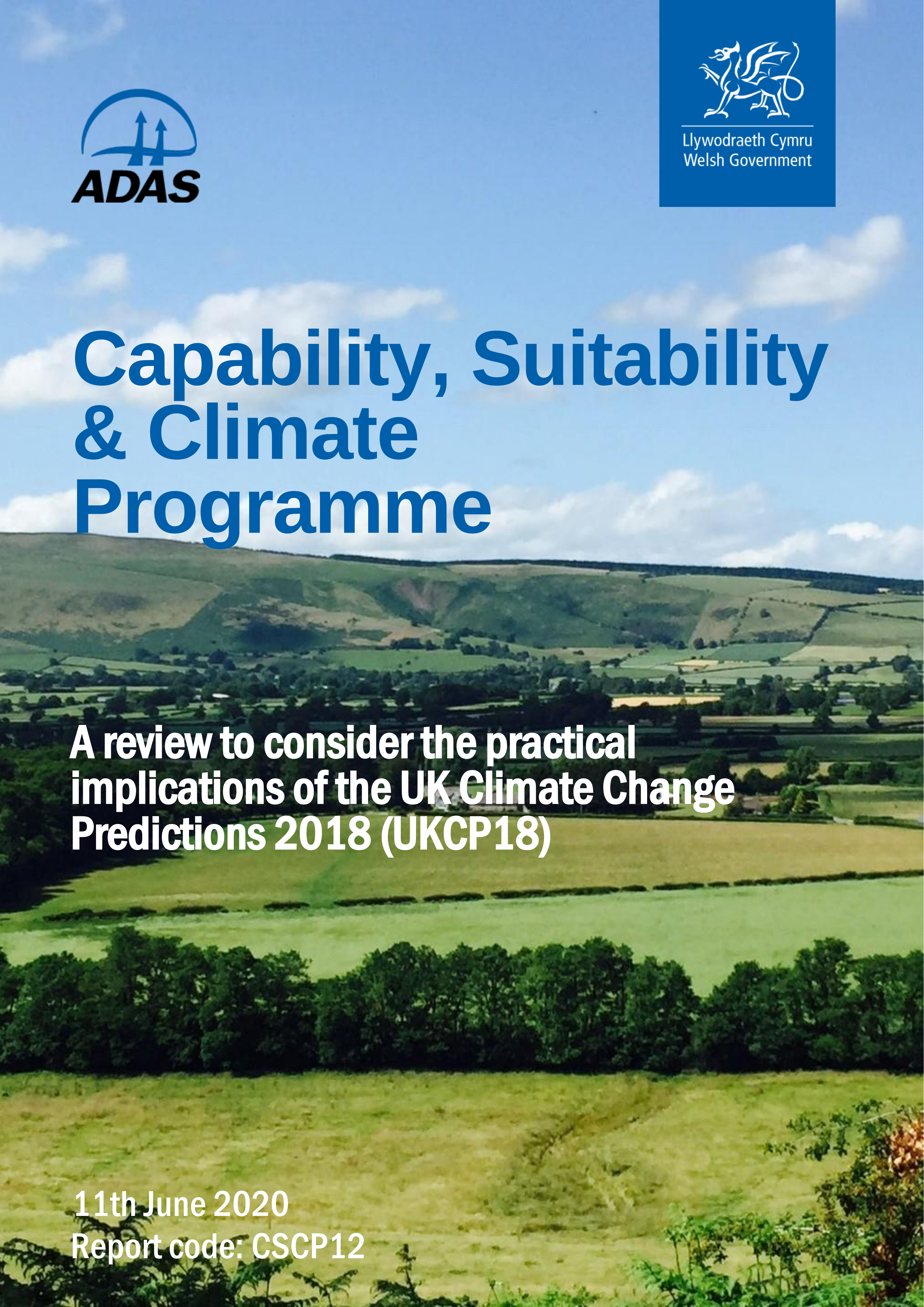

Llywodraeth Cymru
Welsh Government

Capability, Suitability & Climate Programme

A review to consider the practical implications of the UK Climate Change Predictions 2018 (UKCP18)

11th June 2020
Report code: CSCP12

CLIENT: **WELSH GOVERNMENT**

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European Agricultural Fund for Rural Development: Europe Investing in Rural Areas
Llywodraeth Cymru
Welsh Government
ADAS

ADAS GENERAL NOTES

Title:	A review to consider the practical implications of the UK Climate change Predictions 2018 (UKCP18)
Client:	Welsh Government– Soil Policy & Agricultural Land Use Planning Unit
Date:	11 June 2020
Office:	ADAS Cardiff
Status:	Final

Author	C Barrow	**Technical reviewer**	J Evans
Date:	16 June 2020	Date:	17 June 2020
Project manager	C Barrow	**Quality reviewer [optional]**	N/A
Date:	16 June 2020	Date:	N/A

EXECUTIVE SUMMARY

Capability, Suitability & Climate Programme (2020)

Welsh Government – Department for Environment, Energy & Rural Affairs

Programme Background:

The Capability, Suitability and Climate Programme assessed the quality of agricultural land across Wales under current and future climatic conditions using the Met Office United Kingdom Climate Predictions 2018 (UKCP18). The land quality information, current and future climatic datasets were then used to produce a series of maps which predicted potentially suitable locations to grow specific food, fibre, forestry, ornamental, energy and pharmaceutical crops.

The project has been supported through the European Agricultural Fund for Rural Development (EAFRD) from the Welsh Government Rural Communities - Rural Development Programme 2014-2020. The project is led by Welsh Government with partners Environment Systems Limited, RSK ADAS Limited and Cranfield University, and climate data supplied by the Met Office.

The climatic data produced as part of the Capability, Suitability & Climate Programme by Cranfield University and ADAS provides detailed estimates on a 50m grid. The data sets include seasonal rainfall and temperature figures; the number of days when the soil is 'wet' and cannot hold any more water; and an assessment of the agricultural drought and overall climatic limitations. The climatic data sets have been interpolated using the Agricultural Land Classification system methodology (see glossary and references) and the results are detailed in the following Programme reports.

Report Code	Report Title
CSCP04	Agricultural Land Classification & Climate Change in Wales (UKCP18)
CSCP05	Climate Change Impacts on Land Quality in Wales (UKCP18)
CSCP06	Agricultural Land Classification & Climate Change in England & Wales (UKCP18)

To account for uncertainty within the climate model data, the UKCP18 climate change predictions represent a 30-year average: the 2020 models for low, medium and high low, medium and high Representative Concentration Pathway climate change scenarios, for 2020 (2010-2039), 2050 (2040-2069) and 2080 (2070-2099). For the purposes of this report, only the 2020 and 2050 climate periods were selected under the low and medium Representative Concentration Pathway scenarios. The low Representative Concentration Pathway scenario predicts 1.8°C warming by 2100, modelled from RCP 4.5, which represents a scenario of global greenhouse gas (GHG) emissions peaking around the year 2040, then declining. The medium Representative Concentration Pathway scenario predicts 2.2°C warming by 2100, modelled from RCP 6.0, which represents GHG emissions peaking around the year 2080, then declining (Lowe *et al.,* 2018; IPCC, 2019).

The modelled outputs from the programme, predict a general increase in temperature in 2020, 2050 and 2080. Average annual rainfall changes little over these projected periods, but there is an increase in winter rainfall and a reduction in summer rainfall from 2020 to 2080.

The increase in temperature and reduction in summer rainfall results in an increase in the droughtiness limitation across Wales, with an increase in land classified as Grade 3b and 4 for drought by 2050 and 2080, particularly in border areas, South Wales, Pembrokeshire and Anglesey by 2080.

However, the change in climatic conditions also results in a reduction in soil wetness in many formerly 'wet' areas, resulting in improvements in grade such that in the 2020s and 2050s, despite a reduction in the area of Grade 1 and 2 land (mainly due to droughtiness), there is an overall increase in the area of Best and Most Versatile (BMV) land (Grades 1, 2 and 3a combined), providing opportunities for more arable cropping.

Objective:

The objective of this report is to take a limited range of the scenario output data and work through the practical implications for Wales, drawing out the main issues, threats and opportunities to support future planning and policy considerations. A complete analysis of every scenario was impracticable in the time allowed and as such the 2080 scenarios and high Representative Concentration Pathway scenarios were excluded.

This report brings together the detailed climatic and agricultural land quality information, to assess the practical implications of climate change scenarios on various sectors in Wales. It is designed as a starting point for discussion with Welsh Government policy teams and wider stakeholders over some of the broad implications of climate change identified as a result of this Programme.

The purpose of the ADAS expert review is to assess and review the practical implications of the project findings. In particular how the various UK CP18 scenarios might impact on the following areas:

1. Soils
2. Welsh peatlands
3. Other Welsh habitats
4. Welsh woodlands
5. Cereal production in Wales
6. Cropping disease risk
7. Commercial horticultural crops
8. Impact of climate change on ruminant health
9. Agricultural infrastructure
10. Welsh infrastructure (non-agricultural)

Using the report:

This report is split into two parts, the executive summary setting out the approach, purpose and findings of this exercise, and the main report containing detailed analysis of the areas listed above. This approach allows the reader to focus on the specific interests without the need to read each topic and chapter.

The report analysis is not designed to be definitive. It is an exploration of the detailed projected data generated by this Programme which is expected to change as our understanding of natural process, technology markets and the climate evolves.

Summary of findings:

Soils

- "Droughtiness is still the most significant factor in the reduction of Agricultural Land Classification (ALC) grade across England and Wales in the future" (Keay, 2020).
- Increased droughtiness in the east of England could make the Best and Most Versatile (BMV) land in western England and Wales even more important for food production. There is already competition for this land for development purposes in certain areas of SE Wales.The risks for soil degradation would be greater as grasslands are cultivated to enable arable or horticultural production. Therefore appropriate mitigation strategies should be put in place to reduce the risk of Soil Organic Matter (SOM) loss, compaction and erosion. To conserve soil quality, mixed

farming systems could be favoured and the most valuable (*cf*. natural capital valuation) permanent grasslands preserved.

- Climate change in Wales may also be characterised by greater unpredictability and variability of weather pattern, including rainfall events. These would also increase the risks of soil compaction if prolonged waterlogging became more frequent. Late springs and shorter periods of time when the ground is ideal for cultivation/ grazing will increase the risk of soil degradation. Such weather variability would also influence the types of crop rotations and farming systems that farmers are likely to adopt (e.g. Nesbitt *et al*., 2016).
- Preserving upland vegetation cover and type is a key 'win-win' management strategy that will reduce erosion and loss of soil C, and protect a variety of services such as the continued delivery of a high quality water resource.
- The greatest risk to soil quality is the impact that climate change will have on land grade and the potential changes in land use and management that could have knock-on effects for Soil Organic Carbon loss, erosion and compaction. There may be some direct impacts of climate change on the main degradation pressures, but these are likely to be small relative to the potential changes in vegetation and land use. A better understanding of where land-use changes are most likely to occur and what those changes are likely to be will therefore be most important in establishing the potential for soil degradation.

Welsh peatland

- Peatland habitats that are already under stress through sub-optimal management are more likely to suffer detrimental impacts from climate change.
- The key impacts of extreme weather events in relation to peatland habitats are largely centred on heavy (and prolonged) rainfall. Thus, heavy rainfall in the uplands can lead to increased erosion and landslip of peatland habitats.
- Drier summers are likely to lead to changes in species composition in both blanket and raised bogs, favouring those species suited to lower rainfall conditions
- This habitat, perhaps more than most, contains many degraded examples and in many areas, is highly fragmented in distribution. Therefore, any additional impacts are likely to be more severely felt than if the habitat was robust and in good condition.
- A key action for many of the Section 7 Habitats is that of maintaining the quantity and quality of water. This is particularly applicable to those habitats dependent on a seasonally high water table, such as wet woodland, lowland fen, purple moor-grass and rush pasture and reed beds.
- Warmer winter temperatures give a competitive advantage to some species that are detrimental to such habitat. These species include bracken.
- A range of land management regimes are required to prevent further degradation of welsh peatland is required. These include avoiding burning and introducing appropriate livestock and stocking regimes, to prevent further habitat degradation and encourage the restoration of 'active' blanket bog with peat forming processes.

Other Welsh habitats

- An overarching theme in the resilience of Welsh habitats is how they are currently managed. Habitats that are already under stress through sub-optimal management are more likely to suffer detrimental impacts from climate change.

- Severe weather events associated with climate change could potentially have a greater impact on habitats than a more gradual change in the 'mean climate'. An obvious example is in relation to severe storms and wind throw in woodland. Persistent flooding is also detrimental to those habitats that require intermittently high water tables. Drier summers could also lead to changes in species composition.
- There is clearly a wide range of different potential impacts on Section 7 Habitats in Wales as a result of climate change. The inherent complexity of habitats themselves and the range of potential responses, makes it difficult to predict how the combination of different climate change factors will interact to affect individual habitats. At the same time, despite this, it is possible to outline a series of generic actions and approaches to habitat management that could help counteract the effects of worst case scenarios
- Those habitats that are dependent on high or intermittently high water tables are likely to suffer disproportionately. Habitats that are particularly susceptible to disease or invasion by non-native species are also likely to receive greater impacts, woodlands being a key example.
- In some cases, notably wet heath, lowland meadows, purple moor-grass and rush pastures and montane heath, it is likely to be of greater benefit to Wales' biodiversity to address existing land management issues before tackling issues of climate change. Appropriate grazing is of particular relevance to these habitats. Tackling these issues first will not only provide great overall benefit to these habitats, it will also make them much more resilient to the effects of climate change.

Welsh woodland

- The changing climate is a challenge for forest planning and forest management nationally. The main reason for this is that in the past it has been relatively easy to decide on the best species to plant for a given site because the climate has been relatively stable.
- The more extreme rainfall over the winter period will increase the need for tree planting in water catchment areas throughout Wales, in order to help retain and regulate the water supplies and avoid excessive run-off when the soils become saturated.
- Other factors, such as the possibility of more extreme winter storms and an increase in attacks by existing and new pests and diseases, will have a bearing too on the way in which woodlands are planned and managed. There will be a greater chance of tree disease and pest outbreaks with warmer winters which allow pests to extend their range; it should be added that if the change in climate allows pests to move further north, then it could also allow their natural predators to do the same.
- Woodland, being slow growing, can often adapt to changing conditions but only if the changes are gradual. Woodlands are less adaptable to rapid changes as when trees are put under stress, in addition to being less healthy, they become more vulnerable to pests and diseases.
- In Wales, a stimulation of timber productivity due to the warmer climate and increased CO_2 levels might take place. If as a result, there was an increase in GYC of 3 (average of conifer and broadleaf) over the 306,000 ha woodland cover, the increase in productivity would amount to just short of 1 million m3 /yr. Based on the 200,000 ha of woodland that is in a woodland management scheme and accessible on farms, the figure drops to 600,000 m3, with the associated additional sequestration of Carbon. This is still a significant potential increase to come on to the market and into local industry and based on a standing value of £35/m3 the additional revenue to the landowners would be £21m.
- Species selection needs to consider planting a varied, extended selection of trees, some with drought hardiness and provenance from more Southern sources; the more diverse mixture

planted will help to ensure survival of the woodland as some species may fail and others may thrive better than expected. Sitka spruce, which requires a high level of rainfall throughout the year is likely to grow less well in drier conditions and consideration should be given to alternative species which will grow well throughout the drier summer months.

Cereal production in Wales

- The overall area of arable and bare fallow has increased by 9,000 ha in Wales over the past ten years, but in a historical context this level is still relatively low. An area of 138,000 ha of cereals was grown in 1914 which shows the scope for expansion in the current cereal area.
- Overall, the predicted changes in ALC and suitability for wheat growing appear unlikely to have a significant negative impact on cereal growing in Wales. Indeed, the availability of Best and Most Versatile land on which cereals can be grown is predicted to increase.
- A future UK climate will continue to remain favourable for wheat production, but there will be both positive (e.g. dryer summers reducing lodging and improving harvest timeliness) and negative (e.g. wetter winters increasing waterlogging) impacts on wheat crops.
- Growing seasons with potentially high Average Winter Rainfall and low Average Summer Rainfall may lead farmers to establish crops earlier in the autumn. This can benefit crops through better growth before winter, but it can also mean that crops are more susceptible to pests e.g. aphids, and there is less time available to practice cultural weed control methods. Both of these issues may lead to the need for more pesticides to be applied.
- The impact of climate change on the Welsh cereals sector is likely to be less severe than that experienced in England, particularly in the South and East of the UK where higher temperatures and drought are likely to have a greater impact. This may mean that the demand for cereals to be grown in Wales might be greater. This will depend upon demand and farm scale economics. Land used change from grassland to cereal production would impact on soil carbon and potentially soil erosion.
- A range of strategies could be adopted in the sector to minimise the impact of climate change. These include:
    - Resilient varieties- disease, vernalisation, rapid establishment
    - Diversified rotations
    - Resilient soil - those that are well drained to mitigate water logging
    - Integrated pest management - crop rotations, cultivation techniques, use of beneficial organisms, biosecurity
    - Irrigated cereals while bearing in mind the requirements of other sectors and the farm infrastructure required to irrigate large acres of land.

Cropping disease risk

- Four key crops grown in Wales have been identified as Wheat, Barley, Oilseed Rape and Potatoes and are susceptible to a range of diseases caused by fungal pathogens, which are usually crop-specific.
- Climate change and the associated changing weather patterns have the potential to influence the occurrence of these diseases either directly or indirectly, either through optimising/restricting life cycles or influencing agronomic practises.
- There are complex interactions between factors including temperature, rainfall, soil wetness/droughtiness required to generate optimal conditions for disease development.
- Given the predicted climate changes modelled by UKCP18, under all scenarios, risk of septoria is likely to remain high for crops of winter wheat in Wales.

- The effect of the modelled scenarios on yellow rust disease risk is difficult to judge, although it would be reasonable to predict that there might be shift in the timings of any epidemics. It should be considered though, that the population of yellow rust is highly diverse and adaptable, and new races can emerge within a single season, overcoming both varietal resistance and fungicide activity. As such, under the environment predicted by the modelled scenarios, it may be that new races of the pathogen emerge to overcome the limitations.
- Other diseases may become more prevalent in different environments, such as Take-All, and Eyespot. The latter is associated with early sowings and wet winters and therefore may become more prevalent under forecast climate change. Conversely a decrease in average summer rainfall will reduce the incidence of Fusarium Head Blight.
- Overall, given the predicted climate changes modelled by UKCP18, under all scenarios, the risk of rhynchosporium is likely to remain high for crops of winter and spring barley in Wales.
- Over winter establishment of brown rust in barley is seen as likely and may reach epidemic proportions as the weather warms up if left uncontrolled. Predicted increases in average winter rainfall may make travelling the ground difficult in the spring to control the disease.
- Likewise the over wintering development of net blotch in winter sown barley crops might be difficult to control due to ground conditions. Increasing risk of soil compaction in arable areas.
- Increases in average winter rainfall are likely to shorten the autumn drilling window. Crops may well be sown early and reduce the risk of mildew in barley.
- A rise in average summer temperatures, combined with drought scenarios may put the crop under more stress and trigger a range of diseases such as ramularia.
- Climate change could have a considerable impact on the incidence of certain diseases in oil seed rape - Club root and Verticillium stripe, but further research is required.
- Incidences of potato blight are likely to become more severe under UKCP18 predictions. Early Blight is rarely reported in Wales but becoming common in Europe. The increases in UK reporting coincide with favourable weather. It is thought that under UKCP18 predictions, that Early Blight may become a disease of greater significance.
- There will be greater need for disease surveying in order to detect changes in pathogen life cycles to allow adaptation and development of appropriate crop protection measures including:
    - New crop varieties
    - New fungicides
    - Integrated pest management.
- Industry and consumer requirements will impact on any changes in variety.

Commercial horticultural crops

- Commercial horticulture activities occupy only 1.9% of the land used for crop production in Wales in 2018, but contributed 51% of the £108m productivity of cultivated land.
- Wider horticultural production in the UK has become highly consolidated, with supermarket supply chains reliant on a small number of large-scale farming enterprises for supplies. The sector is also heavily localised to specific regions through a combination of geographic or historic influences (e.g. soil conditions) and the availability of supporting infrastructure, particularly for packing and distribution into the supermarket supply chain.
- For a variety of reasons, horticulture in Wales is distinct from more general trends in the wider UK. While there are a number of larger scale commercial operations, (Puffin produce etc.) the

Welsh horticulture sector is typified by small (<1 ha) holdings that produce a variety of crops targeted for local sale.

- The uniqueness of the horticulture sector in Wales also results in a variety of unique challenges while buffering it from changes seen in the wider UK market. A lack of infrastructure in Wales – packing, distribution and transport – has created a significant barrier for many growers to access the main supermarket supply chains although activities of some Producer Organisations have been effective in creating collaborative marketing routes.
- The local focus of many Welsh horticulture businesses has allowed them to maximise the benefit of short supply chains by offering high value, high quality produce at a premium. Significant focus has been made on unique selling points such as Welsh origins such as the protected food name for Pembrokeshire Earlies (early potatoes), or Welsh daffodils.
- The provision of suitable plant protection products to address current and emerging pest and disease issues remains a key challenge across the horticulture sector as growers have access to falling numbers of active ingredients and increasing resistance in target pests and diseases.
- The horticulture industry in Wales faces a number of current and emerging challenges. These are:
    - Access to labour and suitably skilled/ trained staff
    - Lack of infrastructure – packing, distribution and transport
    - Access to independent agronomist and the ability to pay for them
    - In house training difficult on small scale enterprises
    - Access to high cost specialist machinery
    - Infrastructure to support growing such as propagators, media and seed material
    - Succession planning and re-structuring in the industry where vital skills are lost or labour is even harder to source.
- Climate change predictions will see an increase in the proportion of higher Grade agricultural range, the increase in temperatures and rainfall (particularly the variability of weather within a season) has the potential to have a significant impact on horticultural crops.
- Ensuring that sufficient access to water will be a key challenge for horticulture, particularly with regards to the predicted decrease in summer rainfall. The irrigation needs of horticulture will also need to be balanced carefully against other demands on groundwater resources. In instances where there is little above ground water capture and storage from winter rainfall, drier summers will increase pressure on growers, especially those without aquifers to tap into, making water availability an increasing risk.
- For field vegetable production in Wales the decrease in summer rainfall is likely to pose a challenge, especially in crops such as Brassica that need consistent soil moisture.
- The increasing temperatures and availability of Grade 1, 2 and 3a land will mean that field vegetable production Wales could be a strong focus to meet increased demand and address the need to relocate production from Lincolnshire – this will be especially relevant as higher summer temperatures and reduced rainfall in Lincolnshire is predicted to rise significantly by 2050.
- There is considerable Grade 2 land in Monmouthshire, and around the M4 east of Cardiff that could be used for field vegetable production. Root vegetable production is unlikely to be possible on a large scale in Wales, but may be achievable if suitable areas of sandy loam area identified. Onion production requires dry autumns to promote bulb maturation and drying out, so these may be more suitable for South Wales.

- Besides conventional field vegetables, it may be possible to expand the diversity of crops grown. Perennial crops such as asparagus could be promoted as a high value crop that is free of major pest/disease issues once established. Sweetcorn and courgette also offer opportunities. However a supporting infrastructure is needed to unleash any potential.
- Larger holdings formerly under arable production offer the best commercial opportunity to access supermarkets but will need sufficient irrigation. These are likely to be in SE Wales which are also likely to see the lowest summer rainfall levels and other demands on ground water from large urban populations.
- Most soft fruit production in UK now under plastic protection. Soft fruit production is uncoupled from agricultural land and can be grown on converted brown field sites close to market. Climate change will have little effect on this sector besides irrigation water requirements and the emergence of any new pests and diseases.
- Top fruit is niche and added value - Welsh Cider and Perry etc. The main impact of climate change on top fruit production is the reduction in winter chilling which is important for vernalisation in some crops.
- The lack of supply chain infrastructure in Wales has precluded any large scale development of protected edibles under glass (tomatoes and peppers). The primary impact of climate change on this sector, is an increase in pest and disease and demand for control measures such as pesticides and atmospheric control.
- Ornamental production is largely substrate based so unlikely to be impacted by climate change predictions apart from field grown varieties such as bulbs, daffodils etc. Warmer wetter winters will make lifting very difficult and increase risk of soil compaction.
- Increase in Grade 2 land in Wales will increase the opportunity for niche ornamentals such as Christmas Trees that can be grown on acidic grade 2 land.
- Pest and disease issues are the biggest concern in horticulture due to high quality specifications by customers. A general increase in losses due to pest and disease damage is expected across the sector due to warmer wetter winters and early warm springs.
- Higher soil temperatures may increase the severity of soil borne diseases.

Impact of climate change on ruminant health

- Agricultural output in Wales is dominated by ruminant livestock production. By value in 2017, products from this sector amounted to around three-quarters of total output with milk and dairy products accounting for the biggest proportion at 32.5% followed by finished cattle (19.5%) and finished sheep (14.9%) with store cattle and sheep sales responsible for a further 7.7%.
- Increased temperatures are likely to impact on animal health in a number of ways. This can be directly in the case of heat stress or indirectly by affecting the epidemiology of livestock disease. The likelihood of extreme drought and the impact on forage supply is also likely to increase.
- The impacts of heat stress in dairy cows include depressed feed intake, and milk production, impacts on fertility and in extreme cases increased mortality.
- Mitigating factors at grass include provision of adequate water troughs and additional shelter. Where cattle are continuously housed reduction in stocking rate can help as well but it may be necessary to make permanent alterations to improve building ventilation or provide cooling systems for cattle.

- Wetter winters and later springs may result in longer winter housing periods. The quantity of conserved forage required will inevitably increase. This together with summer drought periods could result in a shortage of summer grazing and lack of grass for conservation. This will result in farmers looking for alternative sources of forage to buy, or reducing stocking rates if the scenarios become long term and repetitive.
- There is a move towards spring calving in the National dairy herd to make use of the spring flush of grass in large parts of Wales. The increase in wetter winters and later springs may result in increased soil degradation as cows are put out to graze in non-ideal conditions. There will be a requirement for more farm tracks and methods to protect areas of high footfall on some farms.
- Respiratory disease (pneumonia) is a common cause of illness in calves and young stock and is the most common cause of death and poor performance from weaning to 10 months of age. Problems are most common in housed animals but can also arise outside.
- Changes to the climate (such as increased winter rainfall expected in the current scenarios for Wales) that exacerbate existing poor ventilation within buildings, with resulting high moisture levels, and insufficient fresh air, are likely to increase the incidence of respiratory disease in housed cattle.
- Parasitic disease is a huge cost to the livestock industry with reduced performance in affected stock and potentially high levels of mortality. In addition some conditions can cause rejection in carcases and offal in the abattoir (e.g. liver fluke damage).
- Historically, seasonal and geographical differences have been found between nematode species although changes have been seen in recent years. Haemonchus infection of sheep was typically confined to the South East of England but has now become widespread whilst Trichostrongylus, which was traditionally a problem for lambs in the autumn is now seen earlier in the summer and persisting for longer during mild winters.
- The incidence of liver fluke is higher in the wetter areas of the country and in years with high summer rainfall. Sheep grazing wet fields in the autumn and winter are particularly at risk of infection.
- One of the control methods to reduce liver fluke infection is to exclude animals from areas that can harbour the snail host. Drainage eliminates the snail and offers an effective means of control, but environmental schemes that protect wetland areas have reduced the opportunities for this to be carried out. Hotter drier summers might have a positive impact on some pastures and reduce the areas able to support the snail (intermediary host).
- Blowfly strike is a widespread issue caused by the larvae of the blowfly Lucilia sericata (greenbottle flies) causing significant welfare issues and economic loss if not controlled effectively. High temperatures encourage fly activity and when relative humidity is also high this creates favourable conditions within the fleece that attract flies to lay eggs. In the UK, rising temperatures in late spring allow overwintering fly larvae to complete their lifecycle and the first wave of blowflies to emerge. Blowfly populations peak during the summer months and traditionally the fly strike period runs from May-September. However more recently the risk period has been extended due to favourable climatic conditions and can run from March to December in some lowland areas. Under current climate change predictions the season is likely to extend further.
- The mites that cause sheep scab, live permanently on the sheep and are less likely to be directly affected by changes in climate. However there may be indirect effects as a result of

changes to management practices; for example the length of housing periods (where transmission is increased), timing of shearing and use of anthelmintics that may target both internal and external parasites. In addition the time that the mite can survive off the sheep will affected by temperature and humidity with hotter, drier conditions (as expected in future summer climate scenarios) reducing survival and cooler, more humid conditions extending survival.

- Changes in climate that result in warmer and more humid conditions will result in increased tick activity. The increase in AT0 across Wales in the scenarios reported suggests that ticks may become active earlier in the season as temperatures rise above 7°C. They will however remain dependent on having a moist humid environment in which to survive off the animal.
- Farmers are being encouraged to have emergency plans in place for extreme weather events i.e. adequate storage of fodder, improvements to animal housing, tree shelter belts for shade and protection.
- Farmers are being encouraged to be proactive with veterinary assisted animal health planning via current KT programmes in Wales such as Farming Connect and AHDB interventions.
- Flock/ herd health plans are also being encouraged to control parasites and diseases.
- Modelling of parasite risk has been the focus of a number of research projects with a number of decision support tools available. The impact of climate change will depend on the parasite but some of these tools could be updated using more recent climate change predictions.

Agricultural Infrastructure

- Roads, drains, reservoirs and buildings represent a substantial long term investment on most farms, and are normally expected to have an operating life in excess of 20 years - typically 30 to 40 - with many buildings being adapted and repurposed to some extent on multiple occasions throughout their lifetime. Mobile plant and machinery is more flexible and commonly expected to have a working life of between five and twenty years depending on use and complexity, with the majority being in the region of five to fifteen years.
- Overall changes in average annual rainfall appear likely to have few implications for agricultural infrastructure, whereas changes in seasonality of rainfall will have significant implications.
- Increases in summer temperatures and droughtiness will have implications for water supply and animal welfare, and therefore for the associated hard infrastructure.
- Decreased summer rainfall may have indirect implications for fodder storage if summer grass growth is impacted. There may be a requirement for increased clamp or storage capacity if additional feeds have to be brought in or late/early silage cuts are taken to increased store of fodder.
- Decreased summer rainfall may also increase slurry production as stock are brought in earlier or housed throughout the year. Housing may also need alteration to improve ventilation and prevent heat stress.
- Higher temperatures and lower summer rainfall will increase water demand by livestock and for irrigation purposes. Overall the biggest impact on livestock will be in the uplands where there is little opportunity to provide water for stock other than mountain-rivers and springs that might dry up.

- The consequence of a reduction in summer rainfall is likely to be an increased reliance on mains water supply together with winter storage facilities and supplementing crops and livestock in the summer months.
- Increased soil wetness will have the following impacts
    - Reduced opportunities to spread slurry and requirements for additional storage capacity.
    - Reduction in grass growth and increase the scope to grow winter cereals. This would increase the demand for grain storage facilities.
    - Incidences of pollution from application of slurry may increase as there is pressure to spread slurry in shorter time windows.
- Increased winter rainfall will increase the requirement for slurry storage or roofing over yard areas to exclude rainfall.
- Increased winter rainfall will increase rates of run off from yard areas and farm tracks with potential down-stream flooding. Improvements in surface water handling will be needed i.e. swales, constructive wetlands.
- Effective land drainage will be essential to ensure good quality water supply and free movement of water. Many current systems are old and ill maintained resulting in water logging of soils.
- Increased summer temperatures are likely to increase the demand for ventilation in livestock buildings which could increase operating costs. Increased winter temperatures would result in less frost damage but also problems ventilating buildings leading to a range of livestock diseased such as pneumonia.

Welsh Infrastructure (Non-agricultural)

- A key factor in determining the vulnerability of Welsh infrastructure to climate change is the current condition of infrastructural assets across Wales. Assets that are already in poor or deteriorating condition will be more susceptible to further damage or destruction from extreme weather conditions and future climate change, compared to assets that are newer and/or have been built to a higher specification.
- A review of evidence by the National Assembly for Wales in 2018 indicated that Wales's roads are in no worse condition than those in other parts of the UK.
- The water network in Wales is vulnerable to a number of climate change impacts. Welsh Water outline several key risks, including water supply deficit (e.g. drier summers would lead to diminished water supply) and reduced water quality (e.g. soil erosion and landslips leading to increases in sediment, suspended solids, pesticide and nutrient loadings linked to increased peak precipitation and pollutant mobilisation).
- Considerable investment will be required to future-proof the water network in Wales to ensure that water companies in Wales become more resilient to the projected impacts of climate change (e.g. changing patterns, more variability and more frequent extremes in precipitation).
- In terms of managing capacity and demand in the energy grid, there has been a notable shift in recent years towards decentralised and renewable generation. As a result, requirements for system flexibility have been increasing as the amount of intermittent and decentralised generation grows. In addition, transformation to renewable energy requires a greater amount of generation capacity to be built compared to demand. This is because intermittent generation is not able to produce electricity when, for example, there is no sun or wind.

- Marine energy is also likely to be a more prominent feature in the coming years, including tidal stream energy, wave energy and tidal range energy.
- Large-scale investment will be needed across England and Wales to manage changes in the future supply and demand of electricity, particular as the electrification of trains and electric vehicles continues to grow.
- A better understanding of reservoir capacity and the seasonal distribution of rainfall to replenish stocks will be an important risk management consideration for the water sector when assessing water supply and demand requirements under future climate change scenarios (e.g. through Water Resources Management Plans).
- More winter rain will increase the risk of flooding as well as land-slides and embankment failures causing damage to infrastructure and disruption to travel.
- An increase in incidence of drought may contribute to soils desiccation and soil erosion but also damage to roads and buildings if the sub soil cracks.
- The main risks and impacts of climate change on the water sector have been outlined by Ofwat.

Conclusions

Opportunities

- The impact of climate change on the Welsh cereals sector is likely to be less severe than that experienced in England, particularly in the South and East of the UK where higher temperatures and drought are likely to have a greater impact**. This provides an opportunity for more arable/ horticultural production in Wales.**
- Opportunities to develop horticultural and arable systems in Wales, both largely favored as a result of climate change, will be limited by the supply of water, supply chain infrastructure and sufficient skilled labour.
- **Preserving upland vegetation cover** and type is a key 'win-win' management strategy that will reduce erosion and loss of soil Carbon and protect a variety of services such as the continued delivery of a high quality water resource.
- The more extreme rainfall over the winter period will increase **the need for tree planting** in water catchment areas throughout Wales, in order to help retain and regulate the water supplies and avoid excessive run-off when the soils become saturated. Tree planting also offers economic returns for land owners and farmers.
- A better **understanding of reservoir capacity** and the seasonal distribution of rainfall to replenish stocks will be an important risk management consideration for the water sector when assessing water supply and demand requirements under future climate change scenarios.
- The **opportunity to protect the Best and Most Versatile land** exists currently, particularly in SE Wales. The increasing demand for development land is going to become a major competitor for some of this land, which offers the best potential for future food production.

Threats.

- The availability of **good quality water** will be key to any land use change. Demand for water is expected to increase from all sectors over the next 50 years. There will be competition for water from the domestic sector, industry and agriculture, together with the need to ensure adequate water is available to maintain habitats and river systems.

- The consequence of a reduction in summer rainfall is likely to be an increased reliance on **mains water** supply as private abstractions, such as bore holes and springs, fail to meet demand. There is likely to be increased uptake of winter storage facilities to enable supplementation of crops and livestock in the summer months.
- Considerable **investment will be required to future-proof the water network** in Wales to ensure that water companies in Wales become more resilient to the projected impacts of climate change.
- **Reduced river flows** could mean more carbon-intensive sewage treatment is required to ensure rivers are protected.
- The risks for **soil degradation** would be greater as grasslands are cultivated to enable arable or horticultural production. Therefore appropriate mitigation strategies should be put in place to reduce the risk of Soil Organic Matter (SOM) loss, compaction and erosion. To conserve soil quality, **mixed farming systems could be favoured** and the most valuable (*cf*. natural capital valuation) permanent grasslands preserved
- An overarching theme in the resilience of Welsh habitats is how they are currently managed. Habitats that are already under stress through sub-optimal management are more likely to suffer detrimental impacts from climate change. A range of land management regimes are required to prevent further **degradation of welsh peatland** is required.
- Climate change is likely to impact on both the **severity and type of pest and disease** in all sectors. Improved monitoring and surveillance will be needed together with research into new methods of control and resistant species.
- Increased winter rainfall will **increase the requirement for slurry storage** or roofing over yard areas to exclude rainfall.
- **Effective land drainage** will be essential to ensure good quality water supply and free movement of water.

GLOSSARY

The following section contain the Climate Change maps referred to during Part 2 of the report

Climatic Data Terminology:

The climatic data generated by this project includes:

AAR - Annual Average Rainfall (mm)

ASR - Average Summer Rainfall (mm)

AWR - Average Winter Rainfall (mm)

AT0 – Median Accumulated Temperature above 0 degrees – January to June

ATS – Median accumulated temperature above 0 degrees – April to September

FCD – Field Capacity Days – the number of days when the soil is 'wet', cannot hold any more water against gravity, and with any additional rainfall will start to drain.

MDW – Moisture Deficit for Wheat – adjusted by the crop requirement, the balance between rainfall and potential evapotranspiration over the growing season.

MDP – Moisture Deficit for Potatoes - adjusted by the crop requirement, the balance between rainfall and potential evapotranspiration over the growing season.

Drought – The limitation placed on the reference crops potatoes and wheat as a result of moisture availability and evapotranspiration.

Climate – AAR and AT0 interpolated to a point by altitude (as rainfall increases and temperature decreases, the climate becomes less favourable)

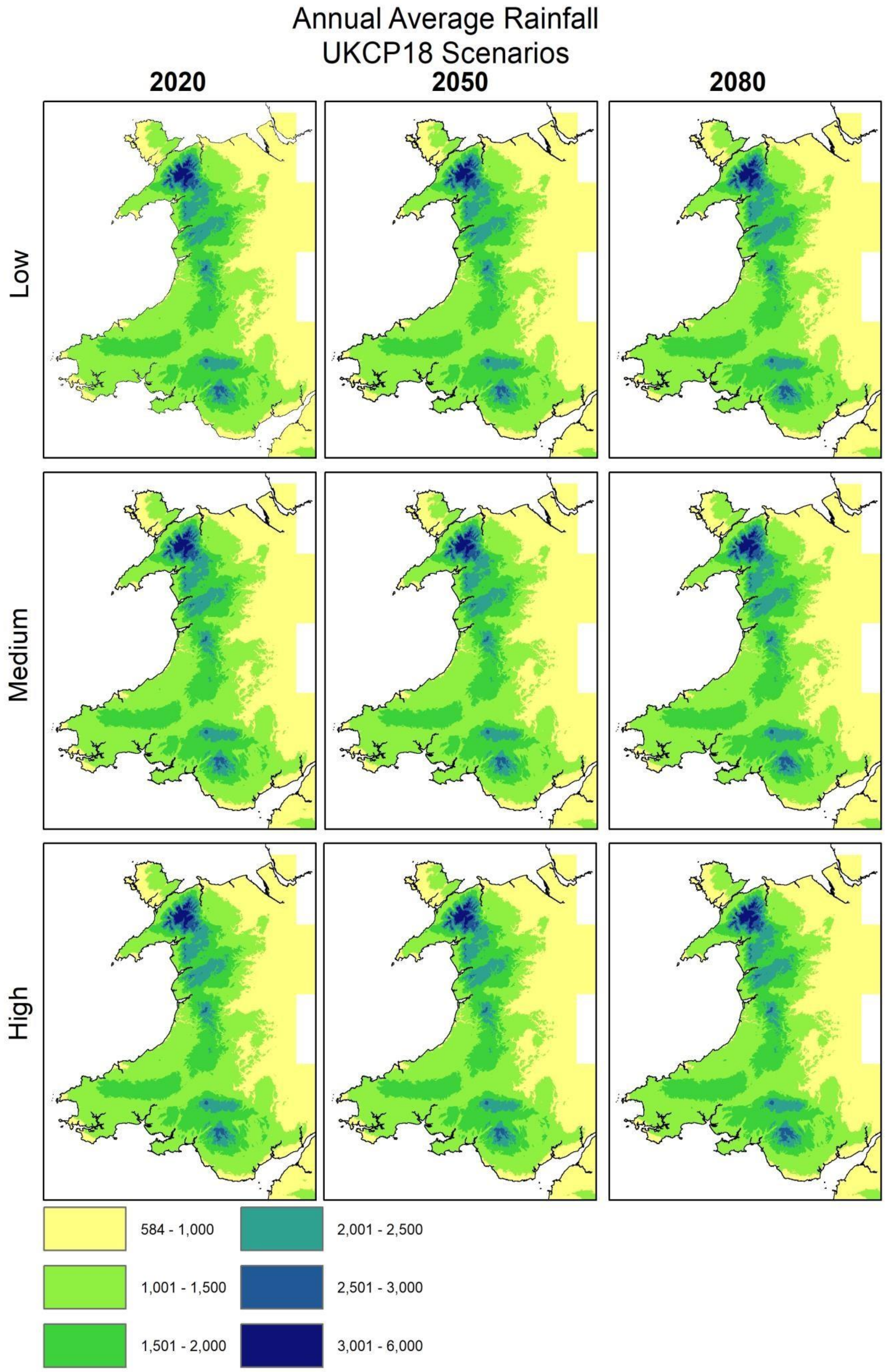

Figure 1 Annual Average Rainfall – AAR - under UKCP18 Scenarios

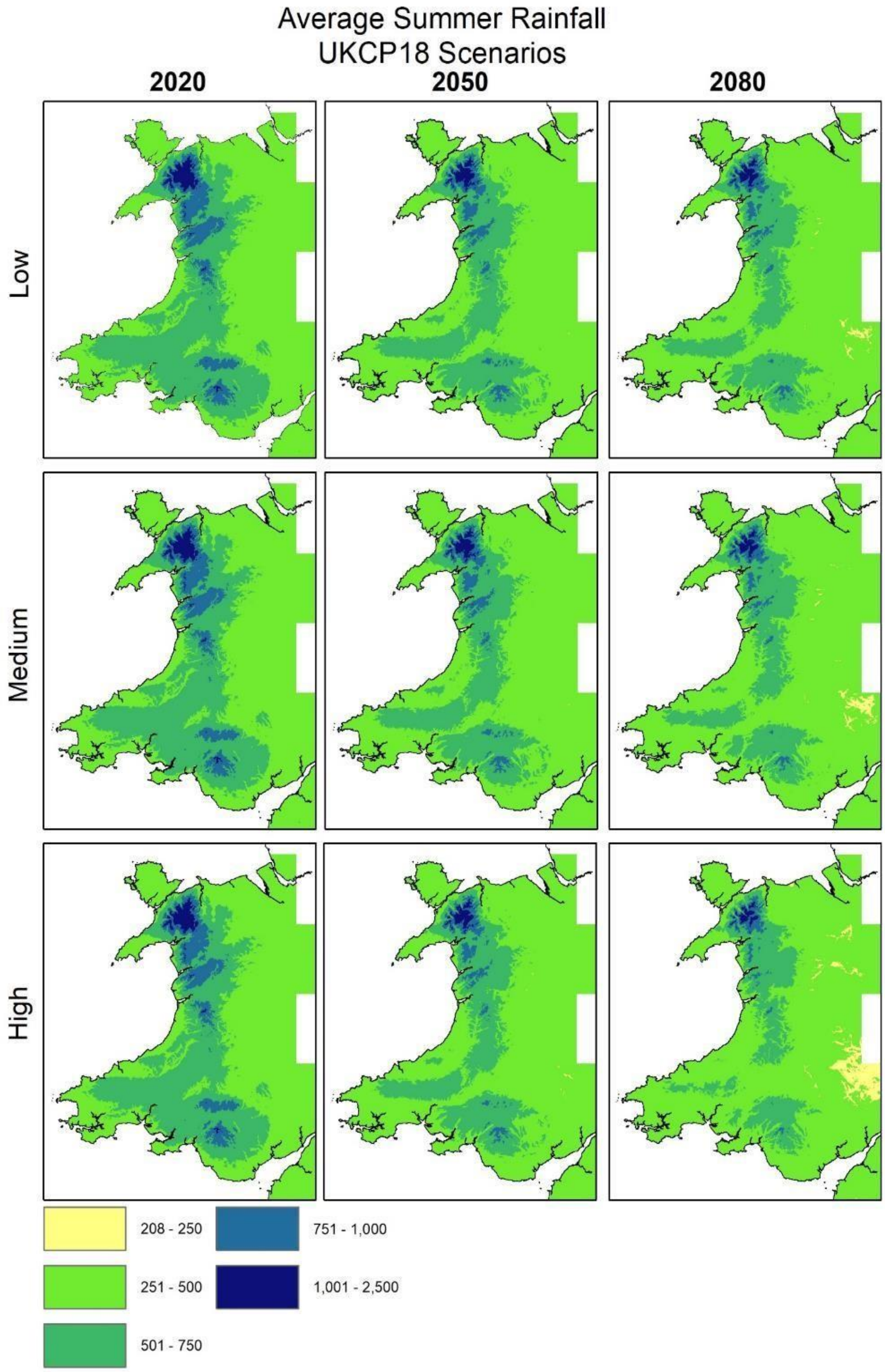

Figure 2 Average Summer Rainfall between April and September– ASR - under UKCP18 Scenarios

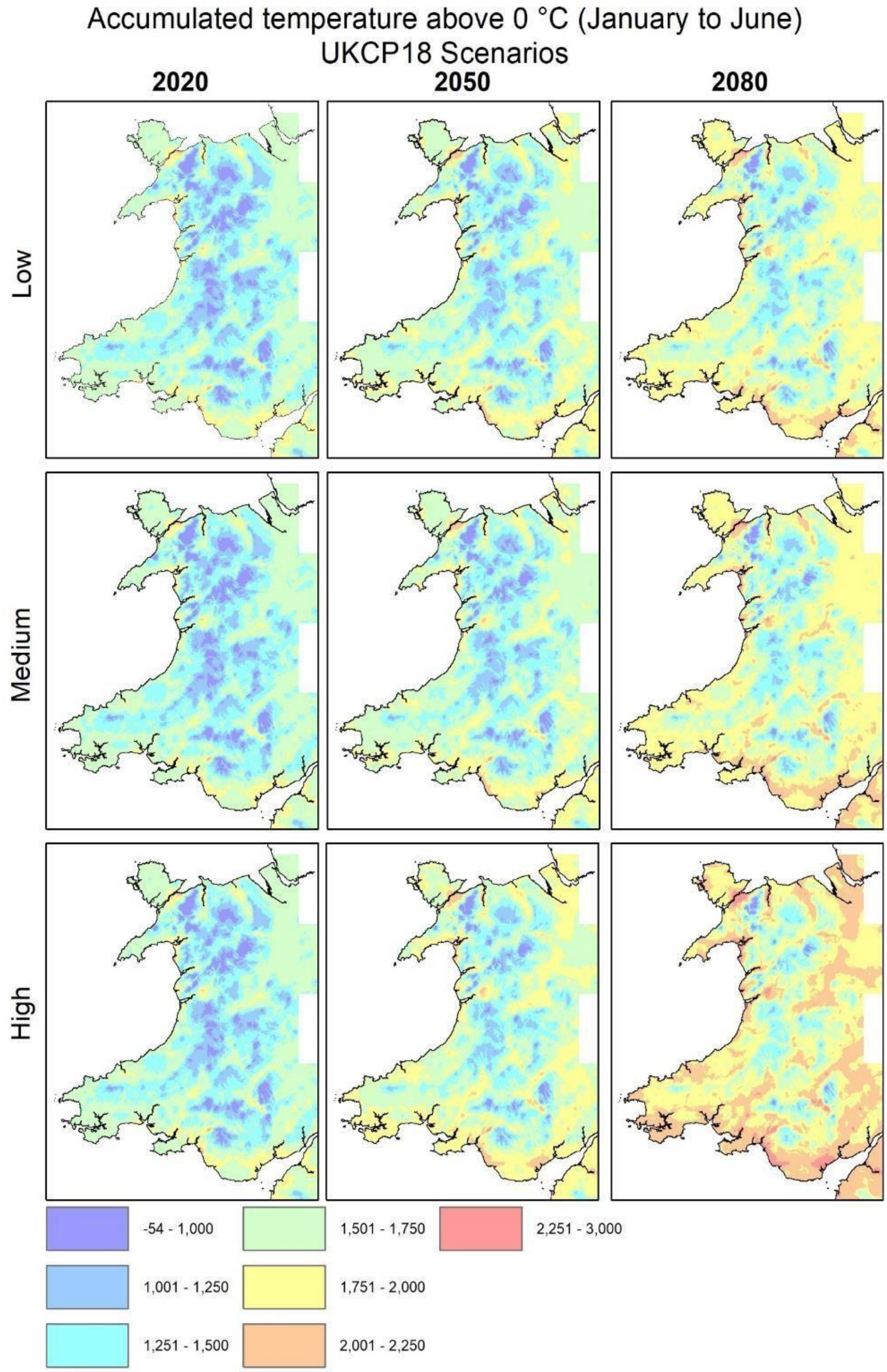

Figure 3 Accumulated temperature above 0° C (January to June) - AT0 - under UKCP18 Scenarios

