UK 2012 | Climate Change Risk Assessment

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Climate Change Risk Assessment for the Agriculture Sector

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Statement of use

This report presents the research completed as part of the UK Climate Change Risk Assessment (CCRA) for a selected group of risks in the Agriculture sector. Whilst some broader context is provided, it is not intended to be a definitive or comprehensive analysis of the sector.

Before reading this report it is important to understand the process of evidence gathering for the CCRA.

The CCRA methodology is novel in that it has compared over 100 risks (prioritised from an initial list of over 700) from a number of disparate sectors based on the magnitude of the consequences and confidence in the evidence base. A key strength of the analysis is the use of a consistent method and set of climate projections to look at current and future threats and opportunities.

The CCRA methodology has been developed through a number of stages involving expert peer review. The approach developed is a tractable, repeatable methodology that is not dependent on changes in long term plans between the 5 year cycles of the CCRA.

The results, **with the exception of population growth where this is relevant, do not include societal change in assessing future risks, either from non-climate related change, for example economic growth, or developments in new technologies; or future responses to climate risks such as future Government policies or private adaptation investment plans**.

Excluding these factors from the analysis provides a more robust 'baseline' against which the effects of different plans and policies can be more easily assessed. However, when utilising the outputs of the CCRA, it is essential to consider that Government and key organisations are already taking action in many areas to minimise climate change risks and these interventions need to be considered when assessing where further action may be best directed or needed.

Initially, eleven 'sectors' were chosen from which to **gather** evidence: Agriculture; Biodiversity & Ecosystem Services; Built Environment; Business, Industry & Services; Energy; Forestry; Floods & Coastal Erosion; Health; Marine & Fisheries; Transport; and Water.

A review was undertaken to identify the range of climate risks within each sector. The review was followed by a selection process that included sector workshops to identify **the most important** risks (threats or opportunities) within the sector. Approximately **10%** of the total number of risks across all sectors was selected for more detailed consideration and analysis.

The risk assessment used UKCP09 climate projections to assess future changes to sector risks. Impacts were normally analysed using single climate variables, for example temperature.

A final **Evidence Report** draws together information from the 11 sectors (as well as other evidence streams) to provide an overview of risk from climate change to the UK.

Neither this report nor the Evidence Report aims to provide an in depth, quantitative analysis of risk within any particular 'sector'. Where detailed analysis is presented using large national or regional datasets, the objective is solely to build a consistent picture of risk for the UK and allow for some comparison between disparate risks and regional/national differences.

This is a UK risk assessment with some national and regional comparisons. The results presented here should not be used by the reader for re-analysis or interpretation at a local or site-specific scale.

In addition, as most impacts were analysed using single climate variables, the analysis may be over-simplified in cases where the consequence of climate change is caused by more than one climate variable (for example, higher summer temperatures combined with reduced summer precipitation).

Executive Summary

CCRA – purpose

This Climate Change Risk Assessment (CCRA) is being undertaken as part of the Adapting to Climate Change (ACC) cross government programme, based in the Department for Environment, Food and Rural Affairs (Defra). The first assessment will be laid before Parliament in January 2012 as required by the Climate Change Act. The CCRA objective is to inform UK adaptation policy in 2012, by assessing the current and future risks and opportunities posed by the impacts of climate change for the UK.

This report covers agriculture – one of eleven reports covering important sectors in the UK. The report explores the main climate related threats to agriculture, identifies those that may have the greatest impact and by deriving ‘response functions’ with specific climatic variables (primarily based on UK Climate Impact Projections 2009 - UKCP09), the potential risks from climate change are explored through the use of ‘risk metrics’. A preliminary assessment of associated costs, potential opportunities, adaptation responses and cross sectoral links is provided.

Agriculture – a multifunctional sector

Agriculture occupies 17.4 million ha or approximately 71% of UK land[1], 9.3 million ha or 70% of land in England (72% Scotland, 80% Wales and 74% NI), and provides a range of important benefits to society. Perhaps the most obvious of these is production of ‘food’ and ‘non-food’ crops with UK agricultural land contributing around 50% to UK food consumption (Defra, 2010). Agricultural ecosystems provide a range of other important services, including regulation of air quality, climate, and water purification. Agricultural land also delivers significant non-material cultural benefits such as land for recreation and valued characteristic landscapes.

The agricultural landscape represents the dominant image of nature for much of the UK’s population and is a valuable part of our heritage, with around 80% of England’s national park land sited on agricultural land[2]. Agricultural land also supports a range of semi-natural habitats, helping to support wildlife and biodiversity, and contributing to ecosystem services (Power, 2010). The importance of agricultural land therefore goes far beyond food production – the actions of farmers can thus have positive or negative effects on the range of services provided (FAO, 2007), all of which are likely to be affected by climate change.

Scope

In the CCRA, the agriculture sector is defined to include outdoor crop production, livestock and dairy farming and housed livestock – the so-called ‘food’ production components. However, we recognise that UK agriculture has a multifunctional role sitting at the interface between the natural environment and society, and contributing to a range of ‘non-food’ services including environmental and landscape enhancement, leisure and recreation as well as providing various raw materials. These ‘non-food’ aspects are considered by other CCRA sectors, including biodiversity, forestry, water and marine and fisheries. This report focuses on the risks and opportunities to

[1] Based on a total UK land area of 244,046km^2 (Collins, 1993)
[2] Although no statistics are available agriculture is a similarly important component of land use for National Parks in Scotland, Wales and Northern Ireland

agriculture and is intended to help manage and mitigate the future risks to agriculture by identifying the opportunities where actions should be focussed and supported.

Key findings

Climate change will influence the way crops grow, develop and yield. As a biological system, the driving force in outdoor crop production is photosynthesis. UK grown crops will be directly sensitive to any future changes in sunshine, rainfall, temperature and CO_2 concentration levels. There will also be indirect impacts on the agricultural potential of soils by modifying soil water balances, affecting moisture availability and land management practices including trafficability and workability. Reduced water availability for agricultural abstraction as a result of lower river flows will impact on supplemental irrigation, both for existing irrigated crops and on new crops which may need watering to cope with increased droughtiness. Climate change may lead to more frequent and extended periods of water logging, and more frequent and larger areas of inundation of high grade (floodplain) agricultural land, with consequences for agricultural productivity. There may be many other indirect effects – including, for example, changes in the range of native/non-native pests and crop diseases (e.g. potato blight, *fusarium*), increased crop damage (e.g. grapes and salads) at extreme temperatures, crop diversification and introduction of new or novel crops (e.g. maize, sunflowers), as well as changes in land suitability. Many of these impacts are inextricably linked and could have either a positive or negative impact, or a combination, depending on the assumed future socio-economic scenario and farmer perceptions to climate risk.

For outdoor livestock and animal farming, the effects of climate change will be complex and variable. Grass production may be enhanced by increases in the length of the growing season especially in upland areas, although future water shortages could limit production in some years especially in lowland areas. A changing climate would impact on livestock health, forage yields, feedstuff quality, availability and cost, water availability, thermal stress and related welfare issues, including disease spread and control measures. The main impacts are likely to relate to changes in CO_2 levels (impacting on grass productivity and dietary quality), temperature (causing heat stress, influencing reproductive capacity and increasing pathogen and fly problems), water availability (for grassland production), and weather extremes (changing housing and supplementary feed needs). Many of the issues identified for outdoor livestock are equally relevant to housed animals, although increasing energy costs pose a significant additional risk.

Assessing climate risks

In the initial review of risks to agriculture, known as the Tier 1 assessment, over 100 potential impacts were identified, although there were many inter-dependencies, with their consequences largely influenced by the assumed future emissions and socio economic conditions under which agriculture might operate. In a subsequent assessment, following disaggregation of agriculture into three sub sectors (arable, horticulture and livestock), these impacts were reassessed and prioritised. A shortlist of approximately 35 impacts was produced (Appendix 3). Impact scoring and ranking identified 9 main areas for metric analysis, known as the Tier 2 assessment.

For outdoor cropping, these metrics focussed on crop yield, flooding risk, pests and disease, aridity/drought, and water abstraction. For outdoor livestock farming (dairying), the risk metrics related to morbidity, milk production and heat stress. Three additional metrics including grassland productivity, soil erosion and new crop opportunities were later added.

For each metric, national and regionally available data were collated and combined with UKCP09 data to derive a set of 'response functions'. These were used to project future changes for selected time slices and emissions scenarios, using the median (50% probability level) projections to provide a 'central estimate'. The 10% and 90% probability levels were also derived and used to frame the uncertainty around these projections and provide a broad range of possible changes in each time period. The study has considered the impacts of using downscaled General Circulation Model (GCM) data from the HadCM3 GCM, as well as including 12 other non-downscaled GCMs, within the UKCP09 climatology. As such, the analysis captures some but not all of the spread of possible outcomes due to future changes in climate.

