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Agricultural Practices Review – Mitigation against GHG Emissions

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Agricultural Practices Review – Mitigation against GHG Emissions

Soil Policy Evidence Programme Report SPEP2019-20/01

Submitted to:

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1 Introduction

- In 2017, 85% of the land area of Wales was utilised as agricultural area (Wiseall, 2018). Welsh agriculture is dominated by grassland (permanent pasture and rough grazing), which accounts for more than 70% (1.3 million ha) of the utilised area. In comparison, tillage accounts for 13% (0.25 million ha) of the area, 10% is common rough grazing (0.18 million ha) and the remaining 5% woodland or other land on agricultural holdings (Welsh Government, 2018a).
- Global climate change, driven by anthropogenic enrichment of the atmosphere with greenhouse gases (carbon dioxide-CO_2, methane-CH_4, and nitrous oxide-N_2O) is likely to be the key environmental challenge of the twenty-first century. In 2017, greenhouse gas emissions in Wales were *c*.42,000 kilotonnes of carbon dioxide equivalent (kt CO_2-eq)[1] (Figure 1).
- Agriculture accounted for 12% of Welsh greenhouse gas emissions in 2017 (*c*.5,500 kt CO_2-eq). Methane emissions from livestock systems account for *c*.65%, nitrous oxide emissions from manufactured fertiliser use and livestock management for *c*.20% and the cultivation of organic soils for *c*.5% of agricultural emissions (NAEI, 2019).
- The challenge for Welsh agriculture is to reduce greenhouse gas emissions whilst considering the balance between food production, food security, land use and carbon leakage (i.e. reliance on imports that effectively export emissions). Effective options to mitigate GHG emissions from land management include optimising nutrient management (e.g. planned and efficient use of fertiliser, manures or nitrification inhibitors), and manipulation of the global carbon cycle to sequester atmospheric CO_2 into long-term storage.

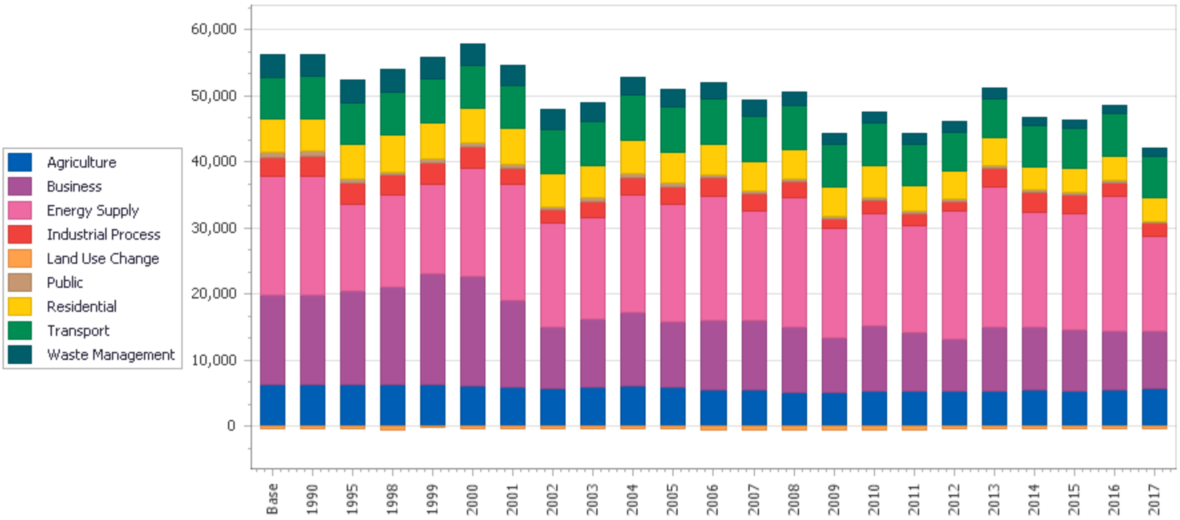

Figure 1. Annual estimates emissions of greenhouse gases for Wales[2]

[1] Carbon dioxide equivalent ($CO_{2\text{-eq}}$) is a measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential. The GWP for methane is 25 and for nitrous oxide 298. This means that emissions of 1 million metric tonnes of methane and nitrous oxide respectively is equivalent to emissions of 25 and 298 million metric tonnes of carbon dioxide.

[2] https://statswales.gov.wales/Catalogue/Environment-and-Countryside/Greenhouse-Gas/emissionsofgreenhousegases-by-year

2 Objectives

- This project has reviewed potential options to mitigate greenhouse gas-GHG emissions from Welsh agriculture. In detail the report has:
    - Assessed the impact that climate change driven extreme weather, changes in rainfall patterns and increases in temperature may have on cropping practices in Wales.
    - Identified the role that grassland plays in storing carbon and the impact of cultivations on carbon storage.
    - Identified management practices that reduce GHG emissions from agricultural soils.
    - Identified potential drivers for increasing the production of arable crops in Wales.
    - Reviewed current, emerging and innovative agricultural practices for minimising and/or increasing the organic carbon content of tilled agricultural soils in Wales.
    - Provided an overview of current Welsh policy and knowledge exchange requirements relating to the impacts of climate change on soils and the public goods they provide.
    - Identified key skills required to support the development of Welsh Government policy relating to the impact of climate change on cropping systems in Wales.

3 Greenhouse gas emission targets

- The Welsh Government has a legally binding target to reduce greenhouse gas emissions by 'at least 80%' (compared to the baseline[3]) by 2050, set by the Environment (Wales) Act. However, in May 2019, the Committee on Climate Change (CCC) published 'Net Zero – the UKs contribution to global warming' in which it recommended that the UK set a net-zero target for all greenhouse gases (i.e. a 100% reduction from 1990 levels).
- For Wales, the CCC recommended a 95% reduction in emissions (relative to 1990), reflecting 'the large share of agriculture emissions in Wales and lower access to suitable sites to store captured carbon dioxide' (CCC, 2019). In June 2019, the Welsh Government accepted the CCC recommendation for a 95% reduction in emissions but also stated their ambition to 'bring forward a target for Wales to achieve net zero emissions no later than 2050'[4]. The Welsh Government will bring regulations to the Assembly in 2020 to amend the existing 2050 target and amend Wales' interim targets and carbon budgets as necessary.

3.1 Climate change

- For Wales, the 2008-2017 decade was 0.8°C warmer than the 1961-1990 average and most of the warmest years have been recorded since 1990 (Lowe *et al*., 2018). Annual rainfall in Wales has increased by 4% from the 1961-1990 average (Lowe *et al*., 2018). Also of note is the run of recent wet summers; of the last ten summers from 2008 to 2017, only summer 2013 has seen a UK rainfall total below the 1981-2010 average. Thus, UK summers for the most recent decade (2008 to 2017) have been on average 20% wetter than 1961-1990 and 17% wetter than 1981-2010 (Lowe *et al*., 2018).
- UKCP18 has produced new projections of how climate might change in the UK over coming decades (Lowe *et al*., 2018). The regional climate projections are based on four 'Representative Concentration Pathways' (RCPs). RCPs are time-dependant projections of atmospheric GHG concentrations based on assumptions about economic activity, population growth, energy sources and other socio-economic factors. The four RCPs together span the range of year 2100

[3] 1990: carbon dioxide, methane, nitrous oxide. 1995: hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride, nitrogen trifluoride.

[4] https://gov.wales/wales-accepts-committee-climate-change-95-emissions-reduction-target

radiative forcing values found in the open literature, i.e. from 2.6 to 8.5 watts per square metre (W/m^2):

1. RCP2.6: low GHG concentration levels, radiative forcing peaks at 3 W/m^2 in around 2050, declining to 2.6 W/m^2 by about 2100.
2. RCP4.5: peak GHG by around 2100, followed by stabilisation. Radiative forcing peaks at 4.5 W/m^2.
3. RCP6: peak GHG by around 2100, followed by stabilisation. Radiative forcing peak at 6 W/m^2.
4. RCP8.5: increasing GHG over time. Radiative forcing peaks at 8.5 W/m^2.

- For each RCP scenario, the predicted changes have been modelled for the 5, 10, 50, 90 and 95th percentile. The 50% level is the median change, and the 5% and 95% levels provide lower and upper estimates of the associated uncertainty ranges. UKCP18 scenarios suggested an increase in both winter and summer temperature from the 2020s to the 2080s, with all areas of Wales experiencing similar relative increases in temperature. The projections for the 50th percentile suggest that by 2080-2099, depending on the scenario, annual mean temperatures will be 1-4°C higher than the baseline (1981-2000). Temperature increases of 1-3°C and 2-5°C, depending on the scenario, are predicted by 2080-2099 for winter and summer, respectively.
- RCP scenarios do not predict a change in total rainfall but instead suggested that there will be a difference in the seasonal distribution of rainfall, with a decrease in summer precipitation and increase in winter precipitation for all scenarios. For summer precipitation, the 50th percentile predicted reductions of 15-19% for 2040-2059 and 20-38% for 2080-2099 (in comparison with the 1981-2000 baseline). In comparison, for winter precipitation, the 50th percentile predicted increases of 5-9% for 2040-2059 and 6-23% for 2080-2099 (in comparison with the 1981-2000 baseline).

4 Climate change influences on cropping practices in Wales

4.1 Introduction

- There is evidence that the biophysical capability of the land to support agricultural production has changed over recent decades as the climate has changed (ASC, 2016). The average length of the growing season has increased by around 60 degree-days over the 87-year period between 1914 and 2000 for England and Wales, with a substantial increase in the last decade of the 20th century. There is evidence that the trend to longer growing seasons and milder winters have provided opportunities for a shift to autumn-sown crops (ASC, 2016).
- Outdoor crops are particularly sensitive to changes in climate, both directly from changes in rainfall and temperature, and indirectly since any changes in climate will also impact on the agricultural potential of soils by modifying soil water balances. This affects the availability of water to plants and impacts on other land management practices (Knox *et al*., 2010).
- The UKCIP scenarios discussed in Section 3.1 do not predict a change in total rainfall but instead suggest that there will be a difference in the seasonal distribution of rainfall, with a decrease in summer precipitation and increase in winter precipitation for all scenarios. However, it will not be the gradual change in climate that will impact on growers, rather the greater annual variability of climate and frequency of extreme events (flooding, droughts, and heat waves) (Knox *et al*., 2010) though both may lead to the need to change the type of agricultural production in certain areas.

- Cranfield University (2019) has applied the Agricultural Land Classification (ALC) climate interpolation routine to the UKCP18 scenarios to produce maps for average annual rainfall (AAR), average summer rainfall (ASR), median duration of field capacity days (FCD) and median accumulated temperature above 0°C January to June (AT0). For each parameter mapped data is shown for 2020, 2050 and 2080 for low, medium and high emission scenarios.
- Cranfield University have also looked at the change in ALC grade resulting from the changes in climate parameters. The predicted changes suggest a reduction in the amount of ALC grades 1 and 2 land under all time period/emission scenarios, with an initial downgrade to ALC grade 3a/3b by 2050 and in some areas a further downgrade to ALC 4 by 2080 (Figure 2). The medium and high emissions scenarios also suggest that some land that is currently ALC 3a/3b will be downgraded to ALC 4 by 2080, particularly in the high emissions scenario.

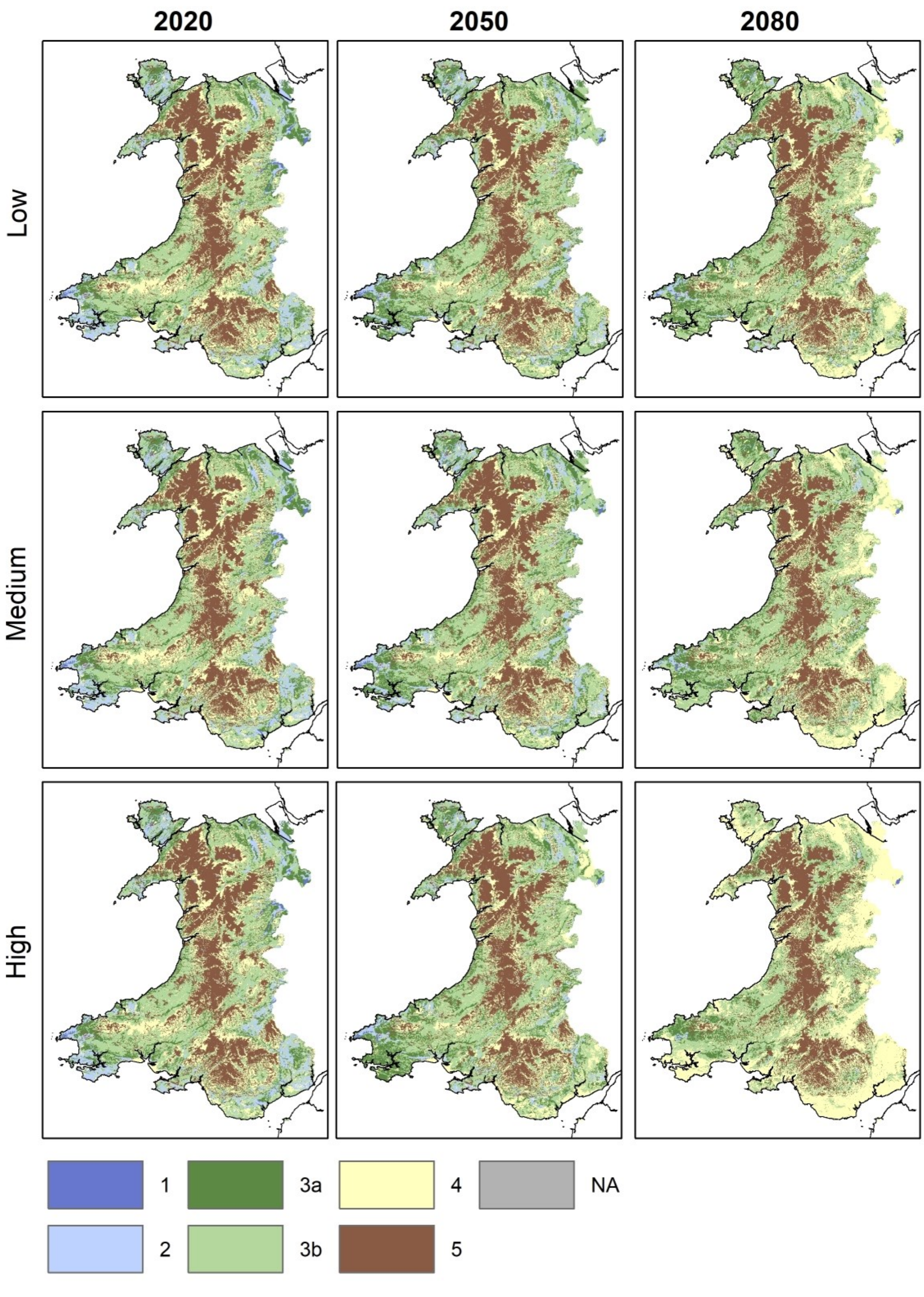

Figure 2. Agricultural Land Classification class for 2020, 2050 and 2080 UKCP18 low, medium and high scenarios.

4.1.1 *Extreme weather*

- Extreme weather events are defined as unusual, severe or unseasonal changes in weather patterns that can occur on time scales as short as hours and include droughts, heat-waves, floods and storms (ADAS and University of Leeds, 2013). They would typically occur <5% of the time and are much less predictable than climate change. The increasing incidence of extreme events can be attributed to anthropogenic climate change (IPCC, 2012) and it is recognised that extreme events are likely to increase in the future and pose an increasing threat.
- The IPCC (2012) has concluded that it is 'very likely' (90-100% probability) the length of warm spells or heat waves will increase over most land areas by the end of the 21st century. This indicates the duration of extreme weather events experienced currently and in the past will be longer by the 2050s and extreme events lasting for months or years rather than days could become more typical.
- Extreme weather events (e.g. extended periods of intense rainfall) and shifts in land use/cropping patterns associated with climate change (e.g. increased ploughing out of permanent grassland) are factors that may increase soil erosion rates in the future.
- A recent example of the economic impacts of extreme events on agriculture is provided by ADAS (2014), who investigated the impacts of the winter 2014 floods, when a series of exceptional rainfall events caused extensive flooding in Somerset, the Severn Valley and the Thames Valley. The floods impacted on the agricultural sector through damage to, or loss of, established crops (grass and winter-sown arable crops), inability to access land to manage crops or drill new crops, damage to stored crops and forage stocks, costs of movement and/or feeding of livestock, damage to infrastructure and costs associated with the clean-up operation. It was estimated that the total agricultural flood damage was £20.9 million equivalent to £470 per hectare (ADAS, 2014).

4.2 Changes in temperature and rainfall

- For annual average rainfall (AAR), predictions suggest that there is little noticeable change in either the distribution or amount of rainfall for Wales for any of the time period/emission scenario combinations (Figure 3). However, the distribution of rainfall changes between seasons. There is an increase in rainfall in the winter and less rainfall in the summer months from 2020 to 2080 for all emission scenarios. Similarly, for England, there is little change in AAR for any of the time period/emission scenario combinations (Figure 4). In comparison, for summer rainfall (ASR) in Wales there is a noticeable reduction in rain between time periods but little difference between low, medium and high emission scenarios (Figure 5). The reductions in summer rainfall are most marked in the south and east of Wales, for example in the medium scenario, ASR in Torfaen decreased by 77 mm from 527 mm in 2020 to 450 mm in 2050 and in Rhondda Cynon Taff by 85 mm from 687 mm in 2020 to 602 mm in 2050 (Figure 6). A decrease in ASR for England is also noted over time but, in line with the predictions for Wales, there is little difference between low, medium and high emission scenarios (Figure 7).
- By 2050, the prediction maps show a noticeable increase in the accumulated temperature above 0°C for the low, medium and high emission scenarios, particularly in the south east of Wales (Figure 8). For example in the medium scenario, AT0 for Monmouthshire increases by 108°C, from 1,516°C in 2020 to 1,624°C in 2050 and for Torfaen by 108°C, from 1,353°C in 2020 to 1,461°C in 2050 (Figure 9). In line with the UKCP18 predictions, by 2080, accumulated temperature is predicted to increase further and there is a noticeable difference in the low, medium and high emission scenarios, with the latter predicting the greatest increases in AT0 for both England and Wales (Figure 10).

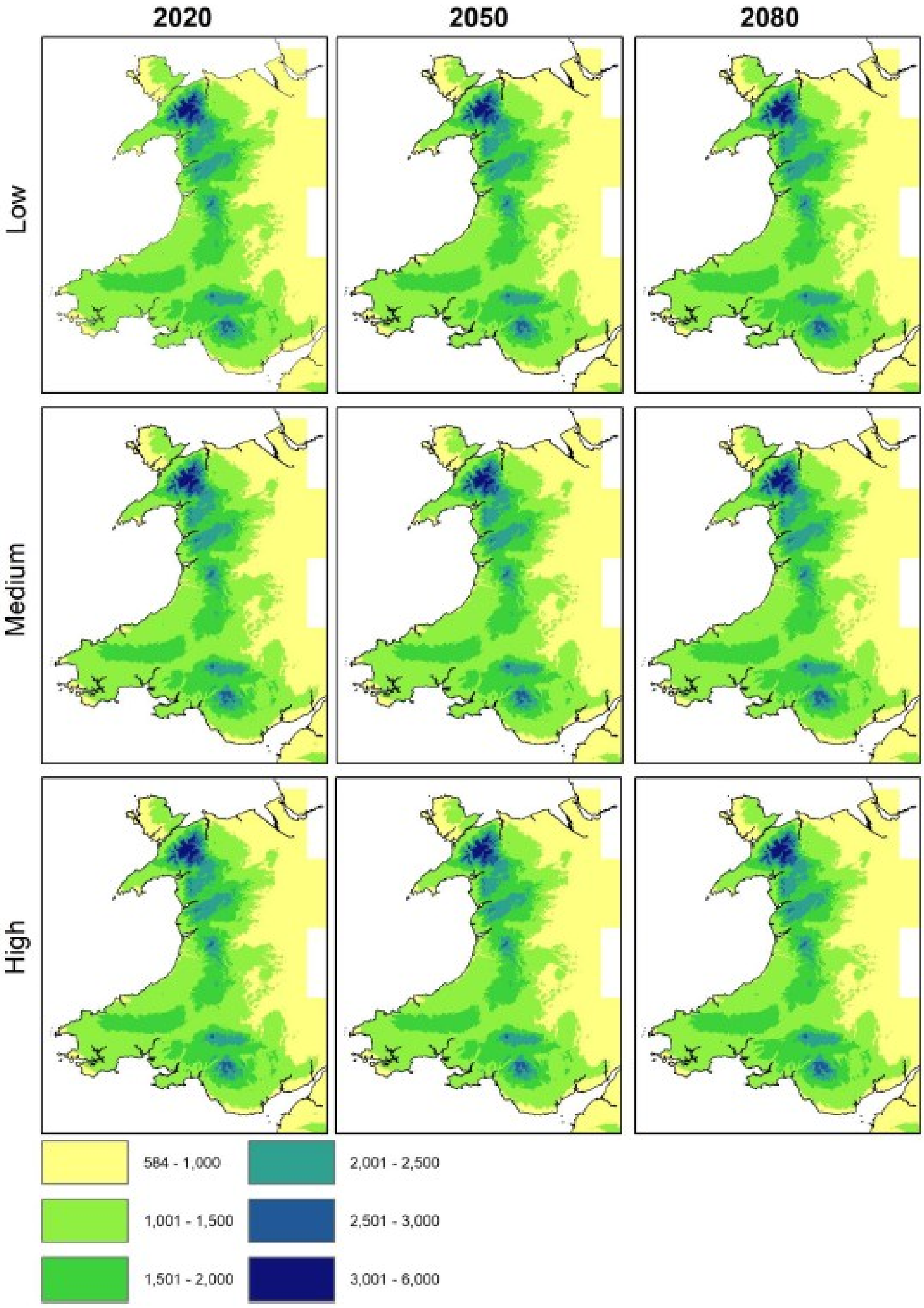

Figure 3. Average annual rainfall (mm) for 2020, 2050 and 2080 UKCP18 low, medium and high scenarios for Wales