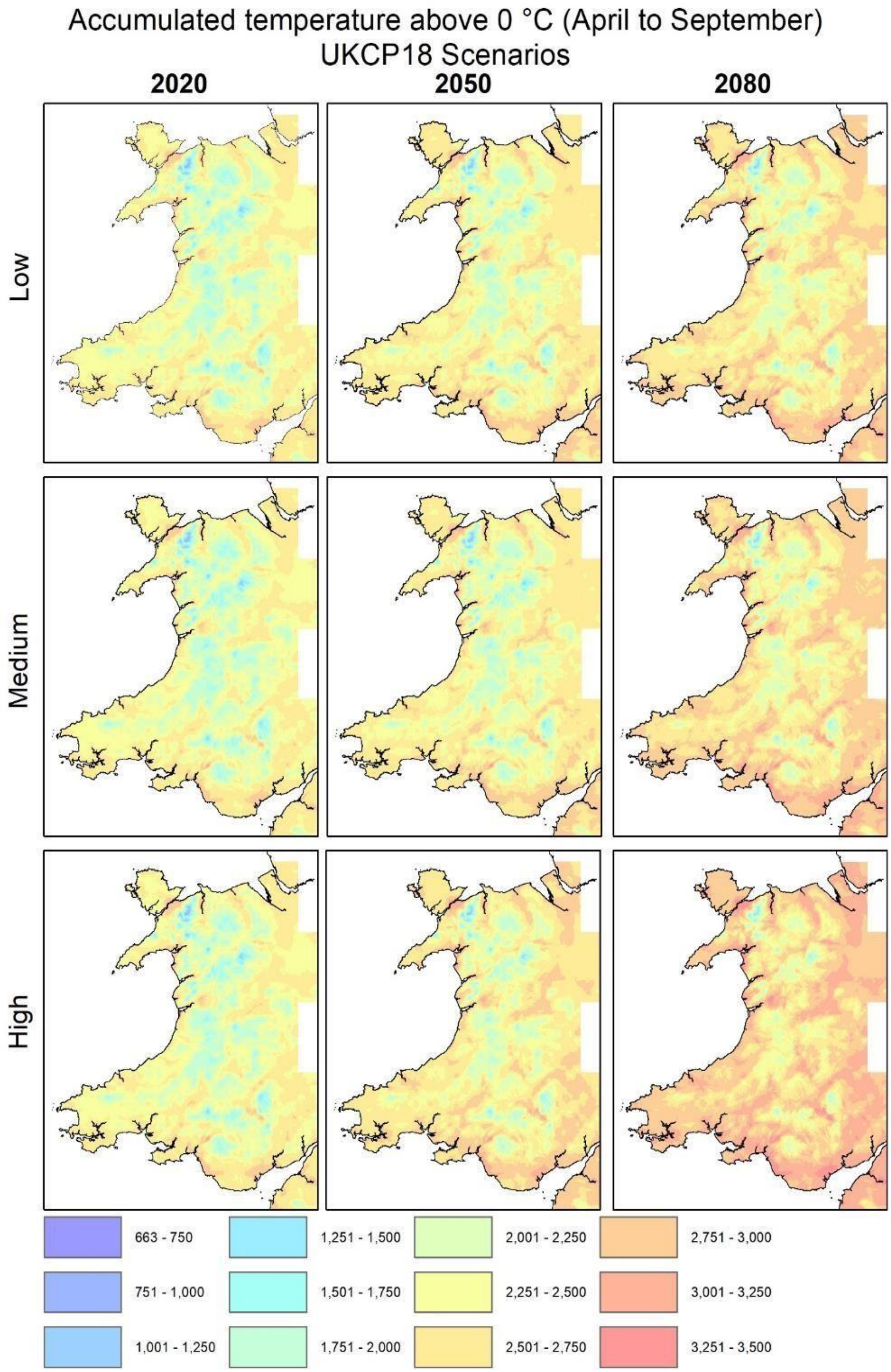

Figure 4 Accumulate Summer Temperature above 0°C (June to September) – ATS – under UKCP18 Scenarios

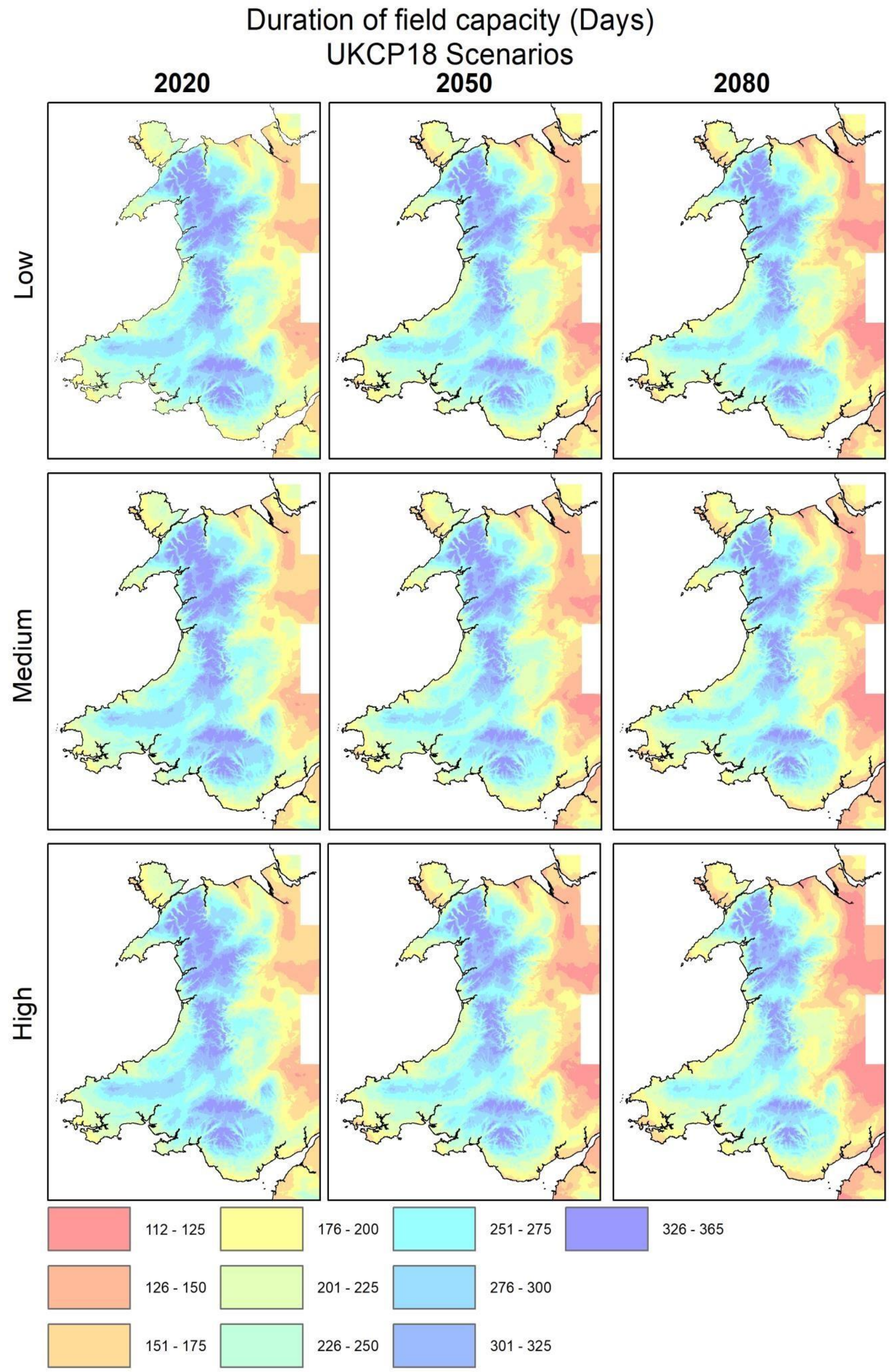

Figure 5 Duration of Field Capacity (days) - FCD - under UKCP18 Scenarios

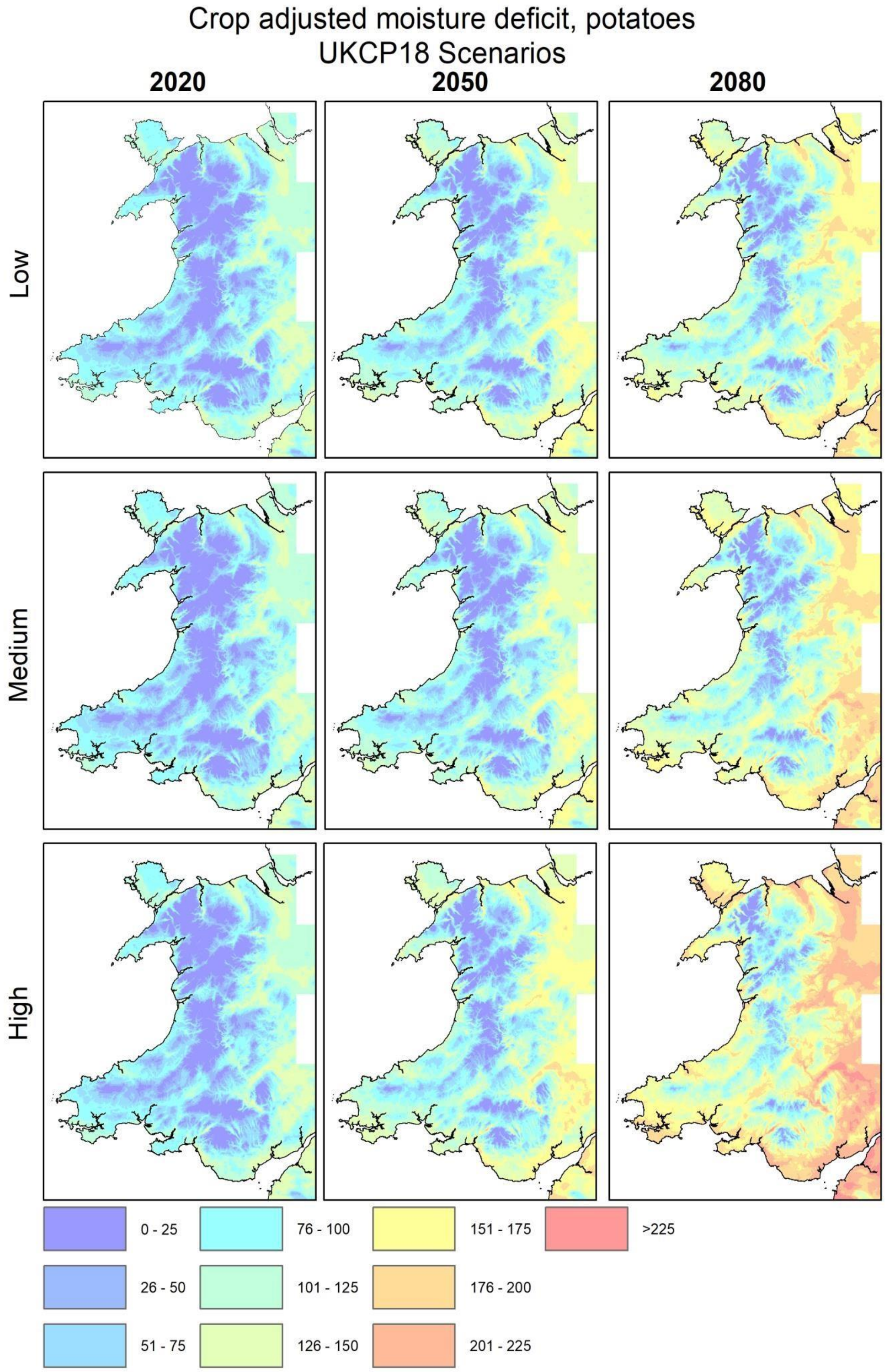

Figure 6 Crop adjusted Moisture deficit, potatoes (mm) - MDMPOT - under UKCP18 Scenarios

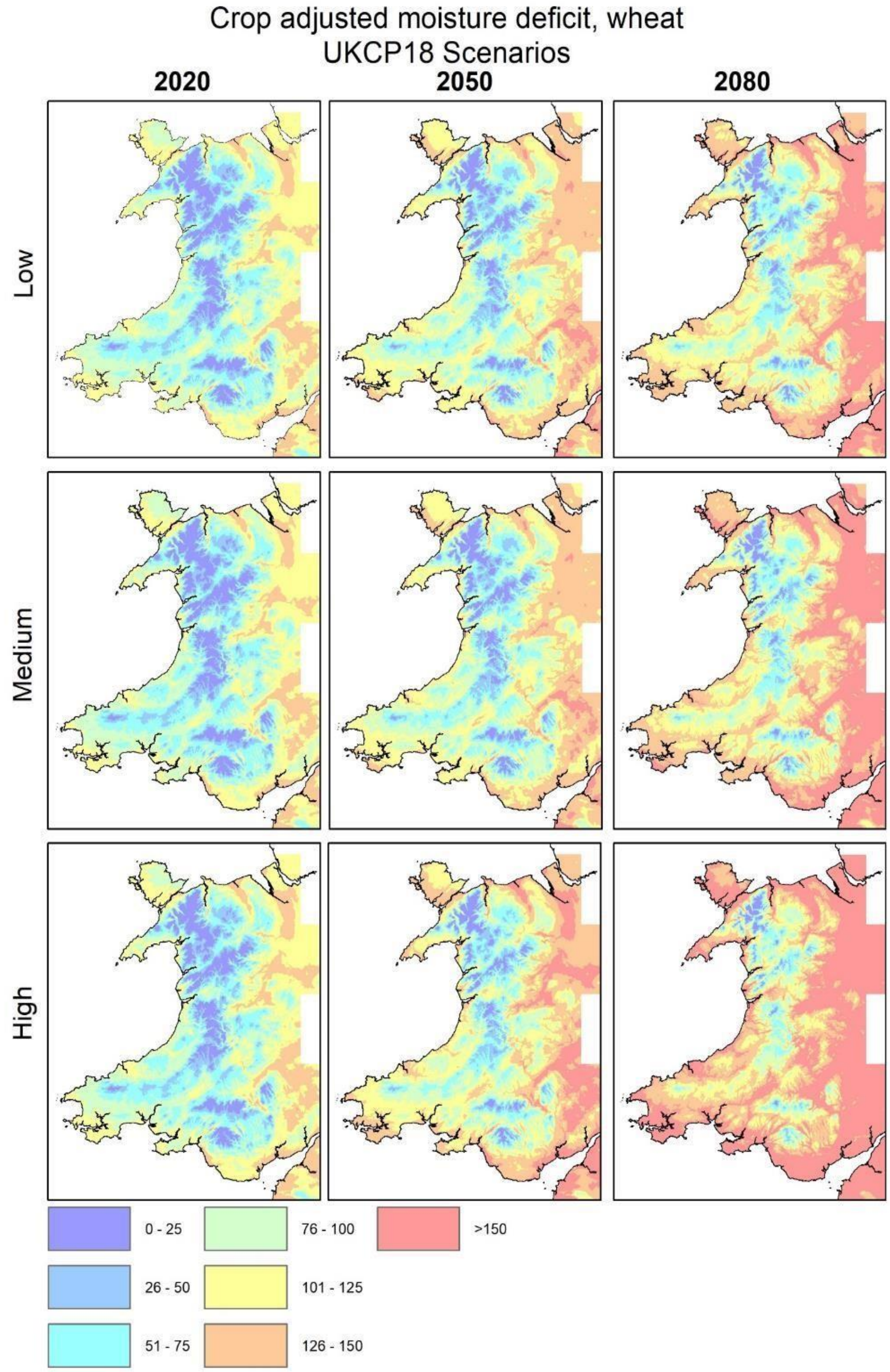

Figure 7 Crop adjusted Moisture deficit, wheat (mm) - MDMWHT - under UKCP18 Scenarios

CONTENTS – PART TWO OF REPORT

SOIL

Author: Dr J Paul Newell- Price Principal Soil Scientist ADAS

Background

The focus of this commentary is on:

1.11 Loss of organic matter

1.12 Soil compaction

1.13 Soil erosion

The modelled outputs from the "Capability, Suitability & Climate Programme" (CSCP) predict a general increase in temperature in 2020, 2050 and 2080. Average annual rainfall changes little over these projected periods, but there is an increase in winter rainfall and a reduction in summer rainfall from 2020 to 2080. The overall number of "Field Capacity Days" (FCDs - when the soil is 'wet', cannot hold any more water against gravity, and with any additional rainfall will start to drain) does not change significantly between 2020 and 2080, but "there may be a delay to the onset of drainage in autumn and a delay to the end of drainage (drier conditions) in the spring". Importantly for soil carbon, there is little change in the duration of FCD in the core upland area of Wales, but there are some subtle decreases in FCDs in border areas.

The increase in temperature and reduction in summer rainfall results in an increase in the droughtiness limitation across Wales, with an increase in land classified as Grade 3b and 4 for drought by 2050 and 2080, particularly in border areas, South Wales, Pembrokeshire and Anglesey by 2080. However, the change in climatic conditions also results in a reduction in soil wetness in many formerly 'wet' areas, resulting in improvements in grade such that in the 2020s and 2050s, despite a reduction in the area of Grade 1 and 2 land (mainly due to droughtiness), there is an overall increase in the area of Best and Most Versatile (BMV) land (Grades 1, 2 and 3a combined), providing opportunities for more arable cropping.

These modelled outputs align with previous assessments, such as Defra projects SP1104 and SP1316. There is a slight reduction in temperature between the UKCP09 predictions used in SP1104 and the UKCP18 data used in CSCP, resulting in a slightly less severe reduction in land grade caused by droughtiness under the UKCP18 predictions. This may have also been partly due to the higher resolution soils data used in CSCP, which was improved by using the new "Soils of Wales" map. Nevertheless, "droughtiness is still the most significant factor in the reduction of Agricultural Land Classification (ALC) grade across England and Wales in the future" (Keay, 2020).

Keay and Hannam (2020) predict no change in the duration of waterlogging or FCD, whereas SP1104 and SP1316 predicted that the duration of waterlogging was likely to reduce due to less rainfall in summer and early autumn, a later return to field capacity and hence shortening the period when the soil is above field capacity and at greatest risk of becoming waterlogged. However, these projects also acknowledge that their projections do not take account of a potential increase in the frequency of extreme events due to climate change, including the possible, but highly uncertain, potential foreshortening of return times for high energy storm events (Leckebusch et al., 2006; Villarini et al., 2011). Future weather variability may be a more relevant feature for changes in land use and soil degradation pressures than the predicted new 'average' conditions.

Further information is available from Climate-Smart Grass (a Research Cluster that ran between 2013 and 2018 from the Sêr Cymru National Research Network for Low Carbon, Energy & Environment: www.nrn-lcee.ac.uk). Climate-SmartGrass analysis confirmed that "hot and wet extremes are becoming more common in south and mid-Wales, suggesting an increased likelihood of flooding and heatwave events". Their analysis also predicts that dry spells will increase in south and mid-Wales, which when coupled with elevated temperature, may increase drought susceptibility.

Changes are also already significant in many other regions of the UK. For example, the eastern parts of the UK have experienced more hot days and less cold days than before, and Scotland has had an increase in wet and warm extremes.

Loss of soil organic matter

Overall soil organic carbon accumulation or depletion depends on the balance over time between the main pathways of gain (principally photosynthesis) and loss (soil/animal/plant respiration, soil erosion and dissolved organic carbon). During the night and during winter months when soil and plant respiration dominates, soils tend to be a CO_2 source, while during the day and during summer months when photosynthetic rates are high, well-drained mineral soils are generally a carbon sink (Zeeman *et al*., 2010). Although the balances are different, the situation is similar for poorly drained soils such as peaty gley soils and peats, which occupy approximately 15% of the land surface in Wales; principally in the hills and uplands (Adams, 2015). These soils tend to be strongly acidic (unless improved by liming) resulting in an organic layer at the surface formed by a combination of a lack of casting earthworms and a very slow rate of plant residue decomposition in topsoils that are 'wet' for long periods of the year. For these soils, the rate of peat/C accumulation or loss depends on the productivity of the system (limited by the acidic conditions and the low vigour of plant species that can survive under these conditions) and the duration of waterlogging during which oxidative breakdown of plant residues is effectively halted (Adams, 2015).

Soils could therefore gain carbon over time due to an increase in productivity (higher rates of photosynthesis) provided that this is not balanced out by higher rates of soil/animal/plant respiration or soil erosion. Indeed, there are a number of processes that could influence C losses and gains over time due to climate change, including changes in precipitation, temperature and CO_2 concentrations, which could all have positive impacts on plant productivity.

Higher CO_2 concentrations in the air activate photosynthesis, decrease photorespiration and decrease stomatal conductance, reducing the transpiration rate, increasing leaf temperature and further increasing photosynthetic rate (Acock, 1990). This increases plant growth and belowground C input, and leads to greater root and microbial activity and respiration (Zak *et al*., 2000). Hungate *et al*. (2009) showed that the effect of elevated atmospheric carbon dioxide concentrations on soil C accumulation increases with the addition of N fertiliser.

Increasing temperature will affect net primary productivity and rates of mineralisation. Dalias *et al*. (2001) found that as well as controlling rates of C mineralisation in soils, increasing temperature can also result in the production of biomass material which is more recalcitrant; a process which could ultimately result in a restriction of the positive effect of increased temperatures on soil carbon dioxide release.

When combined with the effects of changing moisture, which is another important factor driving soil C flux (both photosynthesis and respiration), predicting climate change effects on soil C is challenging, and is illustrated by contradicting findings in the literature including overall decreases (Jabro *et al*. 2008) and no change (Ding *et al*. 2007) in SOC.

Soils that are wet for most of the year can accumulate carbon due to continued photosynthesis (carbon gains) alongside very low mineralisation rates (low rates of loss, under wet and cool conditions). However, due to the complex nature of interacting factors, principally CO_2 concentration, moisture availability and temperature, predictions are very difficult.

Barraclough *et al*. (2015), using National Soils Inventory (NSI) data (1978-1983 to 1995-2003) found that a relatively small proportion of an observed change in soil C could be attributed to changes in climate; only 0-5% for organo-mineral/mineral soils and 9-22% for organic soils. However, using regression models and space-for-time substitution, 'signals' relating to changes in temperature and rainfall were found. In mineral soils, organic carbon content was weakly positively correlated with rainfall, but was insensitive to temperature, while C in organic soils was strongly negatively correlated with temperature, although they also acknowledged that the measured decreases in SOC may be more to do with changes in above ground vegetation, and the related quality of litter material, than the direct effect of temperature on SOC *per se*.

Mineral soils

On this basis, on mineral soils, an increase in temperature and no change to total annual rainfall may not result in SOC changes. Nevertheless, it is possible that an increase in droughtiness (higher soil moisture deficits in the summer) and a resulting reduction in primary production could result in a reduction in SOC contents if the lower productivity (lower CO_2 uptake) in summer was not balanced by higher productivity in the spring and autumn; and this lower overall productivity (C sink) was exacerbated by higher CO_2 losses from ecosystem respiration at night and over winter (C source). However, an eight-year climate impact study in Switzerland that investigated the impact of increasing drought does not support this, particularly when there was no overall change in total annual rainfall (Prechsl et al., 2015). They found that while there were significant reductions in biomass production at grassland sites at 400 m and 2,000 m above sea level (asl) where total annual precipitation was lower, there was no overall reduction in biomass production due to drought (in fact an increase for some periods) at a grassland site at 1,000 m asl where there had been no change in total annual precipitation. All three grasslands were also very resilient in that they recovered rapidly from periods of drought.

This is supported by Fry *et al*. (2014) who investigated the effects of extreme changes in rainfall regimes on ecosystem functioning in a mesotrophic grassland system in Berkshire, south east England. They found that soil extractable P and ecosystem respiration were significantly higher in two rainfall change treatments (prolonged drought with a 30% reduction in rainfall over spring and summer; and a drought/downpour treatments with the same amount of rainfall as the control, but periods of drought followed by downpours), but that on the whole ecosystem functioning in the grassland soil studied was resistant to extreme rainfall changes in the short term (two summers 2009-2010), although they did stress that a prolonged study is needed to measure longer-term impacts.

Organic soils

The Barraclough et al. (2015) study suggests that the predicted increases in temperature may result in overall SOC losses in upland organic soils even if there is little change in the duration of field capacity (FCD) from 2020 to 2080. However, it is important to bear in mind that changes in vegetation may be a more important driver for changes in SOC than temperature. In a re-analysis of Countryside Survey data (1978-2007) Alison *et al*. (2019) found that shifts over time from dwarf shrub (particularly ericoid e.g. heather cover) to grass-dominated habitats were associated with a decline in topsoil carbon.

House *et al*. (2010) also explored the impacts of climate change in the British Uplands. They reported that under low and high Representative Concentration Pathway climate change scenarios, as much as 50% of British Uplands and peatlands will be exposed to pressures from erosion and potential C loss by the end of the 21st century, although process-based model projections are highly uncertain. In their review, House et al. (2010) reflect that over time scales of a few decades, persistent lowering of peatland water tables as a result of drought does not always result in reduced C storage; and that while we have been able to identify and quantify the exposure of upland areas and blanket peat to climate change, we have much less knowledge about the dynamic response of their vegetation and C balance, and current model projections do not give clear results as to how climate change will affect C storage. Nevertheless, they conclude that preserving upland vegetation cover is a key 'win-win' management strategy that will reduce erosion and loss of soil C, and protect a variety of services such as the continued delivery of a high quality water resource.

Interestingly, Adams (2015) and Charman et al. (2013) agreed that the storage of C in peaty gley and peat soils in Wales is likely to be increasing, albeit slowly; at a rate of 250-300 kg C/ha/yr in the case of peatlands.

From 1993 to 2007, Stutter et al. (2011) used long-term soil monitoring datasets to assess trends in Dissolved Organic Carbon (DOC) losses at three UK Environmental Change Network (ECN) moorland sites with contrasting soil types. On a freely-draining podzol they found that soil solution DOC concentrations increased in both surface and subsoil horizons (48% and 215% increases in O and Bs horizons, respectively). By contrast, in a gleyed podzol DOC concentrations declined and in a peat soil there was no change. It was concluded that the effects of the key factors (i.e. ionic strength, acid deposition recovery, soil hydrology and temperature) on DOC solubility could not be separated, but that climate change was probably one of the factors influencing DOC losses.

Other projects have indicated small losses in SOC due to climate change. For example, Defra project SP0571 (Modelling the impact of climate change on soils using UK Climate Projections) predicted relatively small changes in soil C content (-0.003% to -0.02%) in England and Wales over the period 2010 to 2080 using the ECOSSE (Estimating Carbon in Organic Soils - Sequestration and Emissions) model and the HadRM3Q0 climate projection ensemble under a medium Representative Concentration Pathway scenario. For Wales, Abdalla *et al*. (2016), also using the ECOSSE model, reported a small overall increase in SOC losses for all land uses under medium and high Representative Concentration Pathway scenarios to 2050 (-0.003 to -0.013 t CO_2e/ha/yr; changed from a minor sink of 0.013 t CO_2e/ha/yr under the 1961-1990 baseline scenario), but that this was negated by uptake of CH_4 under both climate change scenarios.

Defra project SP0571 concluded that "based on the recent observed rates of soil C change it is likely that other drivers (e.g. land use/management) have a greater potential to affect soil C stocks than climate change". This is supported by Richards *et al*. (2017) who modelled greenhouse gas (GHG) emissions from land-use change in the UK. Indeed, within the 2020 to 2080 time frame it is the possible changes in land use induced by changes in land grade (e.g. grassland to arable or horticultural production) that are more likely to result in SOC changes than climate change itself. Conversion from grassland to arable or horticultural production will inevitably result in SOC losses. However, due to physical limitations such as topography, stoniness and shallowness of soils, land use changes in Wales are not practicable on a large scale (Adams, 2015).

Soil compaction

Soil compaction occurs when soils are worked, vehicles traffic over the land or livestock are grazed in 'wet' field conditions. Holman *et al*. (2003), examined soils prone to structural damage in England and Wales under five common lowland cropping systems: autumn-sown crops, late-harvested crops, field vegetables, orchards and sheep fattening/livestock rearing systems. It was demonstrated that soil structural degradation was prevalent over a wide range of soil types and land uses, with soil structural damage widespread across all five land uses.

The UKCP18 scenarios predict a similar length of the FC period, but a possible delay to the onset of drainage in autumn, wetter winters overall and a delay to the end of drainage in spring. Soil wetness is also predicted to decrease by one wetness class (improvement) in some areas along the border with England and on the west coast. Such a general pattern could result in a lower risk of compaction in the autumn, but a possible increase over winter months and in the spring. This risk would be exacerbated if higher temperatures and improvement in land grade in some areas results in more widespread extended grazing or the growing of forage crops such as fodder beet (for winter grazing) or indeed the growing of spring crops on land that was previously only suitable for grassland (e.g. land that is currently grade 3b or 4 due to soil wetness becoming grade 3b or 3a).

Defra projects SP1104 and SP1315 reported that “the number of field capacity days will decrease (on average) in the period 2020-2080 under three future climate scenarios”. Without any changes to land management or use, this would result in a lower risk of compaction. However, SP1315 also found that “despite a likely reduction in the duration of waterlogging, it is possible that projected increases in winter rainfall in future could increase the severity of waterlogging due to larger winter rainfall volumes overwhelming drainage systems”.

Climate change in Wales may also be characterised by greater unpredictability and variability of weather pattern, which would also increase the risks of soil compaction if prolonged waterlogging became more frequent. Such weather variability would also influence the types of crop rotations and farming systems that farmers are likely to adopt (e.g. Nesbitt *et al*., 2016).

Defra project SP0571 used the Workable Days model of Cooper *et al*. (1997) to predict changes in soil compaction risk associated with climate change. Using a definition of ‘Workable Days’ as days drier than field capacity, and using HadRM3 climate projections combined with the JULES land surface water and energy budget model (Blyth *et al*., 2010), they found that soils would be slightly less vulnerable to compaction. However, they concluded that in some regions, such as southwest England and Wales, localised risk of soil compaction will remain into the future because of very few winter workable days. In other areas such as eastern, central and southern England the reverse was true, with an increase in the number of winter workable days and therefore a slightly lower risk of compaction for many crops.

Soil erosion

For soil erosion, the most relevant changes in climate and knock-on effects on land grade, use and management are potential changes in rainfall intensity, rainfall timing, vegetation cover and soil structural degradation. Increases in rainfall intensity and winter rainfall could have a profound effect, particularly if land use change results in a greater area of cultivated land, and more bare soil on sloping land.

The driving force of water erosion is rainfall, specifically rainfall kinetic energy (KE). Davison *et al*. (2005) found that for 1961-1990 climatic data, overall rainfall kinetic energy (KE) was highly correlated with total daily rainfall, and most of the observed variation in rainfall KE was explained by variations in rainfall quantity. Indeed, for the UK as a whole daily rainfall totals can accurately reflect the differences in mean rainfall KE between locations.

In terms of seasonality, there was a clear pattern in England and Wales with higher KE per mm of rain in the late summer and autumn months (July, August, and September) when the majority of intense storms occur, and lower values in the winter months indicating less intense but more prolonged rainfall events (Davison *et al*., 2005). This has important implications for the seasonality of risks, with greatest risk occurring when bare soil on sloping land coincides with late summer and autumn storms. However, in the future, higher rainfall volumes and possibly higher intensity in winter months could also be an issue if this coincides with bare soil due to more widespread winter sown crops, extended grazing or grazed fodder crops on better grade land.

This is supported by Nearing *et al*. (2004) who stated that at a global scale "rainfall amounts and intensities are expected to continue to increase during the 21st century. These rainfall changes will have significant impacts on soil erosion rates. The processes involved in the impact of climate change on soil erosion by water are complex, involving changes in rainfall amounts and intensities, number of days of precipitation, ratio of rain to snow, plant biomass production, plant residue composition rates, soil microbial activity, evapotranspiration rates, and shifts in land use necessary to accommodate a new climatic regime. Results show cause for concern." To this mix we can also add the land use changes needed to meet current policy targets for woodland.

The complexity of interacting abiotic factors mean that the most predictable factor affecting future soil erosion risk is probably the potential change in land use associated with improved land grade (warmer and drier conditions), from predominantly grassland systems to arable or horticultural systems (i.e. conversion "from continuous to discontinuous vegetation cover over a growing season": Keay and Hannam, 2020). However, a trend to more extended grazing and out wintering in grassland systems due to warmer conditions and an extended grass growing period could also increase the risk of livestock poaching and associated surface runoff and erosion on sloping land, particularly if winters are anticipated to be wetter and FCD similar to 1981-2010.

A number of previous studies support this theory. For example, Defra project SP0571 (Modelling the impact of climate change on soils using UK Climate Projections) used the PESERA (Pan–European Soil Erosion Risk Assessment) model to assess impacts of climate change projections on soil erosion. The results indicated a projected increase in (spatially averaged) erosion to the end of the century due to increased winter rainfall. Increases were predicted to be greatest in upland areas of England and Wales.

Boardman *et al*. (1990) stated that "water erosion rates on arable land in the lowlands will increase markedly in severity, frequency and extent especially if land use changes". By contrast, for the uplands they predicted that "climatic warming suggests a longer growing season and fewer frosts: these may lead to a decrease in erosion of overgrazed eroding slopes", implying that other factors such as stocking rates may be a more important factor than global warming for erosion risk in the uplands.

Using the Water Erosion Prediction Project (WEPP) model, Mullan (2013) considered the impacts of climate change in isolation and when various land use changes scenarios were taken into account. The results indicated a mix of soil erosion increases and decreases, depending on which scenarios were considered. Considering climate change projections in isolation generally resulted in erosion decreases, whereas large increases were projected under many scenarios that accounted for changes in rainfall intensity and land use.

Nevertheless, based on a summary of opinions on priorities for soil erosion research, GarcÍa-Ruiz *et al*. (2015) stated that further long-term monitoring was required to better understand the typical magnitude and variability in observed soil erosion rates and to improve the modelling of "soil erosion rates and sediment yield at regional scales under present and future climate and land use scenarios". Benaud *et al*. (2020) provide some useful insight into "the development of soil erosion research, formulation of effective policy and better protection of soil resources" in the UK. This includes addressing the current "skew in existing studies towards locations with a known erosion likelihood and methods that are biased towards single erosion pathways, rather than an all-inclusive study of erosion rates and processes".

Comparison of ALC interpolated UKCP18 data with the current evidence base.

This section looks at soil degradation in particular.

The impact of climate change on Welsh soils.

Without any changes in land use we may expect small declines in soil organic matter, particularly in organic soils. This mainly concerns the peaty gleys and peatlands in the hills and uplands of Wales, which occupy around 15% of the land surface and store around 35% of the carbon in Welsh soils (Adams, 2015). They include peaty gley Wilcocks series on slopes less than 7^{o}, with organic horizons of around 15-40 cm depth; and peats mainly of the Crowdy series in water receiving hollows, valley bottoms and on some flat hill plateaux, with organic horizons of around 40 cm to several metres deep. However, organic soils also include some humose gleys that occupy a few shallowly sloping valley sites or flat plateaux in the lowlands and peaty podzols of the Hafren and Hiraethog series in the uplands, on slopes more than 7^{o} with an organic surface layer typically 7-15 cm deep, (but in some cases only 1-2 cm). Together, these humose gleys and podzols occupy around 15% of Wales and store around 20% of the carbon.

Soil compaction and soil erosion risk would increase to a small degree due to wetter winters and a possible increase in the frequency of intense (high KE) rainfall events. However, when combined with possible changes in land use due to improvements in land grade and a larger overall area of best and most versatile land, the changes could be more significant, particularly in those areas where soil wetness is reduced and land grade enables cultivation. An extended growing season due to higher temperatures could exacerbate these risks if it results in more widespread extended grazing and growing of maize and winter fodder crops, although the growing of maize in Wales is restricted to some extent, by the physical limitations of topography, stoniness and shallow soils. More widespread arable cropping and extended grazing could be compensated to some extent by formerly BMV land becoming more droughty and unable to support commercially viable crop production without irrigation (although what is 'commercially viable' may also change in the future). This land could be reverted to nature conservation or woodland.

The impact of climate change on English and Welsh soils.

Increased droughtiness in the east of England could make BMV land in western England and Wales even more important for food production. The risks for soil degradation would be as stated above such that if and when grasslands are cultivated to enable arable or horticultural production, appropriate mitigation strategies should be put in place to reduce the risk of SOM loss, compaction and erosion. To conserve soil quality, mixed farming systems could be favoured and the most valuable (*cf*. natural capital valuation) permanent grasslands preserved.

The impact of changes in annual and seasonal rainfall on soils.

Total rainfall is not expected to change under future climate change scenarios, but winters are expected to be wetter and summers drier. In themselves, these changes would not be expected to result in even moderate changes in soil organic matter unless the increased droughtiness in summer is not compensated for by higher growth (photosynthetic rate) in the spring and autumn; or the change in rainfall patterns resulted in changes to vegetation in the uplands. However, soil erosion and compaction risk would increase by a small amount due to higher winter rainfall quantities and wetter soils in the winter and spring. As above, when the changes in land grade and possible changes in land use are superimposed onto the changes in annual rainfall the risks for soil degradation could be significantly increased.

The impact of changes in temperature on soils

Higher temperatures could result in higher C losses from organic soils with little if any change in mineral soils. There would also be an increase in productivity in some areas, but this in itself would not result in greater risk in soil compaction and erosion unless it was aligned with changes in land use or management resulting in periods when the soil is bare (i.e. conversion "from continuous to discontinuous vegetation cover over a growing season"). The potential changes in land use and management would also have implications for SOM loss in all soil types.

How are the sectors preparing for change?

All sectors are being advised to increase the resilience of their production systems. For grasslands, this means considering increasing sward diversity, including introducing deep rooting herbs and legumes; avoiding soil compaction where possible; using low ground pressure tyres; introducing rotational grazing; adjusting stocking rates (this may be increased or decreased depending on the context and the carrying capacity of the land); increasing shelter through sylvopastoral techniques; and using grazing techniques such as leader-follower or mixed grazing practices. Grassland farmers are also advised to consider the suitability of land for growing crops with a higher erosion risk such as maize and fodder beet, particularly where livestock are grazed on the latter over winter. For maize crops, early maturing varieties are generally favoured and some farmers are already using oversown cover crops to protect the soil post-harvest. Other ways of increasing resilience can include more diverse rotations across the farm, and within fields, as well as practices such as reduced tillage, cover cropping and companion cropping. Any practices that increase soil organic matter, such as the regular application of organic manures or the regular growing of cover crops or green manures, will generally increase resilience and reduce reliance on inputs (Abdollahi & Munkholm, 2014; Gregory *et al*., 2009; Powlson *et al*., 2011; Powlson *et al*., 2012; Bhogal *et al*., 2009).

How are the sectors being made more resilient to change?

A number of Defra projects have provided information on how agriculture may have to adapt to climate change. These include Defra projects:

- SP1316 (2015) on "identifying the soil protection benefits and impact on productivity provided by the access to waterlogged land requirements in cross compliance and exploring the impacts of prolonged waterlogging on soil quality and productivity";
- AC0302 (2009) on "a research and innovation network supporting adaptation in agriculture to Climate Change";

- AC0308 (2006) on "ecosystem services for climate change adaptation in land management"; and
- CA0511 (2012) on the "role of payments for ecosystems services in climate change adaptation".

Rivington *et al*. (2013) reported that potential restricted water availability may have implications for irrigation and SOC strategies and a shift to drier soil conditions in autumn and wetter soils in spring may alter crop rotation choices (i.e. more winter cropping), although this is in fact the opposite of recent experience (e.g. 2012-13 and 2019-20), and many farmers are currently anticipating the need for more spring cropping, particularly on heavier soils.

Falloon & Betts (2010) also anticipated that increased flooding and waterlogging risk (mainly in winter) and summer irrigation shortages may present challenges for agriculture. Although the need for effective adaptation could be greatest in southern Europe, all regions should benefit from strategies to increase SOC levels to improve the resistance and resilience of soils to extreme weather events.

Defra project SP1316 concluded that adaptations that could contribute to improving farm profitability and make farm systems more resilient to climate change included:

- Replacing and maintaining field drainage systems on slowly permeable soils
- Applying bulky organic manures to improve soil resistance and resilience
- Avoidance of compaction, including the use of low ground pressure tyres in suitable field conditions
- Visual assessment of soils combined with timely use of sub-soilers and top-soilers, where appropriate
- The use of more efficient machinery to establish crops more rapidly, particularly on larger farms

Adaptation in grassland, peatland and upland systems

Hopkins and Del Prado (2007) identified adaption strategies in grassland systems as a response to projected climate change that is likely to increase herbage growth (Lee et al., 2010) and to favour legumes more than grasses, but limit moisture supply. Further implications for grasslands may arise from increased frequency of droughts, storms and other extreme events (Hopkins and Wilkins, 2006).

Data and information that is currently missing

Information on predicted changes in land use would probably be of most value. Can we gain a better understanding of where the main changes will be (grassland to arable; agriculture to woodland)? What will the response to increase doughtiness be? Will it result in more irrigation or more nature conservation? Any increase in irrigation should be aligned with a policy to support the uptake of sustainable water use efficient irrigation systems. The degree of soil degradation will vary according to water and food production (self-sufficiency and commercial opportunity) pressures in each region and the policy that is implemented to mitigate market effects.

Additional project work required to inform decision making.

Defra project SP0556 ('A compendium of peat restoration and management projects', 2008) highlighted that monitoring of peatland restoration progress is essential to ensure that restoration work objectives are achieved including the provision of a data resource that can be analysed to inform best practice.

For SOC, Barraclough *et al*. (2015) recommended that future monitoring of SOC stocks should focus on soils with soil C concentrations above 250 and 435 g kg^{-1} (i.e. 25-43.5% soil carbon or 40-75% organic matter). This mainly concerns peaty podzols, peaty gleys and peats of the hills and uplands of Wales that occupy *c*. 20% of Wales and store approximately 40% of the carbon in Welsh soils.

Monitoring of soil compaction (soil structure and bulk density) and soil erosion (soil depth and soil erosion features) will be important to determine whether any changes in the nature and timing of rainfall, and its relationship with soil management practices, is affecting the severity of these degradation processes.

For soil erosion, Benaud *et al*. (2020) suggested that the following criteria should be applied to a national scale soil erosion monitoring programme to include "replicable, comparable and robust studies:

1. Unbiased statistical sampling design (as opposed to monitoring erosion where it is known to occur).
2. Including a representative range of environmental conditions from upland to lowland land use and farming practices.
3. Quantifying both visible (i.e. convergent) and less-visible (i.e. diffuse) erosion pathways.
4. Capturing the seasonal and inter-annual variability of erosion rates.
5. Representing a selection of land use categories, including emerging land use under changing climates (for example, vineyards and fodder or biofuel crops such as maize/miscanthus).
6. Standardising erosion measurements (per unit space and time i.e. t/ha/yr) to ensure that results are comparable nationwide, as the same (and best) techniques are deployed.
7. Consistent reporting of environmental and management conditions (for example, precipitation totals and intensities, soil texture and tillage practices)"

Conclusions

The greatest risk to soil quality is the impact that climate change will have on land grade and the potential changes in land use and management that could have knock-on effects for SOC loss, erosion and compaction. There may be some direct impacts of climate change on the main degradation pressures, but these are likely to be small relative to the potential changes in vegetation and land use. A better understanding of where land-use changes are most likely to occur and what those changes are likely to be will therefore be most important in establishing the potential for soil degradation.

Defra projects

Defra SP0556 - A compendium of peat restoration and management projects

Defra project SP0571 - Modelling the impact of climate change on soils using UK Climate Projections

Defra project SP1104 - The impact of climate change on the suitability of soils for agriculture as defined by the Agricultural Land Classification

Defra project SP1315 - Post Harvest Management for soil degradation reduction in agricultural soils: methods, occurrence, cost and benefits.

Defra project SP1316 - Identifying the soil protection benefits and impact on productivity provided by the access to waterlogged land requirements in cross compliance and exploring the impacts of prolonged waterlogging on soil quality and productivity.

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WELSH PEATLAND

Author: Chris Forster Brown Principal Ecologist

Background information

This section considers the potential impact of climate change on peatland, across Wales. For the purposes of this report, peatland in Wales comprises four Section 7 list Habitats (of principal importance for the purpose of maintaining and enhancing biodiversity in Wales under Section 7 of the Environment (Wales) Act 2016). These are blanket bog, lowland raised bog, lowland fen and upland fens and flushes. It is important to discuss peatland in terms of these constituent Section 7 Habitats as they are, for the most part, topographically and geographically distinct. Therefore, they may have very different projected responses to climate change. Each of these Section 7 Habitats will be described in terms of its geographical distribution, as well as with reference to the underlying climatic conditions favouring its distribution. Bogs in particular, are intimately connected with current and historical climatic conditions, often extending back over millennia. Indeed, climate is integral to their formation, in terms of rainfall and temperature. Based on evidence from pollen records, they have shown wide variation in species composition over time, dependent on prevailing climate conditions, as well as human activity and more recently, nitrogen deposition.[1] The report will attempt to draw out particularly Welsh examples or variations of these habitats, for example the large coastal raised bog at Cors Fochno, the Anglesey and Lleyn fens and the preponderance of purple moor-grass across much of the blanket bog in mid and south Wales. Peatland habitats are important constituents of the overall fabric of the Welsh countryside. At the same time, they have been subject to wide variation in management and this needs to be taken into account when reviewing their likely responses to climate change.

Throughout the report, the emphasis will be on examples of these habitats that are projected to show the greatest changes under the various permutations of climate change. A section is also provided on how the changes anticipated under climate change may be best ameliorated. It should be emphasised that the majority of change scenarios are based on predictions and projections and it is difficult to say with certainty what the exact impacts will be for these habitats. Scott (2016) summarises these difficulties in relation to montane habitats (and by extension, other upland habitats). He states that whilst climate change will impact on montane habitats, the exact dynamics of this change will result from a 'complex interrelationship between summer and winter temperatures, occurrence of frost, duration of snow-lie, distribution of rainfall throughout the year and how windy it is'.[2]

In general, the report does not discuss associated species, other than the vegetation that provides the essential make-up of the habitat. However, dependent species are inextricably linked with the habitat itself and climate change impacts on habitat will also be felt by associated species.

Blanket bog

The blanket bog Section 7 Habitat is associated particularly with the main mountain massifs in Wales. These include the Brecon Beacons National Park, Elenydd and Pumlumon in Ceredigion, Llanbrynmair in Powys, Berwyn and Mynydd Hiraethog in the north-east, and the Rhinogs, Migneint and Carneddau in Snowdonia. It reaches its greatest extent on poorly-

[1] Lindsay R (2009) Peatbogs and carbon: a critical synthesis. RSPB Scotland, Edinburgh

[2] Scott, M. (2016). Mountain Flowers. Bloomsbury Natural History

drained upland plateaux over 250m altitude. The total area of blanket peat in Wales is estimated at 70,000ha.[3]

Blanket bog is found in the wettest areas of Wales, where annual precipitation exceeds 1200mm. Annual mean temperatures are also low compared to most other Section 7 Habitats. Blanket bog is an ombrotrophic habitat (i.e. dependent on atmospheric moisture for its nutrients). To this end, precipitation is key in both its development and maintenance. This would include rain, snow and mist. It should be noted however, that it is the number of precipitation days that is the critical factor rather than the overall volume of rain/snow/mist.[4] To maintain optimum condition, blanket bog should be subject to a minimum of 160 days of rain per year. Evapotranspiration is kept low by the prevailing cool and/or wet conditions and should be exceeded by rainfall (i.e. on an annual water balance basis). Precipitation chemistry is also important, for example the amount of nitrogen in the rain.[5]

Good quality blanket bog typically comprises a range of ericaceous sub-shrubs, interspersed with cottongrasses, deergrass and a reasonable representation of sphagnum (bog-mosses). The proportions of each of these vary, according to altitude, aspect and degree of degradation. On higher plateaux, the plagioclimax community has a greater representation of heather and lower extent of sphagnum. Lower altitude blanket bog is dominated by hare's-tail cottongrass, deergrass and a high proportion of sphagna. These last are particularly well represented by *Sphagnum papillosum* and *S. capillifolium*, both of which form hummocks. In between these hummocks, in good quality blanket bog, are pools, largely dominated by sphagnum species (particularly *S. cuspidatum*). Bog pools are intimately associated with some of the best examples of this Section 7 Habitat, though are rather rare in Welsh blanket bog. In addition, a number of other Section 7 Habitats, such as upland fens and flushes and upland heathland, can occur in and around the edges of blanket bog, depending on the local topography and other factors.