Managing risks – new opportunities and adaptation

A qualitative assessment of the major risks and consequences to UK agriculture, grouped by metric, together with the anticipated potential for adaptation has been completed. Although the majority of risks identified were projected to have negative consequences (e.g. flooding, aridity), there are also likely to be a range of new opportunities for agriculture. These include the introduction of new or novel crops, increased production potential and market opportunities for providing other goods and services. For many sub-sectors within agriculture, there remains much uncertainty in the direct impacts, but also uncertainty in the indirect effects, including the future sustainability of rural communities, the viability of particular production sectors and the increasing pressure on the natural resources (land, water, energy) on which agriculture is heavily dependent.

Financial consequences

The identified risks could have an economic impact on the viability and sustainability of UK agriculture. A summary of the estimated financial consequences of climate change on each risk metric (assuming 2010 prices with no uplift or discounting) is shown in Table S.1. The analysis shows the climate change signal with adjustment for socio-economic change on land use and prices, relative to the baseline period for the medium emissions (central estimate). The data monetises the risks as far as is reasonably possible and provides a common metric across sectors and impacts, to allow cross-comparison and an initial indication as to the relative importance of different climate change risks in the UK. As with the risk metric outputs, there is uncertainty in these data, and they should therefore be interpreted with caution.

Table S.1 Summary of projected financial consequences for key agriculture risk metrics

Risk metric	2020s	2050s	2080s	Estimation Method	Confidence Ranking	Notes
AG1a: Changes in sugar beet yield (due to warmer conditions)	+ M	+ M	+ M	Market Prices	M	Includes land use and price scenarios
AG1b: Changes in wheat yield (due to warmer conditions)	+ H	+ H	+ H	Market Prices	M	Includes land use and price scenarios
AG1c: Changes in potato yield (due to combined climate effects and CO_2)	Neg.	Neg.	Neg.	Market Prices	M	

Risk metric	2020s	2050s	2080s	Estimation Method	Confidence Ranking	Notes
AG2: Flooding risk to agricultural land	- M	- H	- H		L	
AG3: Risk of crop pests and diseases	?	?	?	Informed Judgement	L	
AG4: Agroclimate (aridity)	-H	-H	-H	Informed Judgement	L	
AG5: Water abstraction for crops	-	-	-	-		Not assessed
AG6: Livestock water abstraction	Neg.	Neg.	Neg.	Informed Judgement	L	
AG7a: Reduction in milk production due to heat stress	- L	- L	- L	Market Prices	M	Includes price scenarios
AG7b: Reduction in dairy herd fertility due to heat stress	- L	- L	- L	Market Prices	M	Includes price scenarios
AG8: Increased duration of heat stress: livestock	Neg.	Neg.	Neg.	Market Prices	M	
AG9: New crop opportunities	-	-	-	-		Not assessed
AG10: Grassland productivity	+ H	+ H	+ H	Market Prices	H	Assumes hay/silage use, and constant grass price

Notes: - signifies a negative impact or loss; + signifies that these are benefits or cost reductions.
Impact Cost Ranking: Low (L) = £1-9m/pa, Medium (M) = £10-99m, High (H) = £100-999m, Very High (VH) = £1000m+, Negligible (Neg.) <£1m/pa, ? not possible to assess;
Confidence: High (green), medium (yellow) and low (red).

It is also important to remember that UK agriculture also faces a wide range of 'non-climate' risks which also have financial consequences. The majority of these risks occur 'off-farm' and impact on growers and farming enterprises via various national and European agro-economic policy interventions; the increasing pressure of environmental regulations; limitations in the availability of finance; fluctuating exchange rates; and the relative power of supermarkets as these affect the operation of markets, including requirements for auditing and traceability. The most significant economic impacts 'on-farm' relate to the Common Agricultural Policy (CAP) reform, as this could affect farm income support, compliance requirements and incentives for environmentally sensitive farming. The identified climate risks and adaptation responses must therefore be considered in this wider context - this will require new investments in adaptive management and technology, including new collaborations between the public and private sectors, to enable UK agriculture to respond to the potential effects of climate change.

Analysis of future risks

A summary of the key outcomes for each risk metric and response function, its implications for assessing climate risks to agriculture, and the strength of evidence available, is given below. For most, the results are presented at a national scale; regional assessments have not been possible in most cases due to the dominance of nationally aggregated datasets available for the analyses.

Crop productivity

For many crops currently grown in the UK, the projected increases in temperature and elevated levels of CO_2 should provide more favourable conditions for crop growth and development. But these potential productivity gains will only be attained where the growing conditions are not constrained by other factors such as water and nitrogen availability, and the increased incidence of new pests and diseases. Higher energy costs will also affect potential productivity gains, since this will have a direct impact on fertiliser costs. Collectively, these factors will strongly influence the capacity of UK crop production sector to close the 'yield gap' – the difference between future 'actual' (farm) and 'potential' yields.

For the arable crop sector, wheat was chosen as a 'representative' crop. In the UK, average wheat yields have shown little increase over the past decade. At around 8 t ha^{-1} they have failed to increase in line with genetic improvements, suggesting that plant breeding benefits are being given away elsewhere in the production cycle. Like many crops, wheat yield is affected by abiotic (e.g. rainfall and temperature), biotic (e.g. pest and disease) and technology related issues, with interactions between each of these influencing actual farm yield. The plateau in current average yields could thus be attributed to soil management issues (e.g. degradation, compaction, fertility), inadequate crop nutrition, failure to control weeds, pests and diseases or, more likely, a combination of these factors.

As a C3 crop, wheat is highly sensitive to climate variability and change, and particularly to rising temperature and CO_2 levels. By combining national datasets on historical wheat yields with climate data, a simple yield response to temperature metric was developed and used to estimate future yield changes. From this, potential increases of wheat yields were projected to be 47% by the 2020s for the Medium emissions scenario, central estimate (range 22% to 76%), increasing to 79% by the 2050s for the Medium emissions scenario, central estimate (range 36% to 137%) and 111% by the 2080s for the Medium emissions scenario, central estimate (range 46% to 212%). However, it is important to note that these projections relate to changes from a 1961-90 baseline and not from current (2010) production levels. This is because projected changes in climate need to be referenced to a 'baseline' (typically a 30 year period). For the latest UKCP09 climatology the 1961-90 period is used as this corresponds to World Meteorological Organisation (WMO) global standard. The estimates of yield change also ignore any impact of CO_2 fertilisation. The metric developed is thus considered too crude for any objective assessment of the future impact of climate change on yield, but highlights the limitation of using a single climate variable and national statistics for impact assessment. A much more robust approach is to use a biophysical crop model capable of integrating a range of climate factors (including changes in CO_2 concentration) on crop development and yield.

Using a biophysical crop model (Sirius) and UKCIP02 data, Semenov (2009) projected future mean wheat yield (*cv.* Avalon) changes for the 2020s and 2050s using the same climate baseline (1961-90). Although there was wide geographical variation, increases of 17.5 to 20% for the 2050s (high scenario) were reported (with highest gains in south east England). Semonov (2009) noted that average yields would increase mainly owing to yield stimulation with rising CO_2. However, probably of more significance were the projected impacts of drought and heat stress on wheat yield. The analyses by

Semonov (2009) showed that the yield impact of drought stress on wheat was actually predicted to be smaller than that at present, because wheat would mature earlier in a warmer climate and thus avoid severe summer drought. However, the probability of heat stress occurring around flowering which could result in considerable yield losses was predicted to increase significantly, a factor which is reported to represent a much greater risk to sustainable wheat production (Barnabas *et al.*, 2008). UK growers may therefore have to contend with increased heat and drought risks between April and May and may use supplemental irrigation to avoid any negative crop yield impacts. This risk was highlighted in 2011 when drought conditions from April to June in parts of England (notably Shropshire, Suffolk and Cambridgeshire) threatened wheat crops, resulting in a number of farmers using their surplus irrigation capacity to irrigate their wheat in order to minimise any subsequent yield loss. These combined effects of changes in drought and heat stress frequency as well as shifts in longer term average seasonal conditions may thus have complex and significant impacts on arable agriculture. A more recent study by Thomas *et al.* (2011) using the probabilistic UKCP09 projections suggested mean wheat yield increases of 11.5%, broadly similar to those reported by Semonov (2009).