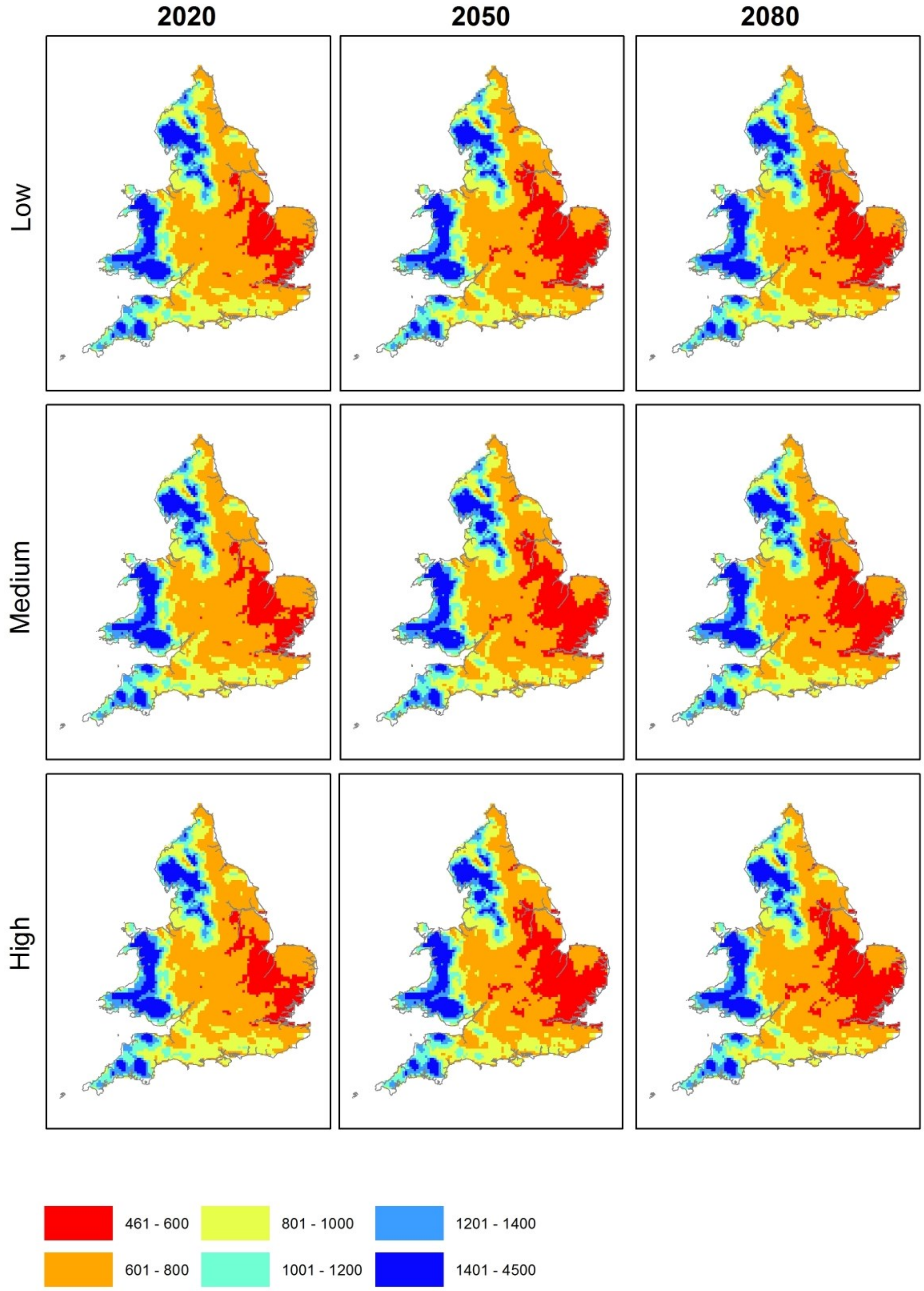

Figure 4. Average annual rainfall (mm) for 2020, 2050 and 2080 UKCP18 low, medium and high scenarios for England and Wales

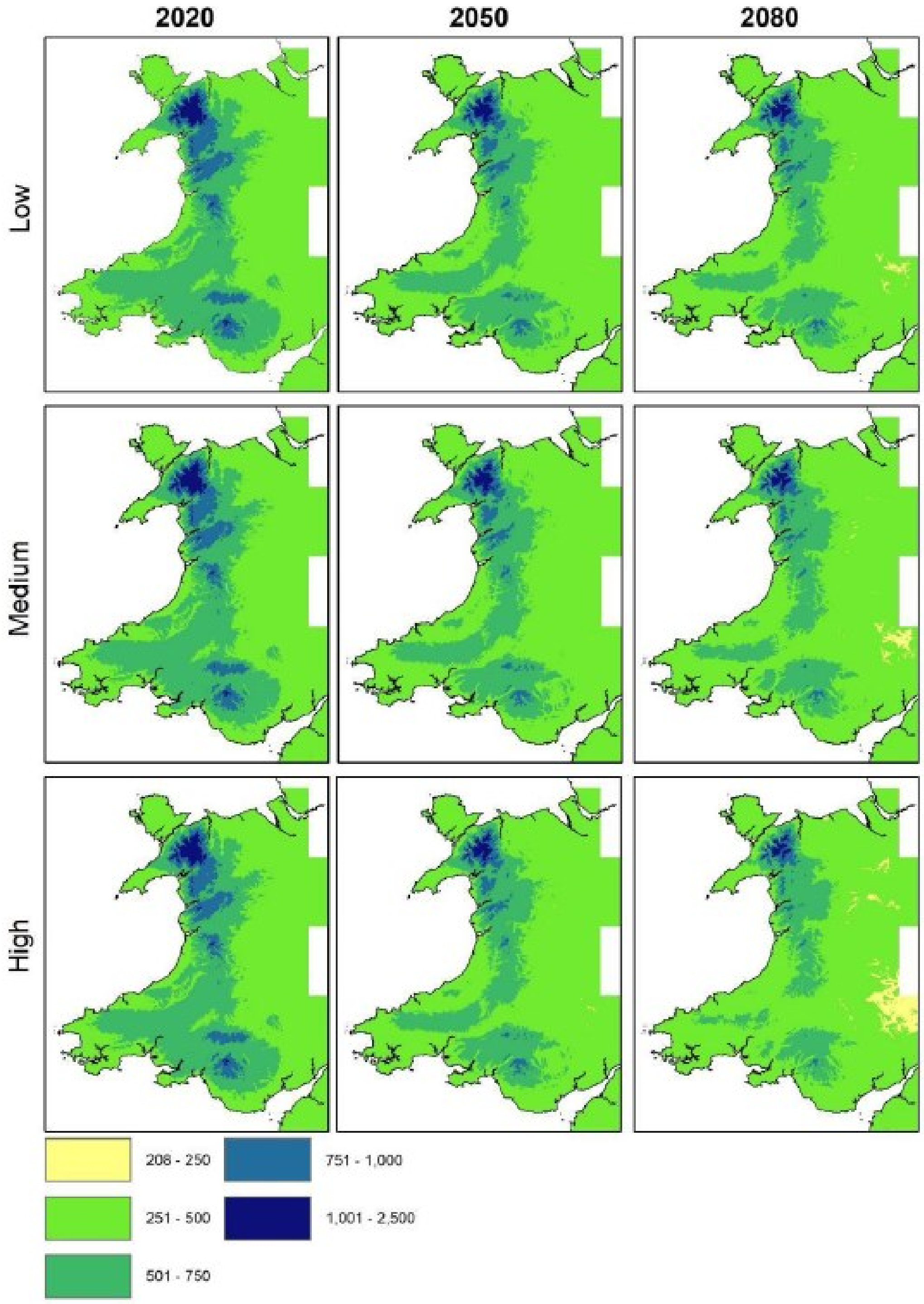

Figure 5. Average summer rainfall (mm) between April and September for 2020, 2050 and 2080 UKCP18 low, medium and high scenarios for Wales.

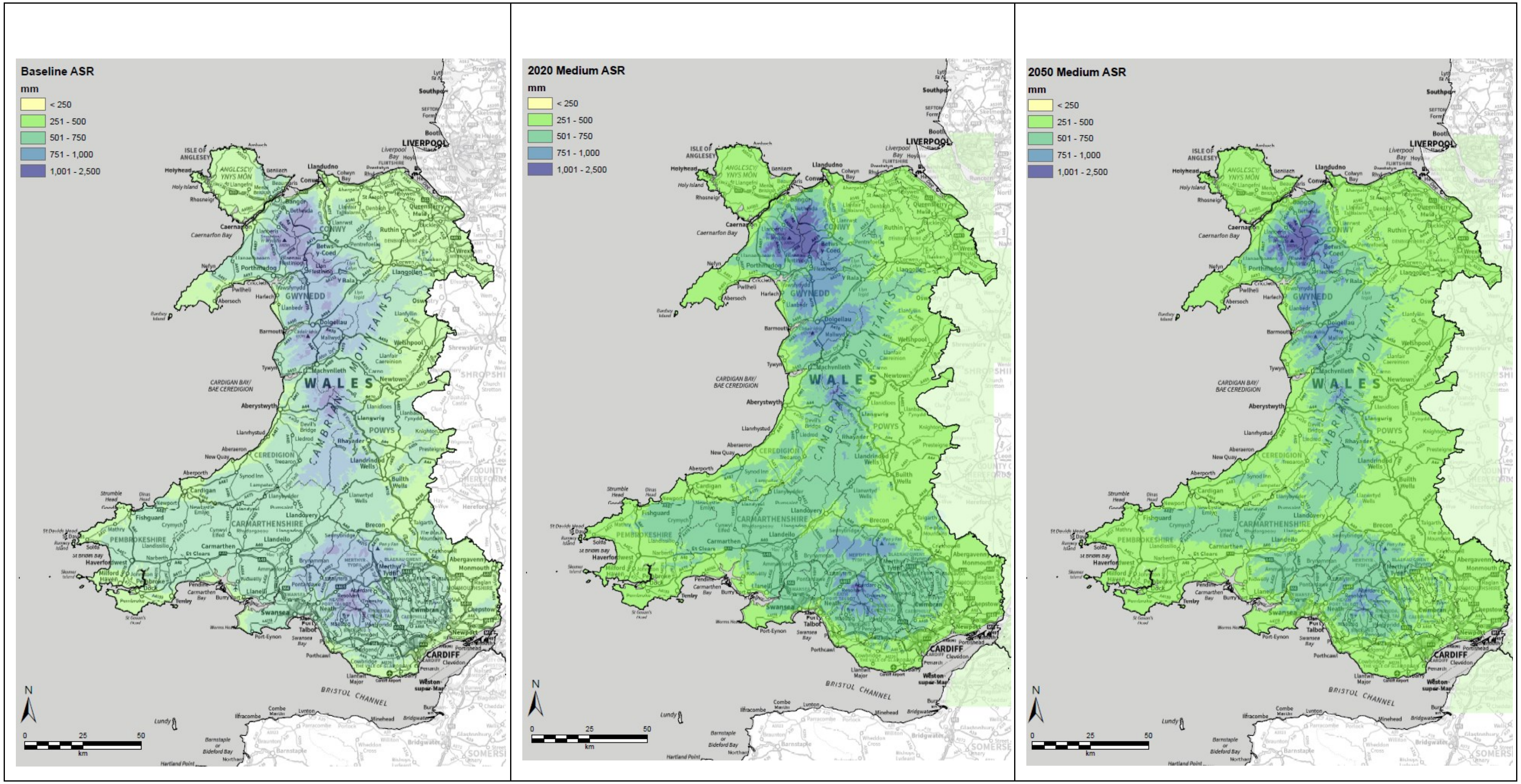

Figure 6. Average summer rainfall (mm) between April and September for the baseline, 2020 and 2050 UKCP18 medium scenarios for Wales.

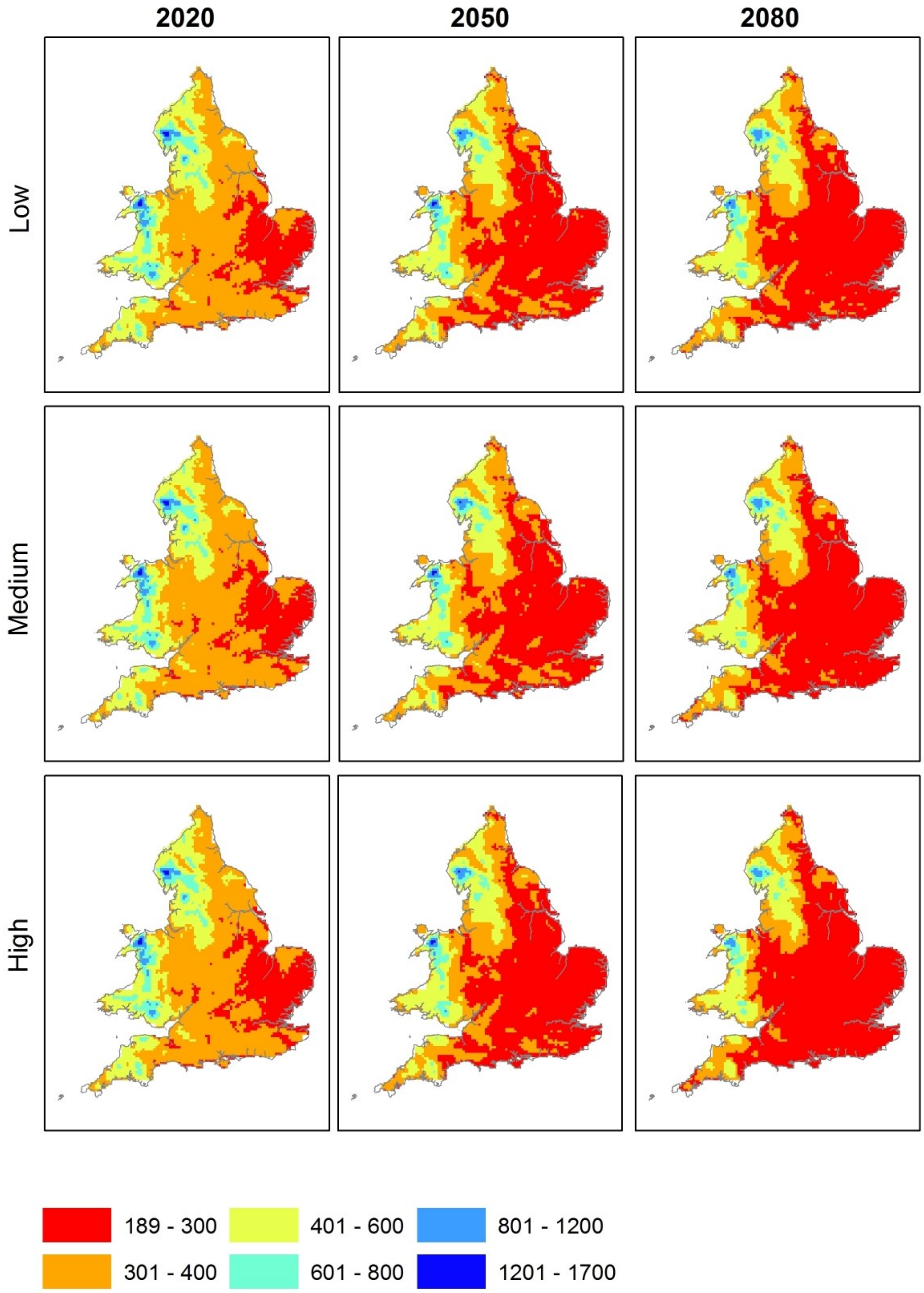

Figure 7. Average summer rainfall (mm) between April and September for 2020, 2050 and 2080 UKCP18 low, medium and high scenarios for England and Wales

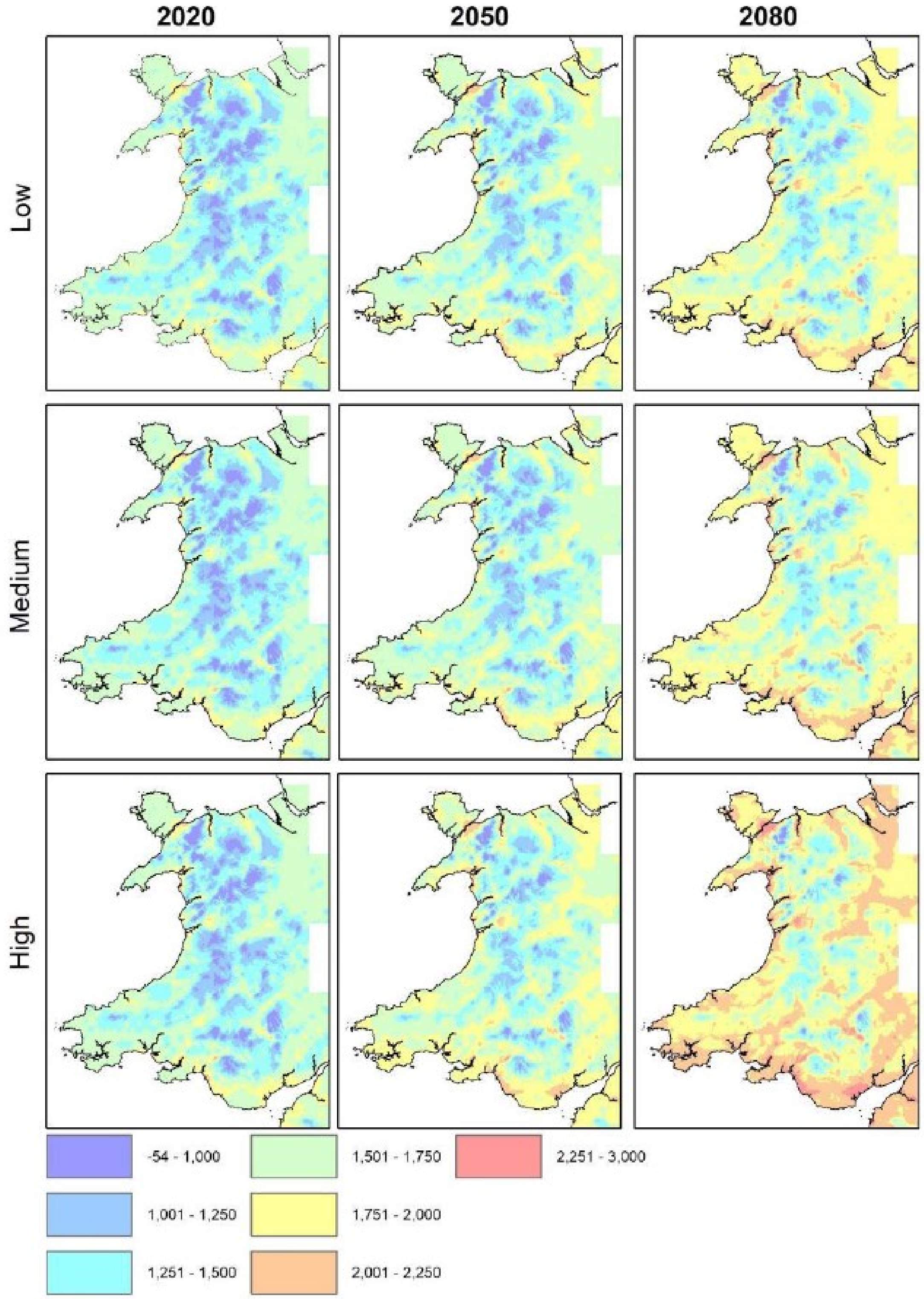

Figure 8. Median accumulated temperature above 0°C from January to June for 2020, 2050 and 2080 UKCP18 low, medium and high scenarios for Wales