The Section 7 Habitat blanket bog also encompasses more modified examples of peatland. Jones et al (2003) argue that well over half of the Welsh resource of blanket bog consists of habitat that is at least partially modified. Modified bog occurs where a history of overgrazing (or other unfavourable grazing regimes), coupled with burning and drainage causes a shift in the characteristic blend of species towards graminoid or ericoid dominance[6]. Thus, sphagna species are much reduced in frequency. Whilst hare's-tail cottongrass can become dominant in some degraded bogs, in others, it can become very subordinate to more competitive species. In addition, ericoids (e.g. heather) tend to be more uncommon in modified bog, though in other contexts (e.g. on some drained sites) can assume dominance over other elements. A particular phenomenon in Wales is that purple moor-grass can become abundant over large areas of wet modified bog. Whilst the management factors mentioned above have obviously benefitted this species, it also appears to be particularly favoured by the wet oceanic climate of mid and south Wales. Large areas of wet modified bog, dominated by purple moor-grass, with few associated 'bog species', are extensive in much

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[3] Jones, P.S., Stevens, D.P., Blackstock, T.H., Burrows, C.R. and Howe, E.A. (2003). Priority Habitats of Wales a technical guide. Countryside Council for Wales, Bangor

[4] Natural England and RSPB, 2014. Climate Change Adaptation Manual

[5] Caporn, S.J.M. and Emmett, B.A. 2009. Threats from air pollution and climate change to upland

systems. In Drivers of Environmental Change in Uplands (Bonn, A., Allott, T., Hubacek, K. And Stewart,

J.Eds), Routledge. Abingdon. Oxon.

[6] Yeo, M.J.M. (1997). Blanket mire degradation in Wales. In: Blanket Mire Degradation: Causes, Consequences and Challenges. Eds: J.H. Tallis, R. Meade & P.D. Hulme. Mires Research Group, British Ecological Society, pp 101-115

of the uplands of south and mid Wales. Purple moor-grass flourishes where bog has been at least partly drained and is perhaps also favoured by run-off. In Wales, modified bog with abundant purple moor-grass occurs predominantly in the upland fringes (though can occur rarely up to 600m).[7]

Lowland Raised Bog

Lowland raised bog is scattered throughout Wales, with the total area previously estimated as 4,068 ha.[8] Natural Resources Wales' recent Lowland Peatland Survey has however, doubled the number of known sites to around 55. Most examples are small sites, less than 10ha in extent. In contrast, by far the two largest sites, making up some 60% of the total resource of this Section 7 Habitat, are found in Ceredigion. These are Cors Fochno and Cors Caron. A third large site, on the eastern Wales/England border (and partially in England), is the Fenns, Whixall and Bettisfield Mosses. The majority of the lowland raised bogs in Wales, and certainly, the large examples, are all found in lowland situations, below 200m. Cors Fochno is at a particularly low altitude, occurring at sea level. It forms the largest UK example of near-natural raised bog in an estuarine context. Smaller examples are also found in the uplands, usually developing in small basins and on concave slopes, as well as on poorly drained upland plateaux. These are often juxtaposed with blanket bog.

Lowland raised bog consists of a low sward of ericoid dwarf shrubs, cottongrasses and sphagnum species. The best quality areas support an almost continuous cover of sphagna species, with particular representation of *Sphagnum papillosum* and *S. capillifolium* forming hummocks, interspersed with bog pools, dominated by *S. cuspidatum*. In contrast to blanket bog in Wales, a number of additional sphagna species are more or less confined to raised bog. These are *S. austinii*, *S. affine* and *S. pulchrum*, and all rare species in Wales as a whole. In addition, a small suite of vascular plants are found principally in lowland raised bog situations. These include bog-rosemary, bog myrtle and brown beak-sedge. The oceanic influence at Cors Fochno increases the diversity of species, with transitional communities supporting such species as black bog-rush.

In general, lowland raised bog, in common with blanket bog, is found in the wettest areas of Wales, where annual precipitation exceeds 1200mm. The exception to this is the (much further east) example at Fenns, Whixall and Bettisfield Mosses, where annual precipitation is much less than 1000mm. The low altitude of most examples means that annual mean temperatures are higher than for blanket bog communities. As for blanket bog, lowland raised bog is largely maintained through frequency of precipitation. To maintain optimum condition, raised bog should be subject to a minimum of 160 days of rain per year. All examples, excluding the eastern one at Fenns, Whixall and Bettisfield Mosses, are subject to this number of days. This eastern example is subject to a lower total of 140 days per year.

Degraded examples of lowland raised bog are widespread, either as standalone features in the landscape, or contiguous with examples of more intact habitat. A similar suite of vegetation communities as for blanket bogs develops under conditions of heavy grazing, burning and/or drainage. The comparative accessibility of lowland raised bogs compared to their upland blanket bog counterparts, means that drainage is a particular issue. Surrounding intensive agricultural use is a key threat to this habitat. Degraded bog can

[7] Averis, A., Averis, B., Birks, J., Horsfield, D., Thompson, D. and Yeo, M. 2004. An Illustrated Guide to British Upland Vegetation. Joint Nature Conservation Committee

[8] Lindsay, R.A. and Immirzi, C.P. (1996). *An inventory of lowland raised bogs in Great Britain*. SNH Research, Survey and Monitoring Report No. 78, Scottish Natural Heritage, Edinburgh.

support areas variously dominated by purple moor-grass, hare's-tail cottongrass and, more locally, wet woodland.

Lowland Fen

Lowland fens are peat or mineral-based wetlands that are found, in various forms, throughout Wales, with particular concentrations in the west. A range of topographical and hydrological features are encompassed by the term fen. Larger fen types include valley, basin and floodplain mires. The distinction between these is somewhat ill-defined. However, important examples of basin fens are found in Anglesey and Lleyn, as well as Carmarthen and Ceredigion. Crymlyn bog is another large basin fen, situated in a glacial depression near Swansea. Valley fens are found on the lower slopes and floors of valleys, again with concentrations in the west (Ceredigion, Snowdonia, Anglesey and Gwynedd). Floodplain fens have tended to be under-recorded but are found on river or stream floodplains, though often much modified by agricultural reclamation and river defences. Thus, the character of individual fens is determined by both landscape setting but also by the quantity, quality and chemistry of the water that supplies them. What unites all of these examples is the fact that, in contrast to bogs, they receive their water and nutrients through soligenous means i.e. through ground and/or surface water sources. In all cases, this supply of 'high quality' water is critical in maintaining their structural and functional integrity. They are thus particularly vulnerable to nutrient enrichment, including enrichment from surrounding farmland.

From a vegetation/water chemistry standpoint, Wales supports two particularly significant fen categories. These are calcareous fens and alkaline fens. The former is found principally in the fen systems of Anglesey, along with the example at Crumlyn. These tend to be dominated by stands of great fen-sedge, a species dependent on shallow, standing base-rich water[9] (Rodwell, 1995). Great fen-sedge stands become particularly well developed in conditions of high calcium and low nitrate-nitrogen and phosphate.[10] Alkaline fens are variously dominated by bottle sedge, black-bog rush, blunt-flowered rush and species of 'brown moss'[11] They are often strongly influenced by the underlying geological conditions (e.g. Carboniferous limestone) and are fed by calcareous groundwater arising from springs and more diffuse seepage zones.

Upland Fen and Flushes

Upland fens and flushes are usually small, discrete features, found in juxtaposition with blanket bog and mosaics of upland heath and grassland. Occasionally they can occur as extensive soligenous complexes. They are widespread in Wales, particularly towards the west. As with lowland fen, they are dependent on the through-flow of water from external sources and exhibit a range of pH and mineral variables. The majority of Welsh examples are of a lower pH and are termed 'acid flushes'. More basic and/or neutral flushes also occur and very occasional bryophyte-dominated springs. Basic flushes are a particular feature of the Brecon Beacons, as well as in other areas that are influenced by underlying base-rich geology.

[9] Rodwell, J.S. (1991). British plant communities. Vol. 2 Mires and heaths. Cambridge University Press

[10] Phillips, G. L. 1977. The mineral nutrient levels in three Norfolk Broads differing in trophic status, and an annual mineral content budget for one of them. Journal of Ecology, 65, 447 - 74

[11] Brown moss communities encompass species in the genera *Drepanocladus*, *Calliergon*, *Scorpidium* and *Campylium*

Comparison of ALC interpolated UKCP18 data with the current evidence base.

The Welsh Government's latest thinking (derived from that of the IPCC) is that Wales is most likely aligned to projected impacts of a low-medium Representative Concentration Pathway scenario by the 2080s. This projection would result in a temperature increase of between 2.2°C and 2.6°C by 2100, as opposed to a temperature increase of ~4.3°C in a high Representative Concentration Pathway scenario. However, a low-medium Representative Concentration Pathway scenario is not simply an outcome of climate action in the UK, but is subject to considerable action being taken globally to reduce greenhouse gas emissions. This includes action being taken by all nations, including the world's largest emitters (e.g. USA and China) who are not currently part of the Paris Agreement, to actively transition to such pathways.

The impacts associated with the latest climate projections under a low-medium Representative Concentration Pathway scenario could be experienced within any given year within the period of assessment. However, ongoing changes to the climate will create more favourable conditions that will increase the likelihood of extreme events and climate changes occurring, including changes in the frequency and magnitude of such events.

This assessment considers the Cranfield projections for 2020 (2010 to 2039) and 2050 (2040 to 2069) under a low and medium Representative Concentration Pathway scenario, which reflect a global mean temperature increase of 2.2°C and 2.6°C respectively by 2100.

What do the scenarios mean for habitats in Wales

Overview of impacts on habitats

This section provides an overview of the types of change envisaged as a result of climate change to habitats in the UK (and by extension, Wales). More detailed assessments, in relation to peatland habitats, are outlined in the sections following. These are discussed according to the different projections for severe weather, rainfall and temperature. The following themes are important in assessing the potential effects of climate change to peatland habitats in Wales:

- A shift in many species further north and at higher altitudes
- Slow dispersal ability of many plant species
- Warmer springs leading to potential phenological mismatches (flowering times, etc.)
- Changes to the composition of plant communities
- Different species responses to changes in precipitation
- Particular vulnerability of individual habitats e.g. montane
- Increased risk of spread of Invasive Non Native Species (INNs)
- Increased risk of wildfires

An overarching theme that runs alongside all these potential changes, is that of land management. Peatland habitats that are already under stress through sub-optimal management are more likely to suffer detrimental impacts from climate change. In addition, land management may be the critical factor for some peatland habitats and for this reason, assumes greater importance than the effects of climate change. Where detrimental land management factors are considered to be key to a peatland habitat's current status, this is highlighted in the text.

Impact of severe weather across England and Wales

The Met Office categorises the weather in Wales as a maritime climate, characterised by weather that is often cloudy, wet and windy, but mild. However, the shape of the coastline, and the central spine of high ground from Snowdonia southwards to the Brecon Beacons, introduce localised differences. Whilst some upland areas can experience harsh weather, the coasts enjoy more favourable conditions, and areas in east Wales are more sheltered with weather similar to neighbouring English counties.[12]

The key impacts of extreme weather events in relation to peatland habitats are largely centred on heavy (and prolonged) rainfall. Thus, heavy rainfall in the uplands can lead to increased erosion and landslip of peatland habitats. Existing gullying can rapidly be deepened and lead to peat slide. In the most dramatic cases, bog burst could occur. This is where an area of peatland is already under pressure from factors such as overgrazing, drainage or potentially wind farm construction. Heavy rain can cause the living plant layer on top of the peat to tear, and large areas of bare peat then slip under gravity.

Persistent flooding as a result of heavy rain is potentially more problematic for raised bog sites. A number of these are at low levels and associated with sizeable watercourses. Should these flood, the raised bog can be rapidly inundated. Prolonged flooding could potentially lead to changes in vegetation composition, particularly where floodwater contains high levels of Phosphorus and Nitrogen. The fact that most lowland raised bogs are surrounded by more intensive agriculture means that they are particularly vulnerable to diffuse pollution issues as a result of flooding.

Persistent flooding and over long periods, is also detrimental to those habitats that require intermittently high water tables. These include lowland fen. For example, a long-term very high water table affecting a fen site would favour species suited to high levels of inundation at the expense of species that are not suited to these conditions. As with raised bogs, such events could also increase nutrient input to the systems, with concomitant effects on species composition.

Tidal surges could potentially have a very large impact on the coastal raised bog of Cors Fochno. Such surges could lead to increased erosion and fragmentation, particularly at the edges of this bog. However, it is highly likely that, before the advent of coastal sea defences and the canalisation of the rivers close to Cors Fochno, that it was regularly partially inundated with salt water. This was only likely to have affected transitional areas of the bog, though has undoubtedly led to the presence of vegetation communities of high value that would otherwise not have been there. The current bog is largely lacking these saline influences.

Impact of projected changes in annual, seasonal and extreme rainfall

Rainfall in Wales varies widely, with the highest average annual totals being recorded in the central upland spine from Snowdonia to the Brecon Beacons. Snowdonia is the wettest area with average annual totals exceeding 3,000 mm. In contrast, areas along the coast and,

[12] Met Office - Wales: climate. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/Wales_-climate---met-office.pdf [Accessed 17 Apr. 2020]

particularly, close to the border with England, are drier, receiving less than 1,000 mm a year.[13]

Annual rainfall

UK Climate Projections 2018 (UKCP18) suggest that, compared with current year-to-year variations, average annual rainfall (AAR) is not expected to differ a highly significant amount. However, the seasonality of when rainfall occurs is expected to change, with typically warmer, wetter winters and hotter, drier summers. Therefore, the assessment of seasonal differences is more important than very slight variations in annual rainfall.

The low Representative Concentration Pathway scenario for 2020 and 2050 AAR show very limited detectable change compared to the baseline. The medium Representative Concentration Pathway scenario also shows very limited change to AAR in 2020, with only slight increases in the expansion of the 1,001-1,500 mm category around the fringes of south Wales in 2050. There is not expected to be any significant, discernible impacts on habitats associated directly with changes in AAR.

Average summer rainfall

UKCP18 suggest that average summer rainfall (ASR) in the UK is expected to decrease significantly, with the greatest changes associated with higher Representative Concentration Pathway scenarios. However, when it rains in summer there may be more intense storms,[14] and thunderstorms (due to a combination of moisture and warmth), increasing the risk of flash flooding.

A 2010 study applied a range of statistical bioclimatic envelope models to present-day peatland extent in Great Britain in order to simulate the future distribution of blanket bog.[15] A range of scenarios were simulated. The high Representative Concentration Pathway scenario predicted a very widespread reduction in areal extent of blanket bog, with a retreat to core areas of western Scotland. Whilst blanket bog may remain in Wales under this scenario, it is likely to be much reduced and not actively growing. The low Representative Concentration Pathway scenario shows a smaller loss, though still highly significant. The general shift in distribution is towards the north and west as the bioclimatic envelope shrinks. The study points to the importance of temperature in determining the future areal extent of blanket bog, as opposed to the less predictable change in rainfall. Peatland ecosystems have been shown capable of adapting to changes in climate in the past.[16] However, the study argues that the dependence of blanket bogs on high water table levels and their strict association with high precipitation and low temperature means that they are highly vulnerable to climate change.[17]

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[13] Met Office - Wales: climate. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/Wales_-climate---met-office.pdf [Accessed 17 Apr. 2020]

[14] Met Office (2018) UKCP18 National Climate Projections – Slide Deck. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-overview-slidepack.ff.pdf [Accessed 17 Apr. 2020]

[15] Bioclimatic envelope model of climate change impacts on blanket peatland distribution in Great Britain (2010). Gallego-Sala, A.V., Clark, J. M., House, J. I., Orr, H. G., Prentice, C. I., Smith, P., Farewell, T. and Chapman, S. J.

[16] Lindsay R (2009) Peatbogs and carbon: a critical synthesis. RSPB Scotland, Edinburgh

[17] Ellis CJ, Tallis JH (2000) Climatic control of blanket mire development at Kentra Moss, north-west Scotland. J Ecol 88:869–889

Drier summers are likely to lead to changes in species composition in both blanket and raised bogs, favouring those species suited to lower rainfall conditions. There could be a shift in species composition from those characteristic of hollows (e.g. *Sphagnum cuspidatum*) towards hummock-forming species such as *S. papillosum* and *S. capillifolium*. In more degraded bog, species such as purple moor-grass may be favoured by drier conditions. Drier conditions are also likely to lead to an increase in INNs and in particular the invasive moss species *Campylopus introflexus* as well as rhododendron (particularly on lowland raised bog sites). Drier conditions could favour the spread of lagg vegetation on raised bog sites (i.e. vegetation surrounding the main bog nucleus). This could include species such as bog myrtle and particularly woodland (e.g. birch).

Bare peat areas in both blanket bog and raised bog situations could be subject to a greater degree of oxidation as surfaces dry. This could be exacerbated by wind blow. In degraded situations, particularly where the bog surface is dominated by heather or purple moor-grass, there would be an increase in fire risk. Again, this risk would be increased as warmer weather is likely to encourage more visitors, particularly in the uplands.

Drier summers will also lead to lower water tables, especially where surrounding agricultural use and drainage ditches are already causing pressure on the bog system. Since both blanket and raised bogs are highly dependent on maintaining a high water level, this is potentially the greatest threat to their integrity. Again, a lowering of the water table will lead to concomitant changes in vegetation composition, favouring species more suited to drier conditions. A further indirect ramification of drier summers is that areas of peat on moorland edges may be more suitable for higher stocking levels.

Average winter rainfall

UKCP18 suggest that average winter rainfall (AWR) in the UK, and Wales, is expected to increase significantly.[18] The scenarios show that, for both a low and medium Representative Concentration Pathway scenario, AWR increases and expands outwards from the central mountain areas towards the East and coastal areas, with the majority of Wales seeing an incremental increase in the amount of AWR in 2020, and a greater increase in the 2050 scenario.

The majority of impacts on peatlands from increased winter rainfall are associated with the increased likelihood of erosion. The most detrimental impacts are likely to be caused by extreme rainfall events as described above. However, persistent rain on already degraded systems could lead to the same consequences (erosion, peat slides, bog burst) over time. Persistent and prolonged flooding is likely to have a greater impact on lowland raised bogs, particularly in terms of changes to species composition (long periods of inundation, nutrient-loading form in-washed sediment). An additional issue with increased winter rainfall is an increase in nitrogen deposition in what are very low nutrient systems (upland peatlands).

Wetter winters could lead to further disruption in the seasonal fluctuations of ground water levels associated with lowland fen. For example, waterlogging could occur in areas of habitat not normally subjected to such conditions. Again, this could lead to changes in species composition as well as an increase in nutrient-loading from in-washed sediment. Longer flooding events could lead to an increased availability of Phosphorus and other nutrients. This could be particularly deleterious for sensitive habitats such as lowland fen and upland fen and flushes.

[18] Met Office (2018) UKCP18 National Climate Projections – Slide Deck. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-overview-slidepack.ff.pdf [Accessed 17 Apr. 2020]

Impact of projected changes in temperature

The mean annual temperature at low altitudes in Wales varies from about 9.5°C to 11°C, with the higher values occurring around or near to the coast. The mean annual temperature decreases by approximately 0.5°C for each 100 metre increase in height, meaning that inland areas in Wales are typically much cooler than this. Temperature shows both a seasonal and diurnal variation. January mean daily minimum temperatures vary from just above 0°C in the higher parts of north and mid-Wales, to 3°C or 4°C around the coast. July is normally the warmest month, with mean daily maximum temperatures varying from about 17°C in the higher inland locations, to 18°C along the west coast, and 21°C in the east of Powys and Monmouthshire.[19]

Accumulated temperatures

The Cranfield projections show that accumulated temperatures above 0°C increase from 2020 to 2080 for all Representative Concentration Pathway scenarios. The analysis included AT0 – Accumulated Temperature > 0°C from January to June (°C days); and ATS – Accumulated Temperature > 0°C from April to September (°C days). Accumulated temperatures have been shown to provide an indication of heat energy input for crop growth and soil drying potential.

Warmer summer temperatures

Current UKCP18 projections suggest that summers will, on average, become increasingly hotter and drier in Wales, with an increased chance of greater daily maximum temperatures. Whilst not a highly frequent occurrence, Wales does experience heatwaves (an extended period of hot weather relative to the expected conditions of the area at that time of year, which may be accompanied by high humidity) and very high daily maximum temperatures above 30°C.

An increase in summer temperatures could lead to a range of effects on bog vegetation. These include the effects of a longer growing season, favouring grasses over herbs and sphagna. This would largely be determined by hydrological conditions on a given site and the local rainfall patterns. Higher summer temperatures could combine with other factors such as nitrogen deposition to favour faster growing, more competitive species. These are likely to include purple moor-grass and potentially bracken in some areas. Species diversity in lowland fen habitats is likely to decrease as the most competitive species are favoured.

A small but sustained increase in mean temperature is also likely to lead to an increase in plant growth. This could lead to a change and potential intensification, of management requirements. In the case of lowland fen, for instance, thicker, lusher vegetation will require a greater need and intensity of cutting in order to maintain species diversity.

Higher mean summer temperatures will also lead to an increased risk of wildfire through either accidental or deliberate agency. Warmer temperatures are likely to encourage a greater number of people into more remote parts of the countryside, with the concomitant risk of starting fires. This would have particularly serious effects on upland habitats such as blanket bog.

A further factor to consider in relation to warmer summers is an increase in the rate of evapotranspiration. If the rate of evapotranspiration outstrips the rate of precipitation, the

[19] Met Office - Wales: climate. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/Wales_-climate---met-office.pdf [Accessed 17 Apr. 2020]

bog will be in a moisture deficit scenario, with consequent changes in vegetation composition.

Hotter summers are also likely to lead to a drying out of peatlands, with a potential increase in the release of particulate and dissolved organic carbon. This effect will be exacerbated during increased autumn and winter rainfall leading to reduced water quality.

Warmer summers are likely to have their greatest effects on those habitats found at the highest altitudes in Wales. This would include blanket bog. The effects of a longer and warmer growing season could be exacerbated by an increase in insect and microbial activity leading to increased herbivory and a faster nutrient cycling. Such insect and microbial activity would have been curtailed in the past by lower temperatures.

Warmer winter temperatures

Warmer winter temperatures appear to confer a particular competitive advantage to bracken.[20] The spread of this species may be detrimental to such habitats as blanket bog, particularly at the fringes of such systems.

How are peatland habitats in Wales being made more resilient?

There is clearly a wide range of different potential climate change impacts on the four Section 7 Habitats making up peatland in Wales. It is difficult to predict how the combination of different climate change factors (increased summer temperature, increased winter temperature, decreased summer rainfall, etc.) will interact to affect individual peatlands. At the same time, the inherent complexity of habitats themselves and the range of potential responses to different factors makes it difficult to manage for climate change scenarios. It should also be emphasised that this habitat, perhaps more than most, contains many degraded examples and in many areas, is highly fragmented in distribution. Therefore, any additional impacts are likely to be more severely felt than if the habitat was robust and in good condition.

Despite this, it is possible to outline a series of management actions and approaches to help counteract the effects of worst case scenarios.

The fact that a large proportion of blanket and raised bogs are already degraded as a result of drainage and burning as well as over grazing and atmospheric pollution, means that there a range of management options that could provide great tangible benefits. Key amongst these is the restoration of water tables to encourage the establishment of true bog vegetation. This can be achieved through grip and drain blocking and the re-vegetation of bare peat. It is an especially important measure as the resilience of bogs to environmental change has been shown to increase if sphagnum cover can be maintained (Gallego-Sala & Prentice 2012).[21] Actions that improve both the quantity and quality of water held on sites will become increasingly important. These would include (i) restoring marginal hydrological regimes to counteract the often steep hydraulic gradients at the margins of peat bodies, (ii) expanding semi-natural habitat to occupy more of the original peat body as a means of increasing resilience and (iii) restoring habitat (tree removal) to reduce evapotranspirative demand. Increasing the resilience of bog vegetation to climate change also has the additional benefit of improving its carbon sequestration properties. It is an ideal opportunity to involve stakeholders at a catchment scale.

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[20] Chapman, D.S., Termansen, M., Quinn, C.H., Jin, N.L., Bonn, A., Cornell, S.J., Fraser, E.D.G., Hubacek, K., Kunin, W.E. and Reed, M.S. (2009). Modelling the coupled dynamics of moorland management and upland vegetation. Journal of Applied Ecology 46, 278-288.

[21] Gallego-Sala AV & Prentice IC. (2012) Blanket peat biome endangered by climate change. Nature Climate Change DOI: 10.1038/NCLIMATE1672.

A key action for many of the Section 7 Habitats discussed is that of maintaining the quantity and quality of water. This is particularly applicable to those habitats dependent on a seasonally high water table, such as wet woodland, lowland fen, purple moor-grass and rush pasture and reed beds. Good catchment management can help to maintain levels and quality of water. It can also prevent issues of persistent flooding and associated impacts such as nutrient loading.

Other potential adaptation options, as adapted from guidance by the RSPB[22], for these habitats are outlined below:

- Adaptation of land management regimes, avoiding burning and introducing appropriate livestock and stocking regimes, to prevent further habitat degradation and encourage the restoration of 'active' blanket bog with peat forming processes.
- Re-vegetate areas of bare peat, using best practice restoration techniques and appropriate plant species mixes. Initially, this should help to prevent or reduce further peat loss, but in the longer term will help to restore 'active' blanket bog.
- Restore natural hydrological regimes through drain and gully blocking and re-profiling, using best practice techniques.
- Encourage structural diversity within areas of blanket and raised bog by, for example, adjusting grazing levels and using a range of species, breeds, ages and sizes of animal.
- In regions where climate change may reduce the area of blanket bog and raised bog, such as towards the east of Wales, identify areas likely to retain the hydrological regime required for bog development and ensure these are protected and are under optimal management.
- Identify areas where the hydrological regime is currently, or in the future may be, sufficiently impaired to prevent bog development, and determine the most appropriate objectives. This might involve retaining a high water table for as long as possible to maintain ecosystem services such as carbon storage and water management.
- Evidence of any relationship between climate change and increased visitor numbers should be investigated through monitoring, and visitor management plans developed to reduce the risk of erosion and wildfire on sensitive sites.

A number of these adaptations assume current management regimes as a starting point. This situation may well change depending on the ramifications of Brexit and changes in agriculture brought about by climate change itself.

[22] Natural England and RSPB, 2014. Climate Change Adaptation Manual

OTHER WELSH HABITATS

Author: Chris Forster- Brown Principal Ecologist ADAS

Background information

This section considers the potential impact of climate change on semi-natural habitats, other than peatland, across Wales. These can be considered under the broad headings of woodland, grasslands (including arable field margins), heathland, wetlands (including fen and coastal and floodplain grazing marsh), standing waters and coastal habitats. Each of these broad groupings will be described in terms of its relevant subdivisions into Section 7 Habitats (for example, heathland is subdivided into lowland heath, upland heath and montane heath). Section 7 Habitats are those that are considered of principal importance for the purpose of maintaining and enhancing biodiversity in Wales (Section 7 habitats, Environment (Wales) Act 2016). In the majority of cases, it is important to discuss habitats in terms of their constituent Section 7 Habitats as these may have very different projected responses to climate change. Section 7 Habitats will be described in terms of their geographical distribution, as well as with reference to the underlying climatic conditions favouring this distribution. The report will attempt to draw out particularly Welsh examples of habitats, for example, 'rhos pastures'. It will also highlight those habitats that are under particular threat in Wales, through agencies other than climate change (e.g. lowland meadows). This is because these habitats are not only of high biodiversity value in their own right, but are important constituents of the overall fabric of the Welsh countryside. They are also likely to show their own particular responses to climate change.

Throughout the report, the emphasis will be on those habitats that are projected to show the greatest changes under the various permutations of climate change. Sections are also provided on how the changes anticipated under climate change may be best ameliorated. It should be emphasised that the majority of change scenarios are based on predictions and projections and it is difficult to say with certainty what the exact impacts will be for specific habitats. This is exemplified by the case of montane habitats. Scott (2016) states that whilst climate change will impact on montane habitats, the dynamics of this change will result from a 'complex interrelationship between summer and winter temperatures, occurrence of frost, duration of snow-lie, distribution of rainfall throughout the year and how windy it is'.[23]

In general, the report does not discuss associated species, other than the vegetation that provides the essential make-up of the habitat. However, dependent species are inextricably linked with the habitat and climate change impacts on habitat will also have ramifications for associated species.

Peatlands, and in particular blanket bog, raised bog and lowland fen, are considered in a separate document.

Woodlands

The following Section 7 Habitats (Environment (Wales) Act 2016) have been considered in relation to the broad heading of woodlands: upland oakwood, upland mixed ashwood, lowland beech and yew woodland and wet woodland. These are in line with the categories provided in Jones *et al* (2003).[24]

[23] Scott, M. (2016). Mountain Flowers. Bloomsbury Natural History

[24] Jones, P.S., Stevens, D.P., Blackstock, T.H., Burrows, C.R. and Howe, E.A. (2003). Priority Habitats of Wales a technical guide. Countryside Council for Wales, Bangor

Upland oakwood is found in conditions of high rainfall, typically > 1000mm per annum (often much higher). Its distribution in Wales is principally concentrated in Snowdonia, Powys, Ceredigion and Carmarthenshire. Most examples of upland mixed ashwood are also found in conditions of high rainfall, typically > 900mm per annum, though somewhat lower than upland oakwood. Small examples are often juxtaposed with upland oakwood, thought the greatest concentrations are associated with the limestone areas of Conwy, Denbighshire, Flintshire, Monmouthshire, central Carmarthenshire and south-east and west Glamorgan. It is likely that Wales provides the optimal climatic conditions for this woodland type in an international context. The native range of lowland beech and yew woodland is largely restricted to the south-east of Wales, encompassing Monmouthshire and the eastern parts of mid and south Glamorgan. To this extent, it tends to be found on drier soils and in areas with lower rainfall. Wet woodland is found in (usually) small quantity throughout Wales, with notable concentrations in Powys, Carmarthenshire, the Brecon Beacons and Snowdonia National Parks, Gwynedd and parts of Glamorgan. It does not appear to be particularly associated with underlying climatic conditions, though is obviously dependent on a high water table.

Grasslands

The following Section 7 Habitats have been considered in relation to the broad heading of grasslands: lowland meadows, lowland calcareous grassland, upland calcareous grassland, lowland dry acid grassland, purple moor-grass and rush pasture and arable field margins.

Lowland Meadows occur within a wide range of climatic variation. Drier types are widely distributed, though much declined and often degraded. There is a greater occurrence in the southern half of Wales, with particular concentrations in Glamorgan, Carmarthenshire and the northern half of Pembrokeshire. Wetter meadows (often termed floodplain meadows and flood-pastures) are restricted to a handful of small sites near the English border in Powys and Wrexham. These wetter types are largely dependent on an intermittently high water table. Lowland calcareous grassland occurs largely in areas with less than 1000mm rainfall per annum (often lower), often where these are warm and dry. Its distribution in Wales is almost wholly dictated by the underlying geology (i.e. limestone). It is therefore found on the south coast of the Gower peninsula, Vale of Glamorgan coast, southern edge of Brecon Beacons National Park, Great Orme and Denbighshire/Conwy border. Upland calcareous grassland has a somewhat different distribution to its lowland counterpart. It is not coastal and is confined to areas of Snowdonia, limestone in Denbighshire and the southern edge of Brecon Beacons National Park. Due to the height at which it is found, it is often subject to higher levels of rainfall than lowland calcareous grassland. However, the underlying climatic conditions are not a key factor in determining its distribution, and as with lowland calcareous grassland, this is more a function of geology.

Lowland dry acid grassland is widespread in the upland fringes, where it is often found in a mosaic with large areas of bracken-dominated lower hills, dotted with hawthorn and rowan. The largest areas of lowland acid grassland are in Snowdonia National Park, Gwynedd, Powys, Ceredigion, Brecon Beacons National Park and Neath Port Talbot. This habitat is not particularly demanding in terms of its climatic requirements. There are also two more ‘specialist’ types of lowland acid grassland, both of which require more exacting climatic conditions; bristle bent grassland is found in moist and warm conditions. In Wales, it is only found in areas of Glamorgan. Good examples of sheep’s-fescue – common bent – sheep’s sorrel grassland are confined to sun-baked igneous rock outcrops, in the east of Wales, close to the English border.

Purple moor-grass and rush pasture grassland largely occurs in areas of high rainfall and over a wide altitudinal range. It is particularly found in the west of Wales, with high concentrations for example in Ceredigion, Snowdonia National Park and Powys. The South Wales Coalfield, encompassing Glamorgan and Carmarthenshire, is also particularly important for this habitat and especially for examples of the meadow thistle community. In these situations, and elsewhere within Wales (e.g. Ceredigion), important examples of this habitat are referred to as 'rhos pasture'. The habitat as a whole is dependent on a high water table, particularly in the winter months.

Arable field margins are found in comparatively low rainfall areas in Wales. These areas tend to also feature above average temperatures. Their distribution is largely dictated by the suitability of growing arable crops and therefore, their main areas of distribution are in the lowlands of Pembrokeshire, Powys, Monmouthshire, Gower (Swansea), Vale of Glamorgan, Denbighshire, Flintshire and Wrexham.

Heathland

Heathland is subdivided into the Section 7 Habitats of lowland heathland, upland heathland and montane heath. Lowland heathland is widespread in the upland fringes. Particular concentrations are found in Ceredigion, Snowdonia National Park and in the Brecon Beacons. Much of this encompasses dry heath. Wetter lowland heaths, dependent on a higher water table, are particularly well represented in Swansea, Pembrokeshire, Snowdonia National Park, Gwynedd and Ceredigion. A humid type of lowland heath is only found in south Wales (principally Glamorgan).

Upland heath (dry) tends to be much more extensive and is largely found towards the east of Wales, in particular in Denbighshire, Blaenau Gwent and the eastern half of the Brecon Beacons National Park. The brown earths and podzolic soils supporting dry upland heath are liable to summer drought. In common with lowland examples, wet upland heaths are found on damper acid soils, where either shallow peat or mineral soils are seasonally waterlogged. They are particularly well represented in Snowdonia National Park, Gwynedd and Ceredigion.

Montane heath in Wales occurs as small and fragmented examples, confined to the higher mountain tops and plateaux, particularly in Snowdonia. Its distribution is particularly limited by temperature and other climatic variables.

Wetlands

For the purposes of this report, wetlands encompass the Section 7 Habitats, reed beds and coastal and floodplain grazing marsh. Fen habitats are discussed in a separate peatland chapter.

Reed beds establish in areas where the water table lies at or above the ground surface for much of the year. They are particularly associated with the coastal areas of the south, south-west and north-west. Anglesey, Pembrokeshire, Carmarthenshire and Swansea hold significant areas of reed bed.

The main areas of coastal grazing marsh are found in the south-east (Gwent Levels), south (Margam Moors) and Anglesey (Malltraeth Marsh). Floodplain grazing marsh is associated with the main watercourses, particularly the Conwy, Clywedog and Dee in the north, the River Severn and its major tributaries in the east, the Usk in the south east and the Tywi in Carmarthenshire. Both these types of grazing marsh can be subject to periodic inundation, either by brackish water in coastal situations (though often modified by sea defences) or river water in the case of floodplain grazing marsh.

Standing waters

Standing waters encompass the Section 7 Habitats, mesotrophic lakes and eutrophic standing waters, aquifer-fed naturally fluctuating water bodies and oligotrophic lakes. Eutrophic lakes are particularly confined to the coastal lowlands whereas mesotrophic lakes tend to be found in the marginal uplands. Aquifer-fed naturally fluctuating water bodies are represented by a single example in Wales, in Carmarthenshire. Oligotrophic lakes are more widespread, with large examples in Snowdonia and smaller ones in Powys, Ceredigion and the Brecon Beacons. Standing waters are particularly affected by influences from surrounding land use, though are also dependent on climate factors such as temperature.

Coastal habitats

Coastal habitats encompass the Section 7 habitats, saltmarsh and coastal sand dunes. The main areas of saltmarsh in Wales are found in the Burry Inlet, around the Dee estuary in Flintshire and elsewhere in Pembrokeshire, Neath Port Talbot and Newport in south-east Wales. Saltmarsh is highly dependent on the frequency of inundation by the tide. Coastal sand dunes are found principally on the southern and north-western coastlines, in Anglesey, Carmarthenshire, Bridgend, Snowdonia National Park, Pembrokeshire, Gwynedd and Swansea. Dunes are dependent both on dynamic coastal processes (supply and removal of sand) and the presence of ground water in order to feed dune slacks.

Comparison between ALC interpolated UKCP18 data and current evidence base.

The Welsh Government's latest thinking is that the UK (and more specifically Wales) is most likely aligned to projected impacts of a low-medium Representative Concentration Pathway scenario by the 2080s. This projection would result in a temperature increase of between 2.2°C and 2.6°C by 2100, as opposed to a temperature increase of ~4.3°C in a high Representative Concentration Pathway scenario. However, a low-medium Representative Concentration Pathway scenario is not simply an outcome of climate action in the UK, but is subject to considerable action being taken globally to reduce greenhouse gas emissions. This includes action being taken by all nations, including the world's largest emitters (e.g. USA and China) who are not currently part of the Paris Agreement, to actively transition to such pathways.

The impacts associated with the latest climate projections under a low-medium Representative Concentration Pathway scenario could be experienced within any given year within the period of assessment. However, ongoing changes to the climate will create more favourable conditions that will increase the likelihood of extreme events and climate changes occurring, including changes in the frequency and magnitude of such events.

This assessment considers the Cranfield projections for 2020 (2010 to 2039) and 2050 (2040 to 2069) under a low and medium Representative Concentration Pathway scenario, which reflect a global mean temperature increase of 2.2°C and 2.6°C respectively by 2100.

What the scenarios mean for habitats in Wales

Overview of impacts on habitats

This section provides an overview of the types of change envisaged as a result of climate change to habitats in the UK (and by extension, Wales). More detailed assessments, in relation to specific habitats, are outlined in the sections following. These are discussed according to the different projections for severe weather, rainfall and temperature. The following themes are important in assessing the potential effects of climate change on habitats in Wales:

- A shift in many species further north and at higher altitudes
- Slow dispersal ability of many plant species
- Warmer springs leading to potential phenological mismatches (flowering times, etc.)
- Lack of frosts coupled with unseasonal heavy frosts, with consequent effects on bud dormancy;
- Changes to the composition of plant communities
- Different species responses to changes in precipitation
- Particular vulnerability of individual habitats to climate change e.g. montane
- Increased risk of spread of Invasive Non Native Species (INNs)

An overarching theme that runs alongside all these potential changes, is that of land management. Habitats that are already under stress through sub-optimal management are more likely to suffer detrimental impacts from climate change. In addition, land management may be the critical factor for some habitats and for this reason, assumes greater importance than the effects of climate change. Where detrimental land management factors are considered to be key to a habitat's current status, this is highlighted in the text.

Impact of severe weather across England and Wales

The Met Office categorises the weather in Wales as a maritime climate, characterised by weather that is often cloudy, wet and windy, but mild. However, the shape of the coastline, and the central spine of high ground from Snowdonia southwards to the Brecon Beacons, introduce localised differences. Whilst some upland areas can experience harsh weather, the coasts enjoy more favourable conditions, and areas in east Wales are more sheltered with weather similar to neighbouring English counties.[25]

Severe weather events associated with climate change could potentially have a greater impact on habitats than a more gradual change in the 'mean climate'. An obvious example is in relation to severe storms and wind throw in woodland. Upland oakwood on steep slopes and shallow-rooted species such as beech, associated with lowland beech and yew woodland, are particularly prone to uprooting by strong winds. This could have a disproportionate effect on veteran and ancient trees and associated lichens, fungi and saproxylic invertebrates. The sudden opening up of woodland could also decrease humidity, an important factor in relation to lower plant communities and ferns. It could also allow the rapid expansion of INNs, particularly rhododendron. Extreme weather associated with storms, can cause erosion and landslip of habitats in the uplands. This is particularly in relation to upland fen and flushes which are vulnerable to peat slippage and increased scour.

Persistent flooding and over long periods, is also detrimental to those habitats that require intermittently high water tables. These include lowland meadow (wet), purple moor-grass and rush pastures, lowland fen and wet woodland. For example, a long-term very high water table affecting a fen site would favour species suited to high levels of inundation at the expense of species that are not suited to these conditions. This is also the case for purple moor-grass and rush pastures and wet woodland. With respect to fens and wet woodland

[25] Met Office - Wales: climate. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/Wales_-climate---met-office.pdf [Accessed 17 Apr. 2020]

in particular, such events could also increase nutrient input to the systems, with concomitant effects on species composition.

Tidal surges can have a very large impact on coastal habitats such as sand dunes and saltmarsh, rapidly altering the dynamics of 'normal' coastal processes. Such surges can lead to increased erosion and fragmentation in the case of saltmarshes, particularly where such incidents are exacerbated by the presence of coastal sea defences. Coastal sand dunes could be impacted by such changes in relation to the amount of sediment supplied and removed.

Impact of projected changes in annual, seasonal and extreme rainfall

Rainfall in Wales varies widely, with the highest average annual totals being recorded in the central upland spine from Snowdonia to the Brecon Beacons. Snowdonia is the wettest area with average annual totals exceeding 3,000 mm. In contrast, areas along the coast and, particularly, close to the border with England, are drier, receiving less than 1,000 mm a year.[26]

Annual rainfall

UK Climate Projections 2018 (UKCP18) suggest that, compared with current year-to-year variations, average annual rainfall (AAR) is not expected to differ a highly significant amount. However, the seasonality of when rainfall occurs is expected to change, with typically warmer, wetter winters and hotter, drier summers. Therefore, the assessment of seasonal differences is more important than very slight variations in annual rainfall.

The low Representative Concentration Pathway scenario for 2020 and 2050 AAR show very limited detectable change compared to the baseline. The medium Representative Concentration Pathway scenario also shows very limited change to AAR in 2020, with only slight increases in the expansion of the 1,001-1,500 mm category around the fringes of south Wales in 2050. There are not expected to be any significant, discernible impacts on habitats associated directly with changes in AAR.

Average summer rainfall

UKCP18 suggest that average summer rainfall (ASR) in the UK is expected to decrease significantly, with the greatest changes associated with higher Representative Concentration Pathway scenarios. However, when it rains in summer there may be more intense storms,[27] and thunderstorms (due to a combination of moisture and warmth), increasing the risk of flash flooding.

Drier summers could lead to a potential decline or loss of lower plants (mosses, liverworts and lichens) and ferns, an important and defining component of upland oakwood and upland ashwood. This could have particular effects on those species regarded as oceanic and tied to areas of high humidity. With respect to oceanic bryophytes (mosses and liverworts), it is the number of days that precipitation occurs that appears to be the key factor, rather than the quantity of rain in a single event.[28] Drier summers could also lead to changes in species

[26] Met Office - Wales: climate. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/Wales_-climate---met-office.pdf [Accessed 17 Apr. 2020]

[27] Met Office (2018) UKCP18 National Climate Projections – Slide Deck. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-overview-slidepack.ff.pdf [Accessed 17 Apr. 2020]

[28] Porley, R. and Hodgetts, N. (2005) Mosses and Liverworts. The New Naturalist Library. Collins

composition in woodlands, favouring those species suited to low rainfall conditions. This could potentially have the greatest impact on wet woodland habitats. Drier conditions are also likely to lead to an increase in INNs (e.g. rhododendron) or the spread of species more characteristic of low rainfall (e.g. beech). Rhododendron encroachment is already one of the greatest existing management problems for oak woodlands in mid and north Wales, and climate change is likely to enhance this. Drought in woodlands will also lead to increased stress on species, particularly where shallow-rooted e.g. beech. Microbial activity, an integral part of woodland and grassland systems, is likely to be reduced.

Drier summers will also lead to lower water tables, and thus have a disproportionate effect on those habitats dependent on such conditions. These include coastal and floodplain grazing marsh, wet heath, wet woodland and purple moor-grass and rush pastures. Greatest effects are likely to be felt by those habitats that are considered most dependent on the inflow of ground water. These include lowland fen, upland fen and flushes and coastal sand dunes (dune slacks). In the case of these habitats, a low water table could have far-reaching consequences for sensitive species mixes. Reed beds are also likely to suffer during long periods of low water levels (reed grows best in conditions of permanent standing water). Wet heath and purple moor-grass and rush pastures (including 'rhos' pastures) are likely to suffer disproportionately greater effects than other habitats. This is because they are already under threat from land management activities. In the case of purple moor-grass and rush pastures, a number of existing threats are evident, including scrub encroachment due to a lack of adequate cattle grazing (light grazing) and conversely, agricultural intensification. Similar factors are at work in wet heath situations. For example, Llŷn has lost 95% of its wet heath since the 1920s.[29] Much heath has been converted to improved grassland. These factors are probably of greater importance than climate change alone; however, the effects of climate change will serve to exacerbate detrimental changes to already threatened habitats.

Average winter rainfall

UKCP18 suggest that average winter rainfall (AWR) in the UK, and Wales, is expected to increase significantly.[30] The scenarios show that, for both a low and medium Representative Concentration Pathway scenario, AWR increases and expands outwards from the central mountain areas towards the East and coastal areas, with the majority of Wales seeing an incremental increase in the amount of AWR in 2020, and a greater increase in the 2050 scenario.

In relation to woodlands, wetter winters are likely to have the greatest impact on drier woodland types. This is particularly the case with beech woodland, which has been shown to have a reduced nutrient uptake and vigour under wet conditions. Wetter winters also appear to confer increased susceptibility to summer drought. Conversely, wet woodland may increase its extent under wetter winter conditions, especially in the lower reaches of river systems.

Wetter winters could lead to further disruption in the seasonal fluctuations of ground water levels associated with some habitats. These include purple moor-grass and rush pastures, coastal floodplain and grazing marsh, wet heath and coastal sand dunes. For example,

[29] Blackstock, T.H., Stevens, J.P., Howe, E.A. and Stevens, D.P. (1995). Changes in the extent and fragmentation of heathland and other semi-natural habitats between 1920-22 and 1987-88 in the Llŷn Peninsula, Wales, UK. *Biological Conservation,* **72**, 33 – 44

[30] Met Office (2018) UKCP18 National Climate Projections – Slide Deck. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-overview-slidepack.ff.pdf [Accessed 17 Apr. 2020]

waterlogging could occur in areas of habitat not normally subjected to such conditions. Again, this could lead to changes in species composition as well as an increase in nutrient-loading from in-washed sediment. Longer flooding events could lead to an increased availability of Phosphorus and other nutrients. This could be particularly deleterious for sensitive habitats such as coastal sand dunes (slacks). Effects in relation to coastal sand dunes could also be exacerbated by the fact that beach plains could remain wetter for longer and therefore sand is not moved as readily by wind processes.

Wetter winters could also have detrimental effects in the uplands. An increase in surface run off could lead to increased erosion around mountain summits, thus impacting on montane heath. Similarly, increased erosion could affect other upland habitats such as upland heath. Increased winter rainfall effects are likely to be disproportionately felt by habitats already impacted by land management issues. This is particularly the case with montane heath, which is already highly fragmented and in poor condition due to overgrazing. Similarly, inappropriate grazing of wet heath and conversion to improved grassland will produce a greater vulnerability to the effects of climate change. In the case of both these habitats, it would be expedient to address current land management issues before future-proofing against climate change.

Impact of projected changes in temperature

The mean annual temperature at low altitudes in Wales varies from about 9.5°C to 11°C, with the higher values occurring around or near to the coast. The mean annual temperature decreases by approximately 0.5°C for each 100 metre increase in height, meaning that in-land areas in Wales are typically much cooler than this. Temperature shows both a seasonal and diurnal variation. January mean daily minimum temperatures vary from just above 0°C in the higher parts of north and mid-Wales, to 3°C or 4°C around the coast. July is normally the warmest month, with mean daily maximum temperatures varying from about 17°C in the higher inland locations, to 18°C along the west coast, and 21°C in the east of Powys and Monmouthshire.[31]

Accumulated temperatures

The Cranfield projections show that accumulated temperatures above 0°C increase from 2020 to 2080 for all Representative Concentration Pathway scenarios. The analysis included AT0 – Accumulated Temperature > 0°C from January to June (°C days); and ATS – Accumulated Temperature > 0°C from April to September (°C days). Accumulated temperatures have been shown to provide an indication of heat energy input for crop growth and soil drying potential.

Warmer summer temperatures

Current UKCP18 projections suggest that summers will, on average, become increasingly hotter and drier in Wales, with an increased chance of greater daily maximum temperatures. Whilst not a highly frequent occurrence, Wales does experience heatwaves (an extended period of hot weather relative to the expected conditions of the area at that time of year, which may be accompanied by high humidity) and very high daily maximum temperatures above 30°C.