The assessment also considered the climate impacts on sugar beet, again using a simple metric combining national beet yield trends with temperature. Potential increases in sugar beet yield were projected to be 23% by the 2020s for the Medium emissions scenario, central estimate (range 11% to 37%), rising to 39% by the 2050s for the Medium emissions scenario, central estimate (range 18% to 68%) and 55% by 2080s for the Medium emissions scenario, central estimate (range 23% to 105%) (all from a 1961-90 baseline). However, UK yield increases in the years since 1961-90 have already outstripped these projections with current average yields of 7 t ha^{-1} (white sugar). The issues highlighted above regarding the simplicity of using a national level metric for crop impact assessment and the preferred approach using a biophysical crop modelling is equally relevant here. Richter *et al.* (2006) suggested that potential growth rates due to increased CO_2 levels and higher temperatures would result in average sugar yields rising by 1.4 and 2 t ha^{-1} (2050 lower limit and 2050 upper limit), although soil variability would have a major impact on yields regionally. In future, sugar yields on sandy soils (8 t ha^{-1}) were reported to increase only slightly (by 0.5 to 1.5 t ha^{-1}), but on loamy soils yields were likely to increase from 11 t ha^{-1} to between 13 t ha^{-1} and 15 t ha^{-1} (2050 upper limit and 2080 upper limit). Earlier sowing and later harvest dates were reported to compensate for any drought-related losses on sandy soils (Richter *et al.*, 2006). Similarly, further work, updating Richter *et al.* (2006) using the probabilistic UKCP09 projections would also be relevant for providing new evidence in support of subsequent CCRAs for agriculture.

For field-scale vegetable production, potatoes were chosen as a ‘representative’ crop. A response function combining national rain-fed yields to national mean summer rainfall variability was developed. Potential change in maincrop potato yields were projected to be -2% (i.e. a reduction) by the 2020s for the Medium emissions scenario, central estimate (range -7% to +3%), -5% by the 2050s for the Medium emissions scenario, central estimate (range -12% to +3%), and -6% by the 2080s for the Medium emissions scenario, central estimate (range -18% to +2%). Higher reductions are representative of the extreme dry scenario (lower limit) and the small positive yield increases were projected for the upper limit (wetter conditions).

However, the outcomes from this analysis are contrary to recent biophysical crop modelling studies which also considered the impacts of CO_2 fertilisation on potato yield. For example, for the 2050s using the UKCP09 climatology, Daccache *et al.* (2011a) showed that ‘potential’ yields might increase by 13-16%, but actual farm yields might only increase by 3-6% due to limitations in water and nitrogen availability. The potential increases are principally due to increased radiation and temperature levels and elevated CO_2 concentration effects. The analyses by Daccache *et al.* (2011a) also highlighted the risks associated with the climate impacts on potato irrigation demand, with the present 'design' capacity for irrigation infrastructure failing to meet future peak irrigation needs in nearly 50% of years. This has important repercussions for adaptation planning.

Whilst potato is an important crop in the field-scale vegetable sector, it is recognised that extrapolating these findings to other vegetable (and some horticultural crops) is not necessarily appropriate, given their very different physiological characteristics and responses to climate variability, particularly where quality assurance is an important determinant of profitability. The crop metrics used to project future yields also lacked sufficient integration of other factors (notably CO_2 fertilisation effects and climate variability) and assumed unchanged future farm practices regarding crop, water and nitrogen management. Whilst the metrics provide a useful context of the likely impact, robust impact assessments should preferably be based on more complex biophysical (crop) modelling approaches. However, for a range of important crops grown in the UK (e.g. field vegetables, soft fruit), the scientific literature highlights significant gaps in robust evidence on the projected impacts of climate change, including climate uncertainty and adaptation responses. In this context, a 'systematic review' of the reported impacts of climate change on crop productivity for the UK could prove highly valuable, adopting a similar approach to that adopted for the international assessment of climate impacts on crop productivity by Knox *et al*. (2011b).

Grassland productivity

Experimental evidence shows that grass production can increase in response to higher temperature and CO_2 concentration, both singly and especially in combination, as long as other factors affecting grass growth are not limiting.

The risk metric for grassland-based livestock production was herbage dry matter (DM) yield. Herbage refers principally to grasses of sown and unsown species, together with non-grass forage species of grassland, such as clovers and other legumes as well as any other non-grass species in the sward.

This study considered experimental and modelling evidence based on the earlier UKCIP02 scenarios. These results provide an indication of the sensitivity of different systems to warmer conditions and suggest a 15 % increase in yield per degree of warming for conditions with adequate water and nitrogen. This relationship can be used, within reason, to scale and estimate possible outcomes for UKCP09 projections. On this basis, grass yields in the UK were projected to increase by 20% by the 2020s for the Medium emissions scenario, central estimate (range 11% to 31%), rising to 35% for the 2050s Medium emissions scenario, central estimate (range 18% to 53%) and 49% for the 2080s Medium emissions scenario (range 24% to 54%)[3]. Increases in yield in Scotland and Northern Ireland may exceed those in England where water stress becomes a limiting factor.

New crops

Changes in agroclimate will influence future land suitability with implications for existing crops (Daccache *et al*., 2011b) and new crops. A wide range of new crops could potentially be grown depending on how changes in rainfall and temperature affect soil conditions (i.e. workability, trafficability). New food crops could include blueberries, maize, table grapes, sunflowers, soya; new energy crops for biogas, biomass or bioethanol production could emerge; new pharmaceutical crops (for drugs or cosmetics) and new industrial crops (e.g. for biopolymers, biolubricants, oil, fibre, paper and pulp) could also all become agronomically viable. However, for many new crops,

[3] 2080s figures are extrapolated based on temperature, CO_2 and precipitation

data on future potential yields and their economic viability is very limited, or non-existent.

Crop pests and disease

For each 'reference' crop, an important climate related 'marker' disease was defined (yellow rust for wheat; beet mild yellow virus, BMYV for sugar beet and blight for potatoes). Unfortunately, despite having access to long-term historical data for each 'marker' disease, no significant relationships were found between incidence of marker disease and climate variability - the underlying reason being that disease treatment methods and improved crop agronomy within each of these crop sectors over the last few decades has significantly reduced disease expression and buffered the effects of climate variability on disease prevalence.

Recent research does show that many pests and pathogens exhibit considerable capacity for generating, recombining, and selecting fit combinations of variants in key pathogenicity, fitness, and aggressiveness traits, so there is little doubt that any opportunities from climate change would be exploited by them (Gregory *et al.,* 2009). But the interactions between crops, pests and pathogens are complex and currently poorly understood in the context of climate change. More mechanistic inclusion of pests and pathogen effects in crop models would lead to more realistic projections of crop production at regional scales and assist in the development of robust climate change risk assessments (Gregory *et al.,* 2009). Based on a qualitative assessment, the evidence available on the climate risks to UK crop pests and disease is considered weak. However, recent research by Thomas *et al.* (2011) does provide new evidence on the impacts of climate change for selected crops and selected diseases.

Animal pests and diseases

A recent comprehensive review of the links between climate and animal disease is provided by Haskell *et al.* (2011). They report that environmental change has been implicated as one of the driving forces for range expansions of several classes of pathogens, with changes in climate affecting both established infectious diseases (parasitic and viral) and the emergence of new diseases, such as a Blowfly strike (Morgan and Wall, 2009) where high blowfly abundance is linked to higher maximum temperatures and higher rainfall. Regarding parasitic diseases, they refer to extensive scientific literature on the links between changes in helminthiasis abundance and distribution with environmental change (e.g. Fox *et al*., 2011).

A changing climate may also be linked to the spread of Bluetongue virus (BTV). The review by Haskell *et al*. (2011 cites evidence from Purse *et al.* (2005) and Wilson and Mellor (2008) on the climate impacts on the vector dynamics and BTV transmission, documenting its spread across Europe which has killed >1 million sheep since 1998 (Saegerman *et al*., 2008). Climate change was identified as a potential influencing driver. Most stages of the culicoides (midge) virus vector life cycle are governed by temperature. Haskell *et al.* (2011) report that these vectors have other traits that raise concerns from a climate change perspective – namely that their high dispersal potential means they are likely to track shifting climate envelopes. Extreme weather events, such as high winds, are also likely to aid the passive dispersal of the violent vectors into the newly viable habitats. Environmental change will also affect the availability of breeding sites, for example due to changes in irrigation, flooding and agricultural practices. Sea level rise, storms and flooding could also lead to an increase in brackish breeding sites for the halophilic *Culicoides pulicaris* groups (Wilson and Mellor, 2008).

Flood risks to agriculture

Agricultural land is at risk from flooding from rivers, coasts and estuaries and groundwater. Response functions for agricultural land at risk of frequent tidal and river flooding were based on GIS analysis of flood risk areas combined with spatial assessments of land suitability using the Agricultural Land Classification (ALC) to estimate the areas of agricultural land flooded from the sea with return periods of less than 1 in 3 years, 3-5 years and 5-10 years, and for ALC Grades 1 to 3 (horticulture/arable) and 4 and 5 (grassland/grazing), for selected time slices and scenarios. Flooding may happen in the short-term due to extreme rainfall events, as well as through long term climate changes. Furthermore, flooding is likely to increase in the long term due to sea level rise which will have a knock-on impact on tidal flooding and estuary water levels.

Flooding of agricultural land from rivers with a frequency of 1 in 10 years on average or greater is projected to increase from a 1961-90 baseline of about 150,000 ha to about 210,000 ha by the 2020s (central estimate) increasing to approximately 310,000 ha projected for the 2080s central estimate.