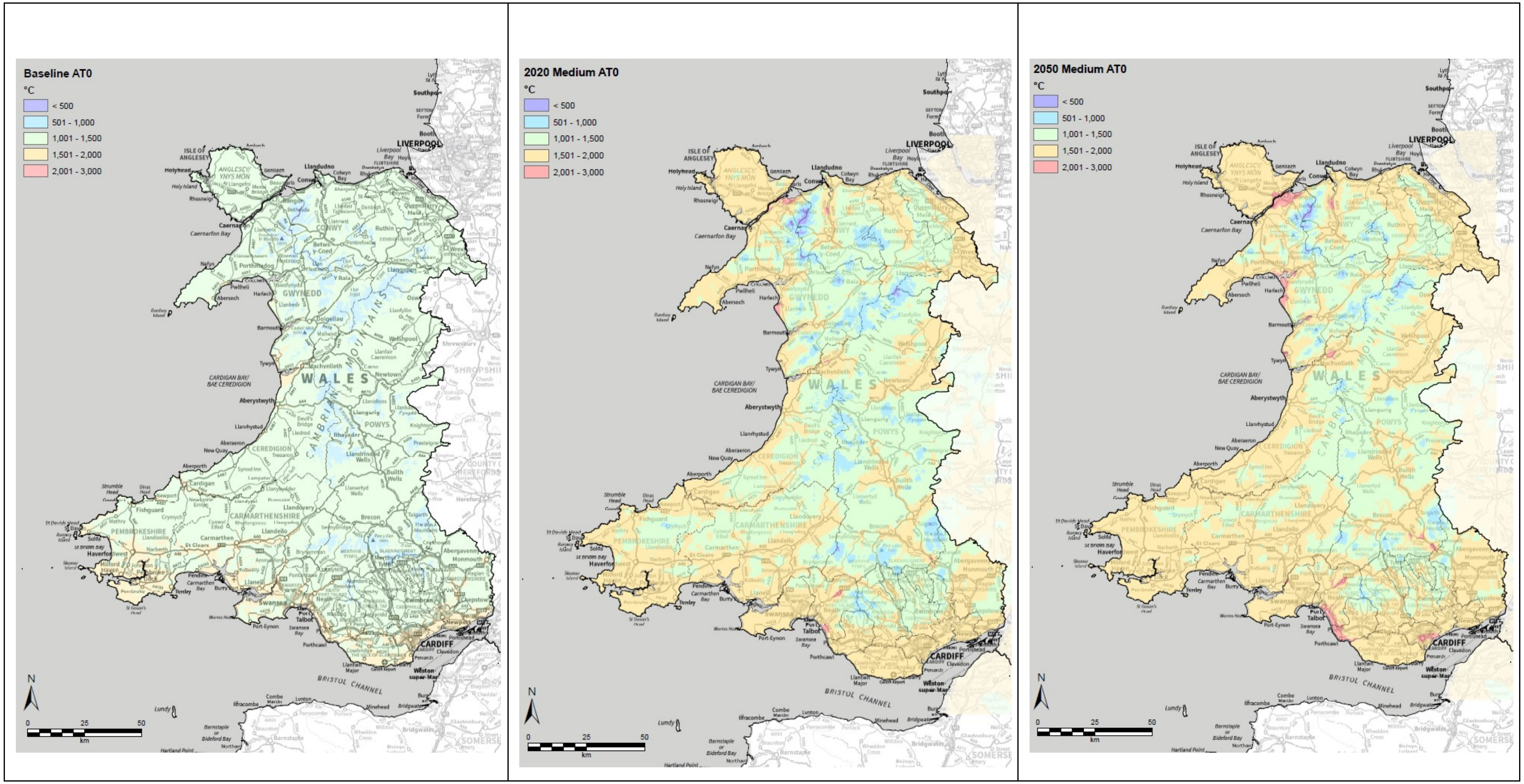

Figure 9. Median accumulated temperature above 0°C from January to June for baseline, 2020 and 2050 UKCP18 medium scenario for Wales

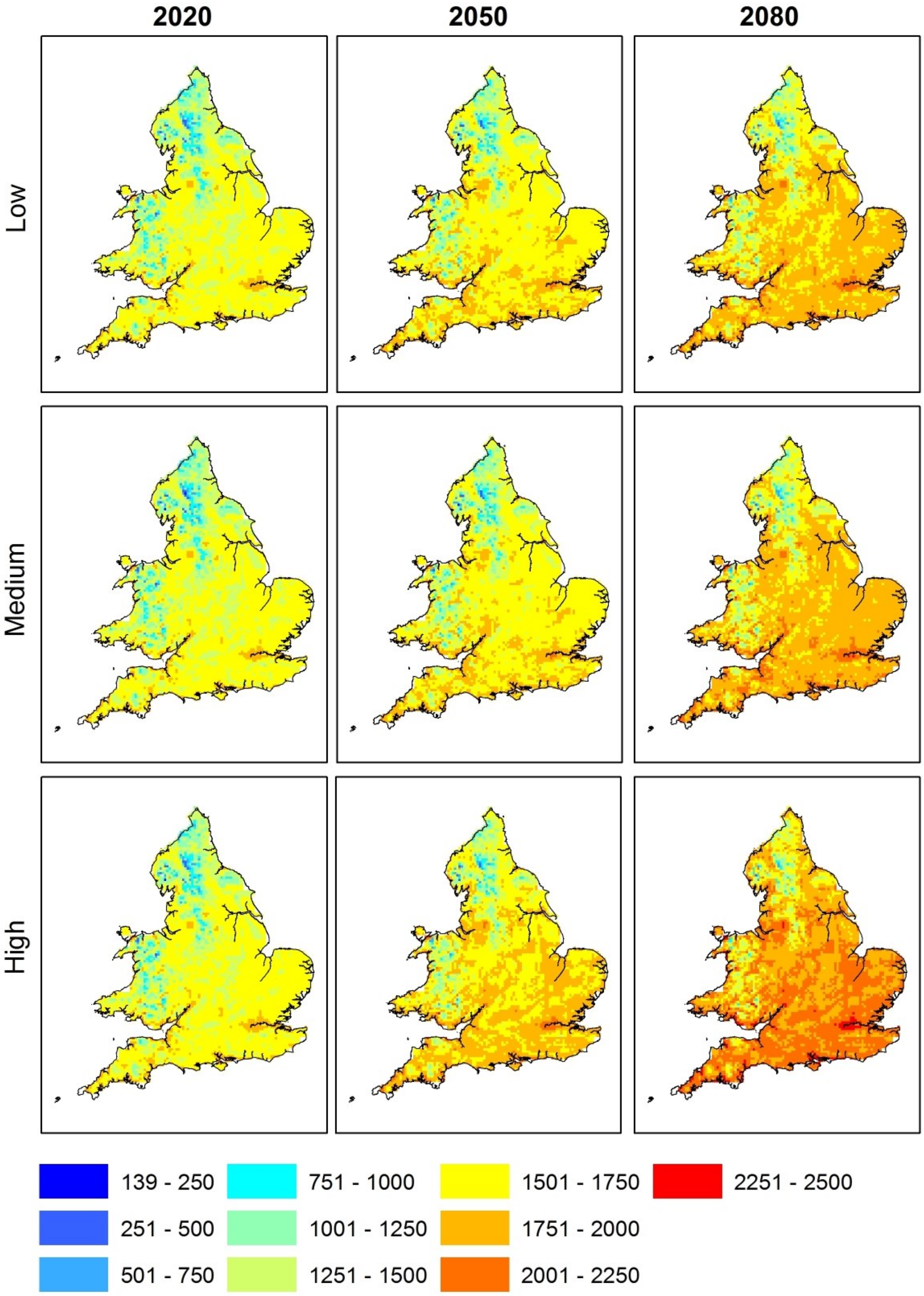

Figure 10. Median accumulated temperature above 0°C from January to June for 2020, 2050 and 2080 UKCP18 low, medium and high scenarios for England and Wales.

4.2.1 *Arable cropping*

- Increases in temperature and radiation coupled with elevated levels of CO_2 have the potential to increase crop yields, but only to a point at which other management factors, including water and nutrient availability, are not limiting. Experiments in enclosed chambers with enriched levels of carbon dioxide have shown positive yield responses. Work carried out by Hatfield *et al*., (2011) showed that in general, doubling CO_2 concentrations increased reproductive yield of crops such as cereals and grass by approximately 30% and small yield responses of less than 10% were observed for maize and vegetable crops. However, the projections for increasing seasonal variation in rainfall, and resulting changes in moisture balances, are likely to offset any positive impacts of increasing CO_2 concentrations on plant growth.
- Crop species respond differently to temperature throughout their life cycles. Each species has a defined range of maximum and minimum temperatures when growth occurs and an optimum temperature at which plant growth progresses at its fastest (Hatfield *et al*., 2011). High temperatures in summer can impact reproductive (flower) development which can be impaired in some arable and horticultural crops (Semenov, 2009). Adaptation actions may include the introduction of new crop varieties that have a greater resilience to heat stress.
- Changes in temperature and rainfall pattern are likely to impact on crop yields and quality and may affect the viability of existing rain-fed crops and create opportunities for new crop types (Knox *et al*., 2010).
- The warming climate allows for a potential expansion of land used for agriculture in Wales. Many areas that are currently marginal for cultivation due to climatic limitations could experience an improvement in land capability. However, there may also be limitations to future agricultural productivity due to increased soil aridity in some locations. Overall, the area of Best and Most Versatile (Grades 1 to 3a) agricultural land in Wales and England is projected to decline from 37% currently to 7% in the 2080s (high emissions scenario) due to increased aridity and doughtiness (ASC, 2016). Over the same time period, the area of Grade 4 land is projected to increase from 2% to nearly 66% (ASC, 2016). In comparison, for Wales, the area of BMV land is projected to decrease from 20% to 18%, 16% or 9% by 2080 under the low, medium and high emissions scenarios, respectively. By 2080 the area of Grade 4 land in Wales is predicted to be similar to the baseline under the low and medium emissions scenario, but increases to 39% under the high emissions scenario (Keay and Hannam, 2020).
- A projected trend towards warmer drier summers would increase the risk of heat stress in sensitive crops (e.g. winter wheat) and reduce yield potentials for those crops with high water demands (e.g. potatoes). Warmer drier summers and increased mean winter temperatures may also be beneficial for some crops (e.g. maize which is sensitive to frost). Warmer temperatures would increase the probability of damage to vulnerable crops (for example wheat and salads) at extreme temperatures. Knox *et al*. (2010), suggest that a longer growing season may lead to increased cultivation of continental crops such as sunflowers, navy beans, soya, lupins and grapevines.

4.2.2 *Grasslands*

- The changing pattern of rainfall (i.e. wetter winters and drier summers) is likely to affect grassland productivity. Grass growth is restricted by drought and drier summers is likely to limit grass growth especially on soils with low soil available water in the summer months (St. Clair *et al*., 2009). Drought may also increase the risk of wild fires affecting extensive grazing areas. Conversely, wetter winters may cause waterlogging which would increase the risks of soil damage by poaching reducing opportunities for overwinter grazing (Thomas *et al*., 2010).

- Grass growth begins above a minimum temperature (5.5°C) and is stimulated by warmer weather, provided there is sufficient soil moisture. Warmer temperatures will increase the length of the grazing season (IGER, 2003) with grass production starting earlier in the spring and continuing later in the autumn (Thomas *et al*., 2010). However, as grass yields improve with warmer conditions, they are also vulnerable to reduced soil moisture availability during drought (Brown *et al*., 2016).
- Studies have shown that grassland ecosystems can adapt to extreme events (Vicente-Serrano *et al.,* 2012) including physiological adaptations to overcome the challenges of drought stress (Craine *et al.,* 2013) and wildfire (Bond *et al*., 2005, Bond and Keeley 2005, Nano and Clarke, 2011). This may limit the effect of climate change on grasslands and a number of authors have noted that anticipated impacts of climate change on grassland dry matter yield are small. For example, the model used by Qi *et al*. (2018) predicted that by 2050, yield under the UKCP09 medium emission scenario would increase to 15.5 and 9.9 t/ha on temporary and permanent grassland, respectively (from 12.5 and 8.7 t/ha) and no significant change in the yield of rough grassland was predicted (2.8-2.7 t/ha). However, any dry matter yield increases will depend on other interacting factors such as soil N fertility (Daepp *et al*., 2001), water productivity and soil water stress (Deryng *et al*., 2016).
- At the time of writing this report, the Welsh Government's Soil Policy Evidence Programme has commissioned a review of the biophysical requirements for particular grass and clover species and development of a spatial mapping tool linking the RB209 grass growth classes to the ALC generated UKCP18 climatic data and the Soils of Wales soil property map. This review will be available under report code SPEP2020-21/01.

4.2.3 Soil moisture (floods and droughts)

- In Wales, water stress resulting from a lack of rainfall is less of a risk than in other drier regions of the UK (ASC, 2016). However, climate predictions suggest that water stress in eastern England may make the production of high value horticultural crops unsustainable which may provide an opportunity for the expansion horticultural production in Wales (ADAS *et al*., 2014).
- Where summer drought is a risk, irrigation is likely to become more important to maintain yields, both on existing irrigated crops and on other currently rain-fed crops such as wheat. Increased use of irrigation will require investment in on-farm storage of water (e.g. reservoirs and storage tanks) to harvest winter rainfall or water abstraction in peak periods (ADAS *et al*., 2014).
- The area of BMV land at a 1 in 75 year risk from all sources of flooding is projected to increase by 35% by the 2050s (to 15% of BMV, *c.*24,000 ha) if global mean temperatures are on a trajectory for a 4°C rise (based on the upper range of the 2009 UK Climate Projections medium emission scenario) by the end of the century (ASC, 2016).
- Flooding, both coastal and inland has the potential to cause waterlogging of crops which can lead to physiological impacts, depending on the flood tolerance of the crop. Waterlogging occurs when the pores within the soil matrix are completely saturated with water and generally results in anoxic (anaerobic) soil conditions. Within 48 hours, plants begin to suffer from oxygen deprivation, which causes a significant reduction in nutrient uptake rates, inhibiting plant growth both above and belowground (Jackson, 2004). In more extreme cases when soils are subjected to prolonged and complete submergence, the availability of carbon dioxide, light and oxygen decrease, severely reducing photosynthesis and respiration rates and ultimately leading to death in many crop species (Jackson and Colmer, 2005) and a significant monetary loss to farmers (Posthumus *et al*., 2009; Li *et al*., 2016).

- Flooded soil is not passable by machinery which will affect crop and soil management operations. Using heavy machinery on waterlogged soils or grazing by livestock can also cause long-term damage to soil structure which can reduce water infiltration which increases run off and the risk of soil erosion If land is particularly prone to flooding various adaptation measures are possible. This may the installation of flood defences, field drainage schemes, or changing to crops less prone to flood damage (e.g. from arable to grass).
- The timing of flooding is also important in relation to cropping. If waterlogging occurs at the time of planting (autumn or spring according to the crop type), it can be detrimental to plant establishment (Trafford, 1974) because oxygen flow to the seed is restricted, limiting germination (Blake *et al*., 2004), nutrient uptake (Malik *et al*., 2002) and photosynthesis efficiency (Parent *et al*., 2008). Autumn waterlogging can also result in poor rooting in winter cereal and oilseed rape crops leading to overwinter plant loss. Winter waterlogging (in isolation) has minimal impacts.

4.2.4 Field capacity days

- Field capacity is defined as the point at which the soil moisture deficit is zero, i.e. when all soil pores other than those that drain under gravity are full of water. Soils usually return to field capacity during the autumn or early winter during periods when rainfall exceeds evapotranspiration. The field capacity period, measured in days, ends in the spring when evapotranspiration exceeds rainfall and a moisture deficit begins to accumulate.
- For the majority of Wales, field capacity days is >250 days for all of the time period/emission scenario combination (Figure 11). However, climate change scenarios suggest that for some areas of Wales (e.g. the south east) there could be a reduction in field capacity days in 2050 and 2080 compared to 2020, reflecting the reduction in summer rainfall noted above. For example, in Monmouthshire under the medium emissions scenario field capacity days are predicted to fall by 18 days between 2020 (209 days) to 2050 (191 days), Figure 12. Similarly, for England the scenarios predict a reduction in field capacity days, particularly in the east of England in the 2080 high emission scenario (Figure 13).
- As weather patterns become more volatile, risks introduced by weather variability will become more critical to agricultural production. The availability of days suitable for field work is driven by soil temperature and moisture, both of which may be altered by climate change (Tomasek *et al*., 2017).
- The availability of field working days is primarily driven by soil moisture, where soil moisture over a certain threshold is deemed too wet to work (Earl, 1997). Different soils are assumed to have the same threshold for workability if the volumetric soil moisture is measured as a percentage of either the field capacity (FC) or plastic limit (PL) of the soil (Rounsevell, 1993).
- Keay *et al*. (2014) reported that although AAR has remained fairly stable between 1921 and 2000 the seasonal pattern has shown noticeable variation, with March and June rainfall increasing (by 20-37%) and July rainfall decreasing (by >40%). The increased rainfall in March and June could result in a delay to the end of FC date, which would reduce the number of days soils can be worked during the crucial spring growing period. In comparison, autumn rainfall patterns have remained stable but accumulated temperature AT0 has risen by 61 degrees days between 1914 and 2000. The higher temperatures suggest that the return date of field capacity will be delayed until later in the year. Hence, although the overall duration of field capacity might not change much, it will start later (in autumn) and end later (in spring) which will favour autumn sown crops (Keay *et al*., 2014).
- Excess winter rainfall is usually lost through runoff to surface drainage systems or percolation to ground water once field capacity has been reached. Once soils begin to dry out in April, the

reduction in summer rainfall combined with the increased evapotranspiration resulting from elevated temperatures is likely to cause a significant reduction in the water available to crops during key growth periods.

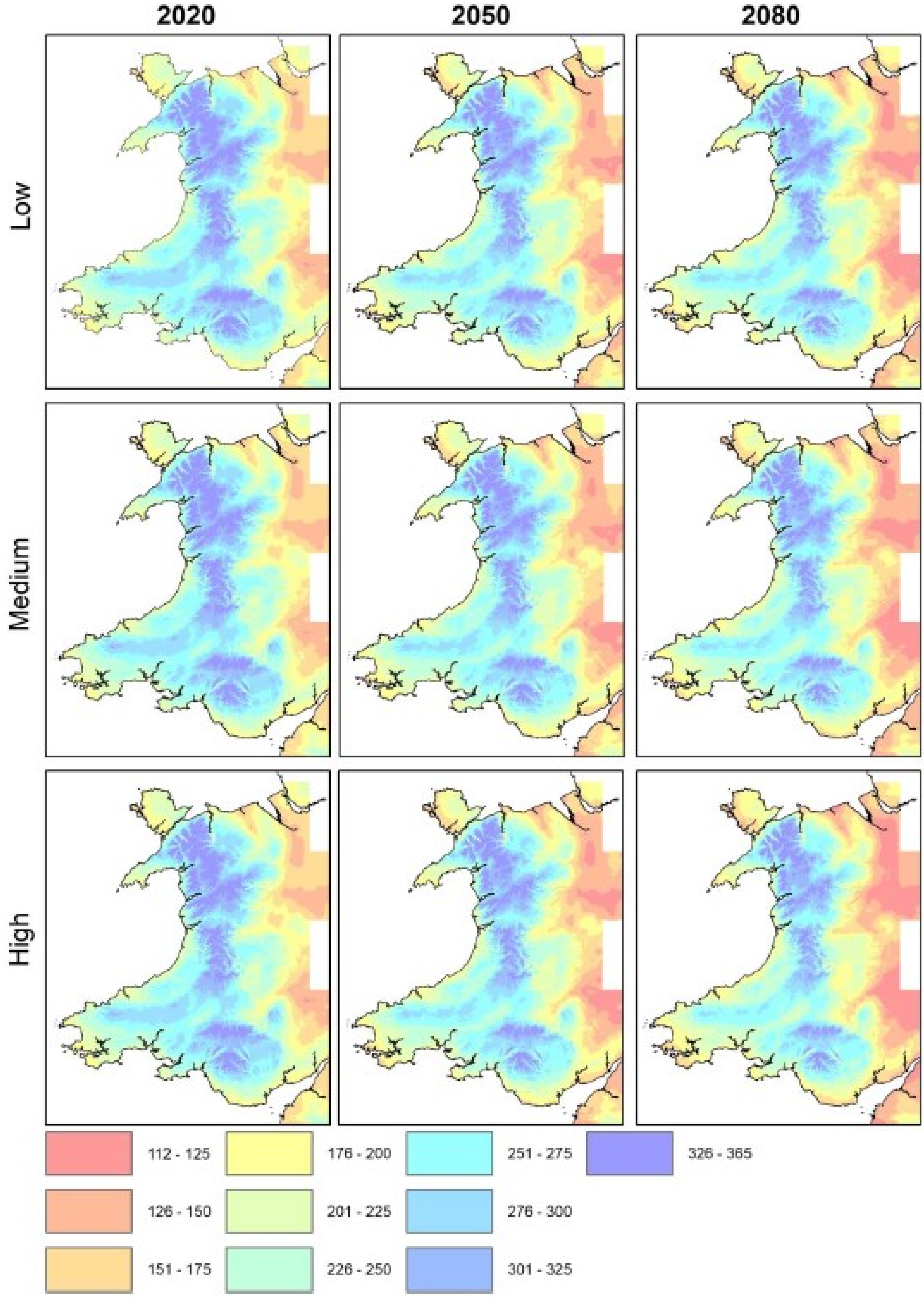

Figure 11. Median duration of field capacity (days) for 2020, 2050 and 2080 UKCP18 low, medium and high scenarios for Wales.