[31] Met Office - Wales: climate. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/Wales_-climate---met-office.pdf [Accessed 17 Apr. 2020]

An increase in summer temperatures is expected to have a range of impacts on habitats. These could include the effects of a longer growing season, favouring grasses over herbs. This could lead to vegetation composition changes in a number of habitats such as woodlands, grasslands and lowland heath. For example, grass species have been shown to increase at the expense of dry heathland species under warmer temperatures.[32] A small but sustained increase in mean temperature is also likely to lead to an increase in plant growth. This could lead to a change and potential intensification, of management requirements. In the case of purple moor-grass and rush pasture, for instance, thicker, lusher vegetation will require a greater need and intensity of cutting in order to maintain species diversity. Warmer temperatures may also increase and quicken the spread of scrub vegetation, to the detriment of habitats such as purple moor-grass and rush pasture, lowland heath and calcareous grassland. Since this is one of the main existing land management issues facing these habitats, any speeding-up of this process through climate change will only worsen the current situation.

Higher mean summer temperatures will also lead to an increased risk of wildfire through either accidental or deliberate agency. Warmer temperatures are likely to encourage a greater number of people into more remote parts of the countryside, with the concomitant risk of starting fires. This would have particularly serious effects on upland habitats such as upland heath, as well as lowland habitats with thick, often dense vegetation (e.g. some types of lowland fen, habitats featuring a high scrub component such as lowland heath).

Warmer springs and summers could have a number of effects on woodland systems. These include altered phenology with respect to bud burst and leaf flushing. In general, warmer spring/early summer temperatures are projected to bring forward these processes. However, many woodland systems also require a period of winter chilling in order to break dormancy. Warmer winter temperatures are retarding this chilling period and thus causing a delay in spring flushing.[33] Warmer temperatures also appear to favour the spread of a number of air and soil-borne pathogens of trees, such as Phytophthora species in oak.[34] Conversely, the spread of Chalara fraxinea in ash may be slowed as both species (ash and Chalara) start to move northwards at different rates and a mismatch in distribution develops between the two.[35] Different woodland Section 7 Habitats may be disproportionately affected. For example, increased temperatures may cause increased sun scorch leading to bark-death in beech (effects on lowland beech and yew woodland). Increased temperatures could also reduce the generation time of insect pests such as oak pinhole borer and oak buprestid[36] (effects upland oakwood).

Warmer summers are also likely to have impacts on standing water systems. These could include earlier and longer-lasting blooms of cyanobacteria (blue-green algae) and an increase in phytoplankton activity. Both these could lead to a reduction in light penetration and a decrease in oxygen concentration, with associated deleterious effects on aquatic

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[32] Wessel W.W., Tietema A., Beier C., Emmett B.A., Peñuelas J. & Riis–Nielsen T. (2004) A Qualitative Ecosystem Assessment for Different Shrublands in Western Europe under Impact of Climate Change Ecosystems 7, 662–671

[33] Yongshuo S. H. Fu, Matteo Campioli, Yann Vitasse, Hans J. De Boeck, Joke Van den Berge, Hamada AbdElgawad, Han Asard, Shilong Piao, Gaby Deckmyn, and Ivan A. Janssens (2014). Variation in leaf flushing date influences autumnal senescence and next year's flushing date in two temperate tree species PNAS 111 (20) 7355-7360

[34] Bergot M., Cloppet E., Pérarnaud V., Déqué M., Marçais B., Desprez-Loustau M.-L. (2004). Simulation of potential range expansion of oak disease caused by Phytophthora cinnamomi under climate change Global Change Biol 10 1539–1552.

[35] Goberville, E., Hautekèete, N., Kirby, R. et al. Climate change and the ash dieback crisis. Sci Rep 6, 35303 (2016).

[36] Read, D.J., Freer-Smith, P.H., Morison, J.I.L., Hanley, N., West, C.C. and Snowdon, P. (eds). 2009. Combating climate change – a role for UK forests. An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change. The Stationery Office, Edinburgh.

macrophytes (plants) and fish.[37] Furthermore, warmer temperatures are likely to benefit the reproductive capacity of introduced species of fish (e.g. common carp). Warmer temperatures also have the potential to have negative effects on naturally cold lake systems. In Wales, these comprise a series of oligotrophic and dystrophic lakes in Snowdonia, which support a range of cold water species, such as Arctic charr.[38]

Warmer summers are likely to have their greatest effects on those habitats found at the highest altitudes in Wales. In particular, warmer temperatures could detrimentally affect montane heath. Effects could occur in a number of respects. A longer growing season could lead to an increased growth in grasses and some dwarf shrubs, outcompeting existing montane vegetation including characteristic bryophytes and lichens. This could be exacerbated by an increase in insect and microbial activity leading to increased herbivory and a faster nutrient cycling. Such insect and microbial activity would have been curtailed in the past by lower temperatures. As well as effects on montane heath, warmer summer temperatures could lead to an increase in lowland species outcompeting the upland vegetation of montane ledges. These species-rich tall herb habitats could be invaded by faster growing, ranker species of lowland habitats.[39] Such montane ledge habitats are characteristic of base-rich rocks in the Brecon Beacons, central Snowdonia and outlying mountains such as Cadair Idris.

Furthermore, as with other upland habitats, warmer summer temperatures are likely to lead to an increase in visitor pressure and consequent increased impacts of erosion (and potential for wildfire). Therefore, montane heath provides a classic example of in-combination impacts. It should also be noted that this habitat, along with some others (e.g. some types of lowland heath, standing waters) may already be in poor condition and highly fragmented. Therefore, any additional impacts are likely to be more severely felt than if the habitat was robust and in good condition.

Warmer winter temperatures

Warmer winter temperatures could have a number of direct and indirect impacts. For woodland habitats, these could potentially include an earlier bud burst (though this should be set against the retardation of chilling and reduction in seed germination) and subsequent phenological mismatch with pollinators. There is also the risk that incomplete winter hardening of woodland vegetation, followed by a severe frost could cause widespread damage to woodland habitats.

Perhaps the greatest threat posed by warmer winter temperatures to woodland habitats, is that of overwinter survival of pest species. This includes greater overwinter survival of pest insect species but also of certain species of mammal. In particular, increased survival of grey squirrel and deer species can lead to detrimental impacts on woodland habitats. For example, warmer winter temperatures will lead to an increase in the survival of young deer, leading to an increase in grazing pressure and subsequent damage to woodland vegetation. Indeed, the spread of several species of deer in Wales is likely to be partly due to increased winter survival.

Warmer winters and higher temperatures generally mean that it may be possible to grow arable crops in more areas of Wales. At the same time, earlier growth of crops may result in

[37] Carvalho L., Kirika A., Changes in shallow lake functioning: response to climate change and nutrient reduction. Hydrobiologia, 506: 789-796.

[38] Morecroft, M.D. and Speakman, L (eds.) (2013) Terrestrial Biodiversity Climate Change Impacts Summary Report. Living With Environmental Change.

[39] Scott, M. (2016). Mountain Flowers. Bloomsbury Natural History

a phenotypic mismatch between flowering and the presence of pollinators. Warmer temperatures could also result in an increase in pests and diseases, leading to an increase in the use of insecticides and fungicides.

Warmer winters appear to confer a particular competitive advantage to bracken.[40] The spread of this species may be detrimental to such habitats as lowland heath. Bracken spread in other Section 7 habitats could also be undesirable where it becomes so dense as to outcompete all other species. In upland heathland areas, warmer winters could lead to increased survival of heather beetle.

Extreme winter temperatures (coldwaves/snowfall/ice)

Coldwaves, snowfall and ice are important meteorological events that shouldn't be forgotten. Whilst climate projections indicate that on average, winters will be warmer and wetter, the occurrence of severe cold and snow events will still occur, particularly in the Welsh uplands and mountains.

The numbers of days with snow falling and snow cover increase with latitude and altitude, so values reflect topography. Snow is comparatively rare near sea level in Wales, but much more frequent over the hills. The average annual number of days of snowfall and snow cover varies from 10 or less in south-western coastal areas to over 30 in Snowdonia. However, this varies enormously from year to year, with some locations over the last 50 years ranging from no snow at all in several winters, to in excess of 30 days during very severe winters.[41]

A decrease in the number of snow days in a winter is likely to have greatest impacts on montane habitats. A number of these high altitude communities are dependent on periods of late snow-lie. Although true snow-bed communities are only really found in the Scottish mountains, outlying forms of this vegetation are found in the higher mountains of Wales. These are reliant on low temperatures and long periods of snow lie are important in their continuation.

What can be done to prepare and future proof habitats in Wales

There is clearly a wide range of different potential impacts on Section 7 Habitats in Wales as a result of climate change. It is very difficult to predict how the combination of different climate change factors (increased summer temperature, increased winter temperature, increased winter rainfall, etc.) will interact to affect individual habitats. At the same time, the inherent complexity of habitats themselves and the range of potential responses to different factors makes it difficult to manage for climate change scenarios. Despite this, it is possible to outline a series of generic actions and approaches to habitat management that could help counteract the effects of worst case scenarios. Natural England and RSPB[42] have produced a comprehensive review of potential impacts of climate change on habitats and an adaptation manual aimed at management of these impacts. The adaptation manual includes the following four key principles:

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[40] Chapman, D.S., Termansen, M., Quinn, C.H., Jin, N.L., Bonn, A., Cornell, S.J., Fraser, E.D.G., Hubacek, K., Kunin, W.E. and Reed, M.S. (2009). Modelling the coupled dynamics of moorland management and upland vegetation. Journal of Applied Ecology 46, 278-288.

[41] Met Office - Wales: climate. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/Wales_-climate---met-office.pdf [Accessed 17 Apr. 2020]

[42] Natural England and RSPB, 2014. Climate Change Adaptation Manual

Building ecological resilience to the impacts of climate change

This principle is about building resilience to the adverse impacts of climate change and enabling habitats to continue in the face of climate change. The emphasis is on reducing other non-climatic sources of potential harm (e.g. pollution and habitat fragmentation). This means that if habitats are in better condition to start with, they will be better able to withstand the effects of climate change. Actions would include the prevention of pests and diseases and invasion by non-native species. A key action for many of the Section 7 Habitats discussed is that of maintaining the quantity and quality of water. This is particularly applicable to those habitats dependent on a seasonally high water table, such as wet woodland, purple moor-grass and rush pasture and reed beds. Good catchment management can help to maintain levels and quality of water. It can also prevent issues of persistent flooding and associated impacts such as nutrient loading. Creating on-site refugia for individual species and vegetation would also result in resilience. This could be achieved for instance through maintaining environmental heterogeneity by protection/creating a range of topographic features, soil types and vegetation. Resilience can also be encouraged in one habitat through accepting or promoting change in a different aspect of the environment. The first step in considering resilience is to determine what the target is – a species, habitat or ecosystem, since the resultant actions are likely to differ widely according to the management objectives.

Preparing for and accommodating inevitable change

This refers to the fact that some change is inevitable and should be encouraged. For example, the spread of certain species adapted to warmer temperatures. Certain management, such as realignment along the coastline and restoring the natural flow and flooding of rivers is also beneficial to certain habitats such as saltmarsh and coastal and floodplain grassland. An important aspect of accommodation is facilitating the movement of species populations in response to changing climatic conditions. This is likely to be achieved through the creation of ecological stepping stones and wildlife corridors. In more extreme cases, it could be achieved through reintroduction and translocation of habitats.

Valuing the wider adaptation benefits the natural environment can deliver

This relates to the use of ecosystem based approaches to encourage adaptation in other sectors wherever possible. Flood management and pollution amelioration are the most obvious examples, in relation to wet woodland, reed beds, saltmarshes and coastal and floodplain grassland.

Improving the evidence base

This relates to improving our knowledge of both climate change itself and its potential impacts on habitats. This will enable us to improve our capacity for change.

It is clear that some habitats are likely to be impacted more than others by climate change. Those habitats that are dependent on high or intermittently high water tables are likely to suffer disproportionately. Habitats that are particularly susceptible to disease or invasion by non-native species are also likely to receive greater impacts, woodlands being a key example. Furthermore, those habitats that are already under threat from inappropriate land management, are more likely to suffer further detrimental impacts under climate change.

In some cases, notably wet heath, lowland meadows, purple moor-grass and rush pastures and montane heath, it is likely to be of greater benefit to Wales' biodiversity to address existing land management issues before tackling issues of climate change. Appropriate grazing is of particular relevance to these habitats. Tackling these issues first will not only provide great overall benefit to these habitats, it will also make them much more resilient to the effects of climate change.

WELSH WOODLAND

Author: Roy Dyer Head of Arboriculture ADAS

Background information

Welsh woodland cover in 2016 was 306,000ha (1[5]% of land area), of which 180,000ha.

(59%) are owned by the private sector and 126,000ha (41%) by the Welsh Govt[1].

Of the total, 49% is conifer woodland and 51% broadleaf which includes native and ancient woodlands.

It is estimated that presently this area of woodland sequesters 1.419 million tonnes of CO_2[1.]

The changing climate is a challenge for forest planning and forest management nationally. The main reason for this is that in the past it has been relatively easy to decide on the best species to plant for a given site because the climate has been relatively stable – i.e. it was unlikely to change significantly over the rotation period of a single commercial tree crop (c. 50 – 60 years). There is now a need to consider how the climate will change during the rotation period and in some regions, there will be a need to choose an alternative species to that planted in the past to guarantee that the crop will remain healthy and productive. Other factors, such as the possibility of more extreme winter storms and an increase in attacks by existing and new pests and diseases, will have a bearing too on the way in which woodlands are planned and managed.

Comparison of ALC interpolated UKCP18 data and current evidence base.

The projected increases in temperature, changes in the seasonality of rainfall, and an increased frequency of extreme events add complexity to species selection and silvicultural practice.

There will be an increased frequency of drought throughout Wales, particularly in the south.

In Wales, the annual rainfall figure will be maintained, but there will be an increase in winter rainfall and a decrease in summer rainfall. The most limiting factor will be the long-term summer droughtiness. Sitka spruce, which requires a high level of rainfall throughout the year is likely to grow less well in these conditions and alternative species, which will grow well throughout the drier summer conditions, need to be considered.

The Representative Concentration Pathway data indicates that in general terms, the average baseline annual rainfall is less than the threshold level of 1000mm required for Sitka spruce in Flintshire, Wrexham and the Isle of Anglesey and this will not change materially within any of the climate change scenarios. However whilst Denbighshire and Monmouthshire generally have sufficient baseline average rainfall for Sitka spruce, the annual average rainfall predicted in these regions will fall below the threshold level of 1000mm in any the of the increased Representative Concentration Pathway scenarios, which is generally insufficient for the growing of Sitka spruce as a commercial crop. Although Powys has an average rainfall that is well in excess of 1000mm the maps show that a greater proportion of the eastern half will drop below 1000mm particularly in relation to the 2050 medium Representative Concentration Pathway scenario, which will reduce the area that is optimal for the growing of Sitka spruce for commercial reasons.

The more extreme rainfall over the winter period will increase the need for tree planting in water catchment areas throughout Wales, in order to help retain and regulate the water supplies and avoid excessive run-off when the soils become saturated.

The low to medium based scenarios are predicting an increase of approx. 2.5 degrees C by 2080 with possibly larger increases in winter compared to summer. The decrease in summer rainfall and increased evaporation rates, together with the increase in winter rainfall and decrease in the number of cold frosty days, will effectively lengthen the growing season. Both commercial conifers and broadleaved varieties of trees will flush earlier and broadleaves will lose leaf cover later in the season.

Combined with the increase of CO_2, these factors suggest enhanced growth rates and increased productivity in most years, but early flushing does increase the probability of frost damage.

Unfortunately, some of the major broadleaved species such as Oak, Ash and beech are particularly frost sensitive whereas many of the minor broadleaved species such as Sycamore, Birch and Alder are frost tolerant. In relation to conifers, Scots pine, Corsican pine and Lodgepole pine are all frost resistant.

This may hamper the success of natural regeneration, requiring the intervention of enrichment planting, which could also improve diversity by using plants from a more southerly source, to maintain stocking density and diversity.

A further potential complication is that warm temperatures during the vernalisation period (typically autumn and winter) can delay dormancy or the fulfilment of chilling requirements of oak and other species, thereby delaying spring events, such as flowering . This will affect all areas of Wales to a greater or lesser degree and the affect will be determined more by topography than region. To maintain the native local genetic stock, autumn seed collection may be considered and plants grown on for specific areas of regeneration. This is probably most important in relation to maintaining the local genetic stock for Ancient Semi-Natural Woodlands, where oak trees are not regenerating naturally due to predation by squirrels and mice. Where this is the case, planting of oak trees may be considered due to the inability to re-stock by natural regeneration (which is normally the preferred option in ancient woodlands). Acorn collections could for instance be carried out by the landowner's staff and issued to a local tree nursery with an arrangement to purchase all oak transplants raised from the supplied acorns.

Future natural regeneration may be restricted to the new species introduced from more Southerly areas. It is likely that in some areas, beech will be the preferred broadleaved species and beech does have the ability to regenerate freely, especially when encouraged by positive forestry management. Beech is a good commercial alternative to other broadleaved species, but there will be a biodiversity trade off where it is being planted as an alternative to oak.

The increase in winter rainfall figures could also have several effects within the industry, such as the reduced stability of trees that may still be in full leaf, which will increase the chances of windblow if a greater number of winter storms prevail in the future. Fine root death in the upper soil horizons and increased waterlogging of soils could limit the access of forest harvesting machinery where soil structure needs to be maintained and compaction avoided. These problems are likely to occur throughout Wales as the Average Winter Rainfall (AWR) across all regions is expected to increase with all climate change scenarios.

Where tree stability becomes a problem, then consideration should be given towards planting broadleaved species instead of conifers (as virtually all commercially grown broadleaves are windfirm species) or use wind firm conifer species as an alternative to wind weak conifer species. Fig 1 shows the wind firmness of the main conifer species:

Wind Firm	Moderately wind firm	Wind weak
Scots pine	European larch	Douglas fir
Corsican pine	Japanese larch	Norway spruce
Lodgepole pine	Hybrid larch	Lawson's cypress
Noble fir	Sitka spruce	
	Western hemlock	
	Western red cedar	
	Grand fir	
	Coastal redwood	

Fig 1 Windfirmness of conifer species

In relation to forest harvesting and maintaining the soil structure, this will simply affect the timing of harvesting operations. It will mean avoiding harvesting operations on vulnerable sites during autumn and winter and starting the work a little later in spring than would otherwise have been the case.

Pests and Diseases

It is not easy to predict changes to insect pest and disease outbreaks, and even harder to quantify any loss in production.

However, as an example, if the extent of a particular pest or disease outbreak reduced the Yield Class (YC) of a plantation from say YC20 to YC18 that would reduce the Mean Annual Increment by 2m 3/ha/annum. Sitka spruce YC18 would be on a rotation of 52 years, so this would reduce the production over the rotation by 104m3. Based on a standing value of £35/m3 that would amount to a loss of £3,640/ha.

It is a known fact that trees under stress are more prone to attack from pests and diseases and that a warmer climate would benefit most forest insects (good and bad) due to reduced winter mortality.

Wetter ground conditions could lead to more root diseases (e.g. Phytophthora) and warmer wetter springs would lead to a greater incidence of foliar diseases such as needle pathogens (e.g. Dothistroma).

Increased tree deaths caused by Phytophthora spp. are likely to occur in wetter soil conditions, especially where the soil wetness class is either V or VI or class III or IV where there is a slowly permeable layer.

The most likely risk of increased damage to trees by insect pests under climate change in Wales are as follows:

- Red Band Needle Blight (Dothistroma septosporum) attacks pine trees and it is likely that this will become more of a problem due to increased rainfall coupled with a trend towards warmer springs, optimising conditions for spore dispersal and infection. Due to the threat of this fungus, the Welsh Government currently avoid the planting of Corsican pine.

- More frequent green spruce aphid (Elatobium abeitinum) outbreaks may reduce spruce growth in west, east and south Wales. This is considered to be a very high risk and is due to the fact that multiple generations in warm weather will result in a rapid population increase, exacerbated by increased winter survival. Drought stress of host trees is also favourable to population growth[2]
- Reduced generation time of Great spruce bark beetle (Dendroctonus micans) may increase abundance. Drought stress of host trees decreases resistance to attack. Range extension will

also result in more widespread damage. This is considered to be a high risk in relation to both spruce and pine[2]

- More windblow due to an increase in stormy weather will increase breeding material for the Common pine shoot beetle (Tormicus piniperda). Sister broods will increase in abundance and host stress through drought or defoliation reduces the resistance of living trees to attack. This is considered to a high risk to pine trees[2]

There is also likely to be a moderate risk of increased damage to trees from:

- Large pine weevil (Hylobious abietis) on spruce and pines
- Two-spotted oak buprestid (Agrilus biguttatus) on oak
- Oak pinhole borer (Platypus cylindrus) on oak
- Larch bark beetle (Ips cembrae) on larch
- Pine looper moth (Bupalus piniaria) on pines
- Winter moth (Operophtera brumata) on spruce and oak
- European spruce sawfly (Gilpinia hercyniae) on spruce

There is a similar scenario with mammals (e.g. squirrels and deer) who would not suffer winter mortality and also benefit from increased vegetation growth earlier in the year.

Tree species selection

Figs 2 and 3 show the existing principal tree species in Welsh woodlands by area and percentage respectively[3]

Woodland area by principal tree species and size							
	Clwyd	Gwyn	Powys	Dyfed	Glam	Gwent	Wales
Species	Ha	Ha	Ha	Ha	Ha	Ha	Ha
Pine	1,711	4,047	1,645	3,221	2,653	860	14,135
Sitka spruce	6,889	14,865	29,529	18,889	12,966	752	83,891
Larch	1,537	3,569	5,729	5,423	3,778	2,377	22,411
Other conifers	3,135	4,632	8,314	7,485	1,590	2,826	27,984
Mixed conifers	0	14	202	176	62	37	492
Total conifers	**13,272**	**27,127**	**45,420**	**35,194**	**21,050**	**6,851**	**148,913**
Oak	3,292	9,002	10,855	11,385	5,204	3,180	42,918
Beech	1,753	910	1,447	2,143	1,316	1,429	8,998
Sycamore	1,227	1,168	560	2,822	634	497	6,907
Ash	1,957	1,812	4,021	7,536	1,783	2,211	19,321
Birch	608	2,625	2,596	3,086	2,562	1,102	12,579
Elm	0	0	14	79	30	0	123
Other broadleaves	1,080	1,622	3,931	7,551	3,125	1,726	19,033
Mixed broadleaves	7	20	1,466	2,814	2,408	909	7,624
Total broadleaves	**9,924**	**17,158**	**24,889**	**37,415**	**17,062**	**11,053**	**117,503**
Total all species	**23,197**	**44,285**	**70,310**	**72,610**	**38,111**	**17,904**	**266,416**

Fig 2 Woodland area by principal tree species and size

Woodland area by principal tree species and percentage							
	Clwyd	Gwyn	Powys	Dyfed	Glam	Gwent	Wales
Species	%	%	%	%	%	%	%
Pine	7.4	9.1	2.3	4.4	7.0	4.8	5.3
Sitka spruce	29.7	33.6	42.0	26.0	34.0	4.2	31.5
Larch	6.6	8.1	8.1	7.5	9.9	13.3	8.4
Other conifers	13.5	10.5	11.8	10.3	4.2	15.8	10.5
Mixed conifers	0	0	0.3	0.2	0.2	0.2	0.2
Total conifers	**57.2**	**61.3**	**64.6**	**48.5**	**55.2**	**38.3**	**55.9**
Oak	14.2	20.3	15.4	15.7	13.7	17.8	16.1
Beech	7.6	2.1	2.1	3.0	3.5	8.0	3.4
Sycamore	5.3	2.6	0.8	3.9	1.7	2.8	2.6
Ash	8.4	4.1	5.7	10.4	4.7	12.3	7.3
Birch	2.6	5.9	3.7	4.3	6.7	6.2	4.7
Elm	0	0	0	0.1	0.1	0	0
Other broadleaves	10.9	3.7	5.6	10.4	8.2	9.6	7.1
Mixed broadleaves	0.1	0	2.1	3.9	6.3	5.1	2.9
Total broadleaves	**42.8**	**38.7**	**35.4**	**51.5**	**44.8**	**61.7**	**44.1**
Total all species	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Fig 3 Woodland area by principal tree species and percentage

The headline information from Figs 2 and 3 is as follows:

- Conifer species are dominant and cover 56% of the woodland area
- Broadleaved species cover the remaining 44%
- Sitka spruce is the dominant conifer species and accounts for 31.5% of the total woodland area and 56% of the conifer area
- Gwent has a noticeable low percentage of Sitka spruce plantations – 4.2%. All other counties have over 20%
- Oak is the dominant broadleaf species and accounts for 16.1% of the total woodland area and 36.5% of the broadleaf area
- Larch is ranked the 2nd most common conifer species and covers 10.5% of the total woodland area and 18.8% of the conifer area
- Ash is currently ranked the 2nd most common broadleaf species and covers 7.3% of the of the total woodland area and 16.5% of the broadleaf area

As the importance of suitable tree species selection for each site is critical to its success, that selection is a vital part of any management tool.

The Ecological Site Classification Decision Support System (ESC - DSS)[4] was designed to help make the decision of what to plant and where for either commercial or landscape and/or environmental purposes. The latest version - ESC 3 incorporates future climate change projections for the 2050 and 2080 low and high scenarios of UKCIP02 to allow users to incorporate future suitability into planting decisions. Users are advised to use of the high- Representative Concentration Pathway scenario for 2050, and to use of the high- Representative Concentration Pathway scenario for 2080.

In relation to commercial forestry, the most suitable species is chosen for each site based on the species that will achieve maximum timber volume production, and as climate change evolves the choice of species will need to change too.

Present predictions of summer soil moisture deficit suggests that Sitka Spruce, the most commonly grown commercial conifer, would reduce its rate of timber production to a large extent in England. However in the North West and the Southwest peninsula, its productivity would increase and also in Wales and Scotland. This suggests that it should continue to be planted in those areas. A further prediction is that Corsican Pine is the only conifer that becomes the most suitable to be planted in all areas of Britain.

The increase in temperature will generally increase timber productivity across Wales, but the level of average annual rainfall and the level of droughtiness will have a direct bearing on choice of species. In areas of high average rainfall, such as Neath Port Talbot, Conwy, Merthyr Tydfil, Rhondda Cynon Taff and Gwynedd, species such as Douglas fir and Sitka spruce should continue to be the preferred timber species subject as always to soil type and other factors. At the other end of the scale, where the average rainfall is likely to drop to below 1000mm, as is the case in Denbighshire and Wrexham, other species will need to be considered as an alternative. These are however subtle changes and the decisions on species choice will need to be taken on a site by site basis taking into account soil type, topography, exposure etc.

Present crops can continue to be managed without any change, but when they are felled at the end of their financial rotation, more thought will need to be given in relation to the choice of species for re-stocking, especially in regions with hotter, drier summers. This will be particularly relevant to the eastern regions where there will be a need on some sites to replace Sitka spruce with other species that will grow well on drier soils. Commercial tree species that are drought tolerant include Scots pine (very tolerant), Sweet chestnut (which thrives on sandy soils) and Sessile oak (which is drought tolerant) should be planted instead of Pedunculate oak.

We may need to consider non-native provenances in place of some native species, or include a mix of native and non-native species. It will however be important to choose species that are compatible in a mixture. A suitable broadleaved mixture would include Oak with cherry or sycamore or sweet chestnut. Mixtures of broadleaves with conifers would include Oak with European larch, Sweet chestnut with European larch, Beech with western red cedar or Scots pine or European larch or Norway spruce.

Opportunities to be considered include the planting of native species outside their natural range in the North and West of the UK. The main opportunities in Wales is in relation to Beech and Scots pine. Beech which would normally be recommended for the majority of the land in Powys, Conway and Denbighshire should be considered along the eastern edges of Carmarthenshire, Ceredigion and Gwynedd. By contrast, Scots pine should be considered along the western edges of Powys and Conwy.

Where existing species are to be replanted, consideration should be given to using planting stock from more Southerly locations and including some genetic variation from provenances of up to five degrees South, where the present growing conditions could be replicated here in the future.

Examples relating to choice of provenance for some of the key species planted in Wales[5]

- The most common broadleaved species planted in Wales is Oak. Pedunculate oak has often been planted in parts of western Britain (including Wales) where sessile oak might be better suited. Material from selected British or north-west European seed stands are to be preferred[7]
- As regards Beech, material from good quality British stands should be preferred with registered western European seed stands as an alternative.
- Sitka spruce, the most common conifer species planted in Wales is native to a narrow zone along the west coast of North America. Provenances from Queen Charlotte Islands (QCI) or

Washington were preferred in the afforestation programmes of the last century, but genetically improved material is now widely available.

The Forest Resilience Guide 2 produced by Natural Resources Wales[6] provides advice on species for tree planting based within four Welsh climatic zones and the range of soil types found within them. The guide includes detailed tables showing the recommended broadleaf and conifer species to plant for each of the main soil categories, but the brief information provided below is restricted to the advice provided in relation to the effects of climate change on species choice.

Climatic zone 1 – predominantly cool and wet/upland Wales/exposed or moderately exposed sites

- Sitka spruce will remain the most productive species on these sites. Other suitable conifers primarily have fibre rather than timber potential but this should not deter their selection if site opportunities allow.
- The presumption is that all areas of deep peat will be reverted to open habitat as part of priority habitat restoration. Where the peat is so modified, native woodland may be appropriate.

Climatic zone 2 – predominantly cool and wet/upland Wales/moderate or sheltered exposure

- On better soils, Douglas fir, western red cedar and sequoias should be favoured where exposure allows.
- Where suitable, grand fir and noble fir will prove useful choices for fibre rather than timber production, as an alternative to Sitka spruce.
- The presumption is that all areas of deep peat will be reverted to open habitat as part of priority habitat restoration. Where the peat is so modified, native woodland may be appropriate.

Climatic zone 3 – Warm moist (currently mainly below 400m but predicted to increase from the east)/mixed woodland/moderate or sheltered exposure.

- Where conifers are chosen, the presumption is that Douglas fir will be the preferred conifer species where site and exposure allow.
- On brown earth sites, a wide variety of species are suitable and in no circumstances should Sitka spruce be selected if an alternative species will yield quality timber of a similar yield class
- Drought will become an issue for some species particularly in the east and south of Wales.

Climatic zone 4 – Warm dry (currently mainly under 50m, mainly in the south east of Wales but predicted to increase from the south and east to cover most of southern and eastern Wales)/mixed forest/pine/moderate or low exposure

- Susceptibility to drought will be the most limiting factor in this zone and the extent is predicted to increase significantly to the North and West in the future climate change scenarios. Spruce should not be selected and the use of beech may be limited.
- Managers should look for all opportunities to establish mixed conifer/broadleaf stands with species such as redwoods, oak and sweet chestnut.
- A wide range of broadleaves including some with growth rates compatible to conifers such as sweet chestnut have significant potential for increased use.

Effect on productivity and timing

The expectation is that productivity of woodland will increase throughout Wales, due to longer growing periods, higher temperatures and increased CO_2 levels. Therefore, rotation length and timing of thinning operations will need to be reviewed, with harvesting operations becoming more frequent.

The exceptional amount of rainfall and storms in February 2020, when Wales recorded the highest amount of monthly rainfall on record, is perhaps likely to be repeated more often in the future. The combination of the high rainfall and storm force winds inevitably increase the amount of windblow in the forests and they also cause significant disruptions to power supplies through trees and branches falling across overhead powerlines. Electricity Distribution Network Operators (DNO's) are already required by the Regulator to make 25% or their overhead line network resilient, by more aggressive tree felling near overhead lines and consideration needs to be given towards increasing this percentage as tree vegetation is currently the single most important factor in relation to the risk to power supplies and this risk is likely to increase.

However in relation to forestry, the climate of central and eastern Wales is likely to remain favourable for growing broadleaved species capable of yielding high-quality timber[7]. In relation to conifers, Sitka Spruce presently growing in Wales at a General Yield Class (GYC) of 20 is producing 20 m3 of timber/ha/year with a rotation length of about 50 years and a first thinning age at about 20 years.

A warmer climate will dry some of the soils during summer whilst maintaining the annual rainfall figure. We would expect that the same crop could increase its yield to GYC 24 with a rotation length of 45years and a first thinning at 17 years. The addition of Douglas fir, as an alternative species better suited to the changing climate, would grow better on a wider range of soils and could achieve GYC 26.

Over an area of 100ha, that increase in production could be in the region of 400 m3 pa, with an increase of 18,000 m3 over that 45 year rotation.

Where there is increased droughtiness however, this will reduce timber productivity and this will have two key effects. Firstly it will have a detrimental impact on the timber production of current crops and it will also be the trigger for forest managers to consider alternative species such as Corsican and Scots pine that will tolerate the dryer conditions.

With regard to broadleaf species, the growing of Oak (pedunculate) would be enhanced with the GYC potentially going up from 2 to 6, and Ash (disease resistance allowing) going from 4 to 7.

Alders and Birch species would also improve in their productivity.

Native woodland (non -commercial planting)

The National Vegetation Classification (NVC) of native woodland in Wales encompasses 6 classes shown below with their reference numbers[8]:

Upland Oak woodland – W17, W11, W01a and W16b.

Upland mixed Ash woodland W8 and W9.

The upland Oak woodland classifications are mainly related to base poor to acidic conditions in areas of high rainfall (greater than 1000mm/pa), not normally at risk to flooding due to the hillsides on which they generally grow.

The species in general include Sessile oak and Birch.

As oak is a variety that demands light, any underplanting to enrich these sites would need to be in felled coupes or natural clearings, and include stock from a more Southerly provenance, such as Northern France.

The upland and lowland mixed Ash woodland classifications are restricted to the base rich conditions and drier soils, with any wetter flushes growing Alder. These conditions are found throughout Wales.

The main species are currently Oak and Ash and should remain so with even with a change in climatic conditions. The Ash component will be dependent on disease resistance.

Opportunities for Woodland in Wales as a result of climate change

The Welsh Government's Strategy is to increase the amount of woodland cover by at least 2,000 hectares per annum from 2020 to 2030 and beyond to meet strategy priorities and to maintain the overall productive potential from Welsh woodlands[9].

- Climate change will affect the way in which new woodlands are planned and managed, but the significant increase in timber production expected will improve the profitability of commercial forestry plantations.
- The increase in productivity will also increase the amount of carbon sequestration and contribute to reducing the amount of $C0_2$ in the atmosphere.
- Sitka spruce should continue to be the main conifer species planted, but in future consideration should be given to planting other species in areas of low rainfall and where subject to droughtiness.
- The planting of more mixed plantations in terms of species and genetic material will be needed to increase stand resilience in a changing climate.
- Contingency plans need to be put in place to mitigate the potential increase in winter storm damage, wildfire occurrences and pest and disease outbreaks.

Conclusions

- Forestry is a very long-term crop in comparison to all agricultural crops.
- Of the ALC measured criteria, many cannot be altered in the long term for growing trees; soil fertility and acidity can be changed annually to optimise growing conditions for arable crops and grass, but only for the first couple of years for woodland establishment, after which the soils will revert to their baseline figures.
- Woodland, being slow growing, can often adapt to changing conditions but only if the changes are gradual. Woodlands are less adaptable to rapid changes as when trees are put under stress, in addition to being less healthy, they become more vulnerable to pests and diseases.
- In Wales, a stimulation of timber productivity due to the warmer climate and increased CO_2 levels might take place. If as a result, there was an increase in GYC of 3 (average of conifer and broadleaf) over the 306,000 ha woodland cover, the increase in productivity would amount to just short of 1 million m3 /yr. Based on the 200,000 ha of woodland that is in a woodland management scheme and accessible on farms, the figure drops to 600,000 m3, with the associated additional sequestration of Carbon. This is still a significant potential increase to come on to the market and into local industry and based on a standing value of £35/m3 the additional revenue to the landowners would be £21m.
- Farmers should look at timber production for a diversified income source.
- A greater potential of south westerly storms would result in greater incidence of windblow on shallow soils due to the increased winter rainfall and water logging.

- Species selection needs to consider planting a varied, extended selection of trees, some with drought hardiness and provenance from more Southern sources; the more diverse mixture planted will help to ensure survival of the woodland as some species may fail and others may thrive better than expected.
- There will be a greater chance of tree disease and pest outbreaks with warmer winters which allow pests to extend their range; it should be added that if the change in climate allows pests to move further north, then it could also allow their natural predators to do the same.

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CEREAL PRODUCTION IN WALES

Author; Sarah Clarke Research Crop Physiologist ADAS

This section is concerned with cereal production in Wales and the likely impact of climate change scenarios thereon. It considers the Cranfield projections for 2020 (2010 to 2039) and 2050 (2040 to 2069) under a low and medium Representative Concentration Pathway scenario. Effects of climate change on cereal physiology, yield, rotations and varieties plus biotic and abiotic stresses are considered here but specific impacts on cereal diseases are dealt with in a separate section.

Background information

In 2019, 17.5 M ha of the UK was utilisable agricultural land and, of this, over a third was croppable[43]. Over half (52%; 3.2 M ha) of the total croppable area in the UK was down to cereals[44]. In Wales, 1.9 M ha was used for agricultural purposes and 0.093 M ha used as arable and bare fallow in 2019[45].

The overall area of arable and bare fallow has increased by 9 k ha in Wales over the past ten years, but in a historical context this level is still relatively low. An area of 138 k ha of cereals was grown in 1914[46] which shows the scope for expansion in the current cereal area.

It has been estimated that, in 2017, 49.6 k ha of cereals were grown in Wales[47]. The most commonly-grown cereal was wheat (21.5 k ha), followed by spring barley (14.4 k ha), winter barley (7.3 k ha) and oats (5.3 k ha). A small area of other cereals was also grown (1 k ha). The greatest area of wheat is grown in South Wales and Pembrokeshire followed by North East Wales and Powys[48]. Spring barley is grown across more Welsh regions, and is the most common cereal grown in North West Wales, Ceredigion and Carmarthenshire[49]

All cereals are vulnerable to a range of adverse weather conditions throughout the season, although vulnerability and potential effects on final yield vary among: cereal species, sowing timing (autumn or spring), variety and how the crop is managed e.g. seed rate, fertiliser amounts and timings. An example of these interactions is heavy summer rainfall. In all cereals, this can cause lodging[50] (displacement of the crop from the vertical) leading to reductions in yield and grain quality. However, some cereals e.g. oats, and taller wheat and barley varieties, are more likely to lodge than shorter

43 Defra farming statistics, December 2019. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/865769/structure-jun2019final-uk-22jan20-rev_v2.pdf

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wheat varieties. Autumn sown crops, and those sown at a high seed rate are also more likely to lodge than spring-sown crops and those sown at a lower seed rate. High levels of nitrogen fertiliser can also lead to a higher likelihood of lodging.

Comparison between ALC interpolated UKCP18 data and the current evidence base

The study into the effect of climate change on agricultural land classification (ALC) in Wales[51] concluded that there will be an increase in ALC grades in 2020 and 2050. Overall, the proportion of land area classified as the Best and Most Versatile (BMV) land is predicted to increase from 20% to 23-24% under low and medium scenarios in 2020 and 2050. However, the predicted changes in area do differ with each land classification grade; grades 1 and 2 are predicted to increase in 2020 but decline in 2050 whereas grades 3a and 3b are predicted to increase in area over both time periods[52].

In terms of the cereal growing regions of Wales, for the majority of the area, there is no change to the ALC in either the low or medium Representative Concentration Pathway scenarios in 2020. However, some changes, both positive and negative, can be seen. In Monmouthshire, it is predicted that some land near the border with England will experience a reduction of 1 or 2 grades in ALC. However, along most of South Wales, a proportion of land is predicted to increase by 1 or 2 grades, particularly in Pembrokeshire. The Powys border region, particularly the area that borders Shropshire, sees a relatively large area predicted to see an increase in ALC by 1 or 2 grades. Across the cereal growing areas on North Wales, under the 2020 scenarios the majority of land is predicted to have an unchanged ALC with some small areas experiencing either increases or decreases in ALC grade.

The changes predicted to be seen in 2020 are exacerbated in the 2050 scenarios: areas of Monmouthshire are predicted to reduce in ALC by 2, or in some cases 3, grades. However, for the majority of Southern Wales, the effect predicted for 2050 is neutral or positive compared to the baseline with some land seeing increases by 1 or 2 grades. There is predicted to be little change in North West Wales between the 2020 and 2050 scenarios but North East Wales sees large areas predicted to experience a downgrade of ALC by 1 or 2 classes.

The areas modelled as suitable for wheat growing in 2020 and 2050 under low and medium Representative Concentration Pathway scenarios, based on UKCP18 data, are those currently used for cereal growing – those at lower altitudes round the periphery of the country. The areas classed as most suitable are found in the North Wales counties (Isle of Anglesey to Flintshire), the South West, Monmouthshire, and in the borders with England. The areas most suitable for wheat growing reduce between the 2020 and 2050 scenarios, but appear to reduce by a greater extent in the medium versus the low scenario, with the biggest impact apparent in the 2050 medium Representative Concentration Pathway scenarios. Greater effects are evident in 2080 and under the high Representative Concentration Pathway scenario but these are outside the scope of this project.

Overall, the predicted changes in ALC and suitability for wheat growing appear unlikely to have a significant negative impact on cereal growing in Wales. Indeed, the availability of BMV is predicted to increase. This aligns with recent modelling work by other groups. Harkness *et al.* (2020)[53] analysed changes in the frequency, magnitude and spatial patterns of 10 adverse weather indices across the

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[51] **Keay C. A. and Hannam J.A. (2020) The effect of Climate Change on Agricultural Land Classification (ALC) in Wales. Capability, Suitability and Climate Programme, Welsh Government Report 95pp**

[52] Keay C. A. and Hannam J.A. (2020) The effect of Climate Change on Agricultural Land Classification (ALC) in Wales. Capability, Suitability and Climate Programme, Welsh Government Report 95pp

[53] Harkness, C., Semenov, M.A., Arealc, F., Senapati, N., Trnkad, M., Balekd, J., Bishop, J. (2020) Adverse weather conditions for UK wheat production under climate change *Agricultural and Forest Meteorology* 282–283 107862 https://doi.org/10.1016/j.agrformet.2019.107862

UK, using climate scenarios from the CMIP5 ensemble of global climate models (GCMs) and two greenhouse gas emissions (RCP4.5 and RCP8.5). They concluded that a future UK climate would continue to remain favourable for wheat production, but conceded there would be both positive (e.g. dryer summers reducing lodging and improving harvest timeliness) and negative (e.g. wetter winters increasing waterlogging) impacts on wheat crops.

What the scenarios mean for cereal production in Wales

Impact of projected changes in annual, seasonal and extreme rainfall

Across Wales, levels of rainfall are generally high but very variable. The regions that most commonly grow cereals are those which receive the least, on average, with areas along the north coast and the borders with England receiving around or below 1000 mm per year.[54]These cereal-growing areas are also regions whose soils experience a below average (259.8) number of days at field capacity.

Annual rainfall

UK Climate Projections 2018 (UKCP18) suggest that total annual average rainfall (AAR) will reduce across Wales in both the low and medium Representative Concentration Pathway scenarios, although by a small amount. On average, AAR will reduce by 22.9 mm and 38.7 mm in 2020 and 2050, respectively, for the low Representative Concentration Pathway scenario, and the same amount (to the nearest mm) for the medium Representative Concentration Pathway scenario. This will take the AAR of the north Wales counties (Isle of Anglesey to Flintshire) to 899 mm and Monmouthshire to 994 mm by 2050. Other cereal-growing areas will remain with an AAR of >1000 mm.

In relation to the reduction in AAR, there is also predicted to be a reduction in the average number of days soils are at field capacity (FCD). The UKCP18 projections show an average reduction in FCD of 12 and 24 days in 2020 and 2050, respectively, with the medium and high scenarios the same to the nearest day. Associated with the reduction in AAR described above, this will reduce the FCD of the north Wales counties by 1.6 and 16 days in 2020 and 2050, respectively.

This level of reduction in AAR will not prevent cereal growing in Wales, and in some regions where AAR and FCD are high, it may be an opportunity to grow more cereals. In England, one of the major cereal growing areas is Eastern England, where AAR levels are commonly <700 mm[55]. Seasonal differences in rainfall under different scenarios are likely to have a greater impact on cereal growing.

Average summer rainfall

UKCP18 projections suggest that annual summer rainfall (ASR) will reduce significantly under low and medium Representative Concentration Pathway scenarios, although they are the same (to the nearest mm) for both. UKCP18 predicts that in Wales there will be average reductions to ASR of 83 mm and 138 mm in 2020 and 2050, respectively, although the areas

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[54] Met Office - Wales: climate. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/Wales_-climate---met-office.pdf [Accessed 02 May 2020]

[55] Met Office – Eastern England: climate. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/eastern-england_-climate---met-office.pdf [Accessed 02 May 2020]

where cereals are more commonly grown are slightly less impacted. Although these reductions are significant, because levels are currently reasonably high compared to some cereal growing areas in England, Wales is less likely to experience the worst of the potential negative impacts of low ASR on cereals.

Low levels of ASR can lead to a number of detrimental effects on cereal growth and yield. Summer (In this context, April to September) incorporates cereal stem extension, ear formation, anthesis (flowering), grain formation and grain filling, all of which are important in determining final yield and all of which can be affected by reduced water availability. Effects can include, but are not limited to: an overall reduction in crop growth and stem carbohydrate formation, a reduction in ear size during ear formation, a reduction in grain numbers due to floret abortion and a curtailing in grain filling. All of these can lead to reduced yield and grain quality in all cereals. As mentioned above, cereals in most areas of Wales are less likely to experience these effects than parts of England, although due to seasonal variation, they cannot be ruled out. Effects on spring sown cereals are likely to be greater as they will not have time to establish a deep root system which could mitigate some of the effects of reduced rainfall. This effect is likely to be exacerbated by higher average winter rainfall (AWR) leading to later sowing (see AWR section below).

A reduction in ASR will also have some advantages for cereal growing. Less ASR is likely to improve the timeliness of harvest which will maintain cereal quality e.g. Hagberg falling number in bread making wheat which reduces if harvest is late or grains start to sprout. A reduction in certain disease may also result (see Disease section).

The likelihood of lodging (displacement of the plant from the vertical), which can reduce yields by up to 80%[56], is likely to be lower with reduced ASR. However, there may be more localised intense storms[57], increasing the risk of lodging to crops where these occur.

Average winter rainfall

The UKCP18 average winter rainfall (AWR) projections show a significant increase under the low and medium scenarios, although the differences resulting from the two are minimal. On average in Wales, AWR is projected to increase by 60 mm in 2020 and 100 mm in 2050. The projections for the cereal growing areas of north Wales and Monmouthshire are below these averages, but those for Pembrokeshire are higher. With Wales already experiencing relatively high levels of AWR, this may lead to significant impacts on cereals.

Waterlogging of soils can have a significant impact on crops. Dickin and Wright (2008)[58] found that 44-58 days of waterlogging (64-93 days after sowing) resulted in 20-24% yield reduction in wheat. Saturated soil leads to several problems, both at soil and plant level. The soil is at higher risk of compaction and the low oxygen levels reduce microbial activity. Plant hydraulic conductivity in the roots decreases which in turn reduces photosynthesis and stomatal conductance. All these factors contribute to reduced plant growth and eventually lower yield. Some indirect effects of waterlogging are increased stem elongation and less root proliferation as well as nutrient leaching and thus a higher chance of nutrient deficiencies. Lack of root growth can increase the risk of lodging and during dry periods later

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[56] Berry, P.M., Sterling, M., Spink, J.H., Baker, C.J., Sylvester-Bradley, R., Mooney, S.J., Tams, A.R., and Ennos, A.R. (2005) Understanding and reducing lodging in cereals. *Advances in Agronomy.* Volume 84: 217-271

[57] Met Office (2018) UKCP18 National Climate Projections – Slide Deck. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-overview-slidepack.ff.pdf [Accessed 17 Apr. 2020]

[58] **Dickin E. & Wright D. (2008). The effects of winter waterlogging and summer drought on the growth and yield of winter wheat (*Triticum aestivum* L.). Europ. J. Agronomy, 28, 234-244.**

in the season as the root system might not have developed enough to cope with reduced water availability in the soil.

High AWR may also mean that the land cannot be travelled on for a long period, leading to delays in spring management (e.g. fertiliser, weed control and disease control applications) and consequently reducing the yield potential of the crop. The delayed ability to travel may also lead to delayed drilling of spring crops which would then be less resilient to cope with lower levels of ASR.

Growing seasons with potentially high AWR and low ASR may lead farmers to establish crops earlier in the autumn. This can benefit crops through better growth before winter, but it can also mean that crops are more susceptible to pests e.g. aphids, and there is less time available to practice cultural weed control methods. Both of these issues may lead to the need for more pesticides to be applied.