In the near term (2020s) small increases are projected in the area at risk of frequent flooding (1 in 3 years or greater) but larger increases are projected for flood frequencies of 1 in 10 years or greater. The area of land flooded by regularly occurring events (33% annual probability or greater) could increase from a baseline of about 53,000ha to about 63,000ha by the 2020s. This is projected to double to about 120,000ha by the 2050s and reach 200,000ha by the 2080s, about four times the present day area.

The area of high quality agricultural land (grades 1, 2 and 3) at risk of very frequent river and tidal flooding (frequency of 1 in 3 years on average or greater) is projected to increase from a 1961-90 baseline of about 30,000 ha to about 35,000 ha by the 2020s, reaching approximately 130,000 ha by the 2080s. The large area of land potentially affected by frequent flooding in the future may have significant impacts on the agricultural sector.

In the longer term (2050s, 2080s) large increases are projected in the areas of agricultural land that would be at flood risk from the sea on a regular basis (almost every other year). Under the highest rates of relative sea level rise for the 2080s High emissions scenario (average sea level rise about 57 cm), a ten fold increase is projected in the amount of good quality agricultural land that would be at risk of regular flooding from the sea, making it untenable for normal agricultural use. There are also large increases projected in the amount of grassland and rough grazing at risk of frequent flooding from the sea, although some of this land may still be used for grazing.

Surface water flooding and waterlogging are also serious problems for agriculture. However, these have not been analysed due to a lack of suitable information on present and future risks.

Based on a qualitative assessment, the evidence available on the climate risks related to flooding of agricultural land is considered to be strong.

Aridity and agroclimate

National level changes in aridity using potential soil moisture deficit (PSMD) as an agroclimate index suggest central projection increases of 38% for the 2020s Medium emissions scenario (range of -33% to 116%), rising to 86% (range of -7% to 183%) by the 2050s and 118% (range of 4% to 277%). The data represent a nationally averaged assessment but mask significant spatial variability. Combined projected changes in rainfall and evapotranspiration (ET) would increase aridity levels and demand for supplemental irrigation, particularly on high-value crops where quality assurance is a key market requirement. Many crops that are currently irrigated would require more frequent and larger applications of irrigation. For some crops dependent on rain-fed production, yields may become limiting; irrigation would then be necessary to maintain current production levels. Maps showing the spatial changes in agroclimate highlight areas of high aridity which generally increase in area and magnitude and spread across England from the south and east towards the north and west. The maps suggest that by the 2050s, eastern, southern, and central England might have irrigation needs greater than those currently experienced anywhere in the UK. Of course, any increases in irrigation water demand would be influenced by water resources availability, which itself is forecast to become considerably more scarce (Knox *et al.*, 2009). Baseline maps for Scotland have also been produced (Knox *et al*., 2009) but further analysis of the impacts on future changes in agroclimate is needed.

Changes in agroclimatic conditions may also influence lowland and upland farming systems. As yields increase, the viability of farming marginal land could also increase, leading to increases in the area of land for agriculture and changes in the composition of farmed land in some areas. For example, grassland productivity in upland areas could increase and some upland areas may become more suited to arable production. This increase in the intensity of farming in upland areas could have indirect consequences for soil erosion and biodiversity.

Other factors such as concerns regarding methane emissions could also affect upland based production systems and the extent of upland grazing.

Based on a qualitative assessment, the evidence available on the climate risks related to changes in agroclimate and aridity is considered to be strong.

Land suitability

Future changes in land suitability were not addressed in this round of CCRA but are acknowledged to be an important factor influencing the future composition and profitability of agricultural land use. This is because changing soil characteristics and agroclimatic conditions greatly influence crop selection, agronomic husbandry practices and the economics of production. For example, recent research by Daccache *et al.* (2011b) highlighted the potential impacts of climate change on land suitability for both rainfed and irrigated potato production, and current Defra funded work is assessing the potential future changes in agricultural land classification (ALC). Understanding the future risks to agriculture in the context of changes in land suitability across the broad spectrum of agricultural crops is recognised as an important gap in current knowledge.

Soil erosion

Increases in annual average rainfall are projected together with an associated increase in periods of heavy rainfall. This has the potential to increase soil erosion. An assessment of soil 'erosivity' has been made based on the number of days with heavy rainfall and rainfall intensity. The UKCP09 variable *"winter precipitation on the wettest day of the winter season*" was used to provide a first order and broad scale estimate of changes in erosivity at the UKCP09 river basin scale. The results show increases in erosivity throughout the UK, with greatest increases in south west and north of England as well as in Wales, Northern Ireland and Scotland.

Soil erosivity provides an indicator of soil erosion potential and the areas that might be at risk. However actual erosion also depends on other characteristics including vulnerability of different soils to erosion. It is therefore not possible from this analysis to provide projections of the potential amount of soil that could be lost.

Agricultural water demand

Agricultural water abstraction in England and Wales constitutes a very small proportion (1-2%) of total national abstraction but is concentrated in the driest years, in the driest catchments and at the driest times of year when resources are most constrained (Knox *et al.*, Undated). By combining historical irrigation abstraction data for England and Wales from the Environment Agency with data on agroclimate, increases in agricultural water demand for spray irrigation were projected to be approximately 15% for the 2020s Medium emission scenario, central estimate (range -20% to +52%), rising to 34% for the 2050s Medium emission scenario, central estimate (range -9% to +76%) and 45% for the 2080s Medium emission scenario, central estimate (range -4% to +108%). In the near term (2020s) this indicates upward pressure on water resources for agriculture for the central and upper bound medium emissions scenario. In the longer term (2050s, 2080s), it is very likely that there would be significant increases in water abstraction for crops as changes in agroclimate and increasing aridity combine with increased demands for food production. These estimates are consistent with research by Weatherhead *et al.* (2008) who considered future agricultural demands under a range of socio-economic scenarios. That study reported increases of +22% to +180%, clearly significantly higher than the estimates produced from this metric analysis. Socio-economic changes would thus add further pressure on the underlying demand for water abstraction, potentially more than doubling agricultural demand over and above that due to climate change.

In the UK, a significant proportion of water abstracted for irrigation is used for quality assurance – mainly controlling the incidence of scab control on potatoes, or in helping to achieve optimum produce standards (e.g. fruit and vegetable size, shape and colour). Changes in dietary preferences due to climate change (e.g. switching to a greater dependence on salads and pasta) and/or changes in consumer attitudes to produce quality (such as potato skin finish, shape, size) could have significant impacts on the volumes of water abstracted for irrigation.

Based on a qualitative assessment, the evidence available on the climate risks related to changes in agricultural water demand (abstraction) is considered to be moderate.

Livestock production

The livestock metric analysis was based on modelling the production system, including the effects of thermal humidity and heat stress on dairy milk production. It is important to note that the losses defined in this study related to the average change in climate and do not include extreme weather events that may result in higher numbers of heat stress losses (e.g., heat wave, drought). Overall, the current UK climate does not result in losses from dairy system production or pose a major risk to dairy production and this is likely to continue in the near term (2020s). The projections suggest that heat stress related losses only begin to become significant by the 2050s. For example, for the 2050s central estimate (medium emissions), the percentage loss of national milk production due to heat stress is projected to be about 3 million kg/annum, less than 0.03% of UK current milk production but there would be costs related to declines in herd fertility. In the longer term (2050s, 2080s) consequences are projected to become more significant under some scenarios with more humid and hotter conditions to the extent that they would impact on farmers operating on low margins and regional economies that rely on export of dairy products.

The livestock production model indicates small and largely insignificant increases in the number of days of heat stress for typical dairy herds. For example, in the 2080s (upper estimate of the high emissions scenario), the model indicates a maximum of 3 days per annum where livestock would be classified as stressed. Consequently the expected number of deaths from heat stress is considered negligible and the overall risk for the production system is related to the metric on decline in milk production and fertility.

Based on a qualitative assessment, the evidence available on the climate risks related to livestock dairying production and heat stress is considered to be strong. The analysis does not however cover other livestock. In particular, pigs and poultry could be more severely affected by heat stress (Haskell *el al*., 2011).

Impacts on livestock

A recent and thorough review of the impacts of climate change on livestock, including dairying, beef cattle, pigs and poultry is provided by Haskell *et al.* (2011). Their evidence relates primarily to the direct impacts of thermal stress on animal well-being and health, as well as indirect climate impacts, including impacts on feed availability, competition for land use and climate induced consequences on animal transport.

‘Non-climate’ risks and food security

Internationally, agriculture is widely regarded as one of the sectors at most risk from a changing climate, due to the impact of increasing temperatures, changing rainfall patterns and increased frequency of extreme events, not only in the tropics (Wheeler and Kay, 2010; Lobell, 2010) but also in temperate environments such as the UK (Falloon and Betts, 2009; Knox *et al.*, 2010c). In the future, producing food sustainably in a changing and uncertain climate will become a higher priority given the rising pressures on land and natural resources due to a growing population (Defra, 2010b). But climate change is just one of a number of stresses on agriculture and responses to these threats need to be sensitive to ecosystems and the diversity of benefits that agriculture provides, and not just to food production.