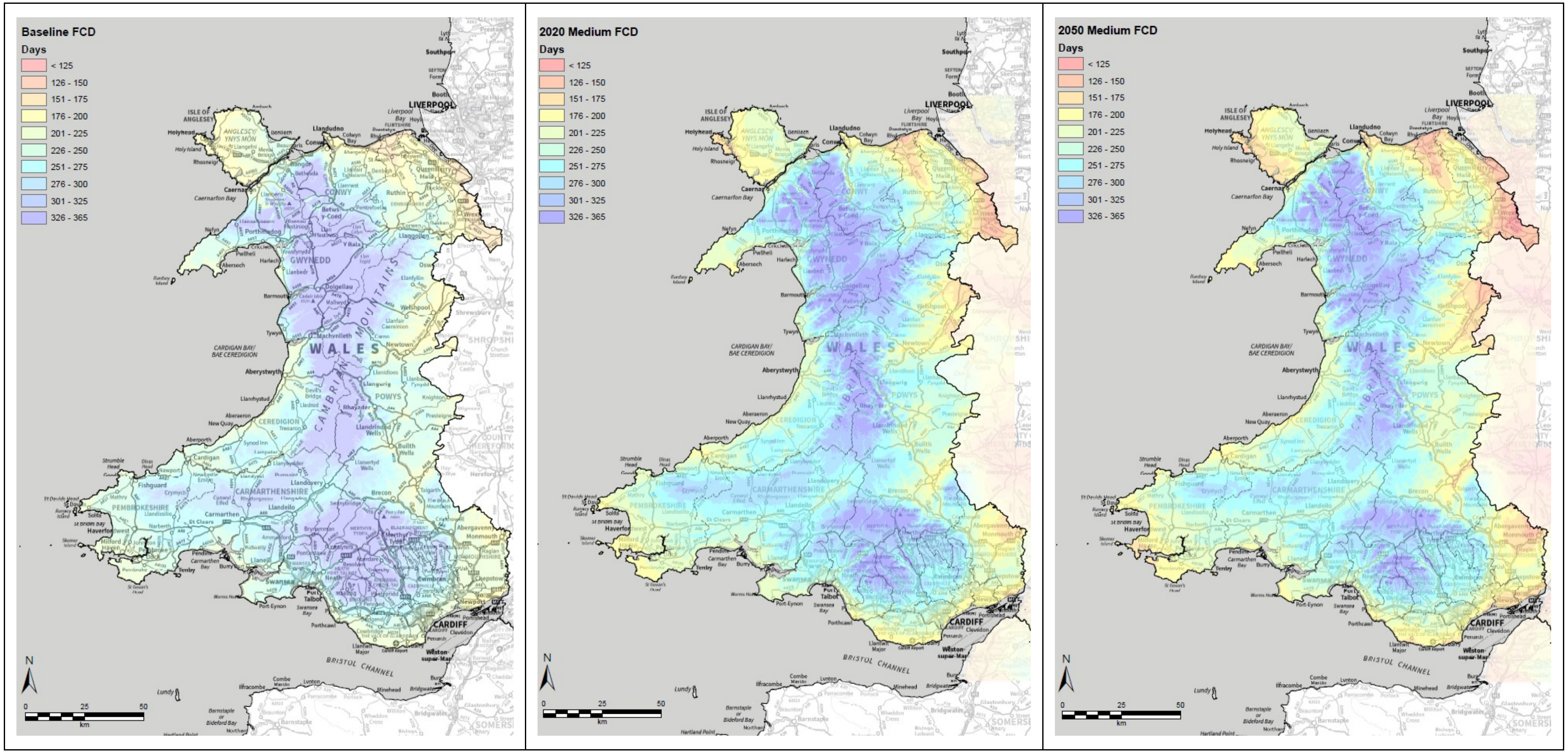

Figure 12. Median duration of field capacity (days) for baseline, 2020 and 2050 UKCP18 medium scenario for Wales

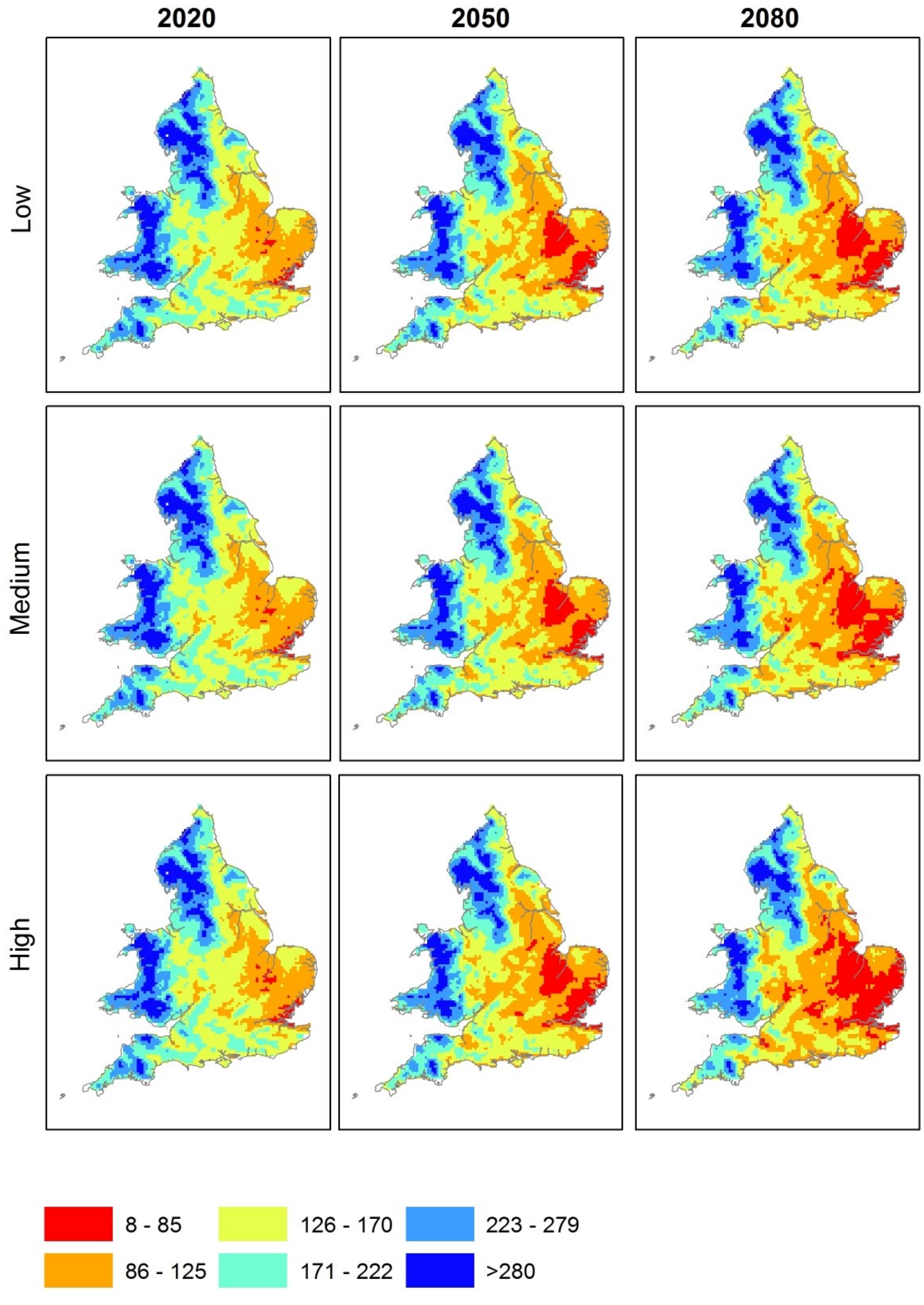

Figure 13. Median duration of field capacity (days) for 2020, 2050 and 2080 UKCP18 low, medium and high scenarios for England and Wales.

5 Climate change mitigation

- Climate change mitigation refers to efforts to reduce or prevent GHG emissions. The main focus of this report is the mitigation of GHG emissions from productive agriculture through the sequestration of carbon and the reduction of GHG (i.e. carbon dioxide, nitrous oxide and methane) emissions from land management.

5.1 Soil organic matter v soil organic carbon

- Soil organic matter (SOM) and soil organic carbon (SOC) are terms that are often confused and mistakenly used interchangeably. However, while soil organic carbon is a component of organic matter it is not the same as organic matter, which also includes other elements such as hydrogen, oxygen and nitrogen as well as fresh (living) and decomposed plant/animal (dead) materials (FAO, 2019). The 'living' organic matter includes plant roots and micro-organisms and the larger 'dead' part is comprised of root and leaf litter, a light fraction (water soluble organic compounds and soil enzymes) and humus (the largest constituent of the 'dead' part).
- The soil carbon pool is composed of both organic (materials derived from the decomposition of plants and animals) and inorganic carbon. The most common inorganic carbon forms are carbonates from geological or parent material sources. Precise determination of changes in SOC stocks is a prerequisite of understanding the role of soils in the global cycling of carbon and to verify changes in stocks due to management (Schrumpf *et al*., 2011).

5.2 Sequestration

- Increasing global soil carbon stock to help mitigate climate change is gaining global attention, as demonstrated by the 4 per 1000 initiative launched at the COP21 in Paris in 2015[5]. The 4 per mil or 4 per 1000 aspires to increase global soil organic matter stocks by 0.4% per year to compensate for the global emissions of greenhouse gases by anthropogenic sources (Minasny *et al*., 2017). However, the feasibility of enhancing soil carbon sequestration will not only depend on natural factors but also on the social and economic conditions in place such as labour cost and sufficient food production (Stockmann *et al.,* 2013).
- Carbon dioxide in the air is absorbed by plants through photosynthesis. Subsequently dead plant material (e.g. leaf litter and dead roots) is deposited into the soil where micro-organisms decompose this organic matter. SOC is a measure of the carbon content of SOM, and is a key component of soil organic matter. If the rate of accumulation of SOC is greater than the rate of decomposition, then the amount of carbon in the soil increases, i.e. it will be sequestered. However, if the rate of loss is greater than the rate of accumulation the soil loses carbon mainly as CO_2 (and also methane from waterlogged soils) to the atmosphere.
- Soils globally have been estimated to contain twice as much carbon (as organic carbon) as the atmosphere and three times as much as the terrestrial biotic pool (Lal, 2010). As a result, even small changes in SOC have the potential to significantly influence atmospheric CO_2 and act as an important climate driver (Gosling *et al*., 2017). Storage of C in soils depends upon the type of inputs, the rate of decomposition of soil organic matter, soil texture and climate (Johnston *et al*., 2009).
- One way to potentially reduce the levels of atmospheric CO_2 is to increase the global storage of carbon in soil. The removal and storage of carbon from the air into carbon sinks (e.g. soil or forests) is known as carbon sequestration, it is defined by the IPCC as 'the process of storing carbon in a carbon pool' (IPCC, 2019). However, it must be recognised that a local increase in

[5] https://www.4p1000.org/

SOC stocks (i.e. ‘SOC storage’) does not necessarily entail climate change mitigation (Alison *et al*., 2019b). As Chenu *et al*. (2019) emphasise, ‘SOC storage’ can be treated as distinct from ‘SOC sequestration’; the latter implies genuine removal of CO_2 from the atmosphere on an annual basis, contributing to net reductions in greenhouse gas emissions.

5.3 Land use

- Land use change, such as deforestation or cultivation is a major source of global GHG emissions. The UK has signed the United Nations Framework Convention on Climate Change and is required to prepare an annual inventory of GHG emissions. As part of that commitment, data on land use, land use change and forestry (LULUCF) is compiled annually for Wales (as well as England, Scotland and Northern Ireland). Land use change to cropland results in soil carbon loss (positive values in Figure 14a) whereas land use change to grass results in C sequestration (negative values in Figure 14b). Overall, for the majority of the country there has been a small net C gain as a result of LULUCF (Figure 15).
- Hence, although the main focus of this report is the mitigation of GHG emissions from productive agriculture it is essential to recognise, particularly in terms of carbon sequestration, that land uses other than productive agriculture are likely to have greater mitigation potential. For example, the meta-analysis of Guo and Gifford (2002), based on 74 publications, showed that soil C decreased when cropland replaced native forest (−42%) and pasture (−59%). Although the potential changes will vary with soil type, for example, afforestation on mineral soils in arable production with low initial SOC are likely to accumulate C whereas afforestation following drainage of wet peaty soils is likely to result in SOC loss.
- It is also important to recognise the importance of protecting and maintaining habitats that already have high SOC stocks. Woodlands, along with peatland, for example, have the potential to sequester more carbon than any other type of habitat (Table 1). Restoring peatland can also avoid the GHG emissions from degraded peatland.
- Converting tillage land to permanent grassland will also have potential benefits for carbon sequestration and is also likely to reduce nitrate leaching, although the scale of the reduction will depend on factors including nitrogen inputs, grassland management etc. (Bhogal *et al*., 2009). However, the conversion of tillage to grassland is unlikely to be a practical option in Wales as the area of tillage land is small and grassland agriculture already dominates. The potential of existing grassland for carbon sequestration and GHG mitigation is discussed in more detail in Section 6.

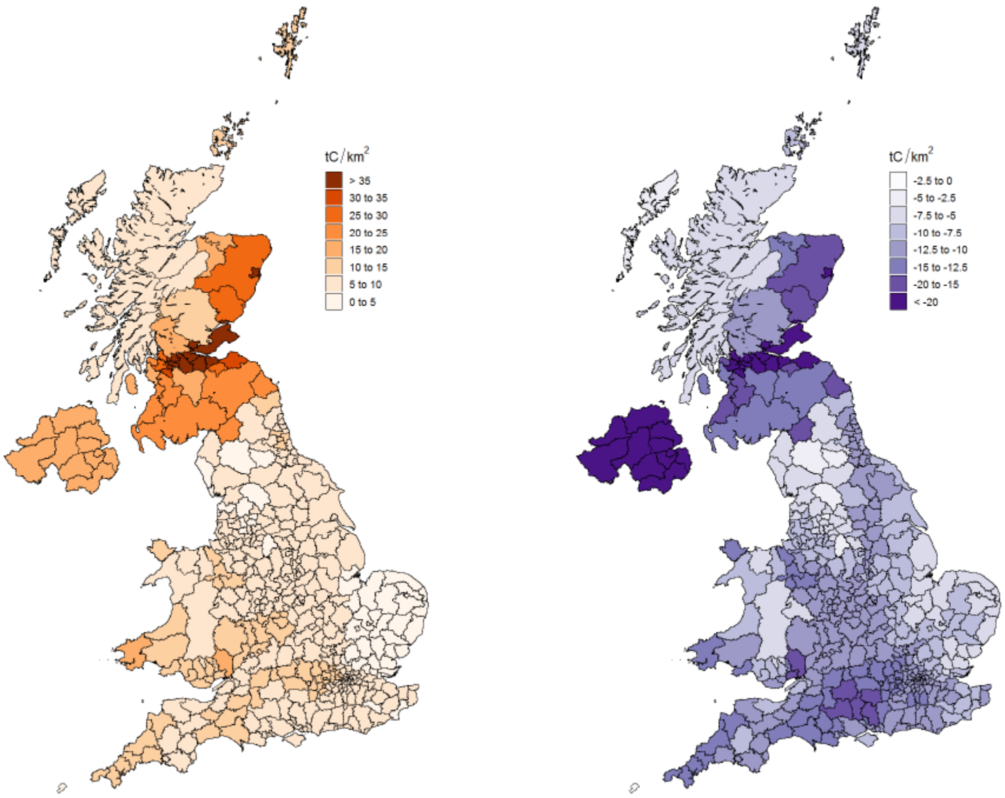

Figure 14. Emissions (positive values) or removals (negative values) in 2017 from soil due to land use change (t C/km^2) for conversion of all land types to a) cropland and b) grassland. Source: Clilverd *et al.*, 2019.

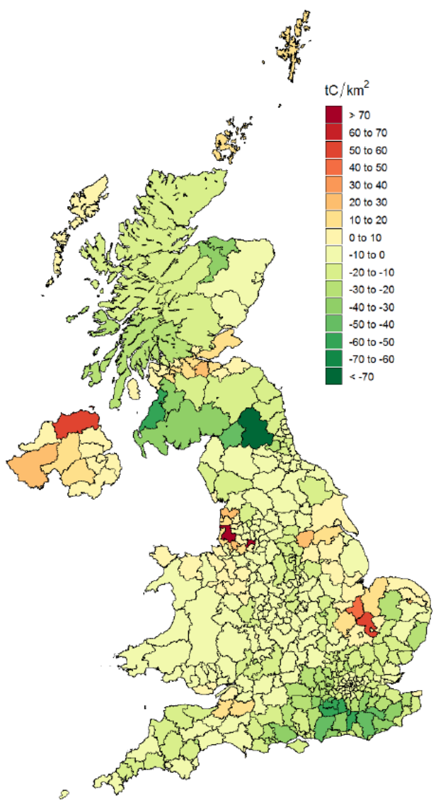

Figure 15. Total carbon emission (positive values) or removals (negative values) in 2015 as a result of LULUCF in the UK (t C/km^2). Source: Clilverd *et al.*, 2019.

Table 1. GHG abatement measures for land use and management in Wales. Source: ADAS *et al.*, 2014.

Mitigation measure	Abatement rate	Annual Abatement $ktCO_2e$ MTP	Applicability (uptake available)	Cost effectiveness of measure*
Woodland planting - 100,000 ha available for planting.	420-694 tCO_2e/ha for a 100-year period	590	Medium	Medium
Natural regeneration of woodland – estimated at 10% of planted area.	420-694 tCO_2e/ha for a 100 year period	59	Medium	Low
Woodland edge expansion and streamside corridor planting (assuming addition of woody linear features to the inventory).	Estimated at 10% of traditional woodland rate	25	High	Medium
Hedgerow restoration / expansion (assuming addition of woody linear features to the inventory).	Increase hedgerow biomass by 10% by 2030	15	High	Medium
Restore all degraded peatland.	Based peatland areas by type and associated abatement (0.9 tCO_2e/ha/yr for rough grassland to 27.3 tCO_2e/ha/yr for arable land).	324	Medium	Low
Reduce agricultural lime use by 10%.	Based on emissions from liming of 54 $ktCO_2e$ (2012).	5.4	Low	Low

5.3.1 *Woodland*

- Expansion of woodlands and restoring degraded peatland mitigate climate change by protecting and/or building carbon stores and reducing GHG emissions associated with management practices. Both can compete with food production but can have potentially large annual abatement potential (ADAS *et al.*, 2014), Table 1. Achievement of 50% of the total potential abatement would represent around 500 kt $CO_{2\text{-}eq}$ per year; barriers to land use change suggest that it is unlikely that the measures outlined in Table 1would be implemented completely.
- The contribution of woodland to carbon sequestration is variable throughout its lifecycle with CO_2 emissions resulting from soil disturbance at planting and harvesting and carbon sequestration over the growing period. In addition, it has been shown that different tree species are able to sequester different amounts of C. For example, Morison *et al.* (2012) concluded that afforestation with Sitka spruce on a peaty gley would sequester a total of 420 t $CO_{2\text{-}eq}$/ha for a 100 year period. In comparison, native broadleaved species such as oak grown on mineral soil might expect to sequester 694 t $CO_{2\text{-}eq}$/ha with minimal interventions during the same period.
- The Welsh Government's Woodlands for Wales Strategy, launched in 2018, aims to increase woodland cover in Wales by at least 2,000 ha a year from 2020 to 2030 (Welsh Government, 2018b). Glastir Woodland Creation grant funding (up to £9,000/ha) is intended to help land

owners deliver planting targets and the planting of new woodlands is supported by £2 million of Glastir funding (increased from £1 million in 2019 in recognition of Welsh policy to plant more woodland to meet GHG reduction targets).

- Afforestation of open habitats and croplands may increase soil carbon content on mineral soils, but the same is not true of plantations on organo mineral and peaty soils. As a result of afforestation, peat-based soil may dry out, releasing large amounts of carbon (Alonso *et al*., 2012). After woodland establishment, carbon sequestration increases substantially as growth rates increase before slowing down when the trees reach maturity. However, mature tree stands continue to show net sequestration with accumulation of litter and dead wood.

5.3.2 Peatland

- There are *c.*90,000 ha of organic/peat soil in Wales, equivalent to about 4% of the land area, 75% is in upland areas and 25% in lowlands (Evans *et al*., 2015). Despite their small land area peatlands represent the largest terrestrial store of carbon in Wales. Bradley *et al*. (2005) estimated the Welsh soil carbon stock to be 340 Mt, a large proportion of which is sequestered in upland peat soils. More recently it has been estimated that the total soil carbon stock in Wales is 410 Mt (Russell *et al*., 2011; Natural Resources Wales, 2016) of which 157 Mt (*c.*40%) is in peat soils and 57 Mt (*c.*15%) in forest soils (Natural Resources Wales, 2016).
- Recent new analysis of the loss of topsoil-C in the 'habitat' category between 2007 and 2016 reported by the GMEP showed that the reported change was driven by trends in upland habitats, in particular the change for dwarf shrub to grass-dominated habitats (Alison *et al.,* 2019a).
- In their natural state peatland has the potential to contribute to climate regulation through ongoing CO_2 sequestration. However, many Welsh peatlands have been detrimentally impacted by centuries of human activity including drainage, over-grazing and conversion to grassland and forestry. Consequently, Welsh peatlands are thought to act as a source of GHG emissions (Evans *et al*., 2015). Measures supported through Glastir, as well as other land management and conservation intervention mechanisms, aim to restore the carbon sequestration function of Welsh peatlands. Glastir options reward a reduction in land-use pressures and management options on a range of both upland and lowland bogs and fens (e.g. option 141: lowland bog and other acid mires – restoration (no grazing)). Management practices included as part of these options include, not clearing out existing ditches, not planting trees, not burning vegetation, lower and upper limits on stocking rates or exclusion of all grazing.
- An estimated three quarters of the Welsh peatland area has been impacted by one or more land-use activity which will encourage organic matter loss e.g. drainage, overgrazing, management neglect, conversion to intensive grassland and afforestation. Recent estimates suggest that Welsh peatlands are currently losing between 380-550 Kg $CO_{2\text{-eq}}$/year (ADAS *et al*., 2014; Evans *et al*., 2015). Differences in loss estimates relate to variations in land attributed to emission categories. The losses were attributed to (in order of magnitude) (i) peatland under improved grassland, (ii) coniferous woodland on peat and (iii) modified and drained bog. The estimated climate change mitigation potential that could be achieved if peatlands were returned to near-natural conditions was estimated to be *c*.300 kt $CO_{2\text{-eq}}$/year (ADAS *et al*., 2014; Evans *et al*., 2015).

6 Climate change mitigation through grassland carbon sequestration

- Welsh agriculture is dominated by grassland (permanent pasture, rough grazing and grassland sown in the last 5 years), which accounts for >85% of the utilised agricultural area (Welsh Government, 2018a). Grassland is well suited to the wet and mild climate, high altitude and sloping land which dominates in Wales. Thus the carbon sequestration potential of grasslands is of vital importance to meeting GHG reduction targets in Wales. However, management practices that increase SOC may have trade-offs that increase other GHG emissions and negate any benefits from increased SOC.