Impact of projected changes in temperature

Most cereals in Wales are grown at lower altitudes where average annual temperature varies from about 9.5°C to 11°C, with the higher values occurring around or near to the coast. In these areas, the mean January temperature is around 3 - 4°C. July is normally the warmest month, with mean daily maximum temperatures in the cereal-growing areas varying from about 18°C along the west coast to 21°C in the east of Powys and Monmouthshire.[59]

Accumulated temperatures from January to June

UKCP18 projections for accumulated temperatures above 0°C between January and June (ATO; °C days) show increases in both the 2020 and 2050 scenarios, although the increases are slightly smaller for the medium than low Representative Concentration Pathway scenario. On average, ATO is predicted to increase by 170 °C days and 273 °C days in 2020 and 2050, respectively, although the main cereal-growing areas are likely to be less affected than the average.

These higher temperatures in late winter and spring are likely to lead to increases in biotic stresses for cereals. This is likely to include increased burdens of pests, weeds and diseases on the crops, and due to the likelihood of wetter conditions, it may not be possible for farmers to travel on the land to control these with pesticides.

Warmer winter temperatures may also lead to direct effect on cereal crops. Winter cereals (those sown in the autumn) require a period of cool temperatures (0-12°C) to advance floral initiation. If the vernalisation requirement is not satisfied, the crop will not flower (or flower very late) and seed set and yield will be severely affected. Vernalisation requirement varies among cereal species. Most wheat varieties respond strongly to vernalisation, although requirements do vary by variety. Oats, on the other hand, do have a vernalisation requirement but this is not obligate so they will always flower, although if they are not vernalised this will be later than normal. Spring-sown cereals may have a slight response to a cold period but do not require a period of vernalisation.

[59] Met Office - Wales: climate. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/Wales_-climate---met-office.pdf [Accessed 17 Apr. 2020]

Accumulates and Extreme summer temperatures

Accumulated summer temperatures (ATS; °C days) are predicted by UKCP18 to increase in both the low and medium scenarios, although the increase is slightly less under the medium scenario. On average, ATS is predicted to increase by 189 °C days and 303 °C days in 2020 and 2050, respectively, although the increase is predicted to be less for most of the main cereal growing areas of Wales. Averaged over the summer months (April to September), this equates to ca. 1 °C and 1.7 °C per day in 2020 and 2050, respectively. However, the UKCP18 projections also indicate that there will be a higher chance of greater daily maximum temperatures in the summer.

Higher overall ATS is likely to have a detrimental effect on cereal yields. Progress of cereals through all their development stages is affected by temperature. Higher temperatures shortens development phases and consequently reduces the growth during those phases. This was demonstrated by an analysis of over 300 cereal crops (predominantly wheat) collected as part of the Yield Enhancement Network (YEN) between 2013 and 2017[60]. Higher yields were associated with cooler temperatures, especially in June, and on average, yields were reduced by 1.7 t/ha per °C rise in average annual temperature.

As well as direct effects on cereal physiology, higher overall ATS is likely to increase the proliferation of certain pests. They may well affect the likelihood of certain diseases, with the risks of some diseases increasing and others decreasing (see Disease section). These can impact on overall yield of the crop and may require additional pesticide applications to control.

Extreme high temperatures (>30 °C), which the UKCP18 predicts are to become more likely, have particular risks for cereals. If the cereal experiences extreme temperatures during flowering (anthesis), this can reduce the numbers of grains that are set by affecting floret fertility[61]. Heat stress during grain filling can reduce grain yield and quality through reduced grain size[62]. However, due to the fact that temperatures in Wales are generally lower than those of cereal-growing areas of England, although the risk of these events are increased, they are still relatively low compared to the East and South East of England.

Strategies that the cereals sector could adopt to prepare and future proof

There are likely to be a range of climate change impacts on the cereals sector in Wales over the coming decades. The reduction in AAR may allow more cereals to be grown, and the reduction in ASR may allow more timely harvest of crops. However, increases in temperatures over winter may lead to an increased burden of biotic stresses and increased AWR may impact crops through waterlogging. Overall, though, the impact of climate change on the Welsh cereals sector is likely to be less severe than that experienced in England, particularly in the South and East of the country. This may mean that there is a greater demand for cereals to be gown in Wales.

There are many ways in which the cereals sector could prepare to either avoid or minimise the impact of the climate change predictions made in UKCP18. A number of these options are outlined below, but this list is by no means exhaustive. Research is required to investigate the best options, and combination of options, for the cereal-growing areas of Wales.

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60 Kindred, D.R. (2018; *pers.* comm). Yield Enhancement Network (YEN) https://www.yen.adas.co.uk/

61 Mitchell, R.A.C., Mitchell, V.J., Driscoll, S.P., Franklin, J., Lawlor, D.W. (1993) Effects of increased CO2 concentration and temperature on growth and yield of winter wheat at two levels of nitrogen application. Plant, Cell Environ 16, 521–529.

62 Nasehzadeh, M., Ellis, R.H. (2017) Wheat seed weight and quality differ temporally in sensitivity to warm or cool conditions during seed development and maturation. Ann. Bot. 120, 479–493.

Resilient varieties

It has been argued that, in the long term, varieties should be bred to mature earlier and cope with stresses better[63] to minimise the impacts of climate change. However, there are many varieties currently available which may be able to cope under the scenarios outlined above. There are varieties which have: high levels of resistance to various diseases; a low vernalisation requirement to cope with warmer winters; and the ability to establish quickly and vigorously. Wheat is known to form aerenchyma (meaning they have more air spaces between their cells) under low oxygen conditions and can therefore cope better with waterlogging, but some varieties create more aerenchyma than others. Another adaptation to waterlogging is the ability to form adventitious roots, and these varieties can cope with waterlogging for a longer period than susceptible varieties[64].

Diversified rotations and considered agronomy

As well as looking at different varieties to improve resilience to climate change effects, implementing diverse rotations on-farm will also be beneficial. By growing a range of species with different susceptibilities to biotic and abiotic stresses will reduce the overall impact of extreme weather events and will allow weeds, pests and diseases to be managed more easily.

Resilient soils

To minimise the impacts of waterlogging on crops, it is important that drainage systems are maintained. AHDB have a guide on field drainage[65] which explains several different methods to improve drainage and thus mitigate waterlogging. These include improvement of already existing drainage systems, choosing the most suitable tillage method, and controlling traffic to make sure the soil structure stays as open as possible. Improving drainage and mitigating waterlogging is, unfortunately, not something that can be done overnight but with continual effort long term improvements can be achieved.

For more details of UKCP18 predictions on the impacts of soils, see the Soils section of this report.

Integrated Pest Management

The UK government has initiated the Sustainable Use Directive and urged all growers to implement an Integrated Pest Management (IPM) plan. This can help growers to build the resilience and increase overall sustainability (economic and environmental) of their farm by integrating a number of tools to reduce pest, weed and disease impact. This could include: crop rotations, cultivation techniques, enhancement of beneficial organisms, careful targeting of pesticides, monitoring of harmful organisms and reviewing success. A new EU project, IPM Decisions[66], will create an online platform to help farmers with on-farm decisions to implement IPM.

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[63] Foulkes, M.J., Sylvester-Bradley, R., Worland, A.J., & Snape, J.W. (2004). Effects of a Photoperiod response gene Ppd-D1 on yield potential and drought resistance in UK winter wheat. Euphytica 135, 63 73.

[64] Ahmed F., Rafii M. Y., Ismail M. R., Juraimi A. S., Rahim H. A., Asfaliza R. & Latif M. A. (2013). Waterlogging tolerance of crops: Breeding, mechanism of tolerance, molecular approaches, and future prospects. BioMed Research international, Article ID 963525

[65] AHDB Field Drainage Guide https://ahdb.org.uk/knowledge-library/field-drainage-guide

[66] IPM Decisions EU Horizon 2020 project https://www.ipmdecisions.net/

Irrigated cereals

The impacts of reductions in ASR in cereal-growing regions of Wales could be minimised through irrigating these crops. However, this would have to be carefully considered based on the capability of cereal growers to irrigate and the needs of other sectors.

An irrigation strategy for the UK has recently been published[67] which considers the distribution of water resources in the face of climate change and what could be done to mitigate impacts of drought and water scarcity. The report identifies the regions of Monmouthshire and Powys where irrigated potatoes are currently grown as at Medium irrigation water risk through over-licensing/over-abstraction in an area where irrigated production is concentrated. No other areas of Wales were identified as at risk, but these are areas where less irrigation is currently practiced and, as such, growers do not have the infrastructure to irrigate. To establish this infrastructure would require significant investment.

In publishing the strategy[68], the authors' vision was to support economic growth and increase food security in the UK through, amongst others,: 1. Sharing risks and benefits in water supply investments by fostering multi-sector collaboration with the public water supply, energy, and environment sectors; 2. Supporting knowledge translation to increase resilience to climate and water risks; and 3. Driving innovation in precision water management to improve irrigation efficiency.

[67] Knox, J.W., Kay, M.G., Holman, I.P., and Hess, T.M. (2020) Irrigation water strategy for UK agriculture and horticulture. Available at https://www.nfuonline.com/nfu-online/science-and-environment/irrigation-and-abstraction/irrigation-water-strategy-for-uk-agriculture-and-horticulture/

[68] Knox, J.W., Kay, M.G., Holman, I.P., and Hess, T.M. (2020) Irrigation water strategy for UK agriculture and horticulture. Available at https://www.nfuonline.com/nfu-online/science-and-environment/irrigation-and-abstraction/irrigation-water-strategy-for-uk-agriculture-and-horticulture/

CROPPING DISEASE RISK

Authors: Rebecca Joynt, Phillip Bounds and Phillip Walker Arable physiologists/plant pathologists ADAS

Background information

Four key crops grown in Wales have been identified as Wheat, Barley, Oilseed Rape and Potatoes. Out of 1,790 000 hectares of utilised agricultural area in Wales in 2018, 93,000 hectares (5%) were used for arable cropping. Of this, 51,000 hectares were used for cereals, including 22,000 hectares of wheat and 23,000 hectares of barley[69]. Oilseed rape area accounted for 5,000 hectares, and there were 4,000 hectares of potatoes. In 2019, the areas grown were broadly similar, with 23,000 hectares of wheat and 20,000 hectares of barley[70]. Wheat, Barley, Oilseed Rape and Potatoes are susceptible to a range of diseases caused by fungal pathogens, which are usually crop-specific. Control of disease is necessary to prevent crop death and loss of yield and as a result, fungicides account for 38% of the total pesticide-treated area of arable crops[71].

Disease can originate from many sources, dependant on the pathogen, including production of air-borne spores from infected stubbles and crop residues, intra cropping spread through conidia spores and soil borne pathogens. Varietal resistance, rotations, cultivations and sowing date can have a role in controlling susceptibility of a crop to infection.

Where the pathogen is present in a crop, the primary driver in initiating the disease life cycles for reproduction and spread of the disease are weather factors; and more specifically when certain temperature and rainfall criteria are met in order for the pathogen to become infectious to the host crop, which can vary between each disease. Climate change and the associated changing weather patterns have the potential to influence the occurrence of these diseases either directly or indirectly, either through optimising/restricting life cycles or influencing agronomic practises. The UK Climate Projections 2018 (UKCP18) predicts that Wales is due to experience from 2020 to 2080 an increase in average winter rainfall (AWR) with a decrease in average summer rainfall (ASR), along with an increase in accumulated temperatures above 0oC (ATO) for all Representative Concentration Pathway scenarios.

The impact on these predicted changes in climate for each specific crop and disease will be discussed in more detail in the sections below.

[69] Welsh Government (2019). Statistical Bulletin – Agricultural Small Area Statistics for Wales 2002-2018. Welsh Government. 20/2019

[70] Welsh Government (2019). Statistical First Release – June 2019 survey of agriculture and horticulture: results for Wales. Welsh Government. 110/2019

[71] Garthwaite D., Ridley L., Mace A., Parrish G., Barker I., Rainford J. and MacArthur, R. (2018) Pesticide usage survey report 284: Arable crops in the United Kingdom 2018. Fera.

Comparison of ALC Interpolated UKCP18 data with current evidence base

Many papers have been written to analyse the relationship between climate change, cropping and associated disease risk[72,73,74,75]. The modelled predictions generated in this project are consistent with those in the literature.

What the scenarios mean for cropping disease risk in Wales

Due to the complex interactions of factors including temperature, rainfall, soil wetness/droughtiness required to generate optimal conditions for disease development, each crop and disease has been discussed independently to evaluate risk.

The UKCP18 models indicate that annual average rainfall (AAR) is likely to remain largely consistent across the various scenarios, however the spread of rainfall throughout the year is expected to change, with an increase in AWR and decrease in ASR between 2020 and 2080 for all Representative Concentration Pathway scenarios. As described in the Cereal Production section of this review, the reductions in ASR are likely to have a less severe effect on crops in Wales, as current rainfall is comparatively high compared to other regions in the UK. The UKCP18 predictions show there is limited change in the total Field Capacity Days, an increase in AWR is likely to cause delay in fields coming out of capacity in the spring and as a result, it will remain necessary to sow the majority of crops prior to substantial winter rainfall.

Wheat

Crops of winter wheat can be affected by a range of diseases affecting foliage, rooting and ears; these can be controlled by a range of agronomic factors as well as fungicide applications. Wheat yield formation is "source limited" and therefore control of foliar disease prevents crop senescence, prolonging green leaf area available for light interception for facilitate grain filling, thus controlling disease improves yield[76].

The Pesticide Usage Survey Report 2018 recorded that septoria was typically the primary focus of disease control in wheat crops across the UK[71]; uncontrolled, septoria can be responsible for yield losses of up to 50%[77]. "Rusts" were also described to be contributory factors of up to 28% of applications (no separation of yellow rust and/or brown rust was detailed) and control of fusarium and ear diseases combined was responsible for 12% of applications.

There can be multiple application timings of fungicides to cereal crops, however most fungicide applications for control of foliar diseases in wheat are applied in May, at "T1": BBCH GS32 (eventual leaf 3 emergence) and "T2": BBCH GS39 (flag leaf emergence). The GS32 application is intended to check early season disease, preventing establishment in the crop, whilst the GS39 application is timed to control disease on the flag leaf and leaf 2, which contribute 65% of total yield. In some circumstances, for example where yellow rust is

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[72] Luck J. Spackman M., Freeman A., Tre̦bicki P., Griffiths W., Finlay K. and Chakraborty S. (2011) Climate change and diseases of food crops. Plant Pathology. **60 (1)**: pp.113-121

[73] Junk J., Kouadio L., DElfosse P. and El Jarroudi M. (2016) Effects of regional climate change on brown rust disease in winter wheat. Climatic Change. **135**: pp. 439-451

[74] Coakley S., Scherm H. and Chakraborty S. (1999) Climate change and plant disease management. Annual review of Phytopathology. **37:** pp.399-426

[75] Launay M., Caubel J., Bourgeois G., Huard F., Garcia de Cortazar-Atauri I., Bancal M-O. and Brisson N. (2014) Agriculture, Ecosystems and Environment. **197:** pp. 147-158

[76] ADHB. (2019) Wheat and barley disease management guide. Agricultural and Horticulture Development Board

[77] Eyal Z., Scharen AL., Prescott JM. and van Ginkel M. (1987) The Septoria Diseases of Wheat: Concepts and Methods of Disease Management. CIMMYT

prevalent, a "T0" spray at BBCH GS30 may be useful, although ADAS trials have rarely shown a yield benefit of T0 applications against septoria. Ear diseases can be controlled by a "T3" spray around BBCH GS65.

Septoria (Zymoseptoria tritici)

Septoria leaf blotch is most important and damaging foliar disease on winter wheat in the UK[71] and is caused by the fungal pathogen, *Zymoseptoria tritici.* It is found most prevalently in the west of the UK and in Wales, where annual rainfall is higher.

The pathogen overwinters as dormant mycelium, pycnidia and pseudothecia on crop debris, early sown crops or volunteers and epidemics are initiated in the winter and early spring by pseudothecia on stubbles releasing sexually produced, airbourne, ascospores. These infect leaf tissue, leading to development of pycnidia and pseudothecia within lesions. Pycnidiospores (produced asexually by pycnidia) transferred by leaf contact and rainsplash allow the epidemic to spread through a crop throughout the spring and summer[77]. Infection of a leaf takes place within 24 hours of spore landing and requires a moist leaf surface.

Once the pathogen has infected a leaf, it undergoes a 14-28 day latent period prior to visible lesions appearing on the leaf surface. Lovell *et al.*, (2004) reported the latent period in field conditions as approximately 250 degree-days[78] and length of latent period reduces as temperatures reaches the optimum. The reported optimum temperature is in the range 15–20°C[79], with temperatures below 7 to 10°C reducing lesion development**78**.

As reported in the Cereal Production section of this review, the modelled increase in summer (April - September) temperatures (ATS) equating to ~1 to 1.7°C per day in the 2020-2050 and 2050-2080 periods, above a baseline temperatures of 9.5°C to 11°C will bring the average daily temperature closer to the optimal conditions for septoria development. The predicted reductions in ASR are unlikely to have any effect on the development of septoria as rainfall will remain relatively high for most areas of Wales, especially those where cereals are most commonly grown. High levels of rainfall maintain a humid microclimate with moist leaves in the crop for septoria infection, despite the predicted downgrading of land classification due to soil droughtiness (associated with Crop Adjusted Moisture deficits for wheat showing a significant increase from 2020 to 2080).

The climate change models also predict an increase in AWR of up to 268mm (2050-2080 Medium mission scenario), which will have an impact on achievable sowing dates, with an increased winter rainfall shortening the autumn drilling period and an increase in early sown crops might be likely. An AHDB/BASF funded study, ran since 2016 has investigated the agronomic factors that affect the development of septoria across the UK and Ireland[80]. Results indicate that sowing date has a significant impact on disease development, with early sown crops (planted in mid-September) more susceptible to septoria, regardless of varietal resistance. Early sown crops emerge during a period of milder temperatures, when ascospore levels are high and temperatures are closer to the optimum for establishment of infection by the pathogen[81]. Where infections are established early in a crop, milder, wetter winters will promote the spread of infection by pycnidiospores in rainsplash; these crops are

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[78] Lovell D., Hunter T., Powers S. Parker S. and Van den Bosch F., (2004). Effect Of Temperature On Latent Period Of Septoria Leaf Blotch On Winter Wheat Under Outdoor Conditions. Plant Pathology. **53 (2):** pp. 170-181

[79] ADHB. (2018) The Encyclopaedia of cereal diseases. Agricultural and Horticulture Development Board

[80] AHDB (2018) Annual Project Report 1 August 2017 to 31 July 2018: Project number 2140003105. Combining agronomy, variety and chemistry to maintain control of septoria tritici. Agriculture and Horticulture Development Board.

[81] Fones H., Gurr S. (2015) The impact of Septoria tritici Blotch disease on wheat: An EU perspective. Fungal Genet Biol. **79**: pp.3-7.

also likely to be well established, thick crops, which is more conducive to maintaining a humid microclimate for disease development.

To summarise, given the predicted climate changes modelled by UKCP18, under all scenarios, risk of septoria is likely to remain high for crops of winter wheat in Wales.

Yellow rust (Puccinia striiformis)

Although yellow rust is a disease more commonly associated with the East of UK, coastal areas can be prone to yellow rust as a result of sea mists generating mild humid weather. The pathogen (*Puccinia striiformis)* overwinters on living plant tissue, volunteers and autumn-sown crops, either as dormant mycelium or active sporulating pustules. Uredospores released by pustules are dispersed by the wind and leaf-to-leaf contact. Optimal conditions for spore germination, penetration and production of new spores are temperatures of 10 to 13°C and a relative humidity of 100%**72**. The life cycle can take as little as 10 days in optimum conditions, such as those found during cool damp springs.

Epidemics usually take off in April and May, however all the modelled climate change scenarios indicate that ATO is expected to increase, meaning that optimal conditions will be reached earlier in year. Additionally, a review of 4475 randomly selected crops of winter wheat from across England and Wales found that temperature/number of frosts below -5°C is an important factor in risk of yellow rust prevalence, with the decreasing number of frosts resulting in an increased prevalence of yellow rust the following season[82]. The review reported that although frosts kill sporulating mycelium, temperatures below -10°C are needed to kill nonsporulating mycelium within the plant tissue. The increase in ATO predicted by UKCP18 is likely to further reduce the number of frosts, generating favourable conditions for development of yellow rust. Early establishment of yellow rust can be difficult to control, with treatments required as frequently as every three weeks to maintain green leaf area and protect yield formation.

Despite these factors, which would suggest an increase in yellow rust, epidemics are less frequent in early sown crops**82** and are often checked in late season by a period of temperatures above 20°C**79**. As already discussed in the Cereal Production section, an increase in AWR is likely to push drilling dates earlier. Additionally, the predicted rise in ATS in all scenarios will mean that temperatures may reach 20°C more frequently and the epidemics may be limited at an earlier point in the season, prior to emergence of key yield forming leaves, which will reduce the importance of this pathogen to the farmer. A reduction in late season disease will also have a knock-on effect of reducing inoculum to overwinter for the following season.

Due to these factors, the effect of the modelled scenarios on yellow rust disease risk is difficult to judge, although it would be reasonable to predict that there might be shift in the timings of any epidemics. It should be considered though, that the population of yellow rust is highly diverse and adaptable, and new races can emerge within a single season, overcoming both varietal resistance and fungicide activity[83]. As such, under the environment predicted by the modelled scenarios, it may be that new races of the pathogen emerge to overcome the limitations**72**.

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[82] Gladders P., Langton S., Barrie I., Hardwick., Taylor M. and Paveley N. (2007) The importance of weather and agronomic factors for the overwinter survival of yellow rust (*Puccinia striiformis*) and subsequent disease risk in commercial wheat crops in England. Annals of Applied Biology. **150:** pp.371-382

[83] Hubbard A., Wilderspin S. and Holdgate S. (2019). United Kingdom Cereal Pathogen Virulence Survey (UKCPVS) 2019 Annual Report. Agriculture and Horticulture Development Board.

Brown rust (Puccinia triticina)

Brown rust is the disease resulting from infection of winter wheat with *Puccinia triticina.* The lifecycle of this pathogen is similar to that of *Puccinia striiformis* (yellow rust). Infection of a leaf requires 100% relative humidity i.e. surface moisture, although the optimum temperature is higher, at around 15°C[73,79] and the pathogen is active between 7-25°C. In optimal conditions, the pathogen can cycle in 5 to 6 days.

In the current climate, the optimal conditions for development of brown rust typically occur in mid to late summer, reducing green leaf area and yield, although the worst epidemics often start early in the season as a result of mild winters[79]. Historically, brown rust is associated with Southern and Eastern areas of the UK, however infections are becoming more common in the North and West and earlier in the season.

The UKCP18 models predict an increase in ATO and AWR, generating favourable conditions for the overwinter establishment of brown rust on early sown crops, and as a result, the incidence of severe epidemics in likely to increase. The forecast rise in ATS will bring temperatures closer to optimal and the decrease in ASR is unlikely to have a significant effect, considering that rainfall is already considerably higher than other regions of the UK. Additionally, early sown crops are likely to have a high plant count and be well tillered, which are favourable for maintaining a humid microclimate for disease development despite the UKCP18 predicted downgrading of land classification due to droughtiness. This is especially relevant in in coastal areas of Wales experiencing sea mists, where the majority of cereal crops are grown; sea breezes may additionally aid spore dispersal of any infection established in a crop, resulting in any epidemics spreading rapidly.

Other diseases

Up to this point, the focus of this section has been to review the effects of the climate change predicted by UKCP18 on diseases currently commonly found in crops of wheat in Wales, however other diseases may become more prevalent in different environments.

An example of which is Take All, a soil-borne disease which effects rooting of both wheat and barley. The pathogen limits growth of roots and is more active in warmer soils[84], hence has a greater effect in early sown crops. Conditions which add stress to the crop promote the disease, including waterlogging over winter (associated with an increase in AWR) and droughting on light soils in the summer (associated with an increase in ATS and decrease in ASR). Take all can be limited by reducing the frequency of cereals in the rotation, and may require more consideration in the future under the modelled scenarios.

Eyespot is another disease associated with early sowings and wet winters, and therefore may become more prevalent under the forecast climate changes. Currently, eyespot is not responsible for significant yield losses in UK crops, however a severe epidemic can reduce yield losses by 10-30%, cause lodging and reduce grain quality[79].

Conversely, a decrease in ASR is likely to reduce incidence of Fusarium Head Blight, a disease associated with summer rainfall around BBCH GS 65. *Fusarium spp.* can produce mycotoxins in the grain, which are toxic and levels in products for human and animal consumption are limited under EU legislation.

[84] Cook R. (2003). Take-all of wheat. Physiological and Molecular Plant Pathology. **62 (2):** pp. 73-86

Barley

Unlike wheat, barley commonly has insufficient grains to store all of the assimilate formed during grain filling, i.e. it is 'sink limited'[85]. There is a very close relationship between grains per square meter and yield in barley, and so maximising grains per square metre is key to maximising yield. Grains per square metre square is influenced by the number of fertile tillers per square metre and the number of grains per ear. Shading trials in spring barley carried out at ADAS Rosemaund and SRUC from 2009 to 2011 showed that maximising light interception between plant emergence and flowering in barley increased grains per square metre[86]. As early season growth is more important in barley, the risk of early disease infections (pre-GS31) is more important that in wheat, as disease can restrict tillering, lower photosynthetic area, thus reducing yield and lowering grain quality. Disease control measures help protect leaf area and minimise the effects of disease on shoot number, grain number/ear and grain weight.

Barley is affected by a range of diseases that are responsible annually for considerable damage to crops and therefore loss of yield and quality. These include rhynchosporium/leaf scald or blotch caused by *Rhynchosporium secalis*, powdery mildew caused by *Blumeria graminis*, net blotch caused by *Pyrenophora teres* (the net form caused by *P. teres f teres* and the spot form caused by *P. teres f.* maculate), brown rust caused by *Puccinia hordei*, yellow rust caused by *Puccinia striiformis,* and Ramularia leaf spot, caused by *Ramularia collo-cygni*[76]*.* The major barley pathogens have varying environmental requirements to produce serious epidemics.

Although there are four key spray timings for applying fungicides to control disease in cereals, T1 and T2 sprays adequately protect most barley crops. Mildew may cause concern in winter barley crops in the autumn/winter and brown rust, rhynchosporium and net blotch may occasionally also cause concern. However, fungicide applications at this stage rarely have a yield benefit and are only necessary if extensive disease levels may affect tiller survival in poorly tillered crops. Yield responses to fungicides are generally variable in winter barley crops at the T0 (GS23-29) timing, and so applications are only made at this time where overwintering disease levels are high in susceptible varieties. The T1 (GS30-32) fungicide application is the main timing in winter barley, with 60% response to fungicides achievable. It is this application that helps to maximise the survival of formed tillers and spikelets, which in turn increases final grain numbers and yield. UKCP18 predictions for higher AWR is likely to reduce the opportunities to travel the ground with a sprayer to apply this early fungicide in a timely manner, which could impact on the level of control achieved. The T2 (GS39—59) application is the other important treatment in winter barley, with 40% of the yield response coming from this application. It is the key timing for ramularia control, with brown rust and net blotch also targets, along with rhynchosporium in wetter western regions and in wet summers. T3 sprays applied after GS50 to winter barley seldom give an economic benefit, and there are few products approved for use in barley at this time. Disease control strategies for spring barley are similar to those for winter barley. T0 sprays are only required in spring barley if mildew is present on a susceptible variety. The T1 treatment in spring barley is the main timing for rhynchosporium control, although brown rust, net blotch and mildew are also targets. About 40% of the yield response to fungicide comes from this timing, although this spray can be omitted in late-sown crops of a resistant variety[86]. The T2 application in

[85] AHDB (2018). The Barley Growth Guide. Agricultural and Horticultural Development Board

[86] Bingham I., Young C., Bounds P. and Paveley N. (2014). Duration of canopy protection required by spring barley post anthesis. 149-152. Paper presented at Crop Protection Northern Britain, Dundee, United Kingdom

spring barley is the main timing for net blotch, brown rust and ramularia control, with about 60% of yield response to fungicides coming from this timing.

Rhynchosporium (Rhynchosporium secalis)

Rhynchosporium is caused by the fungal pathogen *Rhynchosporium secalis,* which can also infect rye and wild grass species as well as cultivated barley. The disease can be very severe, and the control of Rhynchosporium relies on a combination of cultivar resistance, cultural practices and the application of fungicides. Whilst the disease can be seed borne, the most important source of the disease is crop debris from previous crops and volunteers which become infected from the stubble from previous crops. Rhynchosporium is a polycyclic disease (has multiple generations per year), normally involving several pathogen generations during a growing season, and secondary disease spread from infected leaves by splash dispersed *R. secalis* conidia. Mild, wet conditions are particularly conducive to the development of Rhynchosporium, and as a result, the worst infections are generally in the south west and west of the UK[76]. The ideal temperature for rhynchosporium to develop is 18-20°C, although temperatures greater than 20°C slow development[79]. Experiments to examine the effect of temperature and leaf wetness on the latent period of rhynchosporium in barley showed that at 100% relative humidity (continuous leaf wetness), the mean length of the latent period was 24 days at 5°C, 19 days at 10°C, 16 days at 15°C and 13 days at 20°C[87]. The most serious effect on yield in both winter and spring barley results from attacks of rhynchosporium that develop between first node detectable and boot-swollen growth stages which occurs from March to May. As reported in the Cereal Production section of this review, the modelled increase in summer (April - September) temperatures (ATS) equating to ~1 to 1.7°C per day in the 2020-2050 and 2050-2080 periods, above a baseline temperatures of 9.5°C to 11°C will bring the average daily temperature closer to the optimal conditions for rhynchosporium development. A reduction in the length of the latent period due to higher temperatures would also mean that fungicides are being applied in a more curative situation, where they may be less effective. It is unlikely that the predicted reductions in ASR will have any effect on the development of rhynchosporium, as rainfall will remain relatively high for most areas of Wales, especially those where cereals are most commonly grown. UKCP18 models also predict an increase in AWR of up to 268mm (2050-2080 Medium mission scenario), which will impact on soil conditions for autumn sown crops. This is likely to encourage earlier sowing which will result in higher rhynchosporium levels.

Overall, given the predicted climate changes modelled by UKCP18, under all scenarios, the risk of rhynchosporium is likely to remain high for crops of winter and spring barley in Wales.

Brown rust (Puccinia hordei)

Barley brown rust is caused by *Puccinia hordei,* which is a different pathogen to the one associated with brown rust in wheat, and there is no cross infection between the two crops. Although it can infect winter and spring barley, it tends to be more of a problem in autumn sown crops following a mildew autumn and winter. Brown rust can only survive on green living plants, so it overwinters on early sown crops and on volunteers. Cold weather will slow disease development but won't kill it, so the threat can soon increase again when the weather warms up. During mild seasons, brown rust can be found in winter barley crops in the autumn and winter which can then explode in the spring. In the spring, the overwintering disease releases ureospores which are spread by wind and infect the crop. For sporulation and spore germination to occur, temperatures between 15°C to 22°C along

[87] Davis H. and Fitt B. (1994). Effects of temperature and leaf wetness on the latent period of Rhynchosporium Secalis (leaf blotch) on leaves of winter barley. Journal of Phytopathology. **140 (3):** pp. 269-279

with 100% relative humidity are required[79]. Surface moisture on the leaf to is essential to allow germination and formation of the characteristic brown rust pustules. Historically, brown rust epidemics have occurred in the UK during mid to late summer, when there are warm, dry, windy days which allow the spores to disperse, and cool nights with dew which favour germination[76]. However, mild winters and warmer springs would allow brown rust to develop a lot earlier in the season. Apart from weather conditions, other risk factors which favour the development of brown rust are early drilling and barley volunteers that provide a green bridge.

The UKCP18 models predict an increase in ATO and AWR, which will create conditions that are conducive to the overwinter establishment of brown rust, particularly in early sown crops. This is more likely to result in a significant brown rust epidemic as the weather warms up, particularly if left uncontrolled. The predicted increase in AWR may impact on the ability to travel the ground in early spring to apply fungicides to control brown rust effectively. The forecast rise in ATS will bring temperatures closer to optimal for the development of brown rust, and will likely mean that brown rust develops earlier in the season than it has in the past. Early drilling in response to higher AWR, is likely to result in earlier sown crops with a larger biomass that create a humid microclimate that is conducive to the development of brown rust. As with winter wheat, in coastal areas of Wales which experience sea mists, where the majority of cereal crops are grown, sea breezes may additionally aid spore dispersal of any infection established in a crop, resulting in any epidemics spreading rapidly.

Net blotch (Pyrenophora teres)

Net blotch affects a wide range of grasses, but the forms that affect barley are specific to that crop and do not affect other cereals or grasses. It is a very important disease of winter and spring barley and can cause yield losses of between 10% and 40% where not controlled[79]. While it can arise from infected seed, the main sources of net blotch inoculum are infected stubble, crop debris and volunteers. These sources allow net blotch to over-winter, allowing airborne spores to be produced and spread in the wind or predominantly by rain splashing up the plant. Net blotch can be particularly damaging when symptoms continue to develop through the winter and into the early spring, producing an early epidemic as the crop develops. Infection occurs during periods of prolonged high humidity and temperatures between 10°C and 25°C[76]. Research has shown that the optimal conditions for the development of net blotch are a temperature of 20°C and 100% relative humidity[88]. Other factors which favour the development of net blotch are high seed rates, early drilling and min-till or no till regimes. Second barley crops and rotations with a high frequency of barley in the rotation all increase the level of trash and volunteer borne inoculum and therefore the risk of net blotch developing in the crop. The UKCP18 models predict an increase in ATO, which will increase the risk of net blotch developing over the winter, resulting in an early epidemic. The increase in ATS that is predicted by the UKCP18 models would give an increase in temperature that would bring it closer to the optimum for the development of net blotch during the spring and summer months. The predicted reduction in ASR may result in a slight reduction in the spread of net blotch up the plant by rain splash, although summer rainfall levels will still be high compared with other areas of the country and the risk of the disease spreading would still be high. Also, earlier drilling that is likely in response to a predicted increase in AWR is likely to result in the establishment of thicker crops that create a more humid microclimate that is more conducive to the development of net blotch.

[88] Jordan V. (1981). Aetiology of barley net blotch caused by Pyrenophora teres and some effects on yield. Plant Pathology. **30 (2):** pp. 77-87

Powdery mildew (Blumeria)

Although all cereals can be affected by powdery mildew, there are several forms of the disease which are specific to individual crops and do not cross-infect. Barley powdery mildew is caused by *Blumeria graminis* f. sp. *hordei,* which is an obligate, biotrophic fungal pathogen and so it depends entirely on living plant tissue for its growth and reproduction[79]. As such, mildew primarily overwinters as mycelium on volunteers and autumns sown crops. As temperatures rise in the spring, dormant mycelium starts to grow and spores are produced, with humid and warm conditions favouring development. These spores germinate over a wide range of temperatures, from 5°C to 30°C, although 15°C and 95% relative humidity is optimal[76]. Due to the wide range of temperatures over which spores can germinate, the predicted increase in ATO and ATS are unlikely to have a large effect on the development of mildew, although conditions are likely to be nearer the optimal for mildew development. Whilst humid conditions are ideal for mildew development, rain inhibits spore germination and therefore limits disease development. The reduction in ASR predicted by UKCP18 may allow higher levels of mildew to develop during the summer months. Yield losses of 10-15% from powdery mildew are common, although this can be higher in susceptible varieties where left uncontrolled. Rapidly growing, thick crops provided with high levels of nitrogen are most vulnerable, particularly in susceptible varieties.

Anecdotal evidence indicates spring powdery mildew is more prevalent in later sown cereals. This is supported by research that has identified that seedlings leaves are more susceptible and that mildew resistance in leaves increases progressively in winter barley crops. Also, as early sowing can also increase the total number of leaves produced per stem, the maximum degree of resistance expressed by the later-formed (e.g. flag) leaves will often be greater on early-sown than on later-sown plants[89].

As already mentioned, the climate change models predict an increase in AWR of up to 268mm (2050-2080 Medium mission scenario), which will have an impact on achievable sowing dates. As a result, it is likely that the autumn drilling window will be shortened, and more crops will be sown early. In contrast to most other barley diseases, early sowing is likely to reduce the risk of mildew developing in the later formed, more resistant leaves. However, this may be counterbalanced by the development of thick, lush crops which create a humid microclimate for mildew to develop.

Ramularia (Ramularia collo-cygni)

Ramularia leaf spot is caused by the fungus *Ramularia collo-cygni.* It can cause extensive damage to the upper leaves in spring and winter barley once the crops have finished flowering[79]. This can cause extensive losses in yield and quality, and yield losses can be up to 1.0 tonnes/hectare in susceptible varieties. Losses are not only in total grain yield, but also in grain quality, as the number of thin grains increases with severe infections. Seedlings can become infected with ramularia from infected seed, or from air borne spores from barley volunteers and grasses. When seedlings start to emerge, *Ramularia collo-cygni* fungus will grow inside the plant and move into new leaves as they develop, but no visible disease symptoms will develop at this point. Symptoms can develop on dead lower leaves, but symptoms are rarely seen on healthy green leaves until after flowering. There may be a stress or physiological trigger for symptoms to develop, and the toxin rubellin D is also thought to be produced by the fungus when the barley host is stressed. Under certain light conditions, this toxin is activated to trigger the production of reactive oxygen species, leading to typical leaf symptoms[79]. Secondary infections can occur as spores are dispersed

[89] White N. and Jenkin J. (1995). Effects of sowing date and vernalisation on the growth of winter barley and its resistance to powdery mildew (Erysiphe graminis f.sp. hordei). Annals of Applied Biology. **126 (2):** pp. 269-283

from infected leaves, and this is thought to be reliant on leaf wetness, with spores dispersed into the air 24-48 hours after a prolonged period of leaf wetness of several hours. Scottish trials over a number of years showed a positive correlation between ramularia and maximum leaf wetness for 14 days after stem extension. However, an over year analysis carried out in 2018 showed no clear relationship for winter or spring barley, concluding that further work is required to understand the relationship between environmental conditions and development of ramularia[90].

Visual symptoms of Ramularia generally appear in the crop post flowering at growth stages at which fungicide applications are no longer permitted, so growers must decide whether to protect the crop in the absence of visible disease symptoms. There are no fully resistant varieties to ramularia, although there are some differences in resistance between varieties. If leaf wetness is a significant factor in the development of ramularia, the predicted reduction in ASR may lower the risk of ramularia developing. On the other hand, the predicted increase in ATS and likely more extreme temperatures may put the crop under more stress, which could be a trigger for ramularia symptoms to develop.

Oilseed Rape

The latest UK Pesticide Usage Survey Report has shown that the main diseases controlled in oilseed rape were phoma and light leaf spot (combined 53% of all pesticide use) and sclerotinia (25% of all pesticide use)**71**, which will be the main focus of this report. The impact on other diseases in oilseed rape will be discussed briefly.

Phoma Leaf Spot (Leptosphaeria maculans/biglobosa)

Phoma leaf spot, which develops into stem canker in oilseed rape, is caused by two related fungal pathogens: *Leptosphaeria maculans* and, to a lesser extent, *Leptosphaeria biglobosa*. The disease is monocyclic (has one generation per year) and can be controlled routinely by fungicides in the autumn. The main factor in initiating the disease on newly planted oilseed rape crops is infection by air-borne spores (ascospores) that are produced and released from fruiting bodies (pseudothecia) that form on the previous crop's stubbles and crop residues following crop harvest[91]. Rainfall is a key driver for phoma leaf spot epidemics, with ascospores released following 20 rain days (24-hour period where there is at least 0.2 mm of recorded rainfall) and then for ascospores to infect leaf tissue, a minimum of 4 hours leaf wetness is required with infection rates increasing when leaf wetness periods are longer[92]. Leaf spot symptoms will appear after an accumulated mean temperature of 120 degrees days, for example 6 days at 20°C or 30 days at 4°C and typically leaf infections are visible in late October. After leaf infection, the pathogen grows down the leaf petiole and develops into the yield reducing stem cankers at the stem based. Earlier leaf infection (October-early November) causes a greater severity of stem cankers to develop and thus a greater reduction in yield, whereas later leaf infection (December) has less of an impact on yield loss in plants with large canopies but can affect small plants.

The theoretical impact on increased AWR and ATO on phoma leaf spot epidemics is the earlier release of ascospores from infected stubbles to initiative infection and a faster accumulation of degree days in order for the leaf symptoms to become visible. A change of

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[90] Havis D., Evan N. and Hughes G. (2018). Development of a UK wide risk forecast scheme for Ramularia leaf spot in barley. AHDB Project Report PR600.

[91] Aubertot J.N., West J.S., Bousset-Vaslin L., Salam M.U., Barbetti M.J. and Diggle A.J. (2006) Improved resistance management for durable disease control: A case study of phoma stem canker of oilseed rape (*Brassica napus*). European Journal of Plant Pathology: pp 93-94.

[92] Gladders P., Ginsburg D., Ritchie F., Smith J., Waterhouse S., Tucker C. and Tonguc L. (2008) The encyclopaedia of oilseed rape disease. BASF Plc., UK.

air temperatures of just 2°C can significantly reduce number of days required from 30 days when average temperatures are 4°C to 20 days when average temperatures are 6°C, sub sequentially decreasing exponentially as temperatures increase. The phoma epidemic in autumn 2017 was earlier than expected, when higher than average rainfall in September (20 rain days recorded in Cambridgeshire on 11 September) and warm UK average air temperatures of 12.6°C (Source: Met Office) caused in many areas a rapid development of zero to 100% of the disease within the first week of October (ADAS observations). In this situation, the autumn fungicides were applied late with resultant reduced efficacy and high yields losses of 0.2 – 0.4 t/ha were seen in untreated trial plots[93]. Conversely, the autumn of 2018 was dry with 20 rain days recorded in Cambridgeshire 4 weeks later on 10 October (ADAS observations) and the resulting phoma epidemic not seen in many areas until November and a lower reduction in yield loss of 0.1 – 0.2 t/ha seen in untreated trial plots[94]. Therefore the impact of climate change on phoma epidemics will be directly related to the changes in early autumn rainfall, and with seasonal variations being reported it difficult to fully predict what these changes might be.

The other consideration when evaluating the impact of climate change on phoma will be the development of the severity of stem cankers formed after leaf infection. The rate at which phoma stem cankers form at the stem base is associated with how quickly the pathogen progresses along leaf petioles towards the stem in the autumn/winter and can be directly related to the accumulation of degree days after the first appearance of phoma leaf spots[95]. This is important in areas of the UK where there is a cooler climate like Scotland, as there are usually insufficient accumulated degree days for the yield reducing stem cankers to form.

A model was developed to calculate the effect of climate change scenarios on the time for phoma leaf spots to first appear and the subsequent development and severity of stem cankers to form for the years 2020 and 2050[96]. The results found for both scenarios found an increase in the geographic spread and severity of phoma disease epidemics; with a strong effect seen on the timing of the development of cankers in the spring, often 80 days earlier than during 1960-1990, with a greater severity of the disease at harvest. An evaluation of the model predicted that yields will decrease in southern England and Wales by up to 50% and that the range of the disease will extend northwards to Scotland[97].

Although the full effect on the increase ATS and decreased ASR on stem canker development is less clear, as this could give rise to conflicting scenarios for the development of the disease. An increase in summer drought conditions could theoretically lessen the impact of the disease if the plants reaches maturity before the canker can fully develop, or conversely it could increase the impact of the disease as plant stress could reduce the plant's natural resistance mechanism against stem canker. Further research in both areas would be required before any conclusions can be made. Additionally, various disease management adaptation strategies could minimise or negate the predicted yield losses in oilseed rape from phoma stem canker due to climate change[98].

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[93] Knight, S. (2018) Fungicide performance update for wheat, barley and oilseed rape 2018. Agricultural and Horticulture Development Board: pp 46.

[94] ADHB. (2019) Fungicide performance update for wheat, barley and oilseed rape 2019. Agricultural and Horticulture Development Board: pp 46.

[95] Kang M.S. and Banga S.S. (2013) Combating climate change: An agricultural perspective. CRC Press, USA: pp 192.

[96] Evans N., Baierl A., Semenov M.A., Gladders P. and Fitt B.D.L. (2008) Range and severity of a plant disease increased by global warming. Journal of the Royal Society Interface **5**: pp 525-531.

[97] Butterworth M.H., Semenov M., Barnes A.P., Moran D., West J.S. and Fitt B.D.L. (2010) North-south divide; contrasting impacts of climate change on crop yields in Scotland and England. Journal of the Royal Society Interface **7**: pp 123-130.

[98] Barnes A.P., Wreford A., Butterworth M.H., Mikhail A., Semenov M., Moran D., Evans N. and Fitt B.D.L. (2010) Adaptation to increasing severity of phoma stem canker on winter oilseed rape in the UK under climate change. The Journal of Agricultural Science **148 (06)**: pp 2.

Light Leaf Spot (Pyrenopeziza brassicae)

Light leaf spot, caused by the fungal pathogen *Pyrenopeziza brassicae,* is a polycyclic disease (has multiple generations per year) therefore repeated infection can occur more frequently throughout the season. Typically this can make light leaf spot a difficult disease to control, but is routinely managed by fungicides in the autumn/winter and in the spring. Light leaf spot epidemics are derived from air-borne spores (ascospores) produced on previous crop debris and once crops are infected, the pathogen produces rain-splashed spores (conidia) which transfers the disease through the crop canopy and between plants**92**. In parts of the country where crops are harvested later, typically in northern England or Scotland, it has been shown that existing crops can form a 'green bridge' and act as a primary inoculum source for newly sown crops[99]. The disease causes yield loss by decreasing plant growth in winter and by damaging pods in summer[100,101].

The main factor in initiating the disease on newly planted oilseed rape crops are air-borne spores produced in fruiting bodies (apothecia) that survive the summer inter-crop period on infected debris**101**. Weather can affect how quickly light leaf spot infects newly emerging oilseed rape crops with dry conditions known to delay the production of air-borne spores[102]. During a wet summer apothecia will develop rapidly but require intermittent periods of wetting and drying for the apothecia to mature and then decay in order for their ascospores to be released[103]. Controlled experiments have shown that rates of both apothecial development and decay were greatest at c. 17-18°C and decreased as temperature decreased to 6°C or increased to 22°C**102**. These temperature ranges coincide with observed seasonal variations in ascospores numbers seen in the field, where several studies have demonstrated that air-borne spores of light leaf spot tend to be produced from April through to October and less frequently from November to March in the UK, with the main period of ascospores release occurring in August unless it is delayed by dry weather[104,105]. Typically this is the reason earlier sown oilseed rape crops are more at risk of developing light leaf spot symptoms and crops sown later in September can avoid the peak period of air-borne spores.

Some coastal areas of Wales can have delayed harvest due to periods of high summer rainfall, which can lead to subsequent later planting of the following crop including oilseed rape; putting these crops less at risk of developing light leaf spot infections. The theoretical impact of the predicted hotter and drier summers could lead to a shift to crops being harvested and sown earlier and increasing the risk of light leaf spot infections, although conversely the risk could be reduced since these conditions could delay the release of infectious ascospores. Crop moisture is also important for ascospores to infect leaf tissue, with a minimum of 6 hours of leaf wetness required and maximum efficacy of infection occurring within 48 hours of wetness duration**92**. During the dry autumn of 2018, light leaf spot symptoms were not observed in trials plots in Pembrokeshire, Wales until the first week of February and monitoring from other trial sites around the UK were typically seeing

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[99] Sutherland K.G., Wale S.J. and Sansford C. (1995) Effect of different epidemics of *Pyrenopeziza brassicae* on yield loss in winter oilseed rape. Proceedings Ninth International Rapeseed Congress: pp 1004-6.

[100] Boys E.F., Roques S.E., Ashby A.M., Evans N., Latunde-Dada A.O., Thomas J.E., West J.S. and Fitt B.D.L. (2007) Resistance to infection by stealth: Brassica napus (winter oilseed rape) and *Pyrenopeziza brassicae* (light leaf spot). Eur J Plant Pathol **118**: pp 307-321.

[101] Gilles T., Evans N., Fitt B.D.L. and Jeger M.J. (2000) Epidemiology in relation to methods for forecasting light leaf spot (*Pyrenopeziza brassicae*) severity on winter oilseed rape (Brassica napus) in the UK. European Journal of Plant Pathology **106**: pp 593–605.

[102] Gilles T., Fitt B.D.L. and Jeger M.J. (2001) Effects of Environmental Factors on Development of *Pyrenopeziza brassicae* (Light Leaf Spot) Apothecia on Oilseed Rape Debris. The American Phytopathology Society **91:** pp 397.