UK agriculture also faces a range of ‘non-climate’ risks which could be argued present a more immediate threat to sustainable food production than climate change. The majority of these occur ‘off-farm’ and impact on growers via various national and European agro-economic policy interventions; the increasing burden of environmental regulations; limitations in the availability of finance; fluctuating exchange rates; and the relative power of supermarkets as these affect the operation of markets, including requirements for auditing and traceability. The most significant economic impacts ‘on-farm’ relate to CAP reform, as it could affect farm income support, compliance requirements and incentives for environmental sensitive farming. Livestock farmers also face a range of production risks. These include, for example, increased volatility in foreign exchange rates, especially £:Euro and £:US$, coupled with instability in commodity markets (global and European), impacting on crop and feed prices and other agricultural inputs). Livestock enterprises also face disease risks, both endemic (present in the UK e.g. Bovine TB), exotic (not usually present in the UK, except during outbreaks, for example, Foot and Mouth Disease) and new and emerging diseases, which all have the potential to cause significant economic damage, threatening UK food production, the agricultural sector and individual farming enterprises. The climate risks and adaptation responses for the agriculture sector identified in this report must therefore be considered in this wider context.

The UK agriculture sector faces a challenging period ahead, balancing the need to increase productivity whilst controlling spiralling farm costs, particularly in relation to energy. Farmers also need to demonstrate compliance with regulations associated with environmental protection, food safety and biosecurity. In this context, coping with immediate economic, environmental and technological pressures means that farmers are less inclined to give climate change the priority it deserves as a key business risk. Climate change, however, is likely to exacerbate many of the current challenges already facing the agri-food sector. Clearly, it presents both threats and opportunities to UK agriculture, but the key to tackling climate change will be in adaptation – securing access to the relevant skills, resources and knowledge to increase production efficiency, improve management and embrace new technology.

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Glossary: Key Terms

The key terms are defined below.

Adaptation (IPCC AR4, 2007)

- **Autonomous adaptation** – Adaptation that does not constitute a conscious[4] response to climatic stimuli but is triggered by ecological changes in natural systems and by market or welfare changes in human systems. Also referred to as spontaneous adaptation.
- **Planned adaptation** – Adaptation that is the result of a deliberate policy decision, based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state.

Adaptive Capacity -The ability of a system to design or implement effective adaptation strategies to adjust to information about potential climate change (including climate variability and extremes), to moderate potential damage, to take advantage of opportunities, or to cope with the consequences (modified from the IPCC to support project focus on management of future risks) (Ballard, 2009). As such this does not include the adaptive capacity of biophysical systems.

Adaptation costs and benefits

- The costs of planning, preparing for, facilitating, and implementing adaptation measures, including transition costs.
- The avoided damage costs or the accrued benefits following the adoption and implementation of adaptation measures.

Consequence - The end result or effect on society, the economy or environment caused by some event or action (e.g. economic losses, loss of life). Consequences may be beneficial or detrimental. This may be expressed descriptively and/or semi-quantitatively (high, medium, low) or quantitatively (monetary value, number of people affected etc).

Impact - An effect of climate change on the socio-bio-physical system (e.g. flooding, rails buckling).

Response function - Defines how climate impacts or consequences vary with key climate variables; can be based on observations, sensitivity analysis, impacts modelling and/or expert elicitation.

Risk – Combines the likelihood an event will occur with the magnitude of its outcome.

Sensitivity - The degree to which a system is affected, either adversely or beneficially, by climate variability or change.

Uncertainty - A characteristic of a system or decision where the probabilities that certain states or outcomes have occurred or may occur is not precisely known.

Vulnerability - Climate vulnerability defines the extent to which a system is susceptible to, or unable to cope with, adverse effects of climate change including climate variability and extremes. It depends not only on a system's sensitivity but also on its adaptive capacity.

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[4] The inclusion of the word 'conscious' in this IPCC definition is a problem for the CCRA and we treat this as anticipated adaptation that is not part of a planned adaptation programme. It may include behavioural changes by people who are fully aware of climate change issues.

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1 Introduction

1.1 Background

It is widely accepted that the world's climate is being affected by the increasing anthropogenic emissions of greenhouse gases (GHG) into the atmosphere. Even if efforts to mitigate these emissions are successful, the Earth is already committed to significant climatic change (IPCC, 2007).

Over the past century, the Earth has warmed by approximately 0.7°C[5]. Since the mid-1970s, global average temperature increased at an average of around 0.17°C per decade[6]. UK average temperature increased by 1°C since the mid-1970s (Jenkins *et al*., 2009a), however recent years have been below the long-term trend highlighting the significant year-to-year variability. Due to the time lag between emissions and temperature rise, past emissions are expected to contribute an estimated further 0.2°C increase per decade in global temperatures for the next 2-3 decades (IPCC, 2007), irrespective of mitigation efforts during that time period.

The sorts of impacts expected later in the Century are already being felt in some cases, for example:

- Global sea levels rose by 3.3 mm per year (± 0.4 mm) between 1993 and 2007; with approximately 30% due to ocean thermal expansion and 55% to melting land ice (Cazenave and Llovel, 2010).
- Acidification of the oceans caused by greater atmospheric CO_2 concentrations is likely to have a negative impact on marine organisms and there are signs that this is already occurring, e.g. reported loss of shell weight of Antarctic plankton, and a decrease in growth of Great Barrier coral reefs (ISCCC, 2009).
- Sea ice is already reducing in extent and coverage. Annual average Arctic sea ice extent has decreased by 3.7% per decade since 1978 (Comiso *et al*., 2008).
- There is evidence that human activity has doubled the risk of a very hot summer occurring in Europe, akin to the 2003 heatwave (Stott *et al.*, 2004).

The main greenhouse gas responsible for recent climate change is carbon dioxide (CO_2) and CO_2 emissions from burning fossil fuels have increased by 41% between 1990 and 2008. The rate of increase in emissions has increased between 2000 and 2007 (3.4% per year) compared to the 1990s (1.0% per year) (Le Quéré *et al*., 2009). At the end of 2009 the global atmospheric concentration of CO_2 was 387.2 ppm (Friedlingstein *et al*., 2010); this high level has not been experienced on earth for at least 650,000 years (IPCC 2007).

The UK and devolved Governments are committed to action to both mitigate and adapt to climate change[7] and the Climate Change Act 2008[8] makes the UK the first country in

[5] Global temperature trends 1911-2010 were: HadCRUT3 0.8 C/century, NCDC 0.7 C/century, GISS 0.7 C/century. Similar values are obtained if we difference the decadal averages 2000-2009 and 1910-1919, or 2000-2009 and 1920-1929.
[6] Global temperature trends 1975-2010 were: HadCRUT3 0.16 C/decade, NCDC 0.17 C/decade, GISS 0.18 C/decade.
[7] http://www.defra.gov.uk/environment/climate/government/
[8] http://www.legislation.gov.uk/ukpga/2008/27/contents

the world to have a legally binding long-term framework to cut carbon emissions, as well as setting a framework for building the nation's adaptive capacity.

The Act sets a clear and credible long term framework for the UK to reduce its greenhouse gas emissions including:

- A legal requirement to reduce emissions by at least 80% below 1990 levels by 2050 and by at least 34% in the period 2018-2022.
- Compliance with a system of five-year carbon budgets, set up to 15 years in advance, to deliver the emissions reductions required to achieve the 2020 and 2050 targets.

In addition it requires the Government to create a framework for building the UK's ability to adapt to climate change and requires Government to:

- Carry out a UK wide Climate Change Risk Assessment (CCRA) every five years.
- Put in place a National Adaptation Programme for England and reserved matters to address the most pressing climate change risks as soon as possible after every CCRA.

The purpose of this first CCRA is to provide underpinning evidence, assessing the key risks and opportunities to the UK from climate change, and so enable Government to prioritise climate adaptation policies for current and future policy development as part of the statutory National Adaptation Programme which will begin from 2012. The CCRA will also inform devolved governments' policy on climate change mitigation and adaptation.

Climate Change Act: First 5 year Cycle

The Scope of the CCRA covers an assessment of the risks and opportunities to those things which have social, environmental and economic value in the UK, from the current climate and future climate change. This is in order to help the UK and devolved Governments identify priorities for action and implement necessary adaptation measures. The Government requires the CCRA to identify, assess, and where possible estimate economic costs of the key climate change risks and opportunities at UK and national (England, Wales, Scotland, Northern Ireland) level. The outputs from the CCRA will also be of value to other public and private sector organisations that have a stake in the sectors covered by the assessment.