6.1 Grassland

- Under similar soil types and climate conditions, permanent grasslands contain more SOC than arable soils, reflecting the greater organic residue inputs, greater root mass and the absence of soil disturbance. As grassland soils have higher SOC stocks than arable land, introducing grass into a tillage rotation would be expected to increase SOC stocks. However this effect is likely to be more marked for rotations which include several years of grass followed by one or two years of tillage, rather than one year of grass followed by several years of tillage.(Moxley *et al*., 2014).
- Rotational grasslands are temporary in nature and frequent cultivation makes SOM vulnerable to decomposition compared to permanent grasslands (Acharya *et al*., 2012). Approximately, 20-30% of SOC in the top 30 cm of a soil horizon is susceptible to rapid losses due to frequent cultivation in temperate regions (Hutchinson *et al*., 2007). Observations by Attard *et al*. (2016) showed the asymmetry of the mechanisms: the loss of SOC after cultivation of grassland soil was fast whilst the replenishment of SOC was slow, a key factor was the reestablishment and growth of plant roots in the previously cultivated soil.
- In Wales, most lowland soils are in short or long term grassland with a predominance of the latter. Cultivation and reseeding stimulates soil C oxidation but since this is typically carried out at around five year intervals or longer it is probably insignificant in terms of mean soil C storage in the long term (Adams, 2017). In addition, the use of short term leys of one or two years is unattractive practically and economically.
- For mineral soils under improved grassland, nutrient inputs from manufactured fertilisers and manures are generally considered to enhance carbon storage due to enhanced plant productivity and residue and root inputs to soil. Enhancing species diversity and, in particular, introducing new deep-rooted grasses with higher productivity into the species mix has been shown to increase SOC contents, particularly on low-productivity pastures (Moxley *et al*., 2014).
- On lowland grassland, cutting and grazing have several interacting effects on soil carbon stocks. Moderate stocking density can increase carbon sequestration (from low baselines) but urine inputs can raise pH which may mobilise soil organic matter throughout the soil profiles (Moxley *et al*., 2014). Higher stocking densities tend to reduce pasture production and residue returns, which may decrease SOC storage (Moxley *et al*., 2014). Intensification of nutrient-poor grasslands developed on organic soils may increase losses of soil C. Grassland C sequestration per unit area may be favoured by extensive management provided that nutrients are not limiting.
- Carbon sequestration rates in temperate grasslands vary from negative (Schipper *et al*., 2007) to 8 Mg C ha/year (Jones and Donnelly, 2004) and are associated with large uncertainties (Soussana *et al*., 2004) arising from climatic variables (moisture and temperature), and temporal and spatial difference in sink capacities of ecosystems (Hutchinson *et al*., 2007).
- Studies of soil C storage suggest that most of the C in grasslands originates from below ground biomass (Hungate *et al*., 1997; Jackson *et al*., 2002), primarily roots (Adair *et al*., 2009).

Approximately 70-75% of root biomass in grassland is concentrated in the upper 15 cm of the soil horizon (Gleixner *et al*., 2005). The root biomass increases with age of grassland. Estimates show that organic C in soil derived from roots of temperate arable land and grassland species during a growing season is in the range of 0.1–2.8 t/ha (Rees *et al*., 2005).

6.2 Management influences on soil carbon storage in grassland

6.2.1 Carbon equilibrium

- Land use has a significant impact on the ability of soils to store or lose carbon. On mineral and organo-mineral soils changes in SOC stocks following a change in management (e.g. conversion of tillage to grassland) will continue only until new equilibrium stocks is reached; in contrast, undisturbed peats have the potential to sequester carbon over an extended period .
- Whilst the SOC content of grassland is higher than arable land, Moxley *et al*. (2014) note that permanent grassland under a consistent management regime will be at equilibrium and not losing or sequestering carbon. This is likely to be the case for many Welsh grasslands where management practices are consistent and involve minimal or no soil disturbance. For most permanent grasslands the challenge, is therefore, to ensure that carbon remains locked in the soil.
- However, where permanent pasture is ploughed and reseeded on a regular basis equilibrium SOC may not have been reached and carbon sequestration may still occur. Similarly, rotational grassland offers potential for carbon sequestration but the benefits will only be realised under appropriate management that ensures SOC is retained.

6.2.2 Carbon storage in grasslands

- Globally, grasslands are typically managed to increase biomass productivity in order to support livestock production, and are either being directly grazed, or cut for fodder (hay or silage), or a combination of all three. The effect of grassland management on carbon has recently been the subject of two large scale reviews by Eze *et al*. (2018) and Conant *et al*. (2017).
- Eze *et al*. (2018) undertook a meta-analysis of 341 datasets, which looked at how management type and intensity affected SOC levels. Data was extracted from peer-reviewed journal articles published before January 2017 and included datasets from Europe (fertiliser, grazing and liming), North and South America (fertiliser and grazing), Africa (grazing), Asia (fertiliser and grazing) and Australasia (fertiliser, grazing and liming). Liming, fertiliser application and grazing resulted in an overall significant reduction (-8.5%) in SOC levels in comparison to control plots (e.g. plots with no grazing or fertiliser applications). However, the three management activities differed significantly (P<0.05) in their individual effects on SOC content. Grazing significantly reduced SOC content by 15%, liming resulted in a non-significant increase (+5.8%) whereas fertiliser application significantly increased SOC stock by +6.7% (Figure 16).
- The intensity of grazing (light, moderate or high) or the application rate of lime or fertiliser influenced the rate and/or direction of change in SOC. For grazing, there was a reduction in SOC levels as the intensity of grazing increased from light (-6.9%) and moderate grazing (-13.2%) to heavy grazing (-27.1%); the reduction in SOC levels was statistically significant at all the three levels of grazing intensity. Eze *et al*. (2018) used a qualitative description of grazing intensity, in line with that reported in the peer-reviewed papers that made up the meta-analysis. This approach was necessitated due to inconsistencies in reported grazing intensity (e.g. different livestock types and different units of measurement) and also recognised the inherent variation in livestock carrying capacity in different climates.

- For fertiliser, low N rates resulted in a non-significant increase (+0.3%) in SOC stock whereas moderate N and high N rates significantly increased SOC by +5.2% and +13.3% respectively. Similarly, to the grazing categories, the categorisation of fertilizer intensity (low N, moderate N, and high N) was based on qualitative categorisation used by the authors of individual studies. Where the authors did not indicate fertiliser intensity, Eze *et al*. (2018) applied the following classification: low, <50 kg N/ha, moderate, 50-150 kg N/ha and high, >150 kg N/ha.
- The response of soil C content to increasing lime intensity followed a different pattern: there were non-significant increases in SOC stock at both low (+6.8%) and high (+2.8%) lime rates, whereas moderate lime rate led to a significant increase (+14.1%) in soil C stock. Liming was categorised as follows: low, <3 t/ha, moderate, 3-5 t/ha and high >5 t/ha.
- As a result of the moderate increases in SOC from liming and fertiliser additions, Eze *et al*. (2018) suggested that management to improve biomass production does not contribute sufficient organic matter to replace that lost by direct removal by animals. However, in temperate climates the negative effect of grazing on SOC levels reduced significantly with increasing mean annual temperature and mean annual precipitation, suggesting that some temperate grassland soils are potential C sinks. The authors suggested that the strong positive interaction between temperature and grassland management on SOC content could be explained by temperature-induced increases in the length of growing season (Hunt *et al*. 1991) increasing plant growth and C additions to the soil (Chang *et al*., 2016).
- Conant *et al*. (2017) reviewed 126 papers (>6500 data points) quantifying SOC contents under a range of grassland management practices (the review did not include any specific details on management, e.g. fertiliser or stocking rates). Studies contrasted a ‘standard’ management practice with an ‘improved’ management practice and were mostly from North and South America, Europe and Australasia. The management changes implemented were primarily related to fertiliser use (32%), grazing rate (21%) or conversion from cultivation (25%) or native vegetation (16%) to grass.
- The impact of changes in management practice on SOC were: fertiliser use (+12%; 3.44% to 3.58% SOC), grazing rate (+10%, 2.62%-2.89% SOC) or conversion from cultivation (+40%, 0.97% to 1.35% SOC) or native vegetation (-14%, 2.97% to 2.55% SOC) (Figure 17). The magnitude of the change in soil C content generally declined with depth, with an average increase of 23% in the surface 20 cm but just 12% at lower soil profiles (no quantitative data given).
- Conant *et al*. (2017) showed that SOC content increased on average by 10% (from 2.62% to 2.89% SOC) in comparison to the ‘standard’ management practice with changes to grazing management (including lower stocking rate, short duration or seasonal grazing and the removal of grazing livestock). However, although grazing management practices increased SOC contents the results cannot be simply extrapolated to other farming systems. In the studies reported, grazing management improvements were implemented specifically because they were expected to be beneficial under the conditions specific to each site. Also, despite the estimate of an average increases in soil C content, it is not always the case that changes to grazing management increased soil C contents.

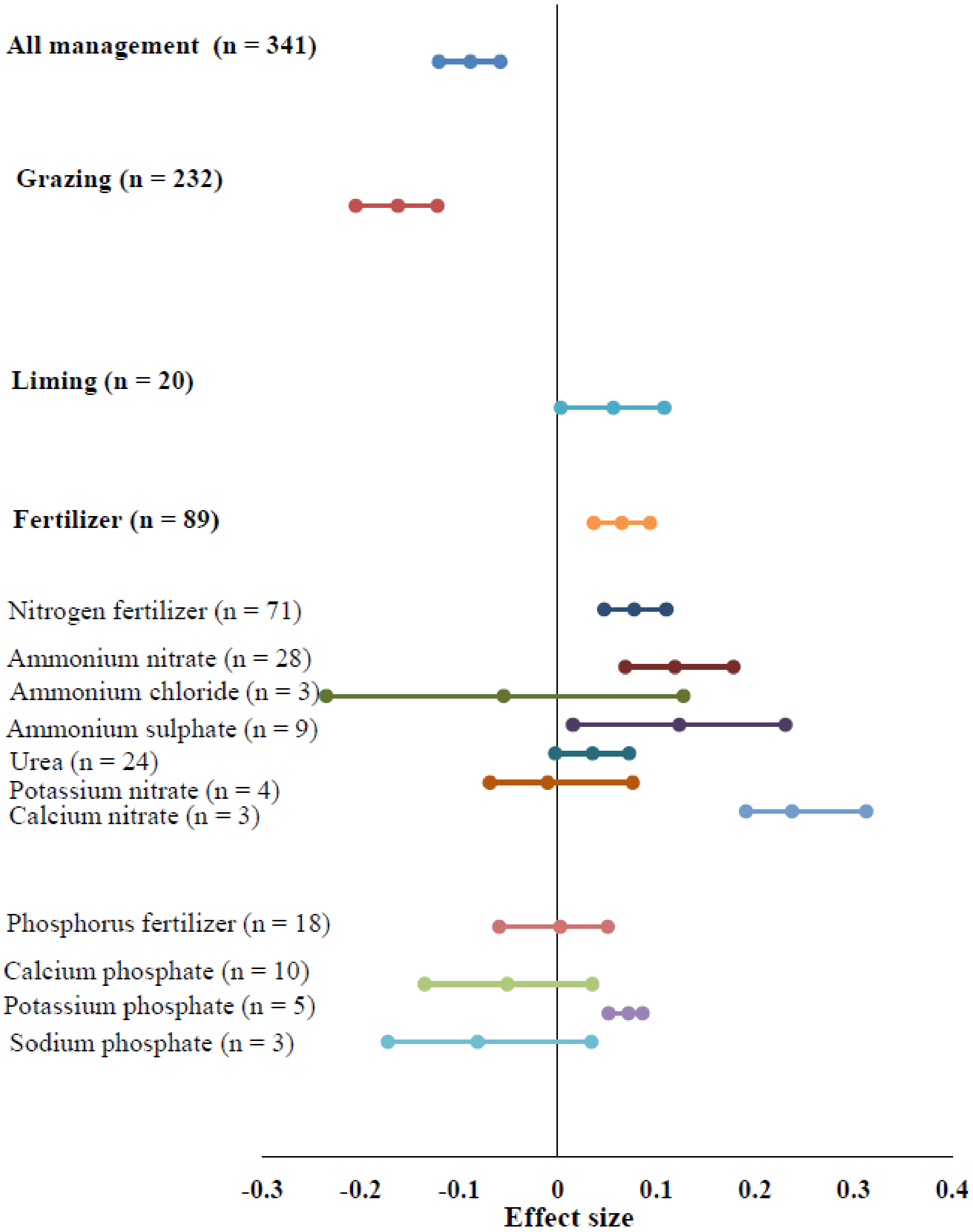

Figure 16. Effect sizes of fertiliser application, liming and grazing on SOC stock (bars represent mean plus and minus 95% confidence intervals). (Source: Eze *et al.*, 2018).

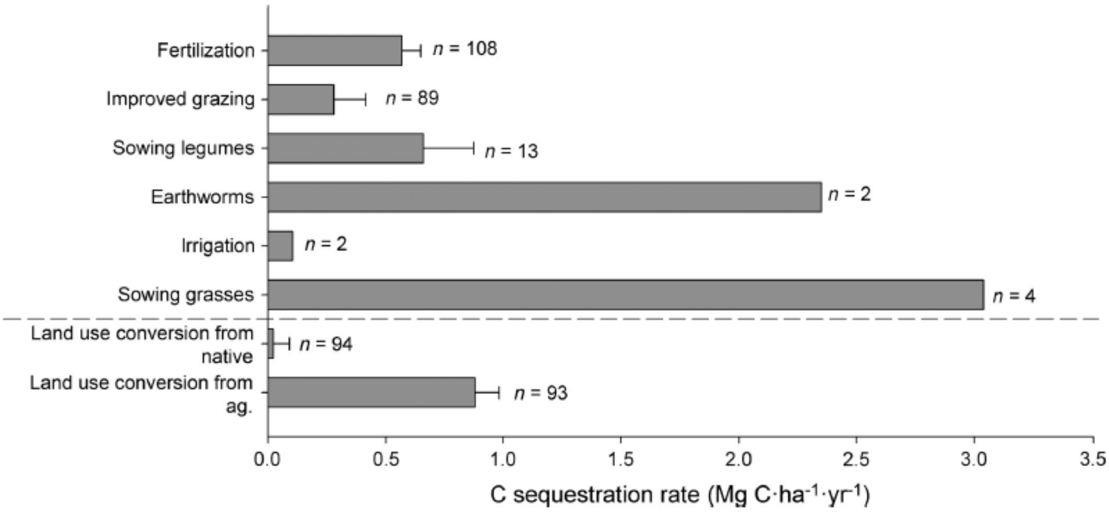

Figure 17. Changes in soil C content driven by grassland management improvements. Bars represent average across all studies containing soil C content change information, error bars represent SEs calculated using meta-analysis across all studies containing information on treatment SEs. The number of studies used to calculate the average is indicated for each type of management change (Source: Conant *et al.*, 2017).

6.2.3 Grazing and carbon storage

- Both Eze *et al*. (2018) and Conant *et al*. (2017) reviewed the effect of grazing on SOC content; Eze *et al*. noted a reduction in SOC at all levels of grazing with heavier grazing causing a greater reduction than light grazing. In comparison, Conant *et al*. (2017) noted that improvement in grazing management (including reduced stocking rates, reduced grazing season) increased SOC compared with previous management practices.
- There is a complex relationship between grazing and SOC dynamics. Both overgrazing and no grazing have been noted to reduce SOC content whilst grazing at appropriate stocking levels (not always specified) has been noted to increase SOC. Abdalla *et al*. (2018) noted that the impact of grazing on SOC was highly complex and climate dependent. For example in moist cool climates (the likely category for most grasslands in Wales) SOC content decreased with grazing intensity.
- Grazing, accelerates annual shoot turnover, changes the form of organic C application in animal excreta, and redistributes C within the plant-soil system (e.g. Reeder and Schuman, 2002). The below-ground biomass, dead root biomass and fine root productivity have been shown to increase on grazed compared to un-grazed sites (Pucheta *et al*., 2004).
- In comparison other authors have shown that soil C stocks in grasslands decline with overgrazing and less frequent cutting and also with no grazing. It is suggested that overgrazing could lead to soil C loss through reduced plant productivity and litter inputs (Conant and Paustian, 2002; Mestdagh *et al*., 2006), or to exposure of bare soil and C loss via erosion (Evans, 1997). In contrast, exclusion of grazing leads to immobilisation of C, reduced growth of fibrous roots and consecutively lower C stocks (Reeder and Schuman, 2002).
- Overall, the evidence from the literature suggests that in most conditions ‘light’ grazing can be beneficial to increasing soil carbon contents on grassland soils.

6.2.4 Organic manure and fertiliser additions and carbon storage

- It is widely recognised that the application of organic materials is one of the most effective ways of increasing soil organic carbon (SOC) levels and improving soil quality (Bhogal *et al*, 2009, Powlson *et al*., 2012, Johnson *et al*, 2009). Fertiliser additions can increase C inputs to the soil by enhancing plant growth which leads to increased organic matter inputs from residues and roots (Buckingham *et al*., 2013).
- Bhogal *et al*., (2018) reported results from a network of seven experimental sites which investigated the effects on soil quality of annual applications (over a minimum of 3 years) of compost and food-based digestate in comparison with farmyard manure (FYM) and livestock slurry. Two of the sites were existing experimental platforms which had previously benefitted from applications of FYM, livestock slurry and green compost allowing the effects of longer-term applications (6–17 years) on soil properties to be quantified. SOC contents were only increased following the long-term (9 years or more) application of bulky organic materials (compost and FYM). SOC increases were associated with improvements in soil biological (microbial biomass) and physical properties (reduced bulk density), although the level of improvement was dependent on the quality of the organic material applied (as determined by its lignin content, an indicator of resistance to decomposition). Applications of low dry matter content materials (digestates and livestock slurries) had a limited capacity to improve soil biological and physical functioning, due to their low organic matter loading.
- Eze *et al*. (2018) and Conant *et al*., 2017) noted increases in SOC content ranging from <1% to 12% following applications of manufactured fertilisers and organic materials. Overall, Eze *et al*. (2018) reported an increase in SOC stock of 7% following nitrogen fertiliser application; in detail, ammonium nitrate, ammonium sulphate and calcium nitrate increased SOC stock by +12.6%, +13.1% and +26.9% respectively, while there were no significant effects of ammonium chloride, urea or potassium nitrate applications. Low N rates resulted in a non-significant increase (+0.3%) in SOC stock whereas moderate N and high rates significantly increased SOC by +5.2% and +13.3% respectively. In comparison, Conant *et al*. (2017) noted that SOC increased from 3.44% to 3.85% following fertiliser application (an average increase of 12%), although the authors to not detail the type or application rate of fertiliser included in the analysis. The authors also noted that organic material applications increased soil C sequestration rates by an average of 0.82 Mg C/ha/year compared with 0.54 Mg C/ha/year from manufactured fertiliser.
- It is important to note that the addition of both manufactured fertiliser and organic materials have implications for emissions of other GHGs especially nitrous oxide (see section 7). An integrated approach to nutrient management, which takes account of soil nutrient supply as well as crop available nutrients from manure applications, is important to ensure that manufactured fertiliser applications meet and not exceed optimum crop requirement.

6.2.5 Liming and carbon storage

- Eze *et al*. (2018) measured a nonsignificant increase in SOC stock of +6.8% and +2.8% at low (<3 t/ha) and high (>5 t/ha) lime application rates, respectively. In contrast, moderate lime application rates (3-5 t/ha) led to significant increases (+14.1%) in soil C stock. Similarly, Paradelo *et al*. (2015) found variable effects of lime additions (rates: <1 to 19 t/ha) on SOC content of mineral soils (from field experiments in Europe, South and North America, Asia and Australia on forest, grassland, arable or bare soils) and concluded that the impacts of liming were highly context dependent. They concluded that there was insufficient evidence to predict the net effect of liming on SOC stocks under different soil/weather/ land use condition.

- Research carried out in England on permanent grassland (the Park Grass Experiment at Rothamsted on silty clay loam) has also suggested that liming (4 t/ha every four years) can increase SOC (Fornara *et al*., 2011). Net organic C sequestration measured in the 0-23 cm layer was 2 to 20 times greater in limed than in unlimed soils. The authors attributed this to greater biological activity in limed soils, which despite increasing soil respiration rates, led to plant C inputs being processed and incorporated into resistant soil organo-mineral pools.

7 Climate change mitigation through the reduction of greenhouse gas emissions from soil

- Greenhouse gas emissions from the agricultural sector are primarily methane (CH_4) and nitrous oxide (N_2O), with some carbon dioxide emissions from fuel use (ADAS *et al.*, 2014).
- The primary source of agricultural methane emissions is enteric fermentation from ruminant livestock (i.e. sheep and cattle) which accounts for *c.*60% of GHG emissions from Welsh agriculture.
- Nitrous oxide emissions from agricultural soil are predominately produced via the microbially mediated processes of nitrification and denitrification (Firestone and Davidson, 1989). The factors which control the magnitude of N_2O emission include soil mineral nitrogen (SMN) content, soil temperature, soil moisture content (Dobbie and Smith, 2001, 2003) and a source of available carbon (Weier *et al.*, 1993).

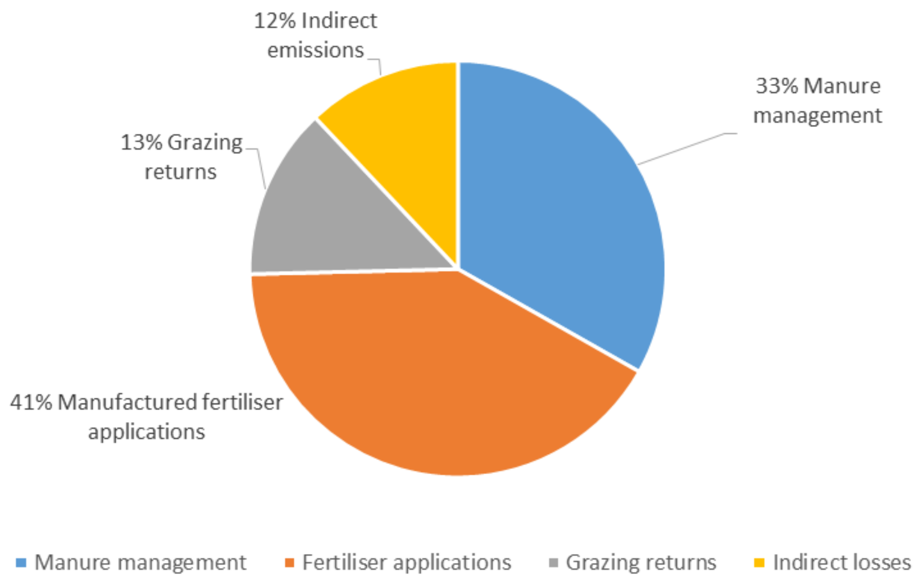

Figure 18. Contribution of different N sources to nitrous oxide emissions in Wales. Nitrous oxide emissions from these sources account for 20% of total agricultural GHG emissions in Wales.