[103] McCartney H.A. and Lacey M.E. (1990) The production and release of ascospores of *Pyrenopeziza brassicae* on oilseed rape. *Plant Pathology* **39:** pp 17-32.

[104] Gilles T., Fitt B.D.L., McCartney H.A., Papastamati, K. and Steed, J.M. (2001) The roles of ascospores and conidia of *Pyrenopeziza brassicae* in light leaf spot epidemics on winter oilseed rape (Brassica napus) in the UK. Annuals of Applied Biology **138:** pp 141-152.

[105] Evans N., Ritchie F., West J., Havis N., Matthewman M. and Maguire K. (2018) Investigating components of the oilseed rape light leaf spot epidermic responsible for increased yield loss to the UK arable industry. Agricultural and Horticulture Development Board: pp 26-30.

symptoms up to 4 weeks later than usual (ADAS observations). Therefore crop debris and leaf wetness can be a key factor for infections to occur, and if temperatures are predicted to increase over the winter months this could extend the period of ascospore release over the winter affecting later sown crops.

Another factor that could see an increase risk to oilseed rape crops in developing light leaf spot infections is the impact that increased AWR and higher temperatures could have on conidia spore development and spread. Conidia spores are produced from the acervuli on leaf lesions and are spread through the leaf canopy and between plants by rain splash. Light leaf spot acervuli initially develops internally within the leaf tissue before it erupts from the leaf surface and becomes visible. This period from initial infection to when the disease becomes visible is referred to as the latent period and can be as long as c. 250 degree-days[106,107]. Controlled experiments have shown that the latent period is directly related to temperature and leaf wetness duration; where the latent period was on average shortest at 16°C and increased as temperature increased to 20°C or decreased to 4°C[108]. The latent period was also shown to decrease further with increasing leaf wetness duration, for example at 24 hours leaf wetness duration latent period was c. 10 days at 16°C and increased to 12, 17, 20 or 26 days as temperatures decreased to 12, 8, 6 or 4°C respectively. Therefore just 2°C change in air temperature can significantly reduce the latent period.

The same experiment also showed that temperature and leaf wetness duration had a direct effect on the number of conidia produced from the acervuli and thus the spread of the disease within the crop. The production of conidia was greatest at c. 12 - 16 °C, decreasing either side of these temperatures, and increased when leaf wetness duration increased from 6 to 24 hours**108**. Therefore the predicted increase in ATO and AWR could directly increase the speed and severity of light leaf spot spread within a crop from the combination of reduced latent period and increased conidia production. Higher than average temperatures seen over the winter of 2019-20, where temperatures stay on average above 5°C (Source: Met Office) with prolonged wet weather, saw the main epidemic of light leaf spot occur earlier at the end of January where typically this is not seen until late February to early March (ADAS observations). Wet ground conditions during this period also prevented fungicide sprays being applied in order to control the disease, which only helped exacerbate the spread of the epidemic. If these winter conditions become more normal with climate change, this could result in light leaf spot becoming a difficult disease to control with resultant high yield losses.

The impact of climate change on the spring to summer phase of the disease is less clear, as the relative importance of ascospores and conidia in the spread of light leaf spot from leaves to stems and pods after stem extension is not fully understood**104**. This spread of infection to the pods can be a major contributor to yield loss and which may be inhibited by the predicted increase in ATS and decrease in ASR affecting the disease life cycle. It has been observed that differing environment conditions in differing seasons can affect the maturation and production of ascospores from decaying leaf tissue, and which may account for the variation between seasons in the severity of light leaf spot seen on pods**104**. It was generally observed that dry conditions experienced in April 2017 (Source: Met Office) reduced the severity of the spring epidemic of light leaf spot in that season compared to previous years. As a result of which, the yield response to spring fungicides was lower than

[106] Figueroa L., Fitt B.D.L., Shaw M.W., McCartney H.A. and Welham S.J. (1995) Effects of temperature on the development of light leaf spot (*Pyrenopeziza brassicae*) on oilseed rape (*Brassica napus*) in relation to temperature and leaf wetness. Plant Pathology **44**: pp 641-654.

[107] Figueroa L., Fitt B.D.L., Welham S.J, Shaw M.W. and McCartney H.A. (1995) Early development of light leaf spot (*Pyrenopeziza brassicae*) on winter oilseed rape (*Brassica napus*). Plant Pathology **44**: pp 51-62.

[108] Gilles T., Fitt B.D.L., Kennedy R., Welham S.J. and Jeger M.J. (2001) Effects of temperature and wetness duration on conidial infection, latent period and asexual sporulation of *Pyrenopeziza brassicae* on leaves of oilseed rape. *Plant Pathology* **49:** pp 498-508.

expected (up to 0.1 t/ha) although relatively high yield responses (0.3 – 0.4 t/ha) were still seen from autumn/winter fungicide applications[109]. This suggests that the inhibition of the spring phase of the disease through climate change may negate some of the yield loss expected through an increase in the autumn to winter incidence of light leaf spot; although an economic yield response could still be seen through controlling the disease in the winter.

These conflicting scenarios on the differences that could be caused between the development of autumn/winter and spring/summer phase of the disease makes it difficult to fully assess what the impact of climate change on light leaf spot might be. Models are already used to provide an annual prediction on the percentage of light leaf spot incidence expected in the spring for each region of the UK; based on incidence of light leaf spot on pods in July and deviations from the 30 year mean for summer temperature and winter rainfall[110]. Annual changes in climate and weather patterns could be inputted into this model to provide updated scenarios for light leaf spot epidemics to help better inform growers on how to response to the disease.

A model was developed using this formula from weather data collected from 14 sites across the UK (including Wales) to calculate the effect of climate change scenarios on light leaf spot epidemics for the years 2020 and 2050[111]. For Wales the results found for low Representative Concentration Pathway scenarios a predicted decrease in light leaf spot incidence from a baseline of 30 – 60% plants affected (1960 – 1990) to 0 – 45% plants affected (2020 – 2050). The same reports suggests that the predicted yield losses from light leaf spot may decrease which could counterbalance the predicted increase in losses caused by phoma and stem canker. Therefore overall the predicted increases in fungicide treated yield potential and the compensating losses for each disease means that the net UK losses from climate change for untreated oilseed rape are potentially small**111**.

Sclerotinia Stem Rot (sclerotinia sclerotiorum)

Sclerotinia stem rot affects oilseed rape during flowering and infection is usually initiated by air-borne spores infecting the crop during April and May. Infection causes stems to die back and resting bodies (sclerotia) to form in the stem which are then returned to the soil as crop debris breaks down or is incorporated. Sclerotia can survive in soil long term and any remaining in the top ~10cm of the soil can germinate forming apothecia that produce air-borne spores (ascospores) that can infect following neighbouring crops[112,113,114]. Ascospores require nutritious plant tissues in order to infect oilseed rape plants and these are often petals that have fallen onto leaves or into leaf axils after which stem lesions form[115,116]. Yield losses of over 50% (>2 t/ha) have been reported in severely affected fields caused by premature plant death and crop lodging from brittle infected stems**92**. Control of the disease

[109] ADHB. (2017) Fungicide performance update for wheat, barley and oilseed rape 2017. Agricultural and Horticulture Development Board: pp 54-60.

[110] Welham S.J., Turner J.A., Gladders P., Fitt B.D.L., Evans N. and Baierl A. (2004) Predicting light leaf spot (*Pyrenopeziza brassicae*) risk on winter oilseed rape (Brassica napus) in England and Wales, using survey, weather and crop information. Plant Pathology **53**: pp 713-724.

[111] Evans N., Butterworth M.H., Baierl A., Semenov M., West J.S., Barnes A.P., Moran D. and Fitt B.D.L. (2010) The impact of climate change on disease constraints on production of oilseed rape. Food Security **2**: pp 143–156.

[112] Abawi G.S. and Grogan R.G. (1979) Epidemiology of diseases caused by Sclerotinia species. Phytopathology **69**: pp 899-904.

[113] Adams P.B. and Ayers W.A. (1979) Ecology of Sclerotinia species. Phytopathology **69**: pp 896-899.

[114] Mitchell S.J. and Wheeler B.E.J. (1990) Factors affecting the production of apothecia and longevity of sclerotia of Sclerotinia sclerotiorum. Plant Pathol. **39**: pp 70-76.

[115] Turkington T.K. and Morrall R.A.A. (1993) Use of petal infestation to forecast sclerotinia stem rot of canola – the influence of inoculum variation over the flowering period and canopy density. Phytopathology **83:** pp 682–9.

[116] Jamaux I., Gelie B. and Lamarque C. (1995) Early stages of infection of rapeseed petals and leaves by Sclerotinia sclerotiorum revealed by scanning electron microscopy. Plant Pathology **44:** pp 22–30.

is usually achieved by protectant fungicide sprays applied at the early to mid-flowering period when the majority of oilseed rape petals have appeared.

Weather conditions are important for the germination of sclerotia. Following a period of cold conditioning during the winter, sclerotia germinate in moist soils at temperatures above 10°C but is partially inhibited at 15°C or above[117]. Germinated apothecia then require a dry period to facilitate the release of ascospores which can be inhibited during periods of wet weather as apothecia become flooded. Typically these weather conditions occur in UK around late March to early April; so sclerotia germination and ascospores release occurs when the majority of oilseed rape crops are at full flower throughout April therefore putting them at high risk of developing infections. There a direct correlation between air temperatures and soil temperature at 10 cm depth; therefore the predicted increase in air temperatures could have an effect on warming soil and extending the potential period when soil temperatures are above 10°C to facilitate sclerotia germination. Theoretically an increase of just 2°C in soil temperatures could cause sclerotia germination to occur 2 weeks earlier; putting crops at risk of infection during earlier flowering periods which may increase the need to apply more than one fungicide application to protect the crop throughout the whole flowering period. Studies have shown that early infections caused twice as much yield loss per unit disease incidence (% plants affected, DI) as late infections (0.45% vs. 0.23 % loss per percent DI, respectively)[118].

Changes in soil moisture conditions could also have an effect on sclerotia survival and germination rates. High soil moisture has been shown to negatively affect the survival rates of sclerotia[119, 120] and in extreme cases where flooding has occurred for more than 24 consecutive days, sclerotial viability has been severely affected[121]. A predicted increase in AWR could therefore decrease sclerotia survival in the soil before germination and effectively lower the risk of the disease developing on the crop. This risk could be lowered furthered by the predicted decrease in ASR, as limiting water availability within the top 5 cm of soil can also have an effect on sclerotial viability[122]. Therefore although the changes in air temperature could increase the risk to the crop through sclerotial germination, this risk might be counterbalanced if soil moisture conditions are not favourable to sclerotia survival. This makes the full impact of climate change on this stage of the disease life cycle difficult to fully predict. The release of ascospores is critical to the development of the disease, as it been shown that when zero petal inoculum is recorded there is zero risk of infection**124**, therefore understanding the effect of climate change on sclerotia germination is vital.

The other consideration when evaluating the impact of climate change on sclerotinia development is the effects this could have on the transfer of infection from flowering petals to leaf and stem tissue. A key part of this progress is weather conditions that allow infected fallen petals to stick firmly to leaf foliage; as light rain is most likely to give good petal stick whilst heavy rain can reduce disease risk as petals are washed off the leaves**92**. Very dry

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[117] Jones D. and Gray E.G. (1973) Factors affecting germination of sclerotia of Sclerotinia sclerotiorum from peas. Transactions of the British Mycological Society **60:** pp 495–500.

[118] Evans, N., Gladders, P., Fitt, B. D. L. and Tiedemann, A. V. (2009) Climate change in Europe: altered life cycles and spread of major pathogens in oilseed rape. Abstracts GCIRC Rapeseed/Mustard Technical Meeting, Delhi, 2-4 February 2009.

[119] Teo B.K., Morrall R.A.A. and Verma P.R. (1989) Influence of soil-moisture, seeding date, and canola cultivars (Tobin and Westar) on the germination and rotting of sclerotia of Sclerotinia sclerotiorum. Canadian Journal of Plant Pathology **11:** pp 393–9.

[120] Wu B.A., Subbarao K.V. and Liu Y.B. (2008) Comparative survival of sclerotia of Sclerotinia minor and S. sclerotiorum. Phytopathology **98:** pp 659–65.

[121] Moore W.D. (1949) Flooding as a means of destroying sclerotia of Sclerotinia sclerotiorum. Phytopathology **39:** pp 920–7.

[122] Kora C., McDonald M.R. and Boland G.J. (2008) New progress in the integrated management of sclerotinia rot. In: Ciancioa A, Mukerhi KG, eds. Integrated Management of Plants Pests and Diseases: Integrated Management of Diseases Caused by Fungi, Phytoplasmas and Bacteria. Dordrecht, Netherlands: Springer, pp 243–70.

weather can also prevent petals from sticking and reduce the risk of disease developing, which could prove critical with the predicted decrease in ASR.

Following petal stick, in order for leaf and stem tissue to become infected weather conditions have to be conductive for the disease to develop, which have been identified as temperatures ≥ 7 °C and RH ≥ 80% for ≥ 23 consecutive hours[123]. These weather events are used to issue alerts when sclerotinia is infectious to the crop and so to help guide growers on the optimum timings for fungicide applications. Monitoring reports have shown that in the presence of positive petal test results for infection, there a positive relationship between these weather events and sclerotinia developing in the crop[124]. An increase in air temperatures could extend the time period when temperatures are greater than ≥ 7 °C and thus increasing the disease risk, because in practice there are relatively few occasions during flowering when these weather conditions occur due to low night-time temperatures**124**. Although this risk will only increase if it is associated with periods of high humidity, as this usually the limiting factor for infections to occur during flowering as there is insufficient rainfall to keep humidity high[125].

With the prediction of the decrease of ASR under all climate change scenarios, this could prove critical for the future development and risk of the disease. This was experienced during the dry April of 2019, when subsequent low humidity resulted in very few infection events seen throughout the flowering period (ADAS observations). As a result of which at trials sites near Cardigan, Wales and in Herefordshire only a very low incidence of c. 1% sclerotinia infection developed in untreated trial plots. As a comparison, in 2016 and 2017 when weather conditions were conductive for disease development, relatively high incidences of sclerotinia of 30% were reported in untreated trial plots in Herefordshire**125**.

This shows that the development of sclerotinia is very dependent on weather conditions and would have to be considered in all future climate change scenarios. Due to conflicting potential changes on the different stages of the life cycle of the disease, it is difficult to fully assess what the impact of climate change could have on sclerotinia. Monitoring work has demonstrated that positive economic yield responses (up to 0.3 t/ha) are seen when fungicides are applied in response to weather infection events for sclerotinia**125**, and futures strategies will involve making best use of these decision supports tools to response to the changes in the disease development from climate change.

Other oilseed rape disease

The potential changes in climate could affect other soil borne oilseed rape diseases like Clubroot (*Plasmodiophora brassicae*) and Verticillium stripe (*Verticillium longisporum*), although limited research has been done in these areas. Clubroot infection is sensitive to soil temperatures, as little spore germination takes place below 16°C and is favoured by temperatures of 18 – 26 °C along with moist soils**92**. Theoretically an increase in temperatures of just 2°C could extend the infection period in the autumn by up to 4 weeks. Similarly, Verticillium stripe has a temperature threshold for infection of 15°C and with a 2°C increase in mean soil temperature, the critical period when the crop is susceptible to infection would extend by about 4 weeks in autumn and 2 weeks in spring**118**. Therefore climate change could have a consider impact on the incidence of these disease and resulting

[123] Koch, S., Dunker, S., Kleinhenz, B., Rohrig, M. and Tiedemann, A. (2007) A crop loss-related forecasting model for Sclerotinia stem rot in winter oilseed rape. Phytopathology **97:** pp 1186-1194.

[124] Young C., Canning G. and West J.S. (2018) Forecasting sclerotinia infection in UK oilseed rape. Integrated Control in Oilseed Crops IOBC-WPRS Bulletin Vol. 136, 2018: pp 196-202.

[125] Young C., West J.S., Velcourt R & D. and Clarkson J. (2020) Project Report No. 617: Sclerotinia risk live-reporting system for oilseed rape. Agricultural and Horticulture Development Board, March 2020.

yield loss, although further research would be required to fully understand the changes to soil conditions and resulting economic losses.

Potatoes

Economically, potatoes are a highly important crop to Wales, with output of £16 million in 2017, compared to a value of £22 million for cereals[126]. The most problematic disease to growers is Potato Late Blight, which can wipe out a crop if uncontrolled.

Late Blight (Phytopaththora infestans)

Late blight is a disease of potatoes caused by *Phytophthora infestans,* affecting both foliage and tubers. The disease was responsible for the Irish potato famine and continues to be a significant concern for growers[127]. *P. infestans* can reproduce asexually in as little as five days but also undergoes sexual reproduction (via oospores), generating various strains with differing pathogenicity.

Blight primarily overwinters in infected seed potatoes, diseased potatoes in outgrade piles and unharvested potatoes left in the soil which are capable of growing the following season. The pathogen reproduces asexually, producing sporangia which can be aerially dispersed and germinate, directly or indirectly (via zoospores) on foliage to initiate infection. Spores can also penetrate the soil during rainfall. Oospores, generated by sexual reproduction can also act as a source of primary inoculum and persist in the soil for a longer period, however, no outbreaks caused by oospores have been reported in Wales.

Specific weather criteria must be met for infection to occur and various models are available to predict these infection events, including the Smith Period, which was, until recently, the industry standard[128]. In 2016, the risk criteria of potato late blight alert systems were reviewed and remodelled to create the Hutton Criteria: two consecutive days with a minimum temperature of 10°C, and at least six hours of relative humidity (90%). The Hutton Criteria was implemented as the new national warning system for late blight on the AHDB "Blightwatch" website from the 2017 season[129].

Infected lesions expand and result in the production of more sporangia, causing defoliation of the crop which can prevent tuber formation, reducing yield if infection and defoliation occur early in the growing season. Later infections can be washed down the stem and into the soil, causing tubers to rot. In the current climate, infections typically reach a peak in July or August, when many varieties have already formed tubers; in these situations, control of foliar disease through use of pesticides or desiccation can protect the foliage and tubers until harvest. Fungicides are typically applied every 7 days from rosette stage onwards, however the armoury is declining through the withdrawal of active ingredients through legislation, companies focussing on alternative modes of action and the development of resistance by *P. infestans.* Varieties with good resistance e.g. Sarpo varieties are available but tend to be

[126] Welsh Government. (2019) Agriculture in Wales. Welsh Government.

[127] Fry W, Birch P., Judelson H., Grünwald N., Danes G., Everts K., Gevens A., Gugino B., Johnson D., Johnson S., McGrath M., Myers K., Ristanio J., Roberts P, Secro G. and Smart C. (2015) Fiver reasons to consider *Phytophthora infestans* a reemerging pathogen. Etiology. **105 (7)**: pp.966-981

[128] Taylor M., Hardwick N., Bradshaw N. and Hall A. (2003) Relative Performance of five forecasting schemes for potato late blight (*Phytophthora infestans)* I. Accuracy of infection warnings and reduction of unnecessary, theoretical fungicide applications. Crop Protection **22 (2):** pp.275-283

[129] Dancy S., Skelsey P. and Cooke D. (20017) The Hutton Criteria: a classification tool for identifying high risk period for potato late blight disease development in Great Britain. Sixteenth Euroblight Workshop Special Report **18**: pp 53-58

used on a small scale and not usually for commercial production. The majority of potatoes grown in Wales (and the UK) are considered to be susceptible to late blight.

The climate change predicted by UKCP18, with a rise in ATO is likely to mean the Hutton Criteria are met earlier and more frequently in the season and, as a result, blight epidemics are likely to become more severe. The crop adjusted moisture deficit shows some minor decreases in the 2020 and 2050 low and medium Representative Concentration Pathway scenarios, which are unlikely to have significant limiting effect. On balance, although decreases in soil wetness and ASR are predicted, these may have less significant effect on the crop humidity, given that the Hutton Criteria are likely to be met earlier in the season, rather than the peak of summer. Additionally, it should be noted that the forecast increase in AWR may delay planting in the spring until field capacity is reduced and may force earlier harvests in the autumn, which will amplify the effects of increased disease.

Early Blight (Alternaria spp.)

Early blight of potato crops is caused predominately by *Alternaria solani* in most countries, although *Alternaria alternata* has also been reported to cause lesions on potato. Early blight is usually only reported on varieties with greater susceptibility e.g. Markies. Like many other pathogens, *Alternaria* spp. overwinters on plant debris, generating spores (conidia) which are dispersed by wind and rainsplash to infect the crop in the spring. In the presence of free water, the disease penetrates the leaf and causes lesions, which cause senescence and reductions in yield. Multiple cycles can occur within each season, with the time between infection and visible symptoms being 5-7 days. Symptoms and spread of the disease can be controlled by fungicide use: there is substantial use of mancozeb for late blight control in potato production and it also has activity against early blight. There are alternative options for early blight control, however, these tend to be more expensive and only active against early blight.

Early Blight is rarely reported in Wales and the UK, however it is becoming increasingly common across Europe. An increase in UK reports usually coincides with reports of favourable weather. The optimum conditions for infection are dry weather (for spore release) followed by warm (24-29°C), wet weather for infection[130]. Under the scenarios modelled by UKCP18, with an increase in ATS, little change in Crop Adjusted moisture deficit and ASR remaining high (albeit reduced from current), it is plausible that Early Blight may become a disease of greater significance to the potato industry.

How is the arable sector preparing for the changes?

The predicted changes in climate could have wide ranging impacts on crop diseases, although further research would be required to fully understand the changes in disease life cycles and the resulting economic yield losses. Correlation between the effect of temperature on the development of disease in experiments under laboratory and field conditions is not always possible: the ability to use laboratory studies to understand field effects is dependent on the pathogen being studied. As previously reported, there will be a greater need for detailed disease surveys in order to detect changes in pathogen life cycles sufficiently early enough to allow adaptation and development of appropriate crop protection measures**118**. These measures may include new crop varieties that have better resistance to problematic pathogens. New varieties are continually being developed and for cereals and oilseed rape, the Agriculture and Horticulture Development Board Recommended Lists are updated each season to acknowledge shifts in resistance to current pathogen strains. New fungicides are also in development, however, the development of better varieties and new fungicides

[130] Kemmitt G. (2002) Early blight of potato and tomato. The Plant Health Instructor.

can take considerable time and both are at risk from the development of resistance. There are also market expectations to consider – there is quicker uptake of new wheat and oilseed rape varieties compared to potatoes due to consumer and industry requirements. The use of a control measure in isolation, for example, reliance on resistance genes or fungicides alone, is likely to be an unsustainable approach to controlling plant pathogens and maintaining yields. Recent modelling research suggests that using both varieties with good resistance to plus fungicides could extend the durability of cultivar resistance[131]. Therefore Integrated Pest Management, where a combination cultural and agronomic practices are implemented to combat disease and mitigate against the effects of climate change is likely to be the most sustainable approach. This will, however, require a better understanding of such strategies to optimise pesticide inputs and associated costs for growers.

[131] Carolan K., Helps J., van den Berg F., Bain R., Paveley N. and van den Bosch F. (2017) Extending the durability of cultivar resistance by limiting epidemic growth rates. Proceedings of the Royal Society of Biology: Biological Sciences. **284 (1863)**

COMMERCIAL HORTICULTURE CROPS

Authors: Ewan Gage and Chris Creed Horticulture specialists ADAS

Background information

This section considers the impact of climate change on commercial horticulture, covering production of fruit, vegetables and ornamental products. While this section primarily focuses on inputs to growing, the influence of wider market conditions are discussed where relevant.

Commercial Horticulture in Wales

Commercial horticulture activities occupy only 1.9% of the land used for crop production in Wales in 2018[132], but contributed 51% of the £108m productivity of cultivated land[133]. This output was set against a total of £2,188m for the UK as a whole, against imports of £6,259m for 2018[134]. Horticulture is a key sector for the UK consumer that has benefited from the significant growth of healthy eating, although consumer demand shows significant variation both within and between seasons requiring constant innovation and new product development. Wider horticultural production in the UK has become highly consolidated, with supermarket supply chains reliant on a small number of large-scale farming enterprises for supplies – for instance, the majority of UK onion crops are grown by two growers, and 40% of UK tomato production is from a single company. The sector is also heavily localised to specific regions through a combination of geographic or historic influences (e.g. soil conditions) and the availability of supporting infrastructure, particularly for packing and distribution into the supermarket supply chain.

Due to a variety of factors, horticulture in Wales in distinct from more general trends in the wider UK. While there are a number of larger scale commercial operations, the Welsh horticulture sector is typified by small (<1 ha) holdings that produce a variety of crops targeted for local scale. A lack of marketing infrastructure – cold stores and pack houses (both on-site and external), distribution hubs and proximity of category manager/intermediate buyers – and low produce volumes have prevented many growers from accessing the supermarket supply chain, resulting in many businesses focusing on local direct-to-customer sales. This may be for farm shop, pick-your-own (PYO), veg box schemes or similar, or as processed products. Holdings may have very small staff numbers and limited turnover, reducing the ability of growers to invest in skills, capital equipment and wider business development. However, Welsh growers have successfully developed a wider range of business formats, reaching their customers in a range of ways in order to sell their produce outside a conventional supermarket or wholesale marketing. There are also a number of larger-scale producers that have been able to develop significant acreages of production, particularly with the help of producer organisations to improve wider market access.

132 Survey of Agriculture and Horticulture 2018. Available at https://gov.Wales/survey-agriculture-and-horticulture-june-2018. [Accessed 5/5/2020]

133 Aggregate Agricultural Output and Income 2018. Available at https://gov.Wales/aggregate-agricultural-output-and-income-2018. [Accessed 5/5/20]

134 Horticulture Statistics 2018, Defra. Available at https://www.gov.uk/government/statistics/latest-horticulture-statistics. [Accessed 5/5/2020]

Opportunities for Horticulture

On a national scale, the impact of Brexit on imported produce (particularly for imports from the EU) may create a strong opportunity for import substitution. The impact of the covid-19 crisis may also stimulate a renewed focus on food security, further driving the need for UK-centric production where possible. This may see an increase drive in UK-sourced produce, potentially reversing the trend seen in recent years where production has moved overseas to access more stable climates and avoid labour shortage issues.

The local focus of many Welsh horticulture businesses has allowed them to maximise the benefit of short supply chains by offering high value, high quality produce at a premium. Significant focus has been made on unique selling points such as Welsh origins such as the protected food name for Pembrokeshire Earlies (early potatoes), or Welsh daffodils. Through the activity of schemes such as Food and Drink Wales, local produce has developed strong links with the tourism sector allowing mutual growth. For example, growers have been able to exploit increasing consumer interest in "farm tourism" with pick-your-own style businesses selling soft fruit, pumpkins and ornamentals (e.g. Christmas trees) directly to the consumer, achieving profit margins significantly greater than that achievable with super market supply as well as developing profitable businesses in areas where access to conventional supply chains would be difficult. Such approaches also integrate well with mixed production, with arable and livestock farmers being able to develop complementary horticulture business streams that fit with other farming activities or integrate with current farming practices.

Customer access continues to be a challenge, especially for businesses marketing direct to the customer (e.g. farm shops or pick-your-own) that require high footfall on site. There has been strong uptake of unique marketing methods (e.g. the uptake of social media and online sales, the exploitation of emergent small business systems) by Welsh businesses, and continuation of this trend will improve the ability of growers to sell their produce. Direct-to-customer sales have also allowed Welsh growers to achieve greater produce value compared with conventional supermarket trade as a result of perceived differences in quality/freshness, unique selling points or "added value" aspects such as the pick-your-own experience. For example, on-farm seasonal sales of pumpkin can achieve £5/fruit direct to the customer compared with £1.50/fruit in the supermarket.

Emerging Challenges

In the wider UK, growers focused on the supermarket trade have seen increasingly difficult trading conditions. The relative value of many conventional crops have decreased through changing consumer behaviour and increased influence of the "discounting" supermarkets, and supermarkets have sought to pass reduced value and associated risk on to producers. This has significantly reduced profit margins across many crop types – although prices have risen as a result of recent shortages due to difficult seasons in 2018 and 2019 – and this is likely to intensify as a result of the deteriorating economic climate as a result of the Covid-19 crisis. Access to labour (especially after Brexit) is a key concern across the sector. The cost of labour provision can be significant (especially on larger holdings). However the greatest concern for growers, is access to sufficient quantities of skilled labour for crop work and harvesting. Poor staff retention can also place additional burdens for training provision. While technological solutions (e.g. automation) may provide a solution these are unlikely to have a meaningful impact within the next few decades due to the diverse nature of specialist tasks required in horticultural production. However although the smaller-scale nature of many Welsh business may offer some immunity to this. The provision of suitable plant protection products to address current and emerging pest and disease issues remains a key challenge across the horticulture sector as growers have access to falling numbers of actives and increasing resistance in target pests and diseases.

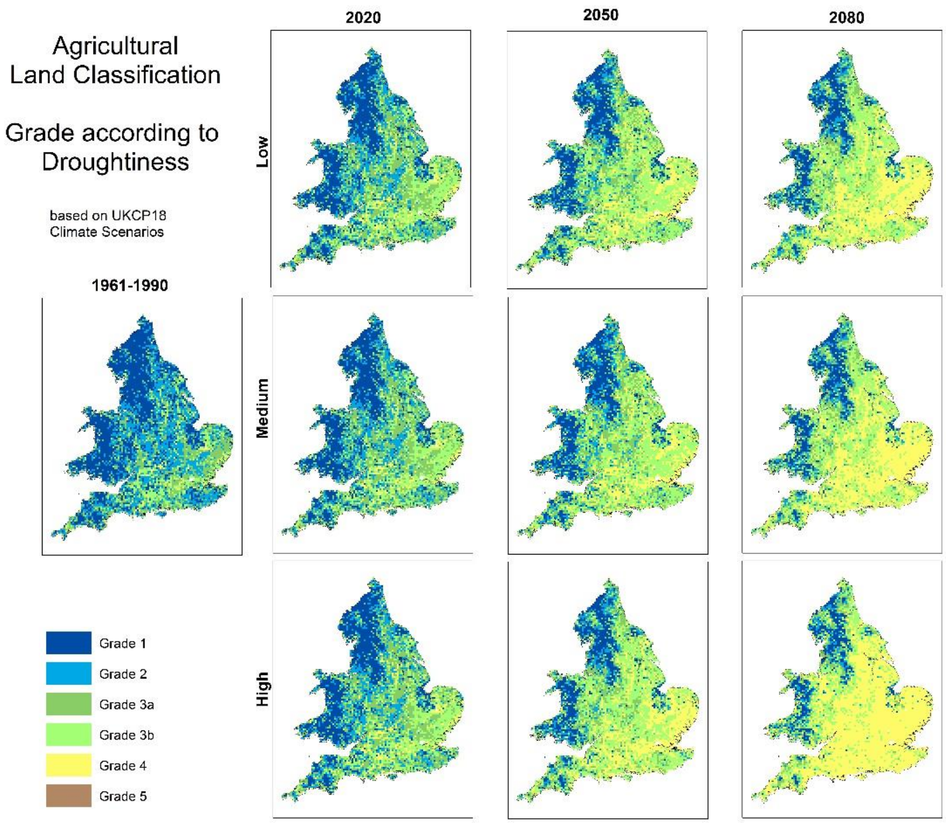
The uniqueness of the horticulture sector in Wales also results in a variety of unique challenges while buffering it from changes seen in the wider UK market. A lack of infrastructure in Wales – packing, distribution and transport – has created a significant barrier for many growers to access the main supermarket supply chains although activities of some Producer Organisations have been effective in creating collaborative marketing routes. The small-scale production of many businesses coupled with a diverse crop range creates a significant barrier for skills and experience development of growers and their staff. Sites may not have access to independent agronomists (either as a result of geography or costs) and a small staff size with limited turnover may severely limit the potential for in-house training. This can impact a business's ability to improve efficiency, adopt new crops/growing practices or mitigate change. While these have been addressed by schemes such as Farming Connect and Tyfu Cymru, there will be a need for ongoing support (e.g. bespoke agronomic consultancy advice season-to-season) to support businesses in adapting to a changing landscape in Welsh horticulture. In addition, smaller businesses may not have access to high cost specialist machinery, creating a dependency on labour intensive crop management approaches. There may also be a need to mitigate the risk of integrating new growing methods, crop types etc. into smaller businesses – the current European Innovation Partnership (EIP) scheme has been effective in aiding the translation of best practice into Welsh businesses. This scheme has provided such support to minimise the risk associated with business development for novel high value crops such as asparagus, or growing methods such as integrated pest management. Infrastructure to support growing (as distinct from infrastructure to support marketing) such as plant propagators and suppliers of fertilisers, media and seed material is largely absent creating additional barriers. While the smaller scale nature of many Welsh businesses means that labour provision issues are not as pressing as in large businesses more typical of the wider UK industry, this may become a problem if larger businesses are created through consolidation in order to access super market trade. There are also concerns for succession planning, especially in smaller family-run businesses where a limited staff means that retirement and career changes will have a disproportionate impact compared with larger businesses.

Climate Change and Horticulture

Many of the themes discussed above are likely to be impact by climate change effects felt by 2050 and beyond. The unique nature of the horticulture sector in Wales means that it will face a series of specific opportunities and challenges as a result of predicted changes. By supporting the sector to identify and respond to these it is possible that significant growth of what is already a highly profitable sector can be unlocked.

On average, a 1.7% to 2.9% decrease in average annual rainfall will be seen by 2050 in the medium to high- Representative Concentration Pathway models, although this will be represented by a wider disparity between winter and summer rainfall: a 13.8 – 23.0% decrease in the summer will coincide with an 8.1 – 13.5% increase in winter rainfall across Wales. Temperatures within the main growing period of April to September are estimated to give an increase in accumulate temperature of 8.5 – 13.5% in Wales. While these changes will see an increase in the proportion of higher Grade agricultural range, the increase in temperatures and rainfall (particularly the variability of weather within a season) has the potential to have a significant impact on horticultural crops.

It is likely that ensuring sufficient access to water will be a key challenge for horticulture, particularly in regard to the predicted decrease in summer rainfall.



At the current time ground water should be of sufficient availability and quality to satisfy horticultural irrigation requirements. The higher value of these crops tend to justify the investment in the necessary infrastructure as long a favourable approach to bore hole licensing for horticulture is taken. Sea level rises and increased abstraction can lead to increased brackishness, and some areas of England (e.g. Sussex) are seeing borehole water becoming unusable for irrigation as a result. Other aspects (e.g. high iron content in underlying rock strata) may require post-abstraction treatment before use in horticulture. High soluble salt levels in irrigation water will reduce the about of soil chloride a crop can tolerate, while reducing the ability of growers to effectively manage the electrical conductivity (EC) of hydroponically grown crops such as strawberry. While the higher elevation in Wales may reduce this risk, it should be considered in the longer term when irrigation needs are likely to increase. The irrigation needs of horticulture will also need to be balanced carefully against other demands on groundwater resources. In instances where there is little above ground water capture and storage from winter rainfall, drier summers will increase pressure on growers, especially those without aquifers to tap into, making water availability an increasing risk. However, these differences are likely to impact separate horticulture subsectors differently, and so likely effects of the predicted climate change impacts are given by subsector below.

Field Vegetables

Field vegetables are likely to see the greatest impact of climate change. This covers a broad range of crop types including conventional brassicas and root crops, alongside rooted perennials (asparagus, rhubarb) although a number of newly emergent crops are showing significant increases in consumer demand such as purple sprouting/tenderstem broccoli and dwarf French bean. Historically field vegetable production has been focused in Lincolnshire, but climate problems in recent years have begun to have significant impact on productivity. The 2018 season was particularly dry, leading to a high crop failure rate especially in brassicas were consistent soil moisture is required for good growth. Borehole irrigation is not possible in Lincolnshire as land is below sea level, giving brackish ground water, leading to significantly greater impacts of recent weather changes on production. While hotter temperature will reduce disease risk, physiological syndromes can effect produce quality (e.g. buttoning in cauliflower) or lead to early flowering, making scheduling difficult. Conversely, overly wet springs can prevent ground preparation and drilling, delaying crops. Furthermore, increased risk of extreme weather events such as summer storms can further risk productivity in crops such as Brassica that have low tolerance for soil water logging.

The increasing unreliability of Lincolnshire produce has led to some supermarkets increasing reliance on imports (e.g. Kenyan tenderstem broccoli) or redirecting production to other regions in the UK to mitigate the risk. Against this background strong consumer demand is seen, with some products such as tenderstem broccoli achieving >10% annual growth over the last 10 years[i], a trend that continues to develop as new varieties are produced which match consumer demand for low-input greens. The low and medium Representative Concentration Pathway forecasts indicate an increasing proportion of Grade 3b and Grade 4 land according to droughtiness in previously productive areas of eastern England, while proportions of Grade 1 and 2 land in Wales will remain high. Therefore, there is strong potential for field vegetable production to be increased in Wales as production in England becomes increasingly unsustainable due to higher temperatures and reduced rainfall.

For field vegetable production in Wales the decrease in summer rainfall is likely to pose a challenge, especially in crops such as Brassica that need consistent soil moisture. Water-intensive crops like salad leaf will also be vulnerable, but these can be grown under protection (e.g. microfleece) which will improve water balance while reducing frost risk. However, this can largely be mitigated with suitable irrigation and the high value of these crops can justify the investment in the necessary infrastructure to provide this as long as sufficient quality and volume of bore hole water is available for abstraction. Increased rates of growth may be of concern in some crops which are targeted to specific periods such as pumpkins in the run up to Halloween, increasing the need for storage or increased risk of postharvest rots of fruit left for maturation and sale in the field. Cauliflower production is already seen in Pembrokeshire despite being a very demanding crop.

The increasing temperatures and availability of Grade 1, 2 and 3a land will mean that field vegetable production Wales could be a strong focus to meet increased demand and address the need to relocate production from Lincolnshire – this will be especially relevant as higher summer temperatures and reduced rainfall in Lincolnshire is predicted to rise significantly by 2050. There is considerable Grade 2 land in Monmouthshire, and around the M4 east of Cardiff that could be used for field vegetable production. Root vegetable production is unlikely to be possible on a large scale in Wales, but may be achievable if suitable areas of sandy loam area identified. Onion production requires dry autumns to promote bulb maturation and drying out, so these may be more suitable for South Wales.

Besides conventional field vegetables, it may be possible to expand the diversity of crops grown. Perennial crops such as asparagus could be promoted as a high value crop that is free of major pest/disease issues once established. Asparagus would benefit from the warmer springs, particularly in south Wales, and would help growers to bridge the gap between overwintered produce and spring plantings. Asparagus is already grown on the Gower peninsula, and there is strong potential for this to be expanded further. Other vegetable crops such as sweetcorn or courgette may also offer good opportunities for diversification. Some of these crops also integrate well with the pick-your-own model (sweetcorn, pumpkin) allowing direct targeting to customers in local areas where a marketing infrastructure is unavailable.

In order to access this potential it will be necessary to promote the development of supporting infrastructure, both for marketing and transport (especially if the UK-wide supermarket supply chain is targeted) and for growing inputs (e.g. propagated plant materials and agrichemicals). However, the M4 corridor transport links should support this. Farm systems may also need to be modified. Larger areas of land should be cultivated as a continuous holding so that high-volume outputs for customers can be achieved, and higher value labour-saving specialist systems can be made viable – typically 300 – 400 acres are required for supermarket access. While the small-scale holding typical of some areas of Wales is not of peak compatibility with this approach, the repurposing of large arable land farms could be deliverable. It would also be necessary to ensure that growers can access sufficient irrigation water, and this may impact the siting of new production.

Soft Fruit

Soft fruit, covering strawberry, raspberry, cherry and other niche berries has seen significant change over the last 10 years. Production has now almost completely moved under protection, with plants grown under plastic to improve resource use efficiency and optimise labour inputs. The switch to hydroponically-fed substrates like coir has uncoupled fruit production from field soil conditions, while mitigating soil-borne disease development. Increased winter temperatures may pose a problem with fruit like raspberry that require significant vernalisation, but the move towards single-season potted plants allows material to be vernalised in cold stores over the winter to avoid this issue while aiding growers to improve programming of fruit across the season. However, for soil-grown raspberries, and overwintered June-bearer strawberries insufficient winter chilling will reduce bud break and flower number/anther quality respectively, leading to lower yields.

Cherries were historically grown on Grade 1 land with deep soils and high levels of water access, but the switch to in substrate along with tunnel protection has largely minimised this requirement. The move to soil less production under plastic has almost completely uncoupled soft fruit production from agricultural land, allowing fruit to be grown even on converted brownfield sites – even those that are unsuitable for crop production or landscape plantings as a result of soil quality or contamination. This can be of benefit as fruit can be grown close to population centres to provide both a readily available market and a labour force for what remains a labour intensive crop. Tunnel construction can create a challenge for local authorities due to landscape impacts in agricultural areas, alongside other atypical agricultural facilities such as pack houses and cold stores.

The uptake of tunnel production, and the switch to single season plantings has ensured that soft fruit production is in a robust position to address climate change. Some specific issues may arise however. Fruit production is reliant on pollinator activity, and production may rely on supplementary supply of native *Bombus terrestris* subspecies and activity of these may reduce with higher temperatures as drones remain in the hive to cool the brood. Increasing temperatures will also require careful control of humidity to mitigate disease risk. High quality water is required for irrigation, and increasing salinity or carbonate content can reduce the ability of growers to achieve target EC for crop production. Higher temperatures are also increasing the requirement for cool chain processing from picking to sale.

Across the UK soft fruit production is becoming an increasingly challenging landscape as consumer demand has declined and increased pressure from supermarkets has driven profit margins from around 15% downwards to 5-10% over the last ten years. However, the current market structure of Welsh soft fruit growers is largely outside of this – soft fruit production is focused on either local supply, direct to the consumer farm gate sales or pick-your-own – and several new businesses have successfully established in recent years. New crop types such as blueberry which require acidic soils and are best grown under protection are seeing increasing growth, and this could be a viable crop is improved quality land is available.

The uncoupling of soft fruit production from conventional growing methods means that the impact of climate change will be relatively minimal outside the availability of irrigation water and any impacts of pest and disease prevalence.

Top Fruit

Top fruit production is more complex than soft fruit production, primarily as a result of the nature of the fruit. The ability to store apples and pears for considerable periods without significant quality losses means that imports, particularly of protected, high demand cultivars. Traditional dessert apple cultivars are seeing declines in demand, with consumers favouring licensed cultivars so that production and marketing is driven by businesses rather than growers. The lead-in time for establishing orchards can also limit the ability of growers to respond to changing customer demand.

Apple production for conventional processing is in decline, while production for cider has also seen a market decline as consumers switch to other products. Despite this, there are a number of niche Welsh cider producers that have profited from local market appeal although there is limited opportunity for growth into larger markets. One market that has seen significant growth is fruit juice processing. While this market is approaching saturation, there may be opportunity for locally-focused marketing and exploitation of Welsh origins as a unique selling point. Top fruit will also include plums, and recent granting of Protected Designation of Origin for the Denbigh Plum may further offer marketing opportunities. Overall, climate change is unlikely to offer any significant impact on top fruit production although there opportunities for growth in response to market forces.

The main concern for top fruit production is the reduction in winter chilling. Dessert and culinary apples will need a significant period of winter chilling to strengthen blossom so if winters are becoming increasingly mild then flower quality and yield will be negatively impacted, and delays in fruit maturity may be seen if inadequate chilling is seen. Conversely, if sufficient winter chilling can be assured then the reduced risk of spring frosts may be of benefit during flowering. For stone fruit like plums warmer winters will bring forward bud break and blossoming, increasing the risk of frost damage to the flowers.

Protected Edibles

Protected edibles (e.g. tomato, pepper, herbs and salad leaf) are unlikely to see a significant impact from the estimated climate change impacts. Wider production in the UK has seen high levels of consolidation, with small numbers of customers producing large volumes of crop under glass. The lack of a supply chain infrastructure in Wales has largely precluded any large-scale development of acreage under glass, although there is increasing interest in small-scale high control vertical farm facilities such as those recently developed in Anglesey. These are entirely uncoupled from external environments due to the use of artificial lighting and feed/irrigation, but can benefit from being sited anywhere, such as brown field sites and close to population centres for market access and labour supply.

There is a small but significant polytunnel-based production of protected edibles across Wales. While these cannot benefit from the high level of environmental management that can be achieved with glass protection (e.g. carbon dioxide enrichment) setup costs are significantly cheaper and can be easily integrated with the mixed produce holding more typical of Welsh horticulture. These can be focused on supplementary production for farm shop/veg box sales, or for high value niche crops such as chilli pepper. In these instances production is still carried out in hydroponic substrates, and so are largely independent of soil conditions so long as sufficient irrigation water is available.

The primary effect of climate change on protected crops is likely to be an increase in the pest and disease risk as a result of early springs and hot summers (e.g. increased establishment of spider mite), especially as humidity management can be difficult to achieve in typical polytunnel set ups, promoting development of diseases such as powdery mildew and *Botrytis*. This is likely to lead to an increased demand for effective pest/disease management of crops.

Ornamentals

Ornamental production is largely substrate-based rather than soil grown, so the majority of ornamental production is unlikely to be impacted by the predicted climate change effects. However, a number of important field-grown ornamentals are likely to be impacted. Warmer, wetter winters will make lifting bulbs difficult, especially with regards to moving machinery around land. Bulb lifting is required for effective disease control (e.g. hot water treatment of daffodils) or transfer of bulbs to deep water hydroponics for cut flower production under protection. Warmer, wetter soils will also increase the risk of disease that would otherwise be held in check by colder weather, with increased white mould development in daffodil grown in milder conditions in Cornwall. However, drier weather will slow disease progression so drier summers may reduce losses to rots over the summer period (although risks will increase if irrigation is required). Warmer conditions will also lead to bulbs breaking dormancy sooner posing a challenge for marketing if harvests are required to meet specific date ranges such as the high demand for cut daffodils in the run up to Easter. This may increase the use of residual herbicides as growers seek to check the crop, or increase the use of fungicides as crops will have an active leaf layer for longer risking greater development of foliar diseases.

The proposed increase in Grade 2 land may increase the opportunity for niche ornamental production, particularly Christmas trees that can be grown in acidic Grade 2 soil. Christmas tree production has shown significant growth over recent years, with plantations being established for the pick-your-own (choose and cut or dig) Christmas tree market, focusing on local sales. This is increasingly be seen as an attractive crop to integrate without other customer-facing sales (e.g. pumpkin) and can achieve a high profit margin. A number of successful Christmas tree sites have developed across Wales (especially on the Gower peninsula) so there is strong scope for expansion here.

Pest and Disease Issues

Pest and disease issues in horticulture are of greater concern than other sectors due to exceedingly high quality specification by customers. While specific details of pest/disease responses to the proposed climate models are beyond the scope of this report, it is noteworthy that a general increase in losses due to pest and disease damage will be seen across the sector. Warmer winters are likely to increase the overwintering survival of many pests (e.g. aphids and thrips) which will lead to earlier and more severe migrations into horticultural crops. Earlier, and warmer, springs will also increase pest population growth rates (generation times and numbers) both in the field and under protection as temperature is the main limiting factor of insect and mite development rates. While similar effects may be seen on predators/biocontrols, these can take longer to establish and are already subject to artificial population dynamics due to regular introductions by growers. While drier summers may reduce disease development in some instances, with rusts and powdery mildews reducing growth rates in hot, dry conditions although rates will increase if it is humid such as in irrigated crops. Higher soil temperatures may increase the severity of soil-borne diseases such as *Verticillium* and *Phytophthora* for which there are limited control options. Bacterial and viral diseases are also likely to see an increasing influence.

It is difficult to predict the overall impact of climate change on wastage due to pest and disease damage, and while the availability of effective actives is a highly changeable landscape these are likely to decline as a result of increasing deregulation and resistance in target pests. Effective mitigation of this risk can only be through knowledge transfer allowing growers to maintain a thorough understanding of best practice, alongside clear and effective regulatory mechanisms to achieve off-label authorisations for new control products such as the current Extension of Authorisation for Minor Use scheme.

Summary

The estimated impacts of climate change in Wales is likely to have a broad range of effects across horticulture, both positive and negative. There is strong polarisation across the sector between crops grown with little to no environmental management (e.g. field vegetables) that are likely to see the significant impact and crops which are grown in artificial systems with a high level of control (e.g. table-top strawberry production) although these may see an increase in pest/disease pressure. The increase in Grade 1 and 2 land will primarily be of benefit for field vegetable production. When set against a background of reduced production potential in England, there is a highly significant opportunity for increasing high-value field vegetable production in Wales to address this gap in the market. A concerted movement west is already seen in many crops, so if the climate change estimates are realised there is a clear opportunity for Wales increase production accordingly. This is predominately as a result of increasing impact of summer droughts and water scarcity, and this is likely to increase in frequency and intensity in come years: the low and medium Representative Concentration Pathway models predict continued declines in summer rainfall and an increased downgrading of land classification by droughtiness in the eastern UK to Grade 3b and 4. The lack of sufficient irrigation reserves in areas such as Lincolnshire will compound this effect further, significantly reducing reliable crop production potential in the longer term. Conversely, land classification in Wales will largely remain Grade 1 and 2 for droughtiness, indicating that field vegetable production could be viable even in the absence of increased irrigation activity (although this may still be required to ensure production risks can be minimised). Therefore, a strong opportunity exists for Welsh production to substitute productivity lost elsewhere in the UK, especially for field vegetables.