The CCRA will be accompanied (in 2012) with a study on the Economics of Climate Resilience[9] (ECR) that will identify options for addressing some of the priority risks identified by the CCRA, and will analyse their costs and benefits. This analysis will provide an overall indication of the scale of the challenge and potential benefits from acting; and, given the wide-ranging nature of possible interventions, will help to identify priority areas for action by Government on a consistent basis.

This will be followed by the first National Adaptation Programme (NAP) for England and reserved matters. The NAP will set out:

- objectives in relation to adaptation
- proposals and policies for meeting those objectives
- timescales

[9] http://www.defra.gov.uk/environment/climate/government/

- an explanation about how those proposals and policies contribute to sustainable development.

The CCRA analysis has been split into eleven sectors to mirror the general sectoral split of climate impacts research; agriculture, biodiversity and ecosystem services, business industry and services, built environment, energy, floods and coastal erosion, forestry, health, marine and fisheries, transport and water.

1.2 Scope of the agriculture sector report

As climate is a primary determinant of agricultural productivity, any future changes will influence crop growth and yield, hydrologic balances, input supplies and other components of managing agricultural systems. Yet the nature of these biophysical effects and the human responses, including adaptation, remain complex and uncertain (Adams *et al*., 1998). For global agriculture these projected spatial and temporal changes in climate (precipitation and temperature) will shift agro-ecological zones (Kurukulasuriya and Mendelsohn, 2008) and have major impacts on the viability of both dryland subsistence (Challinor *et al.*, 2005) and irrigated commodity crop production (Knox *et al*., 2010a). For agriculture in the UK, the changes being projected by the range of GCMs are likely to result in significant impacts across all the dimensions of agricultural production, including outdoor cropping (both arable and horticulture), livestock and dairy farming and housed livestock.

This chapter provides a brief overview of the projected changes in climate, from an agricultural perspective, reviews the various sectors of production likely to be at risk, and sets the policy context. For temperate regions such as the UK, there are also likely to be benefits associated with climate warming, presenting opportunities for diversification, and the introduction of new crops. The risks and opportunities presented by climate change to UK agriculture therefore specifically need to be considered in parallel, given that some negative impacts may well be offset by positive opportunities. For example, recent research suggests that winter wheat and maize yield may increase to a greater extent in UK than areas of southern Europe which may experience substantial reductions in the duration of crop development stages (grain filling) and limited benefit from CO_2 enrichment. This may provide a competitive advantage for UK agriculture in regards to farm production and trade.

1.3 Projected changes in the UK agricultural climate

Over the past century, the Earth has warmed by about 0.7°C, and the underlying rate of warming is accelerating. Since the mid-1970s, the Central England temperature has increased by about 1°C, and it is likely that global emissions of man-made greenhouse gases have contributed significantly to this rise (Jenkins *et al.*, 2009a). Sea levels around the UK have also risen, roughly by about 1mm/year during the 20th century; however the rate of rise during the 1990s and 2000s has been much higher.

There is a significant body of international literature, both peer reviewed and grey, on the projected impacts of climate change on agriculture. These are based on a wide range of contrasting approaches using for example, different types of crop models and GCM downscaling techniques, and for different regions and production sectors. In general, most climate impact assessment research has tended to focus on crop production (notably yield impacts), with livestock and animal impacts being considered in the context of climate change mitigation (i.e. reducing GHG emissions), rather than impacts and adaptation.

For the UK, the most recent studies have used UKCP09 (Jenkins *et al*., 2009a) although outputs were also available in 1998 (Hulme and Jenkins, 1998) and in 2002 (UKCIP02) (Hulme *et al.*, 2002). The climate projections used in this study were based primarily on the UK Climate Projections 2009 UKCP09 (Jenkins *et al*., 2009a), including the application of the Regional Climate Models for the flood risk analysis. This dataset provides probabilistic distributions for each climate variable by using projections from a large ensemble of variants from the HadCM3 GCM (Johns *et al*., 1997) and from 12 other GCMs which were used as part of the international comparisons work for the IPCC Forth Assessment Report (Easterling *et al*., 2007). As a result, 10,000 different sets of possible future monthly changes in climate can be generated for each time slice and emission scenario. This is more informative than previous UKCIP datasets which were based on single projections (for a given emissions scenario), as the ensemble data can be used to present the relative probability of different outcomes based on the strength of evidence (rather than just the average), thus reflecting more openly the state of the science. Also available is a dataset of spatially coherent projections (SCPs) for use in mapping the spatial impacts of climate change. A brief overview of the main projected impacts of climate change based on UKCP09 and their likely consequences for UK agriculture are summarised in Table 1.1 and Table 1.3 below.

Table 1.1 Summary of projected changes in climate for key agriculture variables for the UK based on UKCP09 climatology

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

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

These figures, however, can mask the high degree of spatial and temporal variability projected for the UK and the uncertainty around these projections of future ‘mean’ climate. To highlight this uncertainty, the projected changes in summer and winter rainfall for a site in East Suffolk are shown in Figure 1.1, based on the UKCP09 climatology for the Low and High emissions scenario.

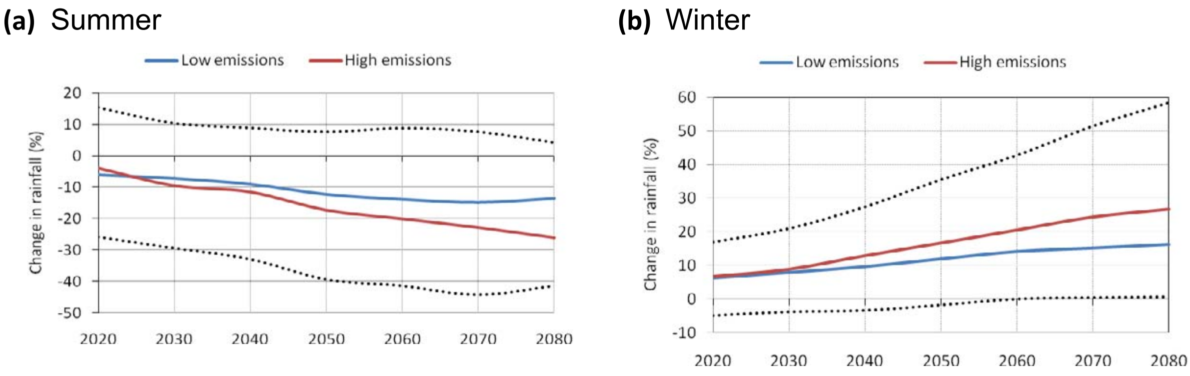


Figure 1.1 Projected seasonal changes in summer (a) and winter (b) rainfall from the baseline (1961-90) for the 2020s to 2080s, for a site in East Suffolk for the low and high UKCP09 emissions scenario

1.4 UK agriculture - a multifunctional sector at risk

Internationally, agriculture is widely regarded as one of the sectors at most risk from a changing climate, due to the impact of temperatures, rainfall and increased frequency of extreme events, not only in the tropics (Parry *et al*., 2005; Wheeler and Kay, 2010; Lobell, 2010) but also in temperate environments (Falloon and Betts, 2009; Knox *et al*., 2010c). To exacerbate the situation, recent studies warn of an unprecedented confluence of pressures on agriculture – with population growth and development driving up global demand for food and competition for land, water and energy intensifying as the impacts of climate change start to take effect (Royal Society, 2009). Recent concerns regarding future global food shortages have also raised questions about food security at global and national scales (IAASTD, 2009). The UK government seeks to achieve 'food security' by guaranteeing households access to affordable, nutritious food (Defra, 2010b). UK agriculture, along with the food industry as a whole, is charged with 'ensuring food security through a strong UK agriculture and international trade links with EU and global partners which support developing economies' (Defra 2010b). In this regard, it is required to be internationally competitive, whether this is delivering to domestic or international food markets. Climate change could affect not only the relative productivity of UK agriculture but also its competitive position in international markets.

Although UK agriculture accounts for a relatively small proportion of the national economy and employment, it occupies almost 75% of the total surface area (Angus *et al*., 2009). But it is strategically important in the provision of 'food production' - including both cropping (arable, horticulture) and livestock (beef, dairying, pigs, poultry) which account for over half of all food consumed in the UK (Defra, 2010a). UK agriculture is also an important contributor to 'non food' production including biofuels and forestry. As in many countries, UK agriculture has a multifunctional role, sitting at the interface between the natural environment and society, whilst also contributing to a range of environmental services including landscape enhancement, leisure and recreation and the provision of non-food raw materials. As agriculture involves the manipulation of natural ecosystems, it is particularly vulnerable to climate change. But because of the interactions and feedbacks that exist between agriculture, the environment and society any risk assessments of agriculture are notoriously difficult. In the future, producing food sustainably in a changing and uncertain climate will clearly be a high priority (Defra, 2010b) but climate change is just one of a number of stresses on agriculture and responses to the threat of climate change need to be sensitive to ecosystems and the diversity of benefits that agriculture provides, and not just to food production.