- Nitrous oxide emissions from manufactured nitrogen fertiliser application, manure management and grazing returns contribute an estimated 20% of GHG emissions from Welsh agriculture, with emissions from manufactured fertiliser nitrogen applications making the largest contribution (Figure 18). In addition, around 3% of agricultural GHG emissions in Wales is emitted indirectly from soils following re-deposition of emitted ammonia and from leached nitrate (NAEI, 2019). Hence to minimise soil related emissions of N_2O is also important to reduce the potential for ammonia losses and nitrate leaching.
- As nitrous oxide emissions are related to nitrogen inputs from manures and fertilisers elevated emissions will occur where nitrogen supply exceeds crop requirement (Figure 19; Cardenas *et al.,* 2010).

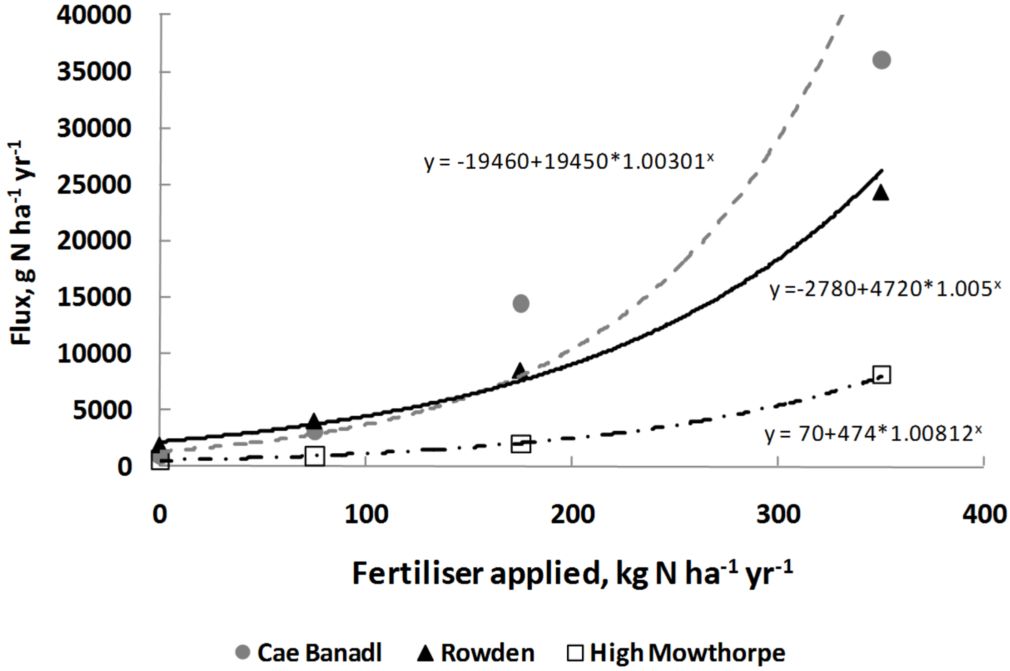

Figure 19. The effect of manufactured fertiliser nitrogen application rate on nitrous oxide emissions at 3 contrasting grassland sites (Cardenas *et al.,* 2010).

- Typically, around 1% of nitrogen inputs to soils are lost by nitrous oxide emission with the magnitude varying according to the source of the N input and soil and weather conditions at the time of application. A meta-analysis carried out by Cowan *et al*. (2020) suggested that emissions were highest from ammonium nitrate (AN) fertilisers (1.1%) with emission factors (EFs) ranging between 1.0% and 1.2% of total N applied. Emissions from AN applications were significantly lower for applications to arable fields (0.6%) than to grasslands (1.3%). EFs associated with urea were significantly lower than AN for grasslands with an EF of 0.6 (0.5-0.7) %, but slightly higher for arable fields with an EF of 0.7 (0.4-1.4) %.
- ADAS *et al*. (2014) estimated the annual abatement of GHG from mitigation measures in agriculture relative to the baseline period for Wales (Table 2). Measures were scored for uptake (allowing for existing implementation and structural or behavioural barriers) and for cost effectiveness (extent of economic incentive for land managers to implement, allowing for current public support measures and market returns). The last two columns in Table 2 are highlighted red, amber and green (to denote low, medium and high scores, respectively). Overall, ADAS *et al*. (2014) suggested that it would be realistic to budget for a 5-10% net emissions reduction or around 400 kt$CO_{2\text{-eq}}$ per year by 2020. This reflects the fact that not all measures will be taken up equally, reflecting the availability and cost effectiveness of each method.

Table 2. GHG abatement measures for productive agriculture in Wales (Source: ADAS *et al*., 2014).

Mitigation measure	Abatement rate	Annual Abatement $ktCO_2e$ MTP	Applicability (uptake available)	Cost effectiveness of measure*
High genetic merit livestock	10% of enteric emissions	229	Medium	High
Improved animal nutrition	10% of enteric emissions	229	High	Medium
Improved animal health	10% of enteric emissions	229	High	Medium
High sugar grasses	10% of enteric emissions	229	Medium	Medium
Nitrification inhibitors for fertiliser and organic manures	30-50% reduction in N_2O	432	High	Low
Calibrate fertiliser spreader	<5% reduction in N_2O	35	Medium	High
Calibrate manure spreaders	5-10% reduction in N_2O	28	Medium	High
Adopt fertiliser recommendation system	5-10% reduction in N_2O	53	Medium	High
Adopt a manure management plan	15-20% reduction in N_2O	81	Medium	High
Use of crop varieties with improved N use efficiency	5-10% reduction in N_2O	53	Low	Medium
Substitute fertiliser N with legume-fixed N	10% reduction in fertiliser N use	71	Medium	High
Improve N availability of manures	2% reduction in N_2O from fertiliser use	15	Medium	High
Controlled release fertilisers for high value arable crops	0.3 tCO_2e/ha	9	Low	Medium
Precision application – crops	5% reduction in N fertiliser use on Welsh cropland	5	Low	Medium

*High cost effectiveness represents a good economic return for land managers.

**The mitigation measures are not all additive and account needs to be taken of interaction and double-counting.

7.1 Nutrient management planning

- The majority of the most cost effective methods for reducing N_2O emissions from soils in Table 2 relate to nutrient management planning, i.e. calibration of fertiliser or manure spreaders, the use of a fertiliser recommendation system and the adoption of a manure management plan. Optimising N inputs from manufactured fertilisers and organic materials use will reduce the need for manufactured fertiliser applications to meet optimum crop demand. Optimising nutrient inputs minimises emissions both from fertiliser production and from direct and indirect nitrous oxide emissions from soils.
- Effective nutrient management planning involves applying nutrients (either fertiliser or organic manures) based on crop requirement. This approach ensures that nutrients are utilised efficiently on farm and only used when and where necessary. Optimal supply of all major and minor nutrients as well as maintaining optimum soil pH and soil structural condition are also

necessary to ensure that crops utilise nitrogen effectively and minimise the amount soil N available for conversion to N_2O or at risk of nitrate leaching.

- Information from the Wales Farm Practice Survey in 2012 suggest that 43% of farmers have a soil nutrient plan (Anthony *et al*., 2012). In comparison, in 2019, 58% of holdings in England had a nutrient management plan (Defra, 2019a). The difference is probably a reflection of the more extensive grazing grassland systems in Wales, where a nutrient management plan is less applicable.
- There are four key stages of nutrient planning which should be followed to maximise nutrient use efficiency and minimise the potential risk of nutrient losses to the environment: 1) quantify crop requirement, 2) quantify soil nutrient supply, 3) quantify the nutrient content of any organic materials (e.g. livestock manures, biosolids, digestate etc.) and 4) account for the nutrients supplied by organic materials when planning manufactured fertiliser additions (Williams *et al*., 2019). These are discussed in more detail below.
    1. *Quantifying crop nutrient requirement:* AHDB's Nutrient Management Guide (RB209) is recognised as the industry standard fertiliser recommendation system for supporting nutrient management planning in Wales. It provides comprehensive guidance on the nutrients required for economic optimum crop production. The fertiliser recommendations were first published in the 1970s and the latest version was published in 2017 based on a series of reviews led by ADAS in 2016 (e.g. Newell Price *et al.*, 2016). Crop requirements vary with species (and sometimes variety of crop) and reflect soil type and over winter rainfall.
    2. *Quantifying soil nutrient supply:* In most situations soil nitrogen supply can be assessed using information relating to soil type, typical over winter rainfall (to assess leaching losses), nitrogen released from crop residues and previous fertiliser N and manure use. In circumstances where previous management has been atypical, soil sampling to 90 cm may be more effective to quantify the soil nitrogen supply on arable fields. Topsoil (0-15 cm on tillage and 0-7.5 cm on grass) analysis is recognised as the most effective method of quantifying soil pH status and extractable phosphorus, potassium and magnesium contents. Soil pH, phosphate, potash and magnesium are usually managed for a rotation rather than an individual crop so soil analysis is recommended every 3-5 years.
    3. *Quantifying the nutrient supply from organic materials*: Understanding the nutrient content of organic materials and quantifying application rates are crucial for making best use of manure nutrients. The nutrient content of organic materials will depend on a number of factors. For livestock manures the main determining factors include livestock type, feeding regime, diet, the amount of rainwater dilution that occurs during storage and the amount of bedding used. For digestates and composts the source of the feedstock material and for biosolids the treatment processes are important factors. Typical figures for the nutrient content of organic materials are available in AHDB's Nutrient Management Guide (2017). However laboratory analysis can give a more accurate assessment of the nutrient content of organic materials from a specific source.
    4. *Accounting for manure nutrients when planning manufactured fertiliser applications:* Crop available nutrient supply from contrasting manure application timings and methods can be calculated by using the MANNER-*NPK* decision support tool or by reference to AHDB's Nutrient Management Guide. It is important that the nutrients supplied by the manures are accounted for when calculating manufactured fertiliser application rates to ensure that crop nutrient requirements are not exceeded and the risks of nutrient losses to the environment are not increased. The approach of integrating fertiliser and manure nutrients to provide optimum levels for plant growth is also used in computer based

nutrient management systems such as PLANET (www.planet4farmers.co.uk) and other software tools produced by commercial software companies such as FarmPlan and Muddyboots.

7.2 Increasing the accuracy of nutrient applications

- Calibration of fertiliser and manure spreaders ensures that the amount of nutrient applied is accurate (i.e. the correct amount is applied) and that the spreading pattern is optimal for crop nutrition. Regular (annual) calibration of fertiliser and manure spreaders are likely to improve NUE from fertiliser N and organic resource use by more uniform distribution. This will reduce N_2O emissions from N loading 'overlap', which are likely to be proportionally greater if localised N loadings are greater than crop demand (ADAS *et al*., 2014). However, data for British farmers (2018) suggest that *c*.40% of farmers with a fertiliser spreader check the calibration of their fertiliser spreaders annually using catch trays, 18% check less than once per year, and 20% have never checked spread patterns in this way (BSFP, 2019).
- Precision agriculture practices have the ability to optimise nutrient inputs, by using techniques which account for in-field variability (Balafoutis *et al*., 2017). Other methods include controlled traffic farming, which confines all machinery to the least possible area of permanent traffic lanes, and machine guidance (e.g. driver assist or auto-guidance). These methods limit the use of tractors to only the necessary passes through the fields avoiding overlapping resulting in decreased use of agricultural inputs and fuel (translated into GHG emissions reduction and lower cost of production).
- Precision application systems such as trailing shoe, trailing hose and shallow injection are effective at increasing the crop available N supply from liquid organic materials (i.e. livestock slurry and digestate applications) by reducing ammonia emissions by between 30-70 % compared with conventional surface broadcasting techniques. The application techniques also ensure even application across known bout widths reducing variability in nutrient supply. Workers have investigated whether manure application techniques which reduce ammonia emissions result in pollution swapping by increasing nitrous oxide emissions. A review carried out by, Chadwick *et al*. (2011) suggested that soil conditions at the time of application were more important than application method in controlling nitrous oxide emissions, with highest losses occurring from warm and wet soils.

7.3 Nitrification inhibitors

- Nitrification inhibitors offer potential to reduce N_2O emissions from the application of manufactured nitrogen fertilisers and organic manures to agricultural soils (de Klein and Eckard 2008). Nitrification inhibitors slow down the rate of the first step of the nitrification process, the conversion of ammonium (NH_4+) to nitrite, and thus to nitrate (NO_3−), by deactivating the responsible enzyme (Amberger, 1989) (Figure 20). Many chemicals have been tested as nitrification inhibitors, but only a few are commercially available, of which dicyandiamide (DCD) and 3, 4-dimethylpyrazole phosphate (DMPP) are the most common.
- Initial interest in nitrification inhibitors was mainly concerned with minimising NO_3− leaching losses following applications of fertiliser N, livestock slurry or urine returns from grazing livestock, as N is retained on soil exchange surfaces in the NH_4+ form rather than leached as NO_3− (Misselbrook *et al*., 2014). However, N_2O emissions from both nitrification and denitrification will also be reduced by inhibiting nitrification, offering a potential mitigation strategy for greenhouse gas emissions from agriculture (Misselbrook *et al*., 2014).
- Misselbrook *et al*. (2014) summarised the results from a UK research programme consisting of 14 experiments (Defra project AC0213) in which, the effect of nitrification inhibitors on

ammonia, nitrous oxide, nitrate leaching losses and crop yields were investigated, following applications of manufactured fertiliser or grazing returns (i.e. urine and dung). They found that, while the nitrification inhibitor DCD could be very effective at reducing N_2O emissions, it had little effect on NH_3 volatilisation, NO_3 leaching losses, crop yield or crop N offtake. Based on the reduction efficiencies results from 14 field experiments carried out in England, it was concluded that, 'an approximate 20% reduction in N_2O emissions from UK agriculture is technically feasible with little risk of increasing NH_3 emissions'. However, controlling N_2O emissions from grazed grassland, particularly upland systems using NIs presents a challenge.

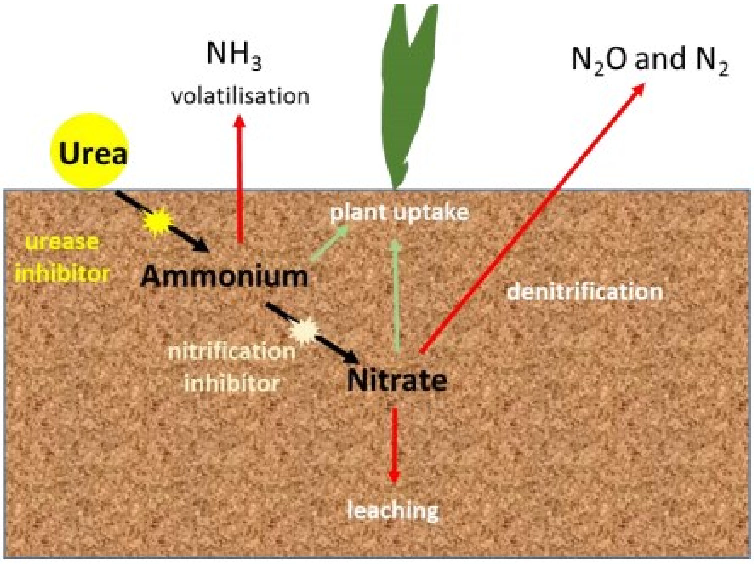

Figure 20. Schematic of nitrogen cycle and mode of action of nitrification and urease inhibitors (Source: Catchment Sensitive Farming).

7.4 Urease inhibitors

- As a direct consequence of the increased risk to human health the Clean Air Strategy suggests that Defra may legislate on urea-based fertiliser use in order to reduce ammonia emissions (losses of ammonia from urea are up to 45% compared with *c*.2% from ammonium nitrate fertilisers). Even if it does not become mandatory it is likely that there will be increasing pressure to reduce ammonia emissions from agriculture.
- Urea is one of the most used N fertilisers worldwide, however, despite its widespread use there are environmental concerns due to emissions of ammonia and nitrous oxide following applications. Urease is a nickel dependent enzyme that catalyses the hydrolysis of urea to two moles of ammonia (NH_3) and one mole of carbon dioxide (CO_2) (Modolo *et al.*, 2018).
- Urease inhibitors are compounds which block the activity of the urease enzyme, slowing the conversion of urea to ammonia (Figure 20). The compounds will degrade in the soil over time (depending on factors including temperature and moisture), and therefore delay, rather than completely stop the conversion process. Research funded by Defra and conducted at several sites in England showed ammonia emission reductions >70% when the urease inhibitor NBPT was used with urea, compared to emissions from urea alone (Chadwick *et al.*, 2005).
- The additional nitrogen remaining in the soil can be used by the crop and the slower conversion of this nitrogen from urea to ammonium can better match crop demand, thereby improving the nitrogen use efficiency compared with urea alone. The inclusion of a nitrification inhibitor as well can further enhance nitrogen use efficiency by reducing losses of nitrate through denitrification and leaching.

7.5 Improve N availability of manures

- ADAS *et al*. (2014) estimated that changes to manure management practices such as spring application timings (to reduce nitrate leaching losses), rapid soil incorporation of solid and liquid manures and the use of precision application techniques for liquid organic material applications had the potential to reduce overall N inputs to Welsh agriculture by *c*.1,500 t per year. The estimated reduction in manufactured fertiliser N inputs resulting from the increased manure N efficiency was estimated to reduce direct and indirect soil N_2O emissions by *c*.2% (equivalent to *c*.50 tonnes of N_2O or 15 K $tCO_{2\text{-eq}}$).

8 Current, emerging and innovative agricultural practices for minimising loss and/or increasing the organic matter and carbon content of tilled agricultural soils in Wales.

- According to Lal (2004) high SOM accumulation is favoured by management systems, which add high amounts of biomass to soil, cause minimal soil disturbance, improve soil structure, enhance activities and species diversity and strengthen mechanisms of nutrient cycling. Such low disturbance, high carbon input (e.g. litter and roots) and SOM content are typified by the permanent and rough grazing grassland soils that predominate in Wales (>80% of agricultural land) and woodland soils (*c.*12% of Wales). Thus most soils in Wales will be at low risk of SOM loss.
- For the minority of soils in Wales that are in arable systems (including grasslands <5 years old), the risk of SOM loss is significantly greater, as SOM loss is triggered by soil disturbance, which increases oxidation of organic matter and by reduced accumulation or removal (i.e. crop residues may not be returned to the soil so levels become depleted). It has been estimated for Europe that conversion of grassland to arable land reduces SOC levels by around 1-1.7 t C/ha/year (Freibauer *et al*., 2004). Hence, to maintain and (potentially) enhance the SOC content of arable soils it is essential that management practices minimise soil disturbance and maximise organic matter inputs.

8.1 Current management practices for SOM in arable systems

- Management practices for arable systems can either protect, maintain and increase SOM for soil quality/fertility or enhance SOM levels for soil carbon storage and climate change mitigation. Practices that enhance soil organic matter levels are likely to benefit other soil properties such as improving soil structural stability, water holding capacity and the availability of crop nutrients. Enhancing and maintaining soil organic matter levels will also reduce the risk of water and wind erosion.
- The most effective methods for increasing SOM can be broadly grouped into the following categories: land use change (e.g. convert tillage land to permanent grassland), reduction in soil erosion, changes to tillage/cultivation practices (e.g. reduced or zero tillage) and increased organic matter additions/returns.
- Lal (2011) reviewed practices to sequester C in soil and suggested that the best strategies for arable systems were to adopt no till farming and crop incorporation, use cover crops, integrated nutrient management (including the use of organic manures) and improvement to soil structure and tilth; components of this strategy are outlined in Figure 21, below.
- More recently, Alison *et al*. (2019b) grouped management practices for increasing SOM into three categories: 1) well tested and proven, with no dis-benefits, 2) Limited evidence and some trade-offs and 3) Limited practical potential, small benefits of significant trade-offs. The authors suggested that the best management practices (i.e. those classified under the first category) for tillage land were cover cropping and conversion to grassland.