In order to fully exploit this opportunity, alongside mitigation of any increased risks as a result of climate change in Wales, a level of change across the sector will need to be promoted. Use of new varieties that respond to both changing conditions (e.g. vernalisation requires or disease resistance) to mitigate effects. New approaches to crop management and the integration of new control approaches (both chemical and biological) will be required if growers are to continue to grow high quality, high value crops. There may also need to be a step change such as the consolidation of land so that sufficient volumes can be achieved if marketing through the wider UK supply chain is to be achieved. It will also be necessary to ensure that sufficient infrastructure (both for marketing and for growing) is available to enable this.

The diverse, small-scale and disperse nature of the Welsh horticulture sector will mean that growers will need cohesive and on-going support to implement these changes. Primarily access to targeted training and knowledge exchange materials and agronomic consultancy will be necessary for growers to implement lasting change in their own businesses, especially when adapting to new crops of growing systems. It will also be necessary to facilitate investment (e.g. farm grant schemes) in new growing infrastructure to provide access to specialist equipment for new crop types, or to further optimise resource provision (e.g. irrigation). However, the sector has shown strong resilience and drive to change from within so there is strong potential for growth if sufficient support is provided.

IMPACT OF CLIMATE CHANGE ON RUMINANT HEALTH

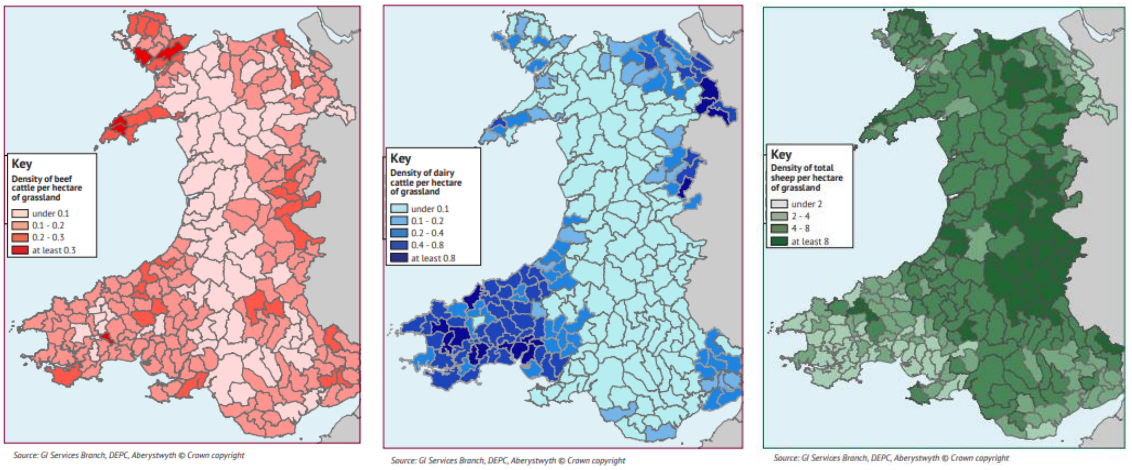
Author: Karen Wheeler Ruminant Livestock specialist ADAS

This report considers the impact of climate change on ruminant health across Wales. The aim is to focus on a small number of health and welfare issues that are likely to be impacted by climate change but does not claim to be an exhaustive list.

Background information

Agricultural output in Wales is dominated by ruminant livestock production. By value in 2017, products from this sector amounted to around three-quarters of total output with milk and dairy products accounting for the biggest proportion at 32.5% followed by finished cattle (19.5%) and finished sheep (14.9%) with store cattle and sheep sales responsible for a further 7.7%.[135] In 2018 Wales reported approximately 254k breeding dairy cows and 137k breeding beef cows (1.1M cattle and calves in total) on 10,430 holdings and 4.4M breeding ewes (9.5M sheep in total) on 13,755 holdings. Overall, cattle and sheep farming in the LFA is the dominant farm type and it is estimated that over 90% of breeding ewes are found in upland areas and over 70% in areas designated as SDA (severely disadvantaged). These enterprises often utilise poor quality land that is traditionally only suitable for rough grazing and permanent grassland.

The following charts illustrate the density of beef cattle, dairy cattle and sheep populations across Wales[136]. These show the highest concentrations of cattle are away from the central upland spine of Wales with the south west in particular dominated by dairy cattle. Dairy and Lowland cattle and sheep holdings are generally found on the southern and SW coastal fringes and in the far north east with the remaining areas LFA cattle and sheep holding.



Source: HCC Little book of meat facts

For beef and sheep farms the number of lambs reared per ewe and calves reared per cow are key factors that contribute to enterprise profitability. It is well recognised that sub-optimal health is responsible for reduced performance in livestock and that this is a significant cost to the industry. A

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135 HCC Little book of meat facts 2019, https://meatpromotion.Wales/images/resources/Little_Book_of_Meat_facts_2019_-_English.pdf

136 HCC Little book of meat facts 2019, https://meatpromotion.Wales/images/resources/Little_Book_of_Meat_facts_2019_-_English.pdf

number of the most common and costly diseases that affect ruminant livestock are caused by pathogens and parasites that are directly or indirectly affected by climatic factors.

Comparison with ALC interpolated UKCP18 data and current evidence bases

The current thinking suggests that the UK including Wales is most likely to be impacted by low or medium Representative Concentration Pathway scenarios. This report focusses on the impacts of the low and medium scenarios for 2020 (covering the period 2010 to 2039) and 2050 (2040 to 2069). These equate to a mean temperature rise of 2.2°C and 2.6°C respectively by 2100.

Overview of rainfall and temperature scenarios

Average annual rainfall (AAR)

The baseline figures illustrate the wide range in average annual rainfall across Wales. The highest rainfall is found in upland/mountain areas stretching down the centre of Wales with Snowdonia recording the highest rainfall (exceeding 3,000mm); in contrast some lower altitude areas record <1,000mm/annum with these generally found in some coastal areas and down the Welsh marches bordering England (e.g. Flintshire, Wrexham and Anglesey).

Based on the current scenarios it appears that AAR (average annual rainfall) is not expected to differ greatly from the baseline in the low Representative Concentration Pathway scenarios for 2020 and 2050. The medium Representative Concentration Pathway scenario also results in little material change in 2020. However, some impact can be seen in 2050 where reduced rainfall is particularly apparent in the north east and south east of Wales with Monmouthshire and Denbighshire both expected to receive <1000mm/annum (moving from the 1,001-1,500mm/annum baseline).

The seasonality of rainfall is expected to change significantly with an increase in winter rainfall (AWR) and reduction in summer rainfall (ASR) across all low-medium scenarios and there is also expected to be an increase in the frequency of extreme rainfall events. Extreme rainfall events can appear throughout the year and can result in flooding either from raised river levels or localised flash flooding (e.g. Storm Dennis that impacted across the UK in 2020).

Average summer rainfall (ASR) and average winter rainfall (AWR)

Average summer rainfall is expected to fall across all regions – baseline figures suggest six regions (out of 22) have ASR typically below 500mm but this is projected to increase to nine regions by 2020 and 15 by 2050 (across low and medium scenarios).

In contrast AWR is expected to increase significantly across both low and medium Representative Concentration Pathway scenarios in all regions. The number of regions with AWR of >1000mm increases from one in baseline (Gwynedd) to four in 2020 and five in 2050. High rainfall is associated with the upland/mountain regions but expands outwards from these core areas in 2020 and 2050.

The low-med scenarios show an increase in droughtiness compared to baseline by 2050, mainly in the marches area bordering England and the southern and northern coastal areas. Alongside this there is an improvement in soil wetness in some areas seen resulting in an improvement in ALC as soils dry.

Temperature overview

The Met Office reports that mean annual temperature in Wales varies from about 9.5 °C to 11 °C at low altitudes with the higher temperatures nearer the coast[137]. This decreases by approximately 0.5°C for each 100 metres increase in height. The lowest minimum reported was -23.3°C in Powys in 1940 and the highest maximum 35.2°C in Flintshire in 1990.

Accumulated temperatures are expected to increase across the Low-Med scenarios for 2020 and 2050. Figures are provided for AT0 (accumulated temperature above 0°C from January to June, °C days) and ATS (accumulated Temperature > 0°C from April to September, °C days). Increases are expected in all regions of Wales, with AT0 increasing by 7-21% and 14-29% above baseline levels for the 2020 and 2050 scenarios respectively. The equivalent for AST is an increase across the regions of 5-14% and 10-20% for 2020 and 2050 respectively.

Increased temperatures are likely to impact on animal health in a number of ways. This can be directly in the case of heat stress or indirectly by affecting the epidemiology of livestock disease. The likelihood of extreme drought and the impact on forage supply is also likely to increase.

Potential impacts of climate change scenarios on ruminant health

Climate change can affect animal health in several ways; it may have a direct effect e.g. heat stress arising from temperature rise or may influence the emergence and proliferation of disease vectors and pathogens. Many pathogens and parasites spend at least some of their lifecycle outside the host in the environment and are therefore exposed to weather conditions. Climate can affect pathogen survival, generation times and seasonality.

The following sections provide some examples of the impact of climate change on conditions that affect ruminant livestock in Wales.

Direct impact of climate change on ruminant health.

Heat stress

All animals have a thermoneutral zone which is optimal for their comfort and productivity. This is affected by environmental factors (environmental temperature and humidity) and animal factors including species, life stage and nutritional status. When the temperature exceeds the upper critical temperature of their thermoneutral range animals can suffer heat stress. The severity is related to both ambient temperature and humidity level with severity increasing as humidity increases[138.] For dairy cows relative humidity levels of above 70% can cause mild heat stress at temperatures around 23°C. The impacts of heat stress in dairy cows include depressed feed intake, and milk production, impacts on fertility and in extreme cases increased mortality. It has been reported that feed intakes can reduce by 8-12% at temperatures above 26°C and milk production can fall by 5-20%[139] .

Dairy NZ provides a Temperature Humidity Index tool that uses the following formula THI = 0.8T+ [RH x (T-14.4)] +46.4 (where T is daily maximum temperature (°C) and RH is mean daily

[137] https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/Wales_-climate---met-office.pdf

[138] Heat stress in dairy cows http://www.thecattlesite.com/articles/1053/heat-stress-in-dairy-cows-implications-and-nutritional-management/

[139] https://www.fwi.co.uk/livestock/health-welfare/preventing-heat-stress-in-dairy-cows

percent relative humidity divided by 100). They recognise that tolerance to high temperatures varies between breeds. When THI reaches 68 for Friesians, 69 for Cross breeds and 75 for Jerseys (equivalent to 21, 21.5 and 25.5°C respectively at 75% relative humidity) feed intake begins to fall and milk solids drop by approximately 10g milk solids per day per unit increase in THI.[140]

Whilst Wales does not currently experience a high number of extremely hot days the low-med 2020-2050 scenarios explored indicate that Wales is likely to experience hotter and drier summers with a greater likelihood of very high temperatures.

Mitigating factors at grass include provision of adequate water troughs and additional shelter. Where cattle are continuously housed reduction in stocking rate can help as well but it may be necessary to make permanent alterations to improve building ventilation or provide cooling systems for cattle.

The use of mechanical cooling systems can be found in countries with extreme heat e.g. in Dubai (and other Middle East states) where misting and fan systems are used in the lying areas to keep cows cool.[141] Their use is also reported in hotter states of the USA.

Advice from Dairy NZ suggests that sprinklers can be used to aid evaporative cooling but notes that this can increase humidity especially when cows are held close together. Effective use of sprinklers therefore depends on the removal of water vapour by air movement, ideally by using a fan. Other advice includes provision of sufficient water with cows requiring >100litres/day, providing high quality feed at grass (to reduce heat of fermentation in the rumen) and reducing walking distance and speed to milking parlours. Where cattle are at grass they recommend providing 5m^2 of shade per cow.[142]

Respiratory disease in cattle

Respiratory disease (pneumonia) is a common cause of illness in calves and youngstock and is the most common cause of death and poor performance from weaning to 10 months of age. It is estimated that it costs the UK cattle industry £50 million per year.[143] Problems with respiratory disease are more common in housed animals but can also arise in outdoor systems. Young calves, autumn housed calves/youngstock and recently purchased cattle can all be at risk.

Cattle succumb to respiratory disease when the disease pressure overcomes their immune system. Strategies to reduce this should aim to improve cattle immunity and reduce stress, as well as managing any other disease present. Controlling respiratory disease depends on managing the animal- environment- pathogen interaction effectively.

Pathogens involved in respiratory disease include a range of viruses (e.g. Infectious bovine rhinotracheitis (IBR), Parainflenza-3 (PI3) and Bovine respiratory syncytial virus (BRSV)) and bacteria (including, Pasteurella multocida, Mannheimia haemolytica and Mycoplasma species. Vaccines are available for a number of viral causes, but not all, so need to be used in conjunction with other management techniques to reduce risk factors. Ensuring calves

[140] https://www.dairynz.co.nz/animal/cow-health/heat-stress/

[141] https://www.dairyglobal.net/Articles/General/2014/11/Managing-heat-in-the-desert-1532117W/

[142] https://www.dairynz.co.nz/animal/cow-health/heat-stress/

[143] https://beefandlamb.ahdb.org.uk/wp-content/uploads/2018/01/BRP-plus-Better-management-of-bovine-respiratory-disease-BRD.pdf

receive sufficient high quality colostrum and nutrition and managing stress will help promote their immune system.

The environment has an influence on both the animal and the pathogens that cause respiratory disease. The key environmental factors that are particularly relevant for housed livestock include moisture levels, air quality and air speed although extreme temperatures will also have an impact. High moisture levels can support/promote microbial growth and development and a lack of fresh air can increase the survival time of air-borne pathogens. Changes to the climate (such as increased winter rainfall expected in the current scenarios for Wales) that exacerbate existing poor ventilation within buildings with resulting high moisture levels and insufficient fresh air are likely to increase the incidence of respiratory disease in housed cattle. The impacts of climate change (particularly higher temperatures) on livestock buildings are described further in the Farm infrastructure section (9).

Extreme weather events

The likelihood of extreme weather events is expected to increase and may take the form of extended drought and heat in hotter drier summers as well as high rainfall events and/or snowfall in winter. All farms should have an action plan in place to deal with potential heat stress, drought and flooding.

The 'Beast from the East' that hit the UK in March 2018 coincided with lambing in some parts of the country and resulted in very high losses in lambs and breeding ewes. It was estimated that the number of sheep and lambs fell in Wales by more than 5% in 2018[144] The year was particularly difficult for the sheep sector with the wet weather of 2017-18 impacting on ewe fertility and then poor conditions at lambing increasing lamb losses. This was followed by a period of drought in the summer that impacted on grazing, conserved forage production and natural water supplies.

Parasitic disease in cattle and sheep

Parasitic disease is a huge cost to the livestock industry with reduced performance in affected stock and potentially high levels of mortality. In addition some conditions can cause rejection in carcases and offal in the abattoir (e.g. liver fluke damage). Factors affecting development and survival of the infective stages of parasites are largely environmental, including in season climatic factors and some farm management practices. Wider climate changes are expected to influence the infective stages of many parasites and/or the prevalence of some intermediate hosts. Liver fluke is an example where trends towards warmer wetter seasons have been linked to increased prevalence in cattle and sheep.[145]

Typical lifecycle of nematode parasites of sheep and cattle.

There are around 20 different species of nematodes of sheep in Britain of which three of the most pathogenic are *Teladorsagia circumcincta, Haemonchus contortus* and *Nematodirus battus*.[146] Cattle can be parasitised by over 18 species of which *Ostertagia ostertagi* is the

[144] https://www.agriland.co.uk/farming-news/beast-from-the-east-knocks-500000-off-welsh-sheep-numbers/

[145] Taylor, M A, Coop, R L and Wall, RL. (2007) Veterinary Parasitology, Blackwell Publishing

[146] Sustainable Worm Control Strategies for Sheep 4th edition. https://www.scops.org.uk/workspace/pdfs/scops-technical-manual-4th-edition-updated-september-2013.pdf

most economically important.[147] The majority of nematodes have very similar life-cycles and do not rely on intermediate hosts. Briefly, worm eggs are passed out in the faeces and hatch and development within the pat or pellets. Once they develop into the infective L3 larvae they migrate onto herbage where they are consumed. In sheep the free-living stage (from egg to L3 larva) typically takes 2 -12 weeks to complete but is highly influenced by climatic conditions (rainfall and temperature). Rain tends to increase the infectivity of pasture by assisting the L3 larvae to move out of the faecal pats and provide moisture to allow migration onto the herbage. Development to the L3 stage may take up to 12 weeks in the spring but only 1-2 weeks in the summer and therefore tend to reach the infective stage at the same time resulting in high levels of pasture infectivity from mid-summer onwards. In dry conditions there are lower levels of infective larvae on pasture but when it rains there can be a huge increase as L3 larvae emerge from the dung.

Historically, seasonal and geographical differences have been found between nematode species although changes have been seen in recent years. Haemonchus infection of sheep was typically confined to the South East of England but has now become widespread whilst Trichostrongylus, which was traditionally a problem for lambs in the autumn is now seen earlier in the summer and persisting for longer during mild winters.

Some important variations in lifecycle are seen including the Nematodirus nematode of sheep where development to the infective stage takes place within the egg. The hatching and release of the infective L3 is triggered by a climatic stimulus, usually a period of chill followed by a mean daily temperature of greater than 10°C although there is evidence that significant numbers of eggs can hatch without a cold spell. This nematode has a much slower life-cycle with infection passing from lambs in one year to those in the following year. Due to the climatic requirements that trigger egg hatching very large numbers of infective larvae can appear at one time. The timing will vary by region. In southern England this is likely to be April/May but could be as late as June in more northerly areas. Where late winter temperatures are unseasonably warm egg hatching will be earlier. Risk factors include a sudden cold snap followed by a spell of warm weather. The increase in AT0 in the scenarios covered here is likely to result in warmer conditions early in the year and in this situation the peak hatch of nematodirus may not coincide with vulnerable lambs (6-12 weeks of age) being present.

SCOPS produces a nematodirus forecast that uses met office temperature data to predict the hatch date for nematodirus across the UK. Combining this with farm specific information e.g. altitude and aspect of individual fields can improve the prediction further and knowing the grazing history can inform the individual risk. In 2020 the peak risk for Nematodirus was forecast to be mid-April for some parts of southern England, with the peak due to occur before or around the beginning of May in most other areas of England, as well as Scotland, Wales and Northern Ireland, particularly if warm weather continues.

Liver Fluke (fasciola hepatica)

The life-cycle is complex compared to other worms as it involves an intermediate host (the mud snail Galba (Lymnaea truncatula) and several free-living stages. The adult fluke lay eggs that are passed out in the faeces and under suitable conditions a miracidium develops within

[147] COWS, Control of worms sustainably. https://www.cattleparasites.org.uk/

the egg, hatches and migrates, seeking out the snail host. Following further development within the snail cercaria migrate to the herbage where they become the infective stage of the parasite (metacercaria). Following ingestion by grazing livestock, the young fluke migrate to the liver. It typically takes 10–12 weeks for fluke eggs to be produced following ingestion with the whole cycle taking around 18-20 weeks, although development within the snail can vary from around five weeks to a few months depending on temperature and moisture. The snail prefers the conditions associated with poor drainage and therefore the incidence of liver fluke is higher in the wetter areas of the country and in years with high summer rainfall. Sheep grazing wet fields in the autumn and winter are particularly at risk of infection so excluding animals from these areas can offer some measure of control.

As the parasite is affected by both temperature and rainfall there can be considerable differences in risk between years. The hatching of fluke eggs and the multiplication of snails depend on having enough moisture and temperatures above 10°C. Typically these conditions are present between May and October in the UK but patterns have changed in recent years with an increase in prevalence and spread. A number of reasons have been given for this including climate change, change in management practices and movement of livestock. In wet summers snail populations multiply rapidly and become infected during May-July before shedding large numbers of cercariae onto the pasture in July to October. If the weather is cold and dry fewer snails appear, fluke egg hatch is reduced and contamination in the autumn is reduced. Less commonly snails can be infected in late summer and development is delayed as snails become dormant, hibernating until the following spring when they produce a spring infection.

The NADIS (National Animal Disease Information Service) parasite forecast[148] provides an assessment of the liver fluke risk based on met office temperature and rainfall data. The current parasite forecast for May 2020 refers to the relatively mild winter of 2019-20 and the likelihood of higher levels of chronic fluke infections due to the extended fluke development season in 2019.

One of the control methods to reduce fluke infection is to exclude animals from areas that can harbour the snail host. Drainage eliminates the snail and offers an effective means of control, but environmental schemes that protect wetland areas have reduced the opportunities for this to be carried out. Hotter drier summers might have a positive impact on some pastures and reduce the areas able to support the snail. However on the majority of farms it is unlikely that this will eliminate the snail habitats completely. Liver fluke management programmes should be tailored to individual farms as within the same region there can be significant differences between neighbouring farms.

External parasites

Blowfly strike in sheep

Blowfly strike is a widespread issue caused by the larvae of the blowfly Lucilia sericata (greenbottle flies) causing significant welfare issues and economic loss if not controlled effectively. It is estimated that 1.5% of ewes and 3% of lambs in the UK may be affected

[148] https://www.nadis.org.uk/parasite-forecast.aspx

each year, despite preventative measures being undertaken by the majority of farmers and at least 75% of sheep farms report cases of blowfly strike each year.[149]

Adult flies lay eggs on the fleece and these hatch within approximately 12 hours. These larvae can develop into mature third-stage maggots in as little as three days at optimum temperature and humidity. Third-stage maggots then drop to the ground and pupate, with adult flies emerging after 3 to 7 days over the summer period. The entire life cycle from egg to adult can occur in less than 10 days in optimal conditions. Flies can also over-winter in the soil as pupae and emerge when soil temperatures rise above 9°C in the spring to provide the first wave of adult flies.

High temperatures encourage fly activity and when relative humidity is also high this creates favourable conditions within the fleece that attract flies to lay eggs. In the UK rising temperatures in late spring allow overwintering fly larvae to complete their lifecycle and the first wave of blowflies to emerge. Blowfly populations peak during the summer months and traditionally the fly strike period runs from May-September. However more recently the risk period has been extended due to favourable climatic conditions and can run from March to December in some lowland areas.

Strategies to control and prevent blowfly strike include applications of products that prevent the development of blowfly larvae and/or treatment of affected animals. Ewes are generally at greater risk in the spring due to their heavy fleeces but once shorn risk falls significantly. Keeping animals clean through effective parasite management and dagging/crutching of animals should also help prevent strike. One outcome of consistently earlier strikes may be that shearing is brought forward to reduce the risk.

NADIS, (in collaboration with Elanco) run an on-line blowfly risk alert to help farmers stay aware of the challenge over the season. This has run for a number of years with farmers (and others) reporting cases of blowfly strike on the website to raise awareness of the risk in their local area. The first reported cases of strike have occurred from April to early May in recent years;[150] in 2020 the first reports were made on 14 April in Herefordshire and Devon and the first report in Wales a week later on 21 April.

Sheep Scab

Sheep scab is caused by the mite *Psoroptes ovis* infesting the skin of sheep and is a major animal welfare problem across the UK. Sheep scab prevention, treatment and the associated production loss of an outbreak is estimated to cost the UK sheep industry in excess of £8M annually.[151]

Sheep scab infestations causes severe itching, wool loss and scratching of affected areas and result in reduced liveweight gain or weight loss and in severe cases, death. The lifecycle from egg to adult is completed in around 10 days. Mites complete their whole life cycle on the sheep although they can survive for a limited time in the environment if they are rubbed off onto fence posts, trees, equipment etc. Scab mites are usually transmitted by direct physical contact between sheep but because the mite can survive off the sheep for a period of time

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[149] https://www.nadis.org.uk/disease-a-z/sheep/blowfly-strike-cutaneous-myiasis-maggots/

[150] https://www.farmanimalhealth.co.uk/blowfly-tracker

[151] Moredun Foundation, (2016) Sheep Scab, News sheet Vol 6. No. 11

(typically around 16-18 days) sheep can be infested via the environment with transmission greater in the cooler winter months. The length of time mites can survive off the sheep is affected by temperature and humidity and at low temperatures (<15°C) and high humidity (>75% relative humidity) survival may be in excess of 18 days.

Most scab outbreaks occur in the winter/spring months when fleece length and environmental humidity provides the optimum conditions for the multiplication and development of the mites. In the summer the mite population generally reduces as the fleece tends to be drier (particularly in shorn sheep) and mite activity reduces. They remain present however in folds of skin and if conditions are suitable outbreaks can occur in the summer.

As the mites live permanently on the sheep they are less likely to be directly affected by changes in climate but there may be indirect effects as a result of changes to management practices; for example the length of housing periods (where transmission is increased), timing of shearing and use of anthelmintics that may target both internal and external parasites. In addition the time that the mite can survive off the sheep will affected by temperature and humidity with hotter, drier conditions (as expected in future summer climate scenarios) reducing survival and cooler, more humid conditions extending survival.

Tick borne disease

Ticks are blood sucking obligate parasites and there are at least 20 species indigenous in the UK. The most common tick in GB is the common sheep tick (Ixodes ricinus) which acts as a vector for a number of important livestock diseases including; louping ill, tickborne fever, babesiosis (redwater fever) and tick pyaemia. The same tick can also transmit Lyme disease to humans. The sheep tick is distributed widely across the UK, preferring areas with dense vegetation and warm, wet conditions that support the free living stages of the life cycle. They spend the majority of time off the host; only feeding for between 2 – 10 days depending on the stage of the life cycle with each free-living stage taking around one year. Traditionally ticks become active in the spring when they seek a host to feed from with activity reducing in the summer months. In the warmer wetter parts of the country there can be a second period of activity in the autumn. Control of ticks in sheep is generally achieved by applying acaricides by plunge dipping or pour on treatments. A vaccination against louping Ill is available for sheep.

Ticks require humidity greater than 85% when off the host and a temperature above 7°C before they become active. These environmental requirements mean that ticks do not survive in well drained pasture because of low humidity whilst the vegetation 'mats' common in upland pasture and woodland area are ideal for their survival. Tick infestations are of particular importance in hill sheep as upland grazing areas are a preferred habitat.

There are reports of both increased geographic spread and increasing numbers of tick populations[152] Factors that may contribute to this include climate change but other factors are also important including, changes to farm management, reduction in sheep dipping and changes to habitat management (e.g. increased areas of woodland, reduced stocking rates on moorland, and rough grazing and inclusion of arable field margins for agri-environment

[152] Scharlemann JP1, Johnson PJ, Smith AA, Macdonald DW, Randolph SE. (2008) Trends in ixodid tick abundance and distribution in Great Britain. ed Vet Entomol. Sep;22(3):238-47 (abstract).

schemes), to support environmental biodiversity. Studies have suggested that increasing temperatures not only increase the distribution of ticks but may encourage them into higher altitudes that were not previously colonised[153]. In addition changes in climate that result in warmer and more humid conditions will result in increased tick activity[154]. Evidence of this has been cited with louping ill having been diagnosed in Scotland in every month except January.[155] The increase in AT0 across Wales in the scenarios reported here suggests that ticks may become active earlier in the season as temperatures rise above 7°C. They will however remain dependent on having a moist humid environment in which to survive off the animal.

The SCOPS initiative provides news on their website to alert farmers to reports on tick numbers. The latest alert for the 2020 season (April 2020) reported a surge in tick numbers in the South of England with large numbers of ticks on lambs on some farms[156].

It is also of note that other tick spp. present in Southern England and Wales are not currently disease transmitting but the industry needs to remain aware of the possibility that this could change.

Bluetongue

Bluetongue is a notifiable viral disease affecting ruminants that is transmitted by biting midges (genus Culicoides). Cattle are the main host but the severity of the disease varies, with symptoms being more severe in sheep.[157] The disease is most likely to be seen in late summer and autumn, coinciding with a peak in midge population activity during periods of high temperature and rainfall and subsides with the first frost or severe cold weather. A vaccine is available for cattle and sheep.

Historically bluetongue was confined to tropical and subtropical areas but climate change (and changes to trade patterns) have seen increasing outbreaks in temperate areas including Northern Europe. Midges can be carried considerable distances on the wind (over 200km) and this has been the primary way the disease has been introduced into new areas. A significant outbreak occurred in N Europe in 2006-2008 and resulted in the disease appearing in Britain for the first time due to infected midges being blown across the English Channel.

A study modelling the impact of climate change (temperature and rainfall) on bluetongue[158] has integrated historic and projected climate data with modelled disease transmission parameters to evaluate the risk of bluetongue emergence in Europe. This model suggests

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153 Medlock et al.: Driving forces for changes in geographical distribution of Ixodes ricinus ticks in Europe. Parasites & Vectors 2013 6:1.

154 Greenfield BPJ, (2011) Environmental parameters affecting tick (Ixodes ricinus) distribution during the summer season in Richmond Park, London.Bioscience Horizons vol 4, issue 2 pp140-148 https://academic.oup.com/biohorizons/article/4/2/140/225643

155 Moredun Foundation, (2015) Ticks and Tickborne Diseases, News sheet Vol 6. No. 6

156 https://www.scops.org.uk/news/6933/tick-numbers-surge-in-southern-england/

157 Bluetongue in cattle and sheep https://www.nadis.org.uk/disease-a-z/cattle/bluetongue-in-cattle-and-sheep/

158 Guis, H et al (2012). Modelling the effects of past and future climate on the risk of bluetongue emergence in Europe, Journal of the Royal Society Interface, 9, 339-350

that for NW Europe temperature is the main driver for changes in transmission rate. In cool conditions (<12°C) midge activity and replication of the virus cease but if mild conditions persist into the winter period both midge activity and virus replication could be extended. This would suggest that the warming seen across Wales would see the risk period for the virus extended should another outbreak occur and the potential for activity at higher altitude.

Bluetongue is currently absent from the UK but there remains a risk of reintroduction from the continent via infected midges or import of infected livestock. Midge control is not likely to be possible so control currently focusses on post-import testing of livestock.

How are the relevant sectors preparing for the future?

Response to extreme weather

An increase in the frequency of extreme weather events means that farmers must have robust emergency plans in place which will need to be revised in the light of actual events. The increase in temperatures in the summer period are likely to lead to more days that cause heat stress and changes to the farm infrastructure may be required to moderate the impact. In addition extended drought periods may cause grass shortages throughout the grazing period – requiring supplementation with conserved forage/alternative feeds and reduced yields of conserved forage. Guidelines for managing heat stress, drought and flooding have been published by AHDB to highlight the key messages for managing cattle and sheep during extreme weather.[159]

Disease and parasites

This report has focussed on the impact of climate change scenarios on the health of ruminants. Whilst this is important other on-farm management factors also impact on prevalence and distribution of disease and parasites. In the case of parasites confounding factors include anthelmintic resistance, parasite evolution, animal movements and farm management practices. The industry is encouraged to use proactive veterinary health plans to identify and control health issues on farms and these have become a requirement for some assurance schemes. Key features of these plans include biosecurity and quarantine, vaccinations and parasite control.

Parasite management and forecasting tools

Managing parasites effectively in cattle and sheep is complex and best addressed through herd/flock health plans that take into account the individual circumstances on farms. As the risk for many parasites varies both between years and within years as a result of local weather conditions plans need to be responsive to ensure treatment choice and timings are appropriate. The livestock sector has two industry led initiatives to manage parasite control; SCOPS (sustainable control of parasite in sheep and COWS (control of worms sustainably). These aim to develop sustainable strategies for parasite control and provide

[159] http://beefandlamb.ahdb.org.uk/wp-content/uploads/2015/10/BRP-Managing-cattle-and-sheep-during-extreme-weather-events.pdf

recommendations for the industry on managing parasites against a background of increasing anthelminthic resistance.

Modelling of parasite risk (prevalence and geographic distribution) in response to current weather and wider climate change has been the focus of a number of research organisations; examples include endoparasites,[160] liver fluke[161], blowfly strike[162] and bluetongue[163] etc. A number of decision support tools in the form of forecasting tools and alerts are available for parasites which are produced by SCOPS and NADIS. These use met office data to generate general parasite forecasts, nematodirus risk forecasts and blowfly alerts.

The monthly parasite forecast published by NADIS uses met office data (temperature and rainfall) to outline the parasite challenge for cattle and sheep on a regional basis in the UK. The forecast promotes the SCOPS and COWS recommendations in a seasonal context and underlines the importance of parasite control being part of a veterinary health plan. The forecast covers parasitic gastroenteritis and liver fluke in cattle and sheep, blowfly in sheep and lungworm in cattle. In addition SCOPS produce a nematodirus forecast in the spring to help farmers judge the timing of egg hatch in their area.

The NADIS Blowfly Alert[164] (in conjunction with Elanco) predicts the emergence of blowflies based on Met Office Data. This can help to predict risk of clinical cases and help plan treatment timings. The model used to generate these predictions uses daily temperatures and rainfall, along with a detailed understanding of fly biology and sheep susceptibility to forecast the patterns of strike incidence.

The impact of climate change as a result of the Low-Medium scenarios up to 2050 is likely to depend on the parasite. Different species have different temperature thresholds, moisture requirements and overwintering strategies. For example, it is suggested that nematodirus may actually reduce if the egg hatching does not coincide with a vulnerable lamb population whereas haemonchus may increase due to increasing temperature.

The impact of climate change on disease and parasite prevalence and distribution have been modelled for a number of disease vectors and parasites. These could be extended/updated using more recent climate projections and potentially predictions could be compared with actual prevalence if sufficient surveillance is in place.

[160] Rose, H. et al. (2016) Climate-driven changes to the spatio-temporal distribution of the parasitic nematode, Haemonchus contortus in sheep in Europe. Global Change Biology, 22(3), pp1271-1285

[161] Caminade, C et al. (2015) Modelling recent and future climatic suitability for fasciolosis in Europe. Geospatial Health, 9(2) pp301-308

[162] Rose, H and Wall, R. (2011) Modelling the impact of climate change on spatial patterns of disease risk: Sheep blowfly strike by Lucilla sericata in Great Britain. International Journal for Parasitology 41 pp 739-746

[163] Guis, H et al (2012). Modelling the effects of past and future climate on the risk of bluetongue emergence in Europe, Journal of the Royal Society Interface, 9, 339-350

[164] NADIS Blowfly alert https://alerts.nadis.org.uk/

AGRICULTURAL INFRASTRUCTURE

Author: Charles Bentley Principal Engineer ADAS

Background information

This section considers the impact of climate change on the physical infrastructure necessary to facilitate the management of agricultural land and the production of crops and livestock, as well as the management of woodland.

Such infrastructure includes but is not limited to:

- Livestock buildings
- Slurry stores
- Silage clamps
- Yards
- Grain stores
- Pack houses and cold stores
- Farm and forest tracks and roads
- Land drains
- Private water supplies and reservoirs

In addition to the civil engineering or fixed equipment aspects of agricultural infrastructure, the term can also cover the mechanical engineering aspects – machinery and mobile plant – such as tractors, tankers, pumps, irrigators and harvesting machinery.

Given the makeup of Welsh agriculture, impacts on facilities associated with the production of ruminant livestock, particularly cattle, are likely to be of greatest economic consequence on a national basis, with impacts on the dairy industry arguably the most significant on a per business basis.

Comparison between ALC interpolated UKCP18 data and the current evidence base.

The modelled outputs suggest likely changes in seasonal rainfall with increasingly wet winters and drier summers, with the net result of little impact on overall average annual rainfall. An increase in average temperatures and reduced summer rainfall is likely to result in increased winter soil wetness, and a shift in the dates of the start and end of field capacity – the point at which a soil can receive no more water without giving rise to soil drainage. The expectation is that whilst there may be some reduction in the number of days during which soils are at or above field capacity, this period will start later in the autumn and end later in the spring and in an arable scenario increase the potential for autumn establishment (soil erosion and run off risks not withstanding) and reduce the opportunities for timely establishment of spring crops which may also perform poorly due to lack of rainfall.

The modelled changes to ALC class suggest a general improvement in the proportion of higher grades, and therefore an assumed increase in the potential for arable and horticultural production and a possible potential consequent decline in the livestock sector. This change has implications in its own right for the nature and extent of infrastructure as this varies with farm type.

The rate of change may also be of consequence. Roads, drains, reservoirs and buildings represent a substantial long term investment on most farms, and are normally expected to have an operating life in excess of 20 years - typically 30 to 40 - with many buildings being adapted and repurposed to some extent on multiple occasions throughout their lifetime. Mobile plant and machinery is more flexible and commonly expected to have a working life of between five and twenty years depending on use and complexity, with the majority being in the region of five to fifteen years.

Overall changes in average annual rainfall appear likely to have few implications for agricultural infrastructure, whereas changes in seasonality of rainfall will have significant implications.

Increases in summer temperatures and droughtiness will have implications for water supply and animal welfare, and therefore for the associated hard infrastructure.

This assessment considers projections for 2035 (2020 to 2050) and 2065 (2050 to 2080) under and low and medium Representative Concentration Pathway scenario, which reflect a global mean temperature increase by 2100 of 2.2°C and 2.6°C respectively. Where a range of figures are quoted for any aspect of temperature or rainfall within this report they refer to the 2035 low Representative Concentration Pathway scenario and the 2065 medium Representative Concentration Pathway scenario respectively.

Low Representative Concentration Pathway scenario (2035 and 2065)

Low Representative Concentration Pathway scenario is based on a 2.2 degree C rise by 2100.

Medium Representative Concentration Pathway scenario (2035 and 2065)

Medium Representative Concentration Pathway scenario is based on a 2.6 degree C rise by 2100.

What the scenarios mean for infrastructure in Wales

Impact of projected changes in annual and seasonal rainfall

Annual rainfall

Changes in average annual rainfall are not anticipated to be significant and are not therefore expected to have substantial implications for agricultural infrastructure. Modelled averages reflect a reduction in 1.5% (2035 low Representative Concentration Pathway scenario) to 2.5% (2065 medium Representative Concentration Pathway scenario) over the current baseline.

Summer rainfall

UKCP18 suggest that average summer rainfall (ASR) in the UK is expected to decrease significantly, with the greatest changes associated with higher Representative Concentration Pathway scenarios. However, when it rains in summer there may be more intense storms. The reduction may be in the order of 13 – 22% from current baseline figures.

Decreased summer rainfall may have indirect implications for fodder storage requirements on livestock farms if production from grazed grass is adversely impacted due to reduced summer grass growth. Greater use is likely to need to be made of conserved forages for buffer feeding or of bought-in feeds. There may therefore be a requirement for increased clamp or storage capacity, in part to allow effective use to be made of a potential increase in early spring grass growth.

Counterintuitively, decreased summer rainfall may also increase slurry production, where stock which would otherwise have been at grass, are brought in earlier or housed throughout the year to make better use of conserved forages. In this situation the existing buildings may also need modification to improve insulation and ventilation for animal welfare reasons – reducing heat stress.

Whilst increased winter rainfall will potentially increase ground and surface water availability for abstraction for public or private supply to agriculture, and extend that availability later into the spring, private abstractions, particularly from surface water may become increasingly limited over the peak summer and early autumn months. Higher temperatures and lower rainfall will also increase water demand by livestock and potentially for irrigation of high value crops. Overall the impact on livestock in the hills and uplands where reliance on natural water supplies is greatest is likely to be the most significant issue since there is often little scope to provide water to stock on inaccessible ground.

Harvested rainwater as an alternative source of private supply will also be further disadvantaged by the need for additional / longer term storage to cover periods without rainfall, potentially making existing tank based systems irrelevant in comparison with pond/reservoir storage.

The consequence of a reduction in summer rainfall is therefore likely to be an increased reliance on mains water supplies, an increased need for supplementary water for grazing livestock and an increase in the need for winter storage reservoirs for both livestock and cropping.

Soil Wetness and Field Capacity Days

Increased winter soil wetness will have different effects in different sectors, and consequently different implications for infrastructure. Fundamentally an increase in soil wetness will reduce the number of days when machinery and livestock can access the land without risk of soil damage, limit the opportunity for the application of organic manures and increase the risk of run off following spreading.

Slurry storage

Reduced spreading opportunities in the early autumn anticipated as a result of proposed legislation will increase volumes of slurry to be stored, as will any reduction in the time spent at grass. A change in seasonality of the period at field capacity is also likely to delay turn out in spring and limit spring spreading opportunities, further increasing storage capacity requirements.

Other facilities

On mixed farms the change in FCD seasonality combined with an increase in droughtiness may reduce the potential for grass growth and increase scope for winter cereals. As a result the production of home grown cereals may increase along with the consequent need for grain storage. It is debatable whether the need for grain drying facilities will be affected as whilst the area and tonnages involved may increase, increased summer temperatures and reduced summer rainfall imply that there should be less need for drying of cereal crops.

The anticipated weather pattern will further increase the benefit associated with effective field drainage systems on heavier soils, whilst periods of summer drought are likely to increase the extent to which natural cracking of heavy soils restores structure and drainage properties.

Pollution risks associated with land application of slurries may increase with greater volumes to be applied in a shorter application window, soils at or around field capacity for longer, and greater cracking of droughted heavy land later in the season increasing the risk on drained soils.

Winter rainfall

UKCP18 suggest that average winter rainfall (AWR) in the UK, and Wales, is expected to increase. Assessment of the modelled data for Welsh administrative districts suggests this could be in the region of 8 - 13% over current levels.

Increased winter rainfall and increased intensity of rainfall will impact on infrastructure in a number of sectors, primarily livestock, but to a lesser extent to horticultural and arable / mixed farming.

Slurry storage

The most fundamental impact of increased winter rainfall is likely to be on the requirement for slurry storage or for roofing of open yard areas to exclude rainfall on livestock farms. Rainwater already makes up around 30% of the contents of a typical slurry store, and can be a much greater proportion with shallow open stores such as earth banked lagoons especially in high rainfall areas.

Current legislation (SSAFO 2010) requires four months storage to be provided for manures handled and stored as slurry together with the worst four months rainfall anticipated in a five year return period (M5 120 days) on the store and any yard areas which drain to it. Short term buffer capacity in reception pits requirement is not less than 48 hours production and the worst 48 hours rainfall in a five year return period (M5 48 hours). These standards are slightly different in a Nitrate Vulnerable Zone where the requirement is for 5 months storage with average rainfall for cattle slurry and 6 months for pigs and poultry. Proposed draft legislation appears likely to extend the NVZ storage requirements across Wales, and to bring in overall stocking rate limits. It is widely accepted that relatively few farms currently achieve full compliance. The advent of the regulations will require facilities to be improved, expanded or replaced, but the immediate benefit is likely to be eroded over time by increased rainfall volumes.

An increase in winter rainfall will increase both long term storage capacity requirements under current and proposed legislation, and probably more significantly an increase in buffer storage capacity.

In order to mitigate the requirement for additional slurry storage the practice of roofing open yard areas and covering slurry stores is widely advocated and has been supported by grant schemes across the UK and in northern Europe (currently the SPG scheme in Wales) Whilst roofing is effective in diverting water from stores, reducing the required storage capacity, extending the available storage period and the volumes to be spread it also results in increased volumes of clean water to be handled. If discharged to surface waters this can increase the risk of downstream flooding. This aspect is addressed in Wales through the requirement for a SUDS design for new roof areas over 100 m^2, but an increase in winter rainfall intensity, soil wetness and roof area means that in future soakaway systems will be less likely to function effectively and attenuation ponds will need to be larger.

Farm and forest tracks and roads

Increased winter rainfall and rainfall intensity will increase rates of run off from hard surfaces, and the volume and velocity of the run off. This will potentially increase the risk of downstream flooding, and the rate and extent of surface erosion of such access routes. In order to protect existing assets, improvements to surface water handling and increased maintenance are likely to be required, whilst measures to dissipate and limit the impact of surface water discharges (swales, grips, constructed wetlands and in-ditch check dams) may also be more widely needed on both new and existing access routes.

Land drainage

The benefits of effective land drainage are likely to increase with increased winter rainfall. Maintenance of field ditch networks and land drainage is believed to have declined significantly in the past 30 years, and the installation of new or replacement piped schemes has virtually ceased since the end of widespread grant aid for drainage. Many grant aided schemes from the 1970s are now beginning to fail through deterioration of early plastic pipes, collapse due to heavy machinery operating on wet soils with limited cover over the drains and lack of maintenance.

Without drainage additional rainfall on a saturated soil results in immediate run off, and without natural or artificial drainage soils remain saturated for long periods over winter whilst water loss through evapotranspiration is reduced. Effective land drainage is designed to transfer excess water from a soil over a period of a number of days, returning the soil from a saturated condition to field capacity and in doing so both improve productivity and smooth peak flows so helping reduce flood risk. An increase in drainage restoration work and potentially in new schemes seems likely to be required to mitigate some of the impacts of increased winter rainfall and more intense summer storms.

Arable and horticulture

With the exception of land drainage aspects, an increase in winter rainfall and rainfall intensity will have little direct effect on the requirement for fixed infrastructure on field scale crop and horticultural units, which currently represent only a small proportion of Welsh agricultural production.

Impact of projected changes in temperature

As outlined above under summer rainfall, an increase in summer temperatures is likely to mean an increase in demand for water for livestock drinking and irrigation, and a potential need for improved ventilation and solar insulation of livestock buildings, which could substantially increase operating costs for the intensive livestock sector and more intensive dairies.

Increased winter temperatures are likely to reduce levels of frost damage to infrastructure, but may also lead to increased problems with ventilation / cooling within naturally ventilated livestock buildings. These will need to be addressed through modifications of existing structures, normally a relatively modest investment.

Increased winter temperatures may also reduce the seasonal check in grass growth, resulting in increased production in conditions when grazing may not be possible. This could result in a change in management with an early first cut prior to slurry application and followed by subsequent further cutting or grazing.

What is being done by the sector to prepare

Whilst some businesses have half an eye to the future, anecdotally there is little evidence of on-going investment and preparation by the vast majority of operations, in part because the cost of such investment is likely to be significant, in part because the scale and extent of the changes in infrastructure are difficult to quantify, and in part because the industry is facing multiple short term issues including Brexit and regulatory changes which will affect infrastructure needs and may call into question the long term viability of some businesses and enterprises. There is no point investing hundreds of thousands of pounds in infrastructure with a 20 - 40 year lifetime if the structure will be non-compliant within ten years or the enterprise unprofitable within five.

What should the sector be doing to future proof

Given the competing threats to the industry and lack of clarity over the detail of likely impact on any one business or enterprise it is difficult to suggest that businesses should be upgrading infrastructure now to meet future challenges, however businesses should certainly be considering options and approaches to mitigation. Where investment is currently or will soon be required to meet regulatory requirements or achieve business needs, businesses should be prepared to upgrade proposed facilities and opt for approaches which offer the greatest flexibility in operation or for further expansion in order to accommodate the potential demands of climate change.

Summary

Climate change is predicted to bring increased winter rainfall and soil wetness, along with a change in the seasonality of field capacity days, increased temperatures and increased rainfall intensity.

The key issue is that additional investment in slurry storage capacity will be required on most dairy units and many other livestock farms. Attention to land drainage systems will help mitigate the impact of increased winter rainfall. Winter abstraction and water storage, and the provision of water supplies to outlying land will also need to be considered by some businesses. Others are likely to need / have the opportunity to diversify production, and therefore be faced with the requirement to investment in infrastructure associated with the new enterprise.

The combination of the effects of changing rainfall patterns and seasonality of soil wetness and probable grass growth makes quantifying the additional storage requirements difficult to estimate, along with a very variable baseline, commonly of limited storage and a variety of different storage systems. As an indication a 10% increase in winter rainfall, when combined with the possible changes in spreading opportunities could necessitate a 20% increase in storage capacity over and above the increase likely to be required to comply with potential future legislation. Overall this could lead to a requirement for some business to double their current capacity.

INFRASTRUCTURE (NON AGRICULTURAL)

Author: Charles Ffoulkes Associate Director Sustainable Food and Farming ADAS.

This section considers the impact of climate change on road and rail, as well as water and power (electricity) infrastructure across Wales. We do not consider any other forms of infrastructure (e.g. ports, airports, schools, phone lines, sewage treatment plants, power for heating etc.), but recognise that these are also important parts of the sector.