Agricultural mitigation falls into three categories:

- Reducing emissions, focussing on more efficient nitrogen additions and better livestock management
- Enhancing removals, increasing practises which use and store carbon
- Avoiding emission through different fuel choice and preventing needless cultivation of land (Smith *et al*., 2007b).

In this assessment, agriculture was defined to include outdoor cropping (comprising arable and field scale horticulture), livestock and dairy farming (principally milk, beef and sheep) and housed livestock (poultry) production. Previous CCRA scoping and methodology reports focussed on arable, horticulture and to a lesser extent, livestock (dairying), mainly due to their relative significance and financial contribution to the UK economy as well as being identified as the sub sectors most likely to be impacted by the 'direct' impacts of climate change. However, this report extends the synthesis to all cropping and livestock sectors, including housed livestock, although the evidence is often very limited. A brief summary of the composition of each of these three main sectors and their particular climate risks is given below.

1.4.1 Climate risks to crop production

As a biological system, the driving force in crop production is photosynthesis, which is primarily dependent on the levels of incoming solar radiation. However, the production potential set by radiation is also influenced by temperature and water availability, technology, fertiliser and crop losses (Olesen and Bindi, 2002). Outdoor crops grown in the UK will be sensitive to changes in climate, both directly (e.g. by changes in rainfall and temperature) but also indirectly, since any changes in climate will also impact on the agricultural potential of soils by modifying soil water balances. This impacts land management practices (e.g. trafficability for seed bed preparation, spraying, harvesting) and hence land suitability. The projected increases in atmospheric CO_2 concentration will also have direct impacts on crop growth by increasing the resource efficiencies for radiation, water and nitrogen (Kang *et al*., 2009; Daccache *et al*., 2011a). As a consequence, for most crops grown in northern Europe, the impacts of warmer temperatures and elevated CO_2 levels are expected to result in more favourable growing conditions (Olesen and Bindi, 2002), although of course there will also be negative consequences, which will vary spatially and temporally.

Climate change is likely to reduce the growing period for determinate (e.g. cereal) crops and increase the growth period for indeterminate (e.g. root) crops. High value horticultural crops will be most vulnerable to water related stresses (droughts, heat waves) and extreme events. Climate change is also likely to lead to more frequent and extended periods of water logging, and more frequent and larger areas of inundation of high grade (floodplain) agricultural land, with consequences for agricultural productivity (Johnson *et al*., 2009). There could also be many indirect effects – for example, changes in temperature would change the range of native/non-native pests and crop diseases (e.g. potato blight, *fusarium*), reduce vernalisation, induce crop damage (e.g. wheat and salads) at extreme temperatures, lead to crop diversification (e.g. maize, sunflowers, navy beans, soya, lupins, grapevines, etc), change agroclimatic conditions and land suitability (some crops may move northwards), modify yields and crop quality, and lead to a lengthening of the growing season for some crops. High value horticultural production would be most vulnerable to water related stresses (droughts, heat waves) and extreme events (Collier *et al*., 2008) (Table 1.2).

High summer temperatures at particular times of the growing season could have major effects on yield losses, especially if they occur around the flowering and seed development as their effect is then translated into quality losses, with consequences for farm incomes. A longer growing season in southern England may enable more ‘continental’ crops such as grape vines and sunflowers to be grown. However, increased risk of water restrictions in dry summers may result in a gradual northward shift of water-intensive production, for example, potatoes and field-scale horticulture.

It is important to bear in mind that the impacts of climate change are already being felt within the agricultural sector, and that many of the projected changes over the short term are more of a continuation of the current scenario, rather than a distinct change. Crop production has changed within the last decade (the warmest on record) as maize in now grown in southern Scotland and new crops, including Chillis, are already being grown in south England.

Table 1.2 Effects of climate extremes on crop development for selected crops grown in the UK

(Derived from Collier *et al*., 2008).

Climate variable	Physiological impact	Example crops affected
Higher summer temperatures	Reproductive (flower) development impaired Flower bud formation, effects delayed until the following year Crop development and yield reduced Crop quality reduced	Cereals, oilseed, peas, tomatoes, apples Apples Vegetables, brassicas and tomatoes Oilseed, cereals, tomatoes, apples, vegetables, brassicas
Higher winter temperatures	Cold hardiness limited Early bud break and frost susceptibility Delayed curd induction Impaired flower development	Winter cereals, winter oilseeds, apples Apples Winter cauliflowers Apples, blackcurrants

The impact of changes in climate being gradual or abrupt will depend largely on individual crop types. For example, the response to increased temperatures in field vegetable crops is likely to be positive, whilst salad and calabrese crops may suffer. Fruit production would be hit hard by increased temperatures with fruit mineral condition (nitrogen) being altered (Atkinson *et al.*, 2005). Severe short spells of hot days can severely reduce yields of wheat (MAFF, 2000). Similarly, heat waves can have a dramatic effect on yield; in 2003, maize production in Italy was reduced by 36% due to excessively high temperatures (Cais *et al*., 2005). For sustainable production, UK agriculture is likely to benefit from improved crop suitability – however, extremes in temperature will impact on yield (and quality) and increase the demand for irrigation to meet higher ET rates.

Changes in precipitation (seasonal quantities, extreme events and projected decreases in summer rainfall) will also impact on irrigation needs. Some crops that are currently irrigated (e.g. potatoes, field-scale vegetables) will require greater irrigation depths (Weatherhead and Knox, 1999); and other previously rain-fed crops are likely to need irrigating. The importance of irrigation for quality assurance will become more important (Knox *et al*., 2010c). Increases in winter rainfall will create new ‘poaching’ (surface soil damage) and waterlogging problems, require additional drainage to cope with higher rainfall intensities, and potentially create harvest problems in late summer due to excess wet ground.

1.4.2 Climate risks to livestock and dairy farming

There is huge variation in soil type and composition of swards on UK farms and so the effects of climate change will vary from farm to farm. Longer growing seasons are likely to result in grass growth starting earlier in the spring and continuing later into the autumn, with potentially higher yields, although these will be dependent on nitrogen availability and available soil moisture. Higher levels of CO_2 are also expected to alter grass growth rates. Earlier and more prolific grass growth will affect both grazing and silage production, and the timing of silage cuts. Changes in rainfall may also affect forage growth and productivity as well as quality, including the balance of species in mixed species swards. Wet weather could produce poor quality feed, while high temperatures could result in spoilage of stored silage. There may also be a reduction in the number of grazing days due to adverse weather (Moran *et al.*, 2009).

Hopkins and Scholefield (2004) reported that the effects of climate change on livestock and dairy production were likely to be extremely complex and variable, depending on a range of factors including future forage and animal feed prices, which themselves would be influenced by climate change. However, an increase in temperature will lead to an increase in growing season, promoting more grass growth for winter forage, grazing and the ability to grow alternative forage crops. Grass production is likely to be enhanced by increases in the length of the growing season especially in upland areas and rainfall changes may be both a positive and negative on grass production (see below). Irrigation of grass, may become viable to sustain stocking levels of livestock, although where water is available, arable crops are likely to take priority.

Climatic variations and change also have direct effects on livestock appetite and health, although larger ruminants are able to tolerate a greater climatic range. Livestock suitability across the UK is unlikely to be affected significantly, but it is noted that there is a lack of research, compared with available research in the arable or horticulture sectors (NFU, 2005). For livestock systems, a changing climate would impact on forage yields, feedstuff quality availability and cost, water availability, thermal stress and related welfare issues, and disease spread and control. These factors may in turn influence greenhouse gas emissions GHG emissions and the effectiveness of practices adopted to minimise them. The main impacts are likely to relate to changes in CO_2 levels, temperature, water availability, and weather extremes.

Increased CO_2 levels are likely to enhance primary production, but could lead to changes in leaf/sheaf ratio, reduced nitrogen and increased fibre contents and, hence, an overall reduction in dietary quality, depending of course on there being sufficient supplies of water available. Reductions in the digestibility of forage may lead to a lower liveweight gain. Many swards of grassland contain a mixture of species, with shifting composition, making prediction of their response to climate change highly complex. Grassland species are likely to change their competitive balance as a result of changing CO_2 concentrations, with dominant perennials subject to the most change (MAFF, 2000). The CO_2 fertilisation effect may stimulate herbage production by 0-20% for the same amount of nitrogen fertiliser, in an average year, in 2025-2035. However, this effect could be countered if regular summer droughts lead to a net reduction in forage production (Hopkins and Scholefield, 2004).

Changes in water availability may force livestock farming to move further north and west. Grassland production is sensitive to water supply, and pasture is not generally well adapted to prolonged periods of drought and water shortages may limit production in some future years especially in the lowlands (Rounsevell and Raey, 2009). Much of the UK's grassland is located on poorly drained soils, so a reduction in moisture might be beneficial in some areas, leading to a reduction in such problems as poaching. A general decrease in water availability could mean a shortening of the grass-growing season, which could lead to an increase in supplementary feeding needs, and increased costs. There is the possibility of using more drought resistant breeds to counteract this. Changing water availability may also necessitate investment in other infrastructure, such as on-farm water storage reservoirs. Drainage systems may also have to be improved to reduce risks associated with water logging.