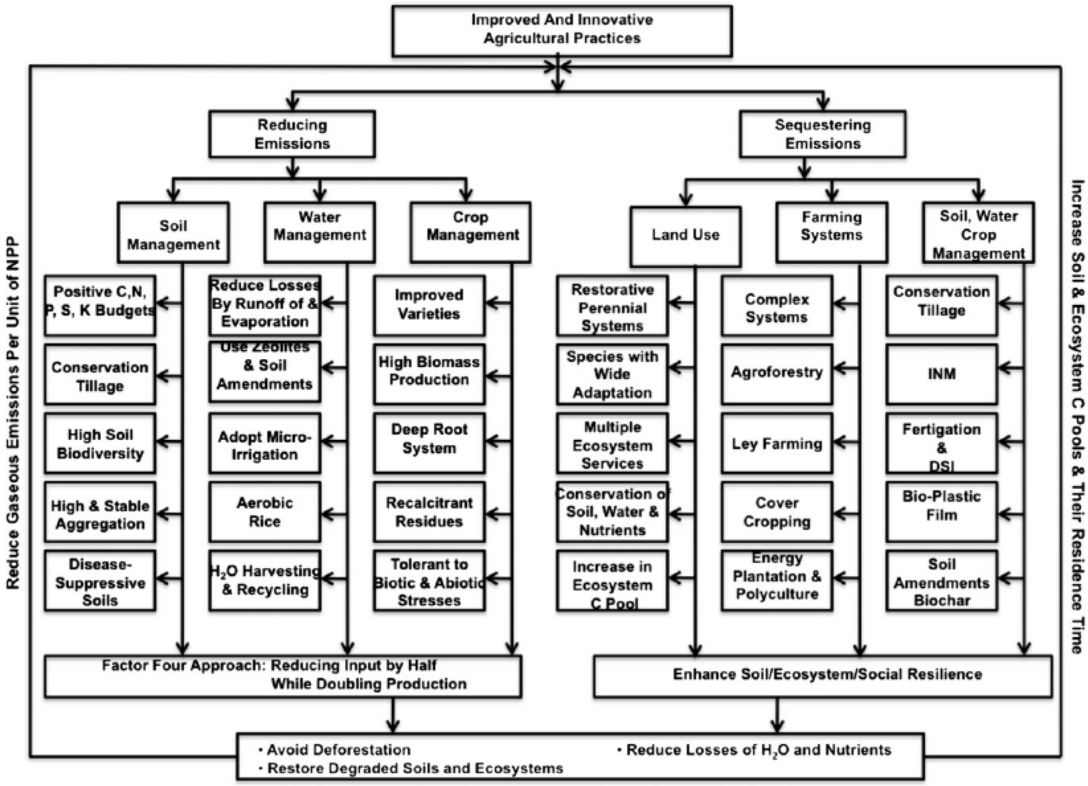

Figure 21. Technological options to reduce emissions and sequester carbon from agricultural ecosystems (Source: Lal, 2011).

8.1.1 *Land use change*

- The conversion of tillage land to permanent grassland and woodland is most effective at increasing SOC content as it avoids the frequent cultivations that under arable cropping stimulate the mineralisation of organic matter. However, taking land out of arable l production is likely to reduce farm productivity and consequently farm income. Newell Price *et al.* (2011) estimated that converting around 10% of tillage land to low intensity grassland would reduce farm income by around £200/year on a typical dairy farm and £35,000 on a farm dominated by roots and combinable cropping. The authors also predicted that conversion of arable land to unfertilised grassland would reduce nitrate and ammonium losses to water by 90% with similar reductions in ammonia and nitrous oxide emissions. Arable reversion was also predicted to reduce particulate P and associated sediment losses in surface runoff were predicted to be reduced by around 50%.

8.1.2 *Conservation tillage*

- Conventional tillage, characterised by inversion of the soil layers through ploughing, leads to rapid mineralisation of SOC, releasing carbon dioxide into the atmosphere. Minimum and no-tillage systems have been promoted as methods for increasing soil carbon content as they disturb the soil less than conventional ploughing.
- Cillis *et al.* (2018) used SALUS model simulations to study the change of SOC over a 15-year period for four zones (characterised by increasing productive potential from A to D); in all cases the modelled predictions suggested that loss of SOC was greater following conventional tillage than either minimum-tillage or no-tillage systems (Figure 22).

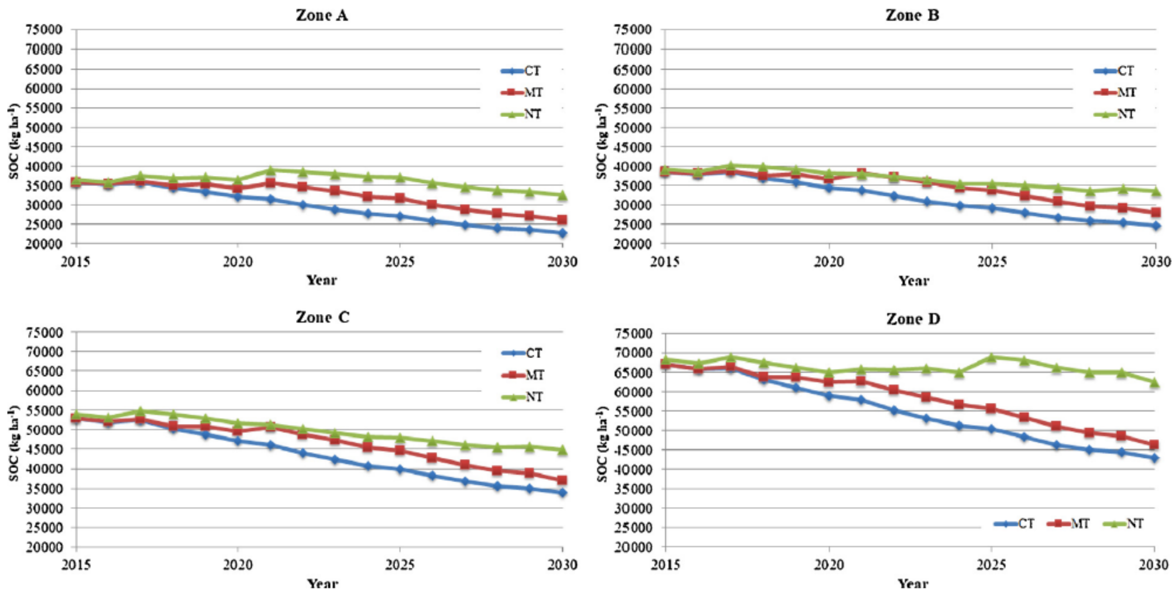

Figure 22. Change in SOC content in 0-0.4 m soil layer over 15 years (2015-2030) in four zones (characterised by increasing productive potential from A to D) following conventional tillage (CT), minimum tillage (MT) and no-tillage (NT).

- A recent meta-analysis highlighted that conservation tillage increases SOC by *c.*5% on average, with more positive effects of no-tillage management in regions characterised by warm climate (15%) or lower fertiliser nitrogen inputs (Bai *et al*., 2019). However, a review by Powlson *et al*., (2014) reported a large body of evidence suggesting that increases in soil carbon content under no till and minimum till systems were small. They also stated that apparent increases in topsoil carbon content resulted from differences in distribution of soil carbon on ploughed compared with minimum and no till systems The authors suggested that no-till was beneficial for soil quality but its role in carbon storage and climate change mitigation was over stated.
- Luo *et al*. (2010) used a meta-analysis of global data from 69 paired-experiments to investigate changes in SOC resulting from conversion from conventional ploughing to no tillage. They found that cultivation of natural soils for more than 5 years, resulted in soil C loss of more than 20 t/ha with no significant difference between conventional tillage and no tillage. Conversion from conventional to no tillage changed distribution of C in the soil profile significantly, but did not increase the total SOC except in double cropping systems (two crops per year). After adopting no till, soil C increased by 3.15 ± 2.42 t/ha (mean ± 95% confidence interval) in the surface 10 cm of soil, but declined by 3.30 ± 1.61 t/ha in the 20–40 cm soil layer. Overall, adopting no till did not enhance soil total C stock down to 40 cm.

8.1.3 Organic matter inputs

- Practices that protect and maintain organic matter in tillage soils include: growing green manure crops, perennial forage crops and cover crops; applying animal manure or compost and incorporating straw and other crop residues into the soil (Bhogal *et al*., 2009).
- The application of organic materials is practical where supply is plentiful and the cost is likely to be minimal; some cost savings are possible due to the reduced use of manufactured fertilisers. The mechanisms for SOC increase are mainly from direct C inputs but also from increased biomass production resulting from nutrient additions and improvements in soil bio-physical properties (Bhogal *et al*., 2009).

- However, repeated applications of bulky organic materials (e.g. farmyard manures, poultry manures and biosolids) are likely to lead to increased soil phosphorus levels as the quantities supplied by regular applications of manure are likely to exceed crop offtakes. For manures that have a high readily available N content (i.e. poultry manures, livestock slurries and digestate) applications should also be managed to minimise the risks of nitrate leaching. It is important that manure applications are included in soil management plans to ensure that the nutrients supplied are accounted for when planning manufactured fertiliser applications and to minimise nutrient loadings which will limit the risks of diffuse air and water pollution (Bhogal *et al*., 2009).
- It has also been suggested that the addition of manufactured N fertiliser increases SOC over time through increasing crop biomass. However, this strategy will only be effective if crop residues are incorporated into the soil (Alvarez, 2005).

8.1.4 Cover crops

- Cover crops are used in tillage systems between harvest and the establishment of the following cash crop. They are usually used in spring cropping rotations and can be effective at reducing nitrate leaching losses and reducing the risk of soil damage from rainfall impact by providing soil cover over winter.
- Studies have shown that cover crops can increase soil organic matter content but the magnitude of the increase will depend on the amount of biomass that is produced and incorporated into the soil. Sainju *et al*. (2002) observed a 25% decrease in SOC following six years of conventional tillage without cover crops, whereas with a hairy vetch cover crop (returning *c.*0.7 t C/ha/year) SOC levels only declined by 1% and with a rye cover crop (returning *c.*3.7 t C/ha/year) SOC levels increased by 3-4%.
- Soil and weather conditions at the time of cover crop establishment are important factors controlling the effectiveness of cover crops. A meta-analysis of 30 studies (37 sites), including sampling depths which ranged from 2.5 cm to 120 cm found that the use of cover crops as a green manure led to a significant increase in SOC stocks (Poeplau and Don 2015); annual SOC sequestration rate was 0.32 ± 0.08 t C/ha/year rising to an average maximum increase of 16.7 t/ha. The authors also noted a linear relationship between the number of years that a cover crop had been included within a crop rotation and SOC stock change. Bai *et al*. (2019) found that leguminous cover crops were associated with greater SOC sequestration than non-leguminous crops.

8.2 Emerging management practices

8.2.1 Agroforestry

- Agroforestry systems combine trees with crops or pasture in the same field. According to Feliciano *et al.* (2018), there are five main forms of agroforestry, namely alley cropping, forest farming, silvopastoralism, riparian forest buffers, and windbreaks. Agroforestry allows the primary use of the land to continue (e.g. growing crops or grass) whilst delivering benefits for carbon sequestration. As a result, the Climate Change Committee (2020) identified agroforestry as a component of potential strategies to reduce agricultural emissions of GHG in the UK.
- Shi *et al*. (2018) used a meta-analysis of 427 soil C data pairs to assess changes in SOC compared to the adjacent cropland or pasture. The authors calculated that the mean SOC contents in agroforestry were 19% more than cropland or pasture (Figure 23).

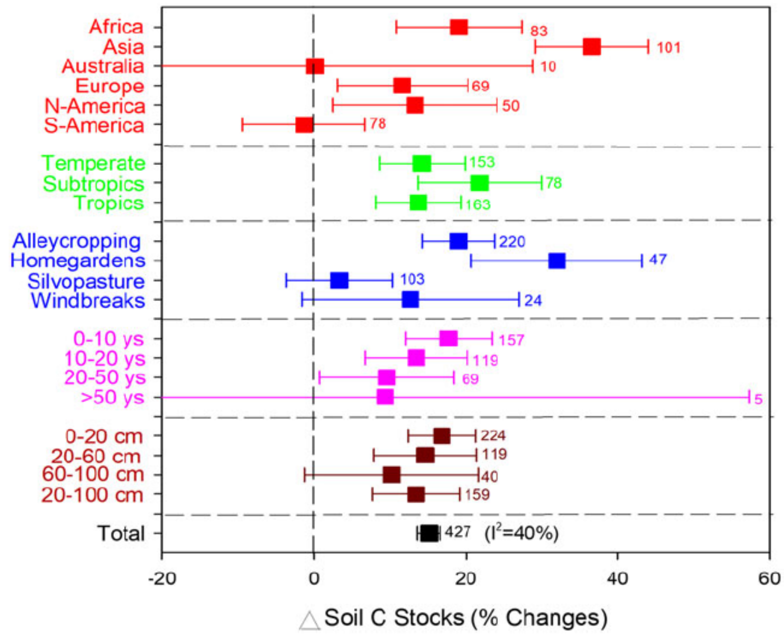

Figure 23. Changes in SOC stocks in agroforestry compared with cropland (or pasture) for six continents, three climate zones, four management systems, four tree age groups and four soil depth categories. Number indicates the number of data pairs included in the comparison; I^2= measure of heterogeneity (40% = low heterogeneity). (Source: Shi *et al*, 2018).

- Few studies have assessed the impact of agroforestry systems on carbon storage in soils in temperate climates, as most have been undertaken in tropical regions. Cardinael *et al.* (2017) quantified organic carbon stocks in soils and trees in six agroforestry system (5 silvoarable and 1 silvopasture) in comparison with adjacent control plots in France (Figure 24). After planting, the soil management of the agroforestry inter-rows was identical to the agricultural control plot. At all sites, the SOC concentration in the top 10 cm was significantly higher in the tree row than in the inter-row; increased SOC stocks were also found in deeper soil layers at two silvoarable sites. SOC content at the silvopastoral site, was also significantly greater at a depth of 30–50 cm than in the control. Overall, the mean organic carbon stock accumulation rate in the soil was 0.24 (0.09–0.46) Mg C/ha/year at a depth of 30 cm. For the UK it has recently been estimated that planting trees on agricultural land, while maintaining their primary use could deliver a 6 $MtCO_{2\text{-}eq}$ savings by 2050 (CCC, 2020).
- Research has suggested that productivity is higher in agroforestry systems compared to monocropping systems due to complementarity in resource-capture, i.e. trees acquire resources that crops alone would not (Cannell *et al*., 1996). Tree canopies can protect crops (and livestock) from wind stress, moderate temperature extremes, increase soil temperatures and improve soil water conditions. Conversely, shading from trees or potential competition for water can lead to reduced productivity.
- To date, much of the research has focused on agroforestry in tropical systems as a means of addressing food security and environmental issues in impoverished areas (Smith *et al*., 2012). However, more recently studies in temperate environments have also suggested yield advantages.
- The Land Equivalent Ratio (LER) calculates the amount of land that would be required for the same yield if two crops were grown separately (e.g. trees and wheat). For example, a LER of 1.1 indicates a 10% advantage of growing crops together (e.g. agroforestry) in comparison with a single crop.

- Graves *et al*. (2007) used the Yield-SAFE (yield estimator for long-term design of silvoarable agroforestry in Europe) model to predict LER for European agroforestry systems (silvoarable). The model predicted LER values between 1-1.4 for scenarios in Spain, France, and the Netherlands, indicating higher productivity when integrating trees and crops than when grown separately. Another study in Switzerland, also using the Yield-SAFE model, showed that in 12 out of 14 scenarios (both silvopastoral and silvoarable) mixed cropping led to LER measurements >1. In addition, 68% of the Swiss financial scenarios were found to be more profitable than current practices (Sereke *et al*., 2015).

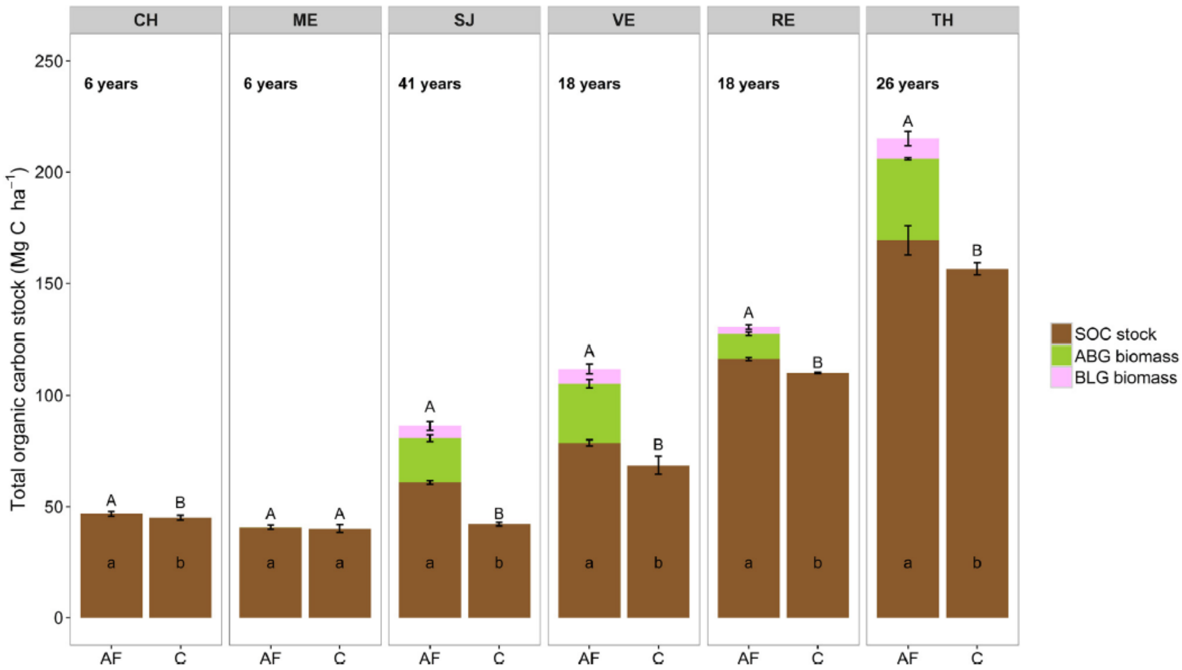

Figure 24. Total OC of the six agroforestry (AF) sites in comparison with control (C) sites. SOC: soil organic carbon; ABG: aboveground biomass and BLG: belowground biomass. Studied depths were 30 cm CH and ME, 20 cm SJ. 60 cm VE, 100 cm RE and 50 cm TH. Different lowercase letters indicate differences in SOC and different uppercase letters indicate differences in the total OC between AF and C plots per site (Source: Cardinael *et al*., 2017).

8.3 Innovative management practices

8.3.1 Perennial arable crops

- The majority of food produced for human consumption is provided by annual cereal crops that require annual cultivations, which can increase the risks of soil erosion, nutrient runoff or leaching, and loss of biodiversity and organic matter (Duchene *et al*., 2019). In comparison, it has been suggested that perennial grain agriculture has the potential to restore many of the ecosystem services that were lost by the conversion to annual grain production systems (Figure 25). Perennial crops, increase root carbon input and reduce soil disturbance thus potentially increasing SOC. Much of the work investigating the management of perennial arable crops has been carried out overseas and further work is required to assess their relevance for Welsh (and UK) agriculture.

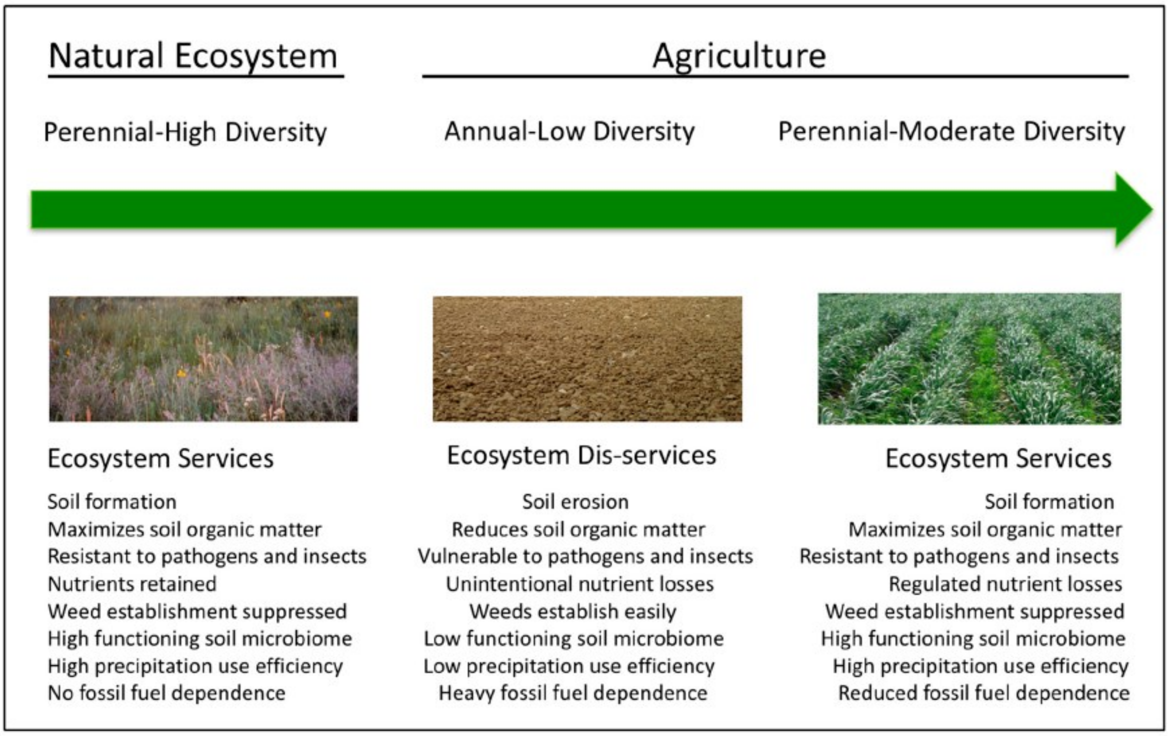

Figure 25. Changes in ecosystem services when 'natural' ecosystems are converted to annual grain ecosystems. Perennial grain agriculture has the potential to re-establish many of the services that were supported by the 'natural' ecosystem (Source: Crews and Cattani, 2018).