Background information

Road Network

In 2019, Great Britain had an estimated 397,700 km of road, of which 77% were in England, 15% were in Scotland, and 9% were in Wales.[165]

The total length of the road network in Wales was estimated at 34,853 km in 2018/19.[166] The Welsh Government is the authority responsible for the motorway and the trunk road network, whilst all other public highways are the responsibility of the local authority they are within. The total road network length is made up of the following road classifications: 135 km (0.4%) were classed as motorway (M); 2,773 km (8%) were County 'A' roads; 1,576 km (4.5%) were Trunk 'A' roads; 12,861 km (36.9%) were 'B' and 'C' roads; and 17,509 km (50.2%) were minor surfaced roads or unclassified (U), such as local distributor and access roads.

Rail Network

In 2018, Great Britain had an estimated 15,878 km of railway and 2,563 stations, of which Wales accounted for around 15% and 10% respectively. Across Great Britain, the number of journeys and distances travelled by rail have more than doubled in the last 20 years.[167]

The Network Rail 'Wales route' is one of five regional splits and 14 route splits within the UK. Network Rail operates and maintains the track across Wales and the border counties of England. This route links the major towns and cities of Cardiff, Newport, Swansea, Wrexham and Shrewsbury, as well as providing connectivity in more rural areas. The rail network in Wales consisted of 1,505 track miles, 248 stations, 1,100 level crossings and 3,002 bridges in 2018.

[165] Department for Transport (2020) Road Lengths in Great Britain 2019. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/860685/road-lengths-in-great-britain-2019.pdf [Accessed 16 Apr. 2020]

[166] StatsWales - Road length (Km), by type of road and local authority, Wales. Available at: https://statsWales.gov.Wales/Catalogue/Transport/Roads/Lengths-and-Conditions/roadlength-by-typeofroad-localauthority-year [Accessed 16 Apr. 2020]

[167] Department for Transport (2018) Rail Factsheet. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/761352/rail-factsheet-2018.pdf [Accessed 16 Apr. 2020]

Water Network

Four water companies provide around three million people in Wales with a supply of water every day; these are: Dŵr Cymru Welsh Water, Hafren Dyfrdwy, Albion Water and Southern and Scottish Energy Water.[168,169]

The water industry in Wales is complex due to the cross-border nature of water company boundaries and transfer of water supplies between Wales and England. For example, millions of litres of clean water is collected from the Welsh hills, via the Elan Valley Reservoirs (a chain of man-made lakes created from damming the Elan and Claerwen rivers within the Elan Valley in Mid Wales), and channelled to Birmingham each day.

Power Network (electricity)

National Grid is responsible for providing a resilient and reliable electricity transmission grid within England and Wales. National Grid own the national electricity transmission system in England and Wales (NETS). The NETS consists of approximately 7,200 kilometres (4,474 miles) of overhead line, 1,500 kilometres (932 miles) of underground cable and 347 substations.[170]

Comparison between ALC interpolated UKCP18 data and the current evidence base.

The Welsh Government's latest thinking is that the UK (and more specifically Wales) is most likely aligned to projected impacts of a low-medium Representative Concentration Pathway scenario by the 2080s. This projection would result in a temperature increase of between 2.2°C and 2.6°C by 2100, as opposed to a temperature increase of ~4.3°C in a high Representative Concentration Pathway scenario. However, a low-medium Representative Concentration Pathway scenario is not simply an outcome of climate action in the UK, but is subject to considerable action being taken globally to reduce greenhouse gas Representative Concentration Pathway. This includes action being taken by all nations, including the world's largest emitters (e.g. USA and China) who are not currently part of the Paris Agreement, to actively transition to such pathways.

The impacts associated with the latest climate projections under a low-medium Representative Concentration Pathway scenario could be experienced within any given year within the period of assessment. However, ongoing changes to the climate will create more favourable conditions that will increase the likelihood of extreme events and climate changes occurring, including changes in the frequency and magnitude of such events.

This assessment considers the Cranfield projections for 2020 (2010 to 2039) and 2050 (2040 to 2069) under a low and medium Representative Concentration Pathway scenario, which reflect a global mean temperature increase of 2.2°C and 2.6°C respectively by 2100.

What the scenarios mean for infrastructure in Wales

Vulnerability of infrastructure in Wales

The Met Office categorises the weather in Wales as a maritime climate, characterised by weather that is often cloudy, wet and windy, but mild. However, the shape of the coastline, and the central spine of high ground from Snowdonia southwards to the Brecon Beacons, introduce localised differences. Whilst some upland areas can experience harsh

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[168] Natural Resources Wales (2020) Water resources management planning. Available at: https://naturalresources.Wales/about-us/what-we-do/water/water-resource-management-planning/?lang=en [Accessed 16 Apr. 2020]

[169] CC Water (2018) Hafren Dyfrdwy – a new water company for Mid and North-East Wales. Available at: https://www.ccwater.org.uk/blog/2018/06/29/hafren-dyfrdwy-a-new-water-company-for-mid-and-north-east-Wales/ [Accessed 1 May 2020]

[170] National Grid https://www.nationalgridet.com/network-and-assets [Accessed 24 Apr. 2020]

weather, the coasts enjoy more favourable conditions, and areas in east Wales are more sheltered with weather similar to neighbouring English counties.[171]

Whilst severe weather can have major impacts on infrastructure in both England and Wales, it is often the case that local communities in Wales are more vulnerable to disruption when an event occurs. This is partly related to, for example, the rural landscape and potential remoteness of impacts; limitations in the available alternative options (e.g. alternative routes or roads); accessibility to access and repair damaged infrastructure (e.g. if a landslip blocks a remote stretch of road or rail, the repair cost could be much higher and take longer); resources to fund or implement repairs; and cascading impacts from event that affect a much wider area (e.g. flooding of a substation in one town could disrupt the supply of electricity in a neighbouring town that wasn't directly impacted by the weather event in the source town). In contrast, there are also opportunities from climate change that might benefit Welsh infrastructure. For example, milder winters may result in a reduction of cold or frost events, reducing the risk of frozen or burst pipes, and relieving pressure on power (gas) through a slightly reduced requirement of heating buildings.

A key factor in determining the vulnerability of Welsh infrastructure to climate change is the current condition of infrastructural assets across Wales. Assets that are already in poor or deteriorating condition will be more susceptible to further damage or destruction from extreme weather conditions and future climate change, compared to assets that are newer and/or have been built to a higher specification.

Condition and capacity of the Road Network

StatsWales provide some indication into the condition of the road network in Wales. In 2018/19, it was estimated that the proportion of the total motorway network requiring close monitoring of structural condition, 6.4% in 2018/19, 3.1% in 0-4 years, 15.6% in 5-19 years and 74.9% in 20 or more years, based on a survey of 99% of the motorway network. Similarly for all-purpose trunk 'A' roads, it was estimated from that the proportion of the all-purpose trunk network requiring close monitoring of structural condition was 2.8% in 2018/19, 2.3% in 0-4 years, 9.6% in 5-19 years and 85.3% in 20 or more years, based on a survey of 86% of the all-purpose trunk network.[172]

The percentage of local authority road network in poor condition, including County A roads, B and C roads and minor surfaced roads was last assessed in 2018-19. The percentage of the network in poor condition was estimated to be 202 km (3.9%) for County 'A' roads, 263 km (4.5%) for 'B' roads, and 2,383 km (14%) for 'C' roads. This assessment was based on inspection of the road surface using machine based SCANNER surveys by the Local Government Data Unit.[173,174]

A review of evidence by the National Assembly for Wales in 2018 indicated that Wales's roads are in no worse condition than those in other parts of the UK. However, severe winter weather in 2016/17 and 2017/18, and reduced

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[171] Met Office - Wales: climate. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/Wales_-climate---met-office.pdf [Accessed 17 Apr. 2020]

[172] Stats Wales (2019) Percentage of Motorway and A Trunk road network requiring close monitoring of structural condition. Available at: https://statsWales.gov.Wales/Catalogue/Transport/Roads/Lengths-and-Conditions/roadnetworkrequiringclosemonitoring-by-roadclassification-workrequired-year [Accessed 1 May 2020]

[173] StatsWales (2019) Length of local authority road network in poor condition by road type and year. Available at: https://statsWales.gov.Wales/Catalogue/Transport/Roads/Lengths-and-Conditions/length-localauthority-roadcondition-by-localauthority-type-year [Accessed 1 May 2020]

[174] StatsWales (2019) Percentage of local authority road network in poor condition by road type and year. Available at: https://statsWales.gov.Wales/Catalogue/Transport/Roads/Lengths-and-Conditions/percentage-localauthority-roadcondition-by-localauthority-type-year [Accessed 1 May 2020]

funding for maintenance, had a negative impact on the surface of roads. This led to more money being spend on short-term fixes, rather than long-term maintenance of the road network.[175]

The long term trend in traffic volume in Wales from 1993 to 2018 shows that over this period, traffic volume has increased by 33%. In 2018, the total volume of motorised traffic in Wales was estimated to be 29.4 billion vehicle kilometres (bvk); of which 7.1 bvk (24%) was associated with North Wales, 8.7 bvk (30%) in mid and South West Wales, and 13.6 bvk (46%) in South East Wales.[176]

Road traffic forecasts by the Department of Transport indicate that traffic in England and Wales is forecast to grow between 17% and 51% by 2050 (averages across all regions, compared to 2015 traffic levels.[177] Forecasts for Wales specifically indicate growth of between 19% and 52% over the same period. This will exert greater pressure on the current road network, which already suffers with considerable congestion on some stretches (e.g. M4 between Newport and Cardiff), as well as seasonal overcrowding across multiple stretches of the network in the summer months due to tourism.

Condition and capacity of the rail network

Much of the railway system in Wales was built in the 19th century. It is not clear exactly what proportion of the network is in poor condition or in need of repair or upgrading, although impacts associated with recent weather events (e.g. track buckling associated with extreme temperatures in June 2018) suggest that parts of the network are, and will continue to be susceptible to the impacts of extreme weather, exacerbated further by climate change.

Key parts of the network have recently been upgraded (e.g. electrification of the south Wales mainline), with much more investment planned in the coming years also. For example, Network Rail announced a £2 billion investment in railways across Wales and its borders in 2019-2024. The funding will support more than 1,000 local initiatives, including £176 million on rebuilding and improving train tracks; £27.7 million towards boosting the rail network's defences against extreme weather events; and £135 million on improvements to signalling technology. The Barmouth viaduct, a prominent architectural icon of the Welsh rail system, will undergo a £22 million renovation.[178]

Around 30.4 million passenger journeys are taken each year in Wales.[179] The railway network in Wales has seen passenger numbers grow by almost 50% in the last decade. This growth is expected to continue, with journeys to and from Cardiff Central station forecast to increase from 13 million to 33 million, by 2043.[180] In the North of Wales, it is predicted that demand between North Wales Coast and Chester, Liverpool and Manchester will grow from 2013 levels by 25% to 2023, and 80% to 2043.[181]

175 National Assembly for Wales (2018) The State of Roads in Wales. Available at: https://www.assembly.Wales/laid%20documents/cr-ld11791/cr-ld11791-e.pdf [Accessed 5 May 2020]

176 Stats Wales (2019) Volume of road traffic by local authority and year. Available at: https://statsWales.gov.Wales/Catalogue/Transport/Roads/Road-Traffic/volumeofroadtraffic-by-localauthority-year [Accessed 5 May 2020]

177 Department for Transport (2018) Road Traffic Forecasts 2018. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/873929/road-traffic-forecasts-2018-document.pdf [Accessed 5 May 2020]

178 Network Rail (2019) Wales, 2019-2024, Route CP6 Weather Resilience and Climate Change Adaptation Plan. Available at: https://cdn.networkrail.co.uk/wp-content/uploads/2019/10/Wales-CP6-WRCCA-Plan.pdf [Accessed 5 May 2020]

179 Network Rail (2019) Network Rail Limited Annual Report and Accounts 2018 – Wales. Available at: https://www.networkrail.co.uk/wp-content/uploads/2019/06/NRL-2018-ARA-Wales.pdf [Accessed 16 Apr. 2020]

180 Network Rail – Wales. Available at: https://www.networkrail.co.uk/running-the-railway/our-routes/Wales/ [Accessed 22. Apr. 2020]

181 Network Rail (2016) Welsh Route Study. Available at: https://cdn.networkrail.co.uk/wp-content/uploads/2016/11/Welsh-Route-Study.pdf [Accessed 5 May 2020]

Condition and capacity of the water network

The water network in Wales is vulnerable to a number of climate change impacts. Welsh Water outline several key risks, including water supply deficit (e.g. drier summers would lead to diminished water supply), reduced water quality (e.g. soil erosion and landslips leading to increases in sediment, suspended solids, pesticide and nutrient loadings linked to increased peak precipitation and pollutant mobilisation), reduced average flows that could reduce the dilution of pollutants (e.g. due to hotter drier summers), and increased domestic water demand (e.g. increased garden watering and increased bathing associated with warmer weather).[182]

Average per capita consumption (pcc) of water was estimated to be 143 litres of water per person per day across all water companies in England and Wales in 2018-19, with a range of between 130 and 163. In Wales, average pcc was 157 for Welsh Water, and 142 for Hafren Dyfrdwy.[183]

It is not clear exactly what proportion of the water network is in poor condition or in need of repair or upgrading, although impacts associated with recent weather events (e.g. drought conditions in 2018, and recent flooding in 2020) suggest that parts of the network are, and will continue to be susceptible to the impacts of extreme weather, exacerbated further by climate change.

Considerable investment will be required to future-proof the water network in Wales to ensure that water companies in Wales become more resilient to the projected impacts of climate change (e.g. changing patterns, more variability and more frequent extremes in precipitation). Welsh Water, for example, has planned a £2.3 billion investment for five years from 2020. Recent investments by Welsh Water include the "Pipes in Dams" programme, to ensure dams (some of which were built in Victorian and Edwardian times) are ready to meet the challenges of a changing climate.[184]

Condition and capacity of the power network (electricity)

National Grid own the electricity transmission network in Wales. Detail on the current condition of National Grid assets and the power network was not available for this research.

In terms of managing capacity and demand in the grid, there has been a notable shift in recent years towards decentralised and renewable generation. As a result, requirements for system flexibility have been increasing as the amount of intermittent and decentralised generation grows. In addition, transformation to renewable energy requires a greater amount of generation capacity to be built compared to demand. This is because intermittent generation is not able to produce electricity when, for example, there is no sun or wind.

Wales is a net exporter of electricity to England, Ireland and the wider European electricity network. In 2018, Wales generated an estimated 30.2 TWh of electricity, but consumed just 14.9 TWh, meaning half of the energy generated was exported. Around 75% of electricity generated was from fossil fuels (predominately gas, and a little coal and diesel) and 25% was from renewable sources, with approximately two-thirds of renewable electricity generated in Wales coming from both onshore and offshore wind. Other key forms of renewable electricity generation include solar PV, biomass electricity and hydropower, as well as (to a lesser extent) anaerobic digestion and landfill gas.[185]

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[182] Welsh Water (2018) Welsh Water 2050. Available at: https://www.dwrcymru.com/en/Company-Information/Business-Planning/Welsh-Water-2050.aspx [Accessed 5 May 2020]

[183] Discover Water - The amount we use. Available at: https://discoverwater.co.uk/amount-we-use [Accessed 5 May 2020]

[184] Welsh Water - Record investment bolsters resilience to future climate change. Available at: https://www.dwrcymru.com/my/Media-Centre/News-Summary/2018/11/Record-Welsh-Water-investment.aspx [Accessed 5 May 2020]

[185] Welsh Government (2019) Energy Generation in Wales 2018. Available at: https://gov.Wales/sites/default/files/publications/2019-10/energy-generation-in-Wales-2018.pdf [Accessed 17 Apr. 2020]

Marine energy is also likely to be a more prominent feature in the coming years, including tidal stream energy, wave energy, and tidal range energy.[186]

Large-scale investment will be needed across England and Wales to manage changes in the future supply and demand of electricity, particular as the electrification of trains and electric vehicles continues to grow.

Recent large-scale infrastructure investments proposed by National Grid in Wales have included the Mid Wales Connection to connect wind farms in Powys to the national electricity network in Shropshire; and the North Wales Connection Project for a second connection to the Wylfa Newydd nuclear power station on Anglesey. However, both have since been withdrawn.[187]

Impact of projected changes in annual, seasonal and extreme rainfall

Rainfall in Wales varies widely, with the highest average annual totals being recorded in the central upland spine from Snowdonia to the Brecon Beacons. Snowdonia is the wettest area with average annual totals exceeding 3,000 mm. In contrast, areas along the coast and, particularly, close to the border with England, are drier, receiving less than 1,000 mm a year.[188]

Annual rainfall

UK Climate Projections 2018 (UKCP18) suggest that, compared with current year-to-year variations, average annual rainfall (AAR) is not expected to differ a highly significant amount. However, the seasonality of when rainfall occurs is expected to change, with typically warmer, wetter winters and hotter, drier summers. Therefore, the assessment of seasonal differences is more important than very slight variations in annual rainfall.

The low Representative Concentration Pathway scenario for 2020 and 2050 AAR show very limited detectable change compared to the baseline. The medium Representative Concentration Pathway scenario also shows very limited change to AAR in 2020, with only slight increases in the expansion of the 1,001-1,500 mm category around the fringes of south Wales in 2050. There is not expected to be any significant, discernible impacts on infrastructure associated directly to changes in AAR.

Average summer rainfall

UKCP18 suggest that average summer rainfall (ASR) in the UK is expected to decrease significantly, with the greatest changes associated with higher Representative Concentration Pathway scenarios. However, when it rains in summer there may be more intense storms,[189] and thunderstorms (due to a combination of moisture and warmth), increasing the risk of flash flooding.

An average reduction in rainfall and/or prolonged periods of dry weather, and the resulting drought conditions that prevail, can lead to low river flows and a reduced recharge of aquifers and reservoirs. This has impacts on the water infrastructure network, as water shortages can lead to temporary restrictions for domestic users (e.g. hosepipe bans), abstraction restrictions on water-intensive industries such as power generation and agriculture (e.g. for irrigation), and environmental impacts. Furthermore, increased demand for water between sectors (e.g. natural

[186] Marine Energy Wales (2019) State of the sector 2019. Available at: https://www.marineenergyWales.co.uk/wp-content/uploads/2019/04/MEW-State-of-the-Sector-Report-2019.pdf [Accessed 17 Apr. 2020]

[187] National Grid – Infrastructure projects. Available at: https://www.nationalgridet.com/infrastructure-projects [Accessed 5 May 2020]

[188] Met Office - Wales: climate. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/Wales_-climate---met-office.pdf [Accessed 17 Apr. 2020]

[189] Met Office (2018) UKCP18 National Climate Projections – Slide Deck. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-overview-slidepack.ff.pdf [Accessed 17 Apr. 2020]

environment vs. agricultural needs), and between regions (e.g. Wales vs. England), can result in economic impacts or environmental consequences.

A better understanding of reservoir capacity and the seasonal distribution of rainfall to replenish stocks will be an important risk management consideration for the water sector when assessing water supply and demand requirements under future climate change scenarios (e.g. through Water Resources Management Plans). Decreased summer rainfall will put increased pressure on water resources (e.g. for industry, domestic use and agricultural needs such as irrigation and animal husbandry) in the summer months. Whilst typical annual rainfall in Wales is likely sufficient to meet demand, the impacts of year-to-year variations and the changes in the seasonal distribution of rainfall will increase the risk of water shortages occurring, which will be greatly exacerbated if there are sequential dry winters and/or dry summers, leading to longer-term drought conditions where reservoirs are not replenished. One option to address this risk is through increasing the stored capacity, for example through new reservoirs, increasing the capacity of current reservoirs, or farm-level reservoirs, all of which could reduce the need for abstraction from rivers during periods of low-flows.

In 2018, for example, Welsh Water noted that reservoir stocks struggled to meet demand during the July/August heatwave, with levels well below average for the time of year, after months of minimal rainfall. Reservoirs hold most of the water that Welsh Water draws upon to supply drinking water to its customers, so long periods of below average rainfall can impact supply. During the 2018 drought conditions, Welsh Water proactively undertook additional measure to safeguard customer supplier and prepare for the hot weather, such as repairing leaks; increasing the level of operations in water treatment works; using 40 tankers to pump extra water into the system to meet demand.[190]

A reduction in summer rainfall and/or increase in temperatures and evaporation may also lead to soils drying out at a rate greater than current, resulting in greater soil moisture deficits in the summer. For the infrastructure sector, soil desiccation can cause subsidence to above-ground assets due to shrinkage of (clay) soils and the movement of buried infrastructure including waste and water pipes. However, the impact in Wales is envisaged to be less than in other parts of the UK (e.g. south-east of England).

The road network can also be indirectly impacted by reduced rainfall. Under normal conditions (i.e. where rainfall happens relatively frequently), materials such as bitumen, oil and rubber from tyres are continuously washed away from the roads. However, during periods of dry weather, these materials build up into a residue. When a rainfall event then occurs, this build-up of residues mixes with the surface water, creating road surfaces that are greasier and more slippery than usual. For road vehicles, this increases the chance of skidding and makes a vehicle's braking distance longer, resulting in an increased risk of accidents occurring.

Reduced summer rainfall could also have impacts on power (electricity) infrastructure, such as hydropower. In 2018, Wales had 364 hydropower projects, with a capacity of 182 MW and an estimated generation of 389 GWh; enough to power the equivalent of 104,000 Welsh homes. Gwynedd remains the local authority area with the greatest number of hydropower projects in Wales, with 141 projects totalling 59 MW. However, due to hosting Rheidol Power Station, Ceredigion has the greatest hydropower capacity with just under 71 MW across 28 projects.[191]

Changes in the quantity and timing of river runoff, together with increased reservoir evaporation will have a number of effects on the production of hydroelectric power. For example, one study that assessed the potential impacts of climate change on hydropower generation in mid-Wales, based on UKCP09 projections, found that climate change

[190] Wales Online (2018) Fresh warning issued over water use as new pictures reveal the state of Wales' reservoirs. Available at: https://www.Walesonline.co.uk/news/Wales-news/fresh-warning-issued-over-water-14992792 [Accessed 1 May 2020]

[191] Welsh Government (2019) Energy Generation in Wales 2018. Available at: https://gov.Wales/sites/default/files/publications/2019-10/energy-generation-in-Wales-2018.pdf [Accessed 1 May 2020]

will significantly decrease both the stream flows and energy production during summer months, but increase flows and power production in the winter, with a net tendency to cancel out over the course of a full year.[192]

Average winter rainfall

UKCP18 suggest that average winter rainfall (AWR) in the UK, and Wales, is expected to increase significantly.[193] The scenarios show that, for both a low and medium Representative Concentration Pathway scenario, AWR increases and expands outwards from the central mountain areas towards the East and coastal areas, with the majority of Wales seeing an incremental increase in the amount of AWR in 2020, and a greater increase in the 2050 scenario.

Some of the most significant impacts from extreme rainfall events are flooding, including fluvial flooding associated with high river flows, and groundwater and surface water flooding, as well as landslides and embankment failures (as rainfall is a major factor in landslide generation) which cause damage to infrastructure and disruption to travel. Many infrastructure assets are already located in areas at risk of flooding, whether that be on coastlines, within floodplains, or simply areas more susceptible to surface water flooding.

Direct impacts on infrastructure include increased scour of bridge supports for both road and rail due to increased river volumes and flows as a result of increased precipitation, and slope or embankment failures due to landslips or soil movement, increasing the risk of damage to vulnerable structures.

The recent flooding in January/February 2020 in locations such as Pontypridd, where the River Taff burst its banks, demonstrate recent examples of the impacts associated with prolonged periods of rainfall on already saturated ground. The impacts associated with the run of storms in early 2020 included considerable damage and disruption to infrastructure, including cancellations and significant delays on trains due to landslides and flooding; road closures across south and mid Wales due to floods; bridge closures and landslips; and power cuts affecting thousands of homes.[194,195]

It is also possible that storms and wind-driven rain may become a greater issue by the 2080s, although there is considerable uncertainty in climate projections around changes to wind speed, so no clear assessment can be made. However, any changes to the frequency or intensity of wind speeds present a risk of increased impacts on infrastructure, whether that be disruption through fallen trees on roads and rail, or damage to assets (e.g. wind-damage to power lines). Storm systems can be a particular risk, where heavy rain and high winds are both prominent, potentially flooding or damaging substations, and lightning strikes can cause significant damage to rail infrastructure (e.g. overhead lines) and power infrastructure (e.g. overhead lines, substations etc.).

Furthermore, impacts on some assets have the potential to cascade onto others as part of interdependent networks. For example, the electrification of vehicles requires the interdependency between transport and electricity, where a failure in the power (electricity) grid could have cascading impacts for road or rail transport.[196]

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[192] Carless D and Whitehead P (2013) The potential impacts of climate change on hydropower generation in Mid Wales. Hydrology Research, 44 (3): 495–505.

[193] Met Office (2018) UKCP18 National Climate Projections – Slide Deck. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-overview-slidepack.ff.pdf [Accessed 17 Apr. 2020]

[194] The Guardian (2020) Wales braces for more heavy rain after devastating floods. Available at: https://www.theguardian.com/uk-news/2020/feb/18/Wales-braced-for-more-heavy-rain-after-devastating-floods-storm-ellen [Accessed 17 Apr. 2020]

[195] BBC News (2020) Storm Dennis: Flood Clean-up under way in Wales. Available at: https://www.bbc.co.uk/news/uk-Wales-51524643 [Accessed 17 Apr. 2020]

[196] Welsh Government (2019) Prosperity for All: A Climate Conscious Wales. Available at: https://gov.Wales/sites/default/files/publications/2019-11/prosperity-for-all-a-climate-conscious-Wales_0.pdf [Accessed 24 Apr. 2020]

Extreme rainfall events

Extreme rainfall events can happen at any time of year and can lead to flooding. In some instances, these extreme rainfall events may be associated with flash flooding, typically in the spring or summer. Flash flooding tends to happen when heavy rainfall runs off the land and quickly swells rivers and streams.[197] The occurrence of flash floods is often exacerbated by periods of dry weather prior to the rainfall event, whereby hardened ground does not allow water to be absorbed as easily as if the ground were moist, which results in increased run-off and thus an increase in the likelihood of flash flood events occurring. Projected reductions in soil wetness will increase the risk of run-off, particularly on bare soils and where drought conditions have prevailed, thereby increasing the risk of flash flood events.

Flash floods can move rocks, tear out trees, sweep away vehicles and destroy buildings and bridges. Recent examples of flash flooding in Wales have resulted in small-scale damage and disruption to infrastructure, including local road closures, disruption to travel, and damage to road vehicles that become submerged, as well as the overwhelming of drainage systems and the sewerage network due to the sheer amount of rainfall falling in a short period.[198]

Other notable risks (i.e. where the likelihood of an event happening is very low, but the impact of an event occurring would be considerable) include potential impacts on key water infrastructure, such as dams or large raised reservoirs. Wales has a large number of reservoirs and dams (the majority of which are in excess of 100 years old), which could pose a significant risk to downstream communities in the event of collapse. The risk that climate change poses to both form and function of dams is heavily influenced by the nature of the catchment, including topography, vegetation, rate of erosion etc. However, it was not possible in this review to assess whether future climate or precipitation changes will affect the resilience of dams already constructed in Wales.

The Reservoirs Act 1975 provides the legal framework to ensure the safety of UK reservoirs that hold at least 25,000 m^3 of water above natural ground level. Approximately 2,500 reservoirs are covered by the Act with some 80% of these formed by embankment dams with the remainder being concrete or masonry dams or service reservoirs.[199]

The cause of a dam failure is unlikely to be through heavy rainfall alone, but driven by a failure in the materials, construction and maintenance of the asset, which is further exacerbated by the rainfall event and could potentially lead to the dams resilience threshold being exceeded. For existing reservoirs, the potential scope of remedial actions and design adaptations ranges from simpler measures such as patching of cracks and joints following heat waves, through to significant works involving the installation of additional toe drainage or refacing of parts of the spillway or dam.[200]

A key example of this risk was highlighted in England in August 2019, when thousands of residents in Whaley Bridge, Derbyshire were evacuated amid fears that a dam wall holding back some 300 million gallons of water in Toddbrook Reservoir was at risk of collapse after it was damaged by floodwaters associated with five days of heavy rainfall.[201]

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[197] Environment Agency (2013) Your community is at risk of flash flooding. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/291430/LIT_8904_df2d47.pdf [Accessed 22 Apr. 2020]

[198] BBC News (2013) Flash flooding hits homes after rain across Wales. Available at: https://www.bbc.co.uk/news/uk-Wales-23576219 [Accessed 22 Apr. 2020]

[199] Atkins (2013) FD2628 Impact of Climate Change on Dams & Reservoirs. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/399993/RFI7086_DG09_Guidance_Final.pdf [Accessed 1 may 2020]

[200] Atkins (2013) FD2628 Impact of Climate Change on Dams & Reservoirs. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/399993/RFI7086_DG09_Guidance_Final.pdf [Accessed 1 may 2020]

[201] Telegraph (2019) Whaley Bridge dam collapse: Derbyshire town evacuated as RAF called in amid flooding fears. Available at: https://www.telegraph.co.uk/news/2019/08/01/whaley-bridge-dam-collapse-latest-news-derbyshire-town-evacuated/ [Accessed 22 Apr. 2020]

Impact of projected changes in temperature

The mean annual temperature at low altitudes in Wales varies from about 9.5°C to 11°C, with the higher values occurring around or near to the coast. The mean annual temperature decreases by approximately 0.5°C for each 100 metre increase in height, meaning that in-land areas in Wales are typically much cooler than this. Temperature shows both a seasonal and diurnal variation. January mean daily minimum temperatures vary from just above 0°C in the higher parts of north and mid-Wales, to 3°C or 4°C around the coast. July is normally the warmest month, with mean daily maximum temperatures varying from about 17°C in the higher inland locations, to 18°C along the west coast, and 21°C in the east of Powys and Monmouthshire.[202]

Accumulated temperatures

The UK CP18rojections show that accumulated temperatures above 0°C increase from 2020 to 2080 for all Representative Concentration Pathway scenarios. The analysis included AT0 – Accumulated Temperature > 0°C from January to June (°C days); and ATS – Accumulated Temperature > 0°C from April to September (°C days). Accumulated temperatures have been shown to provide an indication of heat energy input for crop growth and soil drying potential. Whilst the projected changes in AT0/ATS infer increased soil droughtiness, and may contribute to soil desiccation (e.g. desiccation in clay soils can result in shrinkage of the soil and subsidence of the ground that can lead to damage to buildings), it is not envisaged that accumulated temperature on its own will have a major direct impact on infrastructure in Wales. Rather, extreme temperatures are likely to be of much greater significance.

Extreme summer temperatures (maximum / heatwaves)

Current UKCP18 projections suggest that summers will, on average, become increasingly hotter and drier in Wales, with an increased chance of greater daily maximum temperatures. Whilst not a highly frequent occurrence, Wales does experience heatwaves (an extended period of hot weather relative to the expected conditions of the area at that time of year, which may be accompanied by high humidity) and very high daily maximum temperatures above 30°C. The highest daily maximum temperature recorded in Wales was 35.2°C in August 1990 at Hawarden Bridge (Flintshire).[203] Extreme temperature maximums can have a range of impacts on infrastructure.

For the rail network, high maximum temperatures can cause significant issues. Rails in direct sunshine can be as much as 15-20°C hotter than air temperature. This is due to rail made of steel expanding as they get hotter, which can cause the rail to start to curve, known as 'buckling'. Most of the rail network can operate up to a point where track temperatures heat up to 46°C (roughly equivalent to air temperature of around 30°C). Air temperatures over 30°C therefore present an increased risk of rail buckling occurring and can result in travel disruption and delays (e.g. speed restrictions). Rail buckling causes damage to the line that must be fixed before trains can run which causes longer delays and disruption as line closures are required for track repairs.[204]

For the road network, high temperatures can lead to the asphalt or tarmac on some roads rutting or melting, resulting in a scenario where the soft bitumen and asphalt can stick to the tyres of motor vehicles. At ground level, in prolonged direct sunshine, black asphalt absorbs heat and the temperature can quickly reach melting point. A combination of factors affect the melting point, including the grade of asphalt or tarmac, how heavily trafficked the road is, whether it is a major road or a minor route in a rural area, and exposure of the road to sun and wind. According to Dr Howard Robinson, chief executive of the Road Surface Treatments Association, some roads in the UK that experience a reasonable amount of traffic may start softening at 50°C, whilst for other roads, where new

[202] Met Office - Wales: climate. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/Wales_-climate---met-office.pdf [Accessed 17 Apr. 2020]

[203] Met Office – UK climate extremes. Available at: https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-climate-extremes [Accessed 22 Apr. 2020]

[204] Network Rail - Buckled rail and summer heat. Available at: https://www.networkrail.co.uk/running-the-railway/looking-after-the-railway/delays-explained/buckled-rail-and-summer-heat/ [Accessed 24 Apr. 2020]

asphalt specification is used (made using polymer modified binders), the softening point of the asphalt is typically much higher, around 80°C.[205,206]

High temperatures also pose threats to the electricity system. This can include the sagging of power lines, which causes a hazard to public safety and reduces their effectiveness, and disruption to electricity supply. Electrical equipment can be directly damaged by overheating, or indirectly through wildfires/fires that are caused by the hot weather and affect an area where infrastructure is located. Higher demand for electricity (e.g. air-conditioning or cooling) due to heatwaves or extreme temperatures will also put increased pressure on the electricity grid. Warmer weather can also cause soils to dry out, causing subsidence damages to above-ground assets. For example, soil desiccation can occur in clay soils, causing subsidence or damage to buildings that may provide important infrastructure services.

Hot weather also increases the demand for water, increasing the pressure on the water network, reservoir resources and the natural environment. This can result in restrictions being implemented (e.g. hosepipe bans), a drop in water pressure at peak times, and additional measures implemented to meet demand. Increased requirements are typically associated with domestic uses (e.g. keeping hydrated, watering plants and sprinkler systems, filling paddling pools, washing cars etc.), the agriculture sector (e.g. increased abstraction for irrigation, animal husbandry and water for animals etc.) and industry. The future resilience of water supplies in Wales will be dependent on a number of factors, including climate change, population growth, the implementation of water efficiency measures, and water storage capacity.

Extreme winter temperatures (coldwaves / snowfall / ice)

Coldwaves, snowfall and ice are important meteorological events that shouldn't be forgotten. Whilst climate projections indicate that on average, winters will be warmer and wetter, potentially resulting in a reduction of frost days and snowfall, the occurrence of severe cold and snow events will still occur from time-to-time, particularly in the Welsh uplands and mountains.

The numbers of days with snow falling and snow cover increase with latitude and altitude, so values reflect topography. Snow is comparatively rare near sea level in Wales, but much more frequent over the hills. The average annual number of days of snowfall and snow cover varies from 10 or less in south-western coastal areas to over 30 in Snowdonia. However, this varies enormously from year to year, with some locations over the last 50 years ranging from no snow at all in several winters, to in excess of 30 days during very severe winters.[207]

During the colder winter months, short-term impacts on infrastructure from heavy snowfall, ice accumulations and strong winds can cause transportation delays and closures, tree and power line damage, roof collapse, and other structural damage.

In Wales, closures of roads and the upland passes (e.g. Horseshoe Pass), are a frequent impact of snowfall, resulting in increased journey times and some communities being cut off from surrounding areas (where 'B' and 'C' roads become impassable). Cold temperatures, ice and snow also cause damage to roads through freeze-thaw cycles and increase the risk of accidents due to poor road conditions (e.g. black ice).

On the rail network, speed restrictions, delays and cancellations of trains are common features associated with ice building up on tracks or snow being compacted into ice by passing trains, ice coating the electrified rail or power

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[205] BituChem - Road Surfacing Melts in UK Heatwave. Available at: https://www.bituchem.com/road-surfacing-melts-uk-heatwave/ [Accessed 24 Apr. 2020]

[206] BBC News (2013) Who, what, why: When does tarmac melt? Available at: https://www.bbc.co.uk/news/magazine-23315384 [Accessed 24 Apr.2020]

[207] Met Office - Wales: climate. Available at: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/regional-climates/Wales_-climate---met-office.pdf [Accessed 17 Apr. 2020]

cables preventing trains drawing power, rails or track points freezing together, and indirectly through damage to overhead wires or blockages on the track from falling branches or trees.[208]

Impacts on power distribution are also common, especially where snowfall is associated with an Atlantic depression and combined with strong winds, where localised impacts on the power network (e.g. where overhead lines are brought down) result in power cuts to homes and businesses.

The 'Beast from the East' coldwave in 2018 was a key example of how severe winter weather can impact infrastructure. In south-east England, thousands of homes were left without water due to pipes bursting under the pressure of the freezing temperatures and subsequent thaw. Railways were also affected in some regions from frozen third rails (live rails, electric rails or conductor rails which provide power to the railway) preventing trains from running, whilst other lines saw speed restrictions and delays.[209] In Wales, heavy snowfall and plummeting temperatures, combined with strong winds, led to drifting snow and blizzards. Impacts included the closure of roads and schools, villages being cut off from surrounding areas, and the suspension of train services.[210]

What is being done by the infrastructure sector to prepare and future proof

Road Network

Some of the main effects of climate change identified on the European road network (but which are also relevant to the Welsh road network) include: more flooding and erosion (a challenge for drainage systems and erosion protection and for the design and maintenance of culverts and bridges); landslides (occurring more frequently, at new locations); droughts and high summer temperatures may pose problems for asphalt surfacing, due to softening, but also for run-off conditions, due to lower permeability; deterioration of roads and pavements (as expressed by service life and rutting, mostly in cases where drainage is insufficient); and effects of sea-level rise on coastal stability and importance of ensuring sufficient elevation for roads, quays, and bridges, as well as entrance levels for sub-sea tunnels.[211]

Roads are built with a typical life, influenced by the material used, expected weight of traffic on the road and local climate/weather conditions. Highway Standards identify the administrative and technical requirements for the planning, preparation, design and construction of highway works; through the publication of standards and specifications to be used on the motorway and trunk road network in Wales. The Highway Standards which apply to the Welsh motorway and trunk road network are contained in the Design Manual for Roads and Bridges (DMRB) and the Manual of Contract Documents for Highways Works (MCHW).[212]

Further research is needed to understand what the typical life (durability) of roads are in Wales, which will be affected by the volume of traffic on them, the specification of the road surface, and the current condition of the roads through use and weather impacts. As an indication, new highways in England in 2008 were typically designed and constructed with a nominal design life of up to 40 years, with the expectation that periodic replacement of the surface course will occur every 10 to 20 years. Subsequently, ensuring highway construction and maintenance carried

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208 Network Rail (2020) Keeping trains moving in snow and ice. Available at: https://www.networkrail.co.uk/stories/keeping-trains-moving-in-snow-and-ice/ [Accessed 24 Apr. 2020]

209 New Civil Engineer (2018) Insight – How well did infrastructure cope with the Beast from the East. Available at: https://www.newcivilengineer.com/archive/insight-how-well-did-infrastructure-cope-with-the-beast-from-the-east-07-03-2018/ [Accessed 17 Apr. 2020]

210 WalesOnline (2018) The shocking extremes of weather we saw in Wales in 2018. Available at: https://www.Walesonline.co.uk/news/Wales-news/shocking-extremes-weather-saw-Wales-15493024 [Accessed 17 Apr. 2020]

211 CEDR - Conference of European Directors of Roads (2011) Adaptation to Climate Change. Available at: https://climate-adapt.eea.europa.eu/metadata/organisations/conference-of-european-directors-of-roads/11270918 [Accessed 24 Apr. 2020]

212 Welsh Government (2018) Highway standards. Available at: https://gov.Wales/highway-standards [Accessed 1 May 2020]

out now is suitable for the future climate in 20 or 30 years' time is essential to prevent premature deterioration.[213] In addition, it was not possible in this review to assess whether the current design specification of roads being implemented today are suitable for the conditions that are projected under future climate scenarios.

Welsh Government is responsible for trunk roads and motorways in Wales, supported by two public sector organisations that deliver the maintenance and improvements plans: North and Mid Wales Trunk Road Agent (Gwynedd Council); and South Wales Trunk Road Agent (Neath Port Talbot CBC).[214]

Welsh Government with Public Health Wales will develop policies for transport as part of the development of the new Wales Transport Strategy. This strategy will be published in late 2020 and will contain policy interventions to mitigate and adapt to climate change. In addition, the Welsh Government is supporting Highways England in the publication of new Design Manual for Roads and Bridges environment advice notes. The work will include new advice on road drainage and water environment and will help ensure the resilience of the road network from flood.[215]

Transport for Wales; a new organisation that has been established in Wales, will work with regional teams, the emerging regional transport authorities and partners to create an integrated public transport network, covering the rail and bus networks. The Welsh Government will call upon Transport for Wales to ensure that new, and improvements to existing transport infrastructure for which they are responsible, will be done in consideration of the risks to transport raised in the latest Climate Change Risk Assessment, including the need to address the problem of overheating, the risks from floods and high winds, and risks from slope and embankment failure. [216]

Rail Network

Network Rail's "Weather Resilience and Climate Change Adaptation Policy" outlines the key principles that are being embedded in the organisation, including: consideration of how climate change might amplify risks into analysis and decision-making processes throughout the business; adapting at construction and at asset renewal in order to provide resilience in the most cost-effective manner; replacing like for better rather than like for like, with consideration of the whole life cost and the best strategic approach for managing the railway; and collaboration across the rail industry, government and other stakeholders to improve understanding and management of weather and climate risks.[217]

A specific Weather Resilience and Climate Change Adaptation (WRCCA) Plan has been produced for the rail network in Wales.[218] Network Rail monitors and records weather related incidents and impacts under nine categories: adhesion (i.e. line contamination leading to traction loss, e.g. leaf fall, moisture, oils); cold (e.g. ice accumulations on conductor rails, points and in tunnels); flooding (i.e. standing or flowing water leading to asset damage or preventing trains from accessing the track); fog (i.e. reduced visibility obscuring signals); heat (e.g. high temperature impacts such as rail buckles, Temporary Speed Restrictions (TSRs), overheated electrical components etc.); lightning strikes

[213] TRL (2008) The effects of climate change on highway pavements and how to minimise them: Technical Report. Available at: https://trl.co.uk/reports/PPR184 [Accessed 24 Apr. 2020]

[214] Welsh Government - Road network and our involvement. Available at: https://gov.Wales/road-network-and-our-involvement [Accessed 24 Apr. 2020]

[215] Welsh Government (2019) Prosperity for All: A Climate Conscious Wales. Available at: https://gov.Wales/sites/default/files/publications/2019-11/prosperity-for-all-a-climate-conscious-Wales_0.pdf [Accessed 24 Apr. 2020]

[216] Welsh Government (2019) Prosperity for All: A Climate Conscious Wales. Available at: https://gov.Wales/sites/default/files/publications/2019-11/prosperity-for-all-a-climate-conscious-Wales_0.pdf [Accessed 24 Apr. 2020]

[217] Network Rail (2017) Weather Resilience & Climate Change Adaptation Policy. Available at: https://cdn.networkrail.co.uk/wp-content/uploads/2019/06/Network-Rail-Weather-Resilience-and-Climate-Change-Adaptation-Policy.pdf [Accessed 24 Apr. 2020]

[218] Network Rail (2019) Wales, 2019-2024, Route CP6 Weather Resilience and Climate Change Adaptation Plan. Available at: https://cdn.networkrail.co.uk/wp-content/uploads/2019/10/Wales-CP6-WRCCA-Plan.pdf [Accessed 24 Apr. 2020]

(e.g. track circuit and signalling damage or power system failure); snow (e.g. blocked lines and points failures); subsidence (e.g. the impacts of landslips, rockfalls and sinkholes); and wind (e.g. trees and other items blown onto the track and into the overhead line equipment or TSRs).

The greatest weather impact on the Wales route is flooding, which cost an estimated £5.3M between 2006/07 and 2017/18. Over the same time period, costs due to wind were £4M and snow were £3.3M. Network Rail's prioritisation of resilience actions, based on weather-related impacts on the Wales route, include: a high prioritisation for wind, subsidence and flooding; medium prioritisation for adhesion, snow, lightning and heat; and low prioritisation for cold and fog.

Network Rail has a planned WRCCA investment for the Wales route (2019-2024), as well an in-depth maintenance schedule, which aims to increase the resilience of the Wales route at key locations from specific impacts. Rail assets have a typical lifetime before being replaced, and where replacements are made, these are being replaced with "better" materials that consider future projected climate change. Through a combination of replacement, maintenance and adaptation, the rail is becoming more resilient.

For example, to prevent tracks from getting too hot or buckling, measures being taken include: strengthening any weak parts of the rail before summer; painting certain parts of the rail white so they absorb less heat and expand less (a rail painted white is 5°C to 10°C cooler than one left unpainted); laying long pieces of track that are stretched and welded together to reduce compression (reducing the chance of buckling in very high temperatures); leaving small gaps between tracks where short rails are bolted together so that expansion doesn't cause a problem; and laying tracks on reinforced concrete slabs, rather than on sleepers and ballast (the bed of stones that supports the sleepers) to prevent rails from buckling.

Planned investment in the Welsh and Borders rail network (2019-2024) for maintaining and renewing the existing railway includes investment of £27.7m to improve the railway's extreme weather resilience, £176m on track renewals and refurbishments and £135m to improve signalling in West Wales.[219]

Water Network

The Welsh Government and Natural Resources Wales are responsible for the management of water resources, including the regulation of water abstraction.[220] The Welsh Government's Water Strategy for Wales, which was published in 2015, covers a 25 year period and aims to maintain high levels of water quality and protect the health of Welsh people. The strategy identifies the risks from climate change and is underpinned by an all Wales action plan.

The long-term goals of the water sector include continuous adaptation to climate change and reducing the industry's carbon footprint. Wales is not forecast to have a water supply deficit over the next 30 years. Policies are in place to safeguard the continuity of public water supplies during droughts and from burst pipes in cold weather.

Water companies have duties to develop robust plans to ensure effective management, maintenance and development of Welsh water resources and supply systems. These plans include: Water Resource Management Plan every five years to set out how the water company intends to maintain the balance between supply and demand for water over the next 25 years; and Drought plans setting out how they will continue, during a period of drought, to discharge its duties to supply adequate quantities of wholesome water.

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[219] Infrastructure Intelligence (2019) Network Rail sets aside £2bn for Wales and Borders railway. Available at: http://www.infrastructure-intelligence.com/article/apr-2019/network-rail-sets-aside-%C2%A32bn-Wales-and-borders-railway [Accessed 5 May 2020]

[220] Welsh Government (2019) Prosperity for All: A Climate Conscious Wales. Available at: https://gov.Wales/sites/default/files/publications/2019-11/prosperity-for-all-a-climate-conscious-Wales_0.pdf [Accessed 24 Apr. 2020]

The main risks and impacts of climate change on the water sector, as outlined by Ofwat[221], include:

- Changing rainfall patterns may make it harder to meet demand and could increase the risk of droughts affecting the supply of water.
- Higher temperatures and less rainfall in the summer means there will be more stress on already scarce water resources when they are needed the most.
- More frequent heavy downpours and changes to the ecology of rivers may reduce the quality of the water we take from the environment, requiring more treatment.
- Key assets may be at greater risk of being flooded and changes in soil moisture levels may lead to changing patterns of pipe bursts and leaks.
- As the climate warms, demand for water is likely to increase from both household and non-household consumers. In some areas, there may also be increased competition for raw water resources from other sectors, especially during the summer months.
- Changing rainfall patterns challenge the current approach to drainage. Climate change will increase the risk of surface water flooding and sewer flooding, which is one of the most serious types of service failure. Climate change may also increase the damage caused by overflows of untreated wastewater into the environment.
- Reduced river flows could mean more carbon-intensive sewage treatment is required to ensure rivers are protected.

Power Network (electricity)

Responsibility for energy transmission and distribution is not devolved to Welsh Government and is instead managed by the UK Government's Department for Business, Energy & Industrial Strategy (BEIS). National Grid is responsible for providing a resilient and reliable electricity transmission grid. Distribution Network Operators (DNOs) are required by law to keep distribution power lines free of vegetation and undertake programmes of resilience vegetation management. It is also the responsibility of the owners of infrastructure networks to ensure resilience for surface and sea water flood. [222]

National Grid provides progress reports to the Department for Environment, Food and Rural Affairs (Defra) as part of the second round of the adaptation reporting powers under the Climate Change 2008 Act. The report sets out progress by National Grid in adapting to the current and future predicted effects of climate change on the organisation.[223]

[221] Ofwat – Climate change. Available at: https://www.ofwat.gov.uk/regulated-companies/resilience-2/climate-change/ [Accessed 5 May 2020]

[222] Welsh Government (2019) Prosperity for All: A Climate Conscious Wales. Available at: https://gov.Wales/sites/default/files/publications/2019-11/prosperity-for-all-a-climate-conscious-Wales_0.pdf [Accessed 24 Apr. 2020]

[223] National Grid (2016) Climate adaptation reporting second round. Available at: https://www.gov.uk/government/publications/climate-adaptation-reporting-second-round-national-grid [Accessed 24 Apr. 2020]