- Opportunities exist to develop a range of perennial crops through hybridization, as numerous annual grain or row crops such as maize, oats etc. have closely related wild perennial relatives (Cox *et al*., 2006). In the USA, the perennial wheat relative, intermediate wheatgrass (IWG) *Thinopyrum intermedium* marketed as Kernza is already being used in US food products. IWG, is much less productive than annual wheat varieties, due to a low harvest index of around 0.10 (i.e. only 10% of the total biomass is made up of grain, in comparison to annual wheat which typically has a harvest index of 0.45-0.55). For example, Culman *et al*. (2013) measured Kernza grain yield of <1-1.6 t/ha and vegetative biomass of 4-17 t/ha, compared to winter wheat grain yield of 3-5 t/ha and vegetative biomass of 3.5-4.5 t/ha. However, research has suggested that the IWG post-harvest residue could offer a beneficial low cost forage source for over-wintering cattle which could provide additional value.
- King and Blesh (2018) compiled a database of 169 cropping systems, which categorised rotations into three broad groups: 1) grain only, 2) grain with cover crops and 3) grain with perennial crops. The most effective crop rotations for increasing SOC concentrations relative to grain-only rotations were those that included a perennial crop (+12.5%) or a cover crop (+6.3%); the benefits were more pronounced in low N input systems. Thus the periodic use of a perennial phase in crop rotation will potentially improve soil carbon in the long term. Specifically, Crews and Rumsey (2017) have suggested that the conversion from annual to perennial grains could potentially accumulate up to 1.7 t/ha/year of soil organic carbon depending on soil and climate conditions.

8.3.2 Plant breeding

- Carbon sequestration in soils could be increased using plants specifically bred for the purpose. For example, increased root mass, could increase plant tolerance to both drought and flooding as well as potentially increasing C sequestration. The Salk Institute's Harnessing Plants Initiative is using genetic and genomic techniques to optimise a plant's natural ability to store carbon[6]. The aim is to produce plants that will have a deeper and larger root system which can store carbon for longer compared to common plant varieties. Once the methodology has been developed in model plants the aim is to transfer the genetic traits to six crops: maize, wheat, oilseed rape, soybean, rice and cotton. However, producing a new plant variety can take several years (decades) and consequently any benefits of this approach will only be felt in the long-term.

[6] https://www.salk.edu/science/power-of-plants/

9 Key drivers for potential increases in cultivated land in the UK

- Drivers for potential increases in cultivated land may be direct or indirect and affect both demand and supply of land. Direct drivers include land for expansion of existing uses such as development or afforestation, while indirect drivers are those higher-level factors which affect this demand such as markets and population growth (Elliot *et al.*, 2016). However, some drivers, such as climate change are both direct and indirect.
- The food system in Wales is currently integrated into the UK and European systems and is profoundly influenced by the wider global context (Welsh Government, 2010). Post Brexit, the close link to both the UK and Europe is still expected, at least in the short-term, to be an important driver of land use in Wales.

9.1 Demand for food and population growth

- The population of Wales is projected to increase by 3.1% to 3.21 million by 2026 and by 4.6% to 3.26 million by 2041 (Office for National Statistics, 2017). As such, there is expected to be a concurrent increase in the demand for food.
- Market trends, such as a drop in the demand for red meat and the desire for plant based protein or, for alternatives to dairy products could also influence the type of crops that are grown in Wales.

9.2 Exit from the EU

- The agriculture sector is a significant contributor to the Welsh gross domestic product and job market - in 2018 agriculture contributed £498 million (Gross Value Added) to the Welsh economy[7].
- The vast majority of international exports of Welsh agricultural produce go to EU nations (National Assembly for Wales, 2018). Currently the trade of agricultural produce between Wales and the EU is facilitated by the UK's membership of the Single Market and Customs Union, which remove all tariffs, customs and regulatory barriers to the movement of goods.
- Post-Brexit, there is a range of possible outcomes for the UK's future trading relationship with the EU, and negotiations between the UK and EU are ongoing. It therefore remains to be seen what the future UK-EU trade relationship will look like, and what this will mean for the agricultural sector. The UK and EU have agreed to a transition, or implementation, period which means that current trading arrangements are expected to continue until 31 December 2020[8].

9.3 Energy crops and biofuels

- Pressures on global energy supplies along with the desire to move away from fossil fuel sources will potentially increase the demand for land to grow energy crops for biomass or biofuels. Energy crops are grown solely for energy production rather than for food and there is some concern that the use of crop based biomass or biofuels can have negative consequences when land is taken out of food production, although some may be grown on poor land that would normally not be used for food production (JRC, 2010). Tilman *et al*. (2009) referred to this as the food, energy and environment trilemma, for example, replacing native grassland ecosystems with biofuels will release CO_2 (negating any GHG benefits of the biofuel). Similarly, replacing arable food crops with biofuel crops could lead to farmers elsewhere clearing native ecosystems to grow food crops – i.e. the negative impacts are displaced elsewhere in the world.

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[7] https://gov.wales/sites/default/files/statistics-and-research/2019-04/aggregate-agricultural-output-and-income-2018.pdf

[8] https://publications.parliament.uk/pa/cm201719/cmselect/cmwelaf/402/40205.htm

- The EU renewable Energy Directive states that by 2020 10% of transport fuel must come from biofuel, however, of this 10% only 5.5% can be from food crops, requiring increased bioenergy crop production while not impacting food crop production. In 2017, *c*.5% of UK transport fuel was from renewable energy suggesting that the demand for bioenergy crops is likely to increase.
- In 2017, the area of bioenergy crops (perennial and annual species) accounted for 2.2% of all arable land in the UK, of which 48% of the land used was for biofuel for the road transport market (Defra, 2019). Wheat (3% of UK land area in 2017/18) and sugar beet (5% of UK land area in 2017/18) can be grown for use in bioethanol. Over 60% of the crop-derived bioethanol for road transport originated from crops grown outside the UK.
- The main crops grown for use in the heat and electricity markets (burnt in power stations, combined heat and power units or heating systems) are miscanthus (0.1% of total arable area in England) and short-rotation coppice (0.1% of total arable area in England). Crops may also be purpose grown for use as feedstock in AD plants to produce biogas and digestate; in 2016/17, 32% of total feedstocks were crops grown purposely for AD (Defra, 2019). The most commonly grown crops for AD plants are maize, oilseed rape and grass.
- A recent report by the Climate Change Commission (2020), suggested that if the UK average planting rates of miscanthus, short rotation coppice and short rotation forestry were scaled up to 23,000 ha per year from the 2020s this would deliver 2 $MtCo_{2\text{-eq}}$ emission savings in the land sector.

9.4 Protein and pulse crops

- Protein rich plants (crude protein >15%) include oilseeds, sunflower seeds, beans, peas, lentils, lupins etc. (EC, 2018). The EU's self-sufficiency rate varies from 79% for rapeseed to only 5% for soya; the figures are likely to be even lower for Wales.
- The main market is for livestock feed, however, although the food market for plant protein is smaller it is potentially more profitable and growing. By 2054, global plant protein consumption is forecast to reach 943 m tonnes in the UK[9]. Most plant protein for the food market (e.g. lentils and chickpeas) is at present imported so there may be an opportunity to grow more in Wales.

9.5 Other crops (e.g. pharmaceutical or fibre)

- There is growing interest in the cultivation of a range of crops for non-food uses such as oil production or medicines, e.g. borage, calendula, camelina and starflower. For example, hemp, also known as *Cannabis sativa*, has been grown under licence in the UK since 1993, with the focus on the fibre market. However, the recent passing of the Cannabis for Medicinal Use Act has seen the demand for cannabis grow by over 500% in 2019[10]. This has been mainly driven by the demand for CBD oil, which is marketed for a range of aromatherapy and medicinal properties.

[9] https://www.fwi.co.uk/arable/crop-selection/market-opportunities/the-new-crops-that-could-soon-profit-uk-farmers

[10] https://www.farmersguide.co.uk/2019/05/one-crop-has-seen-demand-grow-by-500-across-europe-and-investors-are-taking-notice/

9.6 *Self sufficiency*

- The UK is not self-sufficient in food production; it imports just under half of the total food consumed and the proportion is rising[11]. Therefore, as a food-trading nation, the UK relies on both imports and a thriving agricultural sector to feed itself and drive economic growth.
- The level of self-sufficiency can be affected annually by factors such as crop disease, excess rainfall or drought. In addition, it varies according to sector with the UK 80% self-sufficient in meat and meat products, 84% in dairy products and eggs, 50% in cereals but only 19% in fresh fruit and vegetables (Welsh Government, 2010). The drive to increase self-sufficiency in cereal and fruit/vegetables may increase the demand to cultivate land for crops rather than for livestock production.
- A significant proportion (35-40%) of Welsh lamb and a small proportion (*c*.14%) of Welsh beef is exported to the EU; restricted access to the EU export market would therefore have an adverse effect on the red meat sector (AHDB, 2018). If new export markets are not found or are not a viable or profitable option then there could be economic and/or political pressure to use the previously grazed grassland for the production of other crops.

9.7 *Climate change*

- There is evidence that the biophysical capability of the land to support agricultural production has changed over recent decades as the climate has changed (ASC, 2016). The average length of the growing season has increased by around 60 degree-days over the 87-year period between 1914 and 2000 for Wales and England, with a substantial increase in the last decade of the 20th century. UKCIP predictions for Wales suggest that there will be an increase in both winter and summer temperature from the 2020s to the 2080s. In addition, although total annual rainfall is not expected to change over the same period the seasonal distribution will change so that winters will be wetter, and summers drier, than the present day.
- Published recommendations or guidelines on land use by Government or scientific institutions can also influence or direct land use management. For example, in 2018, the Climate Change Committee (CCC, 2018) suggested that as >50% of agricultural emissions were from sheep or cattle it would be of benefit to reduce livestock numbers considerably. If this advice was followed then it is likely that a significant area of grassland may become available for alternative uses. When considering any land use change it will be important to assess the impact that cultivating grassland soils is likely to have on carbon dioxide emissions to the atmosphere as well as other losses to the environment including nitrate, sediment and phosphorus losses to water, soil erosion etc.

[11] https://www.gov.uk/government/publications/food-statistics-pocketbook-2017/food-statistics-in-your-pocket-2017-global-and-uk-supply

10 Climate change mitigation policy in Wales

- The Welsh Government currently has a legally binding target to reduce greenhouse gas emissions by 'at least 80%' (compared to the baseline[12]) by 2050, set by the Environment (Wales) Act. In March 2019, the Welsh Government published, Prosperity for All: A Low Carbon Wales, which bought together existing policies and proposals across a range of sectors. The plan set out how Wales aimed to meet the first carbon budget (2016-2020) and established plans for future actions. However, in May 2019, the Committee on Climate Change (CCC) published 'Net Zero – the UKs contribution to global warming' in which it recommended that the UK set a net-zero target for all greenhouse gases (i.e. a 100% reduction from 1990 levels). For Wales, the CCC recommended a 95% reduction in emissions (relative to 1990), reflecting 'the large share of agriculture emissions in Wales and lower access to suitable sites to store captured carbon dioxide' (CCC, 2019).
- In April 2019, Lesley Griffiths (Minister for Environment, Energy and Rural Affairs) declared a climate change emergency in Wales and in June 2019, the Welsh Government accepted the CCC recommendation for a 95% reduction in emissions. However, the Government also stated their ambition to 'bring forward a target for Wales to achieve net zero emissions no later than 2050'[13]. The Welsh Government will bring regulations to the Assembly in 2020 to amend the existing 2050 target and amend Wales' interim targets and carbon budgets as necessary.
- At the end of last year the Welsh Government published Prosperity for All: A Climate Conscious Wales. The plan was the second climate change adaptation plan for Wales and responded to the risks identified in the Climate Change Risk Assessment for Wales. It details actions to reduce the risks of climate change to Wales over the next five years. Of relevance for this report are the plans to increase woodland cover (addressed by the Woodland for Wales strategy) and the need for change in future farm support (addressed by the consultation on future farm support outlined in Sustainable Farming and our Land).

11 Knowledge exchange for land managers to mitigate climate change

- The main provider of knowledge exchange in Wales is the Farming Connect (FC) programme[14]. It provides knowledge exchange, innovation and advisory services for farming and forestry businesses in Wales. It is designed to deliver greater sustainability, improved competitiveness and improved environmental performance. The programme focuses on climate change mitigation, biodiversity, forestry, red meat, dairy, grassland, arable, horticulture, organic production and pigs and poultry. Activities include one-to-many activities (including farm walks, visits to demonstration farms and strategic awareness events), group discussions and development sessions (including business clubs and Agrisgôp – an action-learning programme), and one-to-one advice (including planning and succession surgeries, the Farm Advisory Service etc.). There are also mass media events and impersonal forms of advice (such as fact sheets and articles in the newspaper directed at farmers). Mindful of the wide differences in messages to be communicated and the heterogeneous nature of the farming community, virtually the complete array of techniques encountered in international literature on agricultural extension is employed within FC (Hill *et al*., 2017).

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[12] 1990: carbon dioxide, methane, nitrous oxide. 1995: hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride, nitrogen trifluoride.

[13] https://gov.wales/wales-accepts-committee-climate-change-95-emissions-reduction-target

[14] https://businesswales.gov.wales/farmingconnect/

- The knowledge transfer programme is delivered by Menter a Busnes in conjunction with the Institute of Biological, Environmental and Rural Science (IBERS) (Aberystwyth University). Other providers include ADAS Wales, Welsh Innovation Farm Network (including FE colleges that deliver agricultural and forestry training in Wales) and Bangor University.
- The levy body organisations operating in Wales, Hybu Cig Cymru-HCC (Meat Promotion Wales) and the Agriculture and Horticulture Development Board-AHDB, also work alongside Farming Connect ensuring an integrated approach to KE.
- Farming Connect website includes technical advice on reducing GHG emissions and also the interactive farm tool, which allows users to click on the map (Figure 26) and find out about emission reduction strategies for particular areas.
- Farming Connect also hosts the Knowledge Exchange Hub, which provides an interface between researchers, advisory professional and land managers. It aims to increase the uptake of research outcomes and to increase researcher's awareness of on the ground issues. The hub provides links to a number of high level technical articles related to climate change produced by IBERS.
- In Wales, IBERS at Aberystwyth University and Bangor University are involved in research that addresses climate change. Also, in March 2019, it was announced that Cardiff University had been selected as the main hub for a £5 million research centre which will explore opportunities to achieve the emission cuts required to address climate change[15]. In the UK, as a whole, there are many universities, agricultural colleges and research institutes that undertake research of relevance to the mitigation of GHG emissions a selection of which are listed in Table 3.
- Food & Farming Future[16], is a free initiative to facilitate access to research and technology transfer publications. It incorporates OpenFields an online library of literature, which includes recent articles and guidance on climate change mitigation. It includes details on KE events throughout the UK.

[15] https://www.cardiff.ac.uk/news/view/1462532-uk-gets-new-5-million-climate-change-research-centre

[16] https://www.foodandfarmingfutures.co.uk/Library/home/home.aspx

Figure 26. The Farming Connect interactive farm tool detailing ways to increase profitability and reduce GHG emissions. Users click on the hotspots or headings to discover more detailed information (Source: https://businesswales.gov.wales/farmingconnect/reducing-ghg-emissions).

Table 3. A selection of agricultural research and knowledge transfer providers in the UK.

Research Providers & Expertise	Overview
ADAS	• ADAS undertakes research and consultancy in a wide range of areas (including soil use and management, soil quality, water regulation and carbon storage, nutrient management, climate change mitigation etc.)
Agricultural Colleges,	• E.g. Askham Bryan, Bishop Burton, Duchy, Myerscough, Hartpury, Writtle University College, University Centre Reaseheath etc.
Allerton Project https://www.gwct.org.uk/allerton/	• The Allerton Project (run by the Game & Wildlife Conservation Trust) combines commercial farming, research and demonstration. It aims to research the effect of different farming methods on wildlife and the environment. Research includes, tillage systems, soil biology and health, cover cropping etc.
Bangor University https://www.bangor.ac.uk/	• The research portfolio of the School of Natural Sciences includes soil science, climate change impacts and mitigation, catchment science, environmental microbiology, environmental pollution, crop science and breeding, conservation, ecological economics, forest and agroforestry science and ecosystem services.
Centre for Ecology and Hydrology https://www.ceh.ac.uk/	• Expertise includes, atmospheric chemistry and effects (air pollutants and greenhouse gases), hydro-climate risks (extreme weather, floods and droughts), soils and land use (measuring and modelling change).
Centres for agricultural innovation https://www.agritechcentres.com/	• Agritech centres are a collaboration between government, academia and industry. • The Centre for Crop Health and Protection https://chap-solutions.co.uk/ aims to increase crop productivity through the uptake of new technologies. • Agrimetrics https://agrimetrics.co.uk/aims to solve the challenges of economically and environmentally sustainable food production through the use of data, analytics and AI. • Agricultural Engineering Precision Innovation Centre https://agri-epicentre.com/, aims to accelerate the adoption of new technology to boost production.
Cranfield University https://www.cranfield.ac.uk/	• Environment and Agrifood: Improving precision agriculture and soil health, investigating atmospheric emissions and their impact on the environment, plant breeding and food storage solutions.

Food & Environment Research Agency (Fera) https://www.fera.co.uk/	• Interdisciplinary investigation and problem solving across plant and bee health, crop protection, sustainable agriculture, food and feed quality and chemical safety in the environment.
Food Security and Land Research Alliance http://www.fslra.ac.uk/	• An alliance between the University of Bath, University of Bristol, University of Exeter, Rothamsted Research and Cardiff University. • Expertise in plant breeding and disease, farm animal welfare, climate change, soil and nutrient science, sustainability and governance.
Harper Adams University https://www.harper-adams.ac.uk/	• Crop and Environment Research Centre: field trials – sustainable production, crop protection, post-harvest quality, efficient use of water by plants • National Centre for Precision Farming: the application of precision farming methods • Soil & Water Centre: training, workshops, demonstrations and advice • Centre for Evidence-based Agriculture: 'synthesises' existing agri-food evidence to support decision-making in policy, industry, practice and research • Drought mitigation group: drought tolerance in a wide range of crops
Innovation for Agriculture https://www.innovationforagriculture.org.uk/	• Connects farmers with farming research through workshops, farm walks and on-farm demonstrations.
Innovative Farmers https://innovativefarmers.org/	• A network of farmers and growers who are running on farm trials of innovative management practices.
Institute of Biological, Environmental and Rural Sciences (IBERS) https://www.aber.ac.uk/en/ibers/	• Research in response to global challenges such as food security, bioenergy and sustainability, and the impacts of climate change. IBERS' scientists conduct research on genes and molecules, whole organisms and the environment.
James Hutton Institute https://www.hutton.ac.uk/	• Expertise in soil science, soil microbiology crop improvement, modelling of natural systems and research related to climate change.
John Innes Centre https://www.jic.ac.uk/	• Expertise in plant science, plant breeding and genetics, interactions between the environment and crops, plant health/diseases and microbiology.
Lincoln University https://www.lincoln.ac.uk/home/	• Lincoln Institute for Agri-food technology aims to support and enhance productivity, efficiency, and sustainability in food and farming through research, education, and technology. The Institute's researchers are engaged in the development of technologies which add value or solve challenges across the food chain, 'from farm to fork'.

National Institute of Agricultural Botany (NIAB-TAG) and NIAB East Malling Research https://www.niab.com/	• NIAB research, information focuses on the sustainable intensification of crop production through improved genetics, precision agronomy and knowledge-based decision support tools (e.g. variety and husbandry trials, climate change effects on production and food security).
Newcastle University https://www.ncl.ac.uk/	• Institute for Agri-Food Research and Innovation (IAFRI): a joint venture between Newcastle University and Fera. The focus is on agri-diagnostics and biosecurity, agri-food production and protection and food safety and nutrition.
Nottingham Trent University https://www.ntu.ac.uk/	• Centre for Animal, Rural and Environmental Sciences Research: natural environment (nutrient cycling, pollutants in soils water and sediments) and sustainable agriculture and food security.
Organic Research Centre http://www.organicresearchcentre.com/	• ORC's research programme focuses on organic/agro-ecological approaches to food and farming. Research areas include plant breeding, reduced tillage, cover cropping, agroforestry, sustainable resource use, GHG emissions and mitigation.
Rothamsted Research https://www.rothamsted.ac.uk/	• Rothamsted focuses on strategic agricultural science including sustainable agriculture (including soil processes in arable and grassland systems, greenhouse gas emissions and climate change), plant sciences (including crop productivity and quality, nutrient use efficiency) and crop protection.
Royal Agricultural University https://www.rau.ac.uk/	• A range of applied research projects including sustainable agriculture (e.g. crop establishment techniques, weed management, bi-cropping and whole crop forage).
Scotland's Rural College (SRUC) https://www.sruc.ac.uk/	• Research groups include, crop and soil systems (e.g. minimising GHG emission, soil management), future farming systems, rural economy, environment and society (e.g. sustainable agricultural technologies, sustainable use of natural resources etc.).
University of Aberdeen https://www.abdn.ac.uk/	• School of Biological Sciences: soils and global change, soil microbial diversity, soil physics and the impacts of climate change on soil carbon.
University of Edinburgh https://www.ed.ac.uk/	• Global Academy of Agriculture and Food Security: agri-food systems innovation (soil biogeochemistry, sustainable agricultural production, climate change etc.).
University of Exeter https://www.exeter.ac.uk/	• Centre for Rural Policy Research: interdisciplinary team focusing on all aspects of the rural economy and society. • Land, Environment, Economics and Policy Institute (LEEP): aims to develop knowledge and understanding about how land and the environment are managed and used; the policies that affect this; the impact upon people and how policy should be better designed, appraised and evaluated.

University of Nottingham https://www.nottingham.ac.uk/	• Research addresses key real-world issues in microbial, plant, animal, food and environmental sciences (research themes include plants and crops, soil and the environment and sustainable agriculture).
University of Reading http://www.reading.ac.uk/	• Agriculture, food and health, including sustainable agriculture and food (e.g. sustainable intensification through plant physiology, crop modelling and seed science). • Environment, including understanding climate change.
University of Warwick https://warwick.ac.uk/	• Warwick Crop Centre: translational research in sustainable agriculture, horticulture and food security including crop production systems, pest, disease and weed control and plant and crop sciences.

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