Prolonged or extreme high temperatures increase the risk of heat stress on animals, particularly the young. The reproductive capacity of livestock also tends to decrease at elevated heat levels, although this can be partly countered by reducing the number of native breed livestock and the introduction of more drought or heat tolerant species from arid areas such as the Middle East, Australia and Africa (NFU, 2005). More shelter may be needed and an increase in ventilation of dairy parlours could be necessary. Warmer temperatures in winter may mean that the housing period is decreased, reducing feed and bedding costs, and there may be the opportunity for lambing and calving to start earlier without the need for housing. Projected warmer temperatures could allow an expansion in the land area available for finishing cattle and sheep, with upland areas becoming a possibility. However, prolonged warm and dry conditions, and an increase risk of drought, may increase the requirement to house year-round with zero graze grass for forage (NFU, 2005).

Warmer temperatures and a milder climate could also increase pathogen and fly problems and an increase in invasive species such as giant hogweed or Japanese knotweed may also occur (MAFF, 2000). There could also be significant effects on the composition of weed communities of agricultural land. Some perennial species in southern UK areas could become invasive in upland grasslands in a warmer, drier climate. Invasions of grasslands by southern weed species may occur more slowly and will be more pronounced in perennials seed banks.

Considering forage crops for livestock, Hopkins and Scholefield (2004) forecast that in western dairying areas there would be net increases in herbage production of 10-15% by the 2020s, increasing to over 20% by the 2050s, due to temperature changes. Grass-white clover benefits proportionally more because of warmer spring temperatures. In the drier eastern areas they forecast increased sward productivity, with earlier season growth and higher yields of legume based silage crops. However, increased frequency of current extreme weather events may offset these apparent gains.

Changes in water availability may force livestock farming to move further North and West. Grassland production is sensitive to water supply, and pasture is not generally well adapted to prolonged periods of drought. Much of the UK's grassland is located on poorly drained soils, so a reduction in moisture might be beneficial in some areas, leading to a reduction in such problems as poaching. A general decrease in water availability could mean a decrease in the grass-growing season, which could lead to an increase in supplementary feeding needs, and increased costs. There is the possibility of using more drought resistant breeds to counteract this. Changing water availability may also necessitate investment in other infrastructure, such as on-farm water storage reservoirs. Drainage systems may also have to be improved to reduce risks associated with water logging.

An increase in winter rainfall could increase the need for housing and, therefore, cost. This could occur earlier as animals and machinery poach the land, particularly if supplementary feeding is required. Greater storm frequency could lead to a rise in stress levels and an increase in housing, impacting on stocking rates, as these may have to be decreased if housing space is limited; however, there is currently a large uncertainty surrounding storm intensities and frequency and therefore storm projections are not considered for the CCRA. Torrential rains could also increase flooding of silage and grazing ground, and increase the potential for soil erosion. Other risks include increased damage to agricultural buildings, potentially changing agricultural building specifications, or lead to those already built requiring adaptation (e.g. drainage systems).

An increase in extreme weather events may lead to a lack of grazing land and therefore an increase in need for supplementary feeds, and a possible increase in the use of hardier breeds. There may be the opportunity for a change in livestock breeds (e.g. native Galloway or Highland cows) to cope with a change in extreme event occurrence; however, warmer drier summers may impact on native breeds more than those currently reared. Both global and local climate changes could alter the availability of feeds, which may have an indirect impact on livestock production, with stocking numbers needing to be reduced.

1.4.3 Climate risks to housed livestock

Effects of climate change on housed livestock production are extremely complex, based on a number of factors such as animal feed prices, animal appetite and health. There are also issues with rising and increasingly variable energy costs impacting on production. Many of the issues highlighted for livestock (above) are also equally relevant to housed livestock.

There could be an increased risk of heat stress due to higher summer temperatures and hot weather extremes, with implications for housing systems which are designed to cope with current ambient weather conditions. Investment in ventilation and cooling systems might be needed. Poultry flocks would be particularly vulnerable, because they can only tolerate a narrow range in temperature. Their reproductive capacity also tends to decrease in elevated heat levels. Defra research found that broiler hens in a poultry house under a future climate change scenario would exceed critical temperature on 30% more occasions, despite a 10% increase in ventilation (Farming Futures Fact Sheet 9). Defra also found that the frequencies of heat stress in pigs increased by 20%, despite an increase in ventilation. Energy costs to cool buildings would increase during summer, but decrease during winter with the reduced need to heat buildings. The stocking density of buildings may also have to be decreased, which would raise costs. Running costs may be reduced with the introduction of such measures as energy saving lighting. Heat stress during transport may become increasingly important, with active (rather than passive) ventilation becoming essential.

A summary of the possible impacts of climate change on UK agriculture is given in Table 1.3.

Table 1.3 Summary of possible impacts of climate change on UK agriculture, based on UKCP09

Data adapted from NFU (2005).

UKCP09 projected climate change	Possible range of impacts on UK agriculture
Carbon dioxide Concentration increases	Potential stimulated photosynthesis and yield (e.g. potatoes, wheat and forage) Changes in the quality and/or composition of land use (e.g. new crops, grassland)
Temperature Increase in winter and summer Increases in number of 'hot' (20°C) and 'very hot (27°C) days Marked decline in number of frosts	Growing season lengthens Increased/change in range of native/non-native pest and disease problems (e.g. potato blight, Fusarium) Reduced vernalisation (cold winter weather required for flowering) Leave animals in fields for longer/housing period decreased House design changes; cooling and ventilation system installation, increasing costs to minimise heat stress, increased need for shade Increased grazing opportunities in winter especially on free draining soils Damaged crops (e.g. wheat, salad crops) at extreme temperatures

UKCP09 projected climate change	Possible range of impacts on UK agriculture
	Heat benefits some crops (e.g. onions, legumes, carrots) Changes in crops grown (e.g. diversification into sunflowers, navy beans, soya, lupins, borage, grapevines etc, most notably in the SE) Less frost damage Lengthening of growing season leading to greater availability of UK grown produce throughout the year (e.g. soft fruit)
Precipitation Decrease in summer rainfall Increase in winter rainfall (regionally variable)	Drop in some crop yields Increased irrigation needs and changes in methods (e.g. potatoes) Decrease in summer soil moisture Changed poaching/water logging risk in some areas Late harvest problematic (e.g. increased drying costs and working on wet ground) Increased housing needed for livestock Increase in drainage systems Increase in wet weather related animal health problems/pest and disease problems
Weather extremes Increased frequency of extreme events, such as droughts and high temperatures, torrential rains and very strong winds	Crop damage/total crop loss (e.g. lodging of wheat, un-harvestable fields) Damage to agricultural buildings/change in building specifications Changing cropping practices Increased soil erosion Lack of grazing in drought events; Increased heat stress in livestock Increase in housing needed for livestock
Sea level rise Increase in sea level	Loss of coastal, estuary and floodplain agricultural land Erosion of land and salinisation of ground water
Other impacts	Increase in cost and range of insurance; increasing diversification; New skills training/differing agricultural workload; changes in agricultural markets, demand and competition

1.5 UK agriculture and climate change - policy context

UK Policy Landscape

The UK rural economy is worth £300 billion pa and employs 5.5 million people. The wider agri-food sector generates £85 billion and employs 3.6 million people. Agriculture contributes £7.1 billion in Gross Value Added to the UK economy and employs 534,000 people.

The agriculture sector is administered and managed in different ways according to devolved responsibilities and operates within the overall context of the European Union's CAP and European policies. Defra has responsibility for agricultural policy at a UK government level, but this responsibility is devolved to appropriate departments in Scotland, Wales and Northern Ireland.

UK agriculture is also shaped by other EU directives that influence the manner in which land is managed, such as the Water Framework Directive (WFD) and Nitrates

Directive. The adaptive capacity of the EU policy making process will impact on the UK's ability to be flexible and respond to climate risks.

The Water Framework Directive (WFD) will have an impact on agriculture through the control of pollution, especially that occurring due to diffuse discharge via runoff and leeching, and water abstraction. Agricultural practises which contribute to pollution discharge include fertilization of crops, slurry spreading and the spraying of pesticides. The WFD legislation means farmers will have to carefully manage land and farm practises to meet the targets of a good ecological status for all water bodies.

Environmental aspects of the agricultural sector are regulated by the Environment Agency in England and Wales, by the Scottish Environment Protection Agency in Scotland, and by the Northern Ireland Environment Agency in Northern Ireland. As custodians of around 71% of the UK's land agricultural practice impacts on the environment, therefore Natural England, the Countryside Council for Wales, Scottish Natural Heritage and the Northern Ireland Environment Agency are key stakeholders in the sector.

Stakeholders also include a number of sector organisations such as the Agricultural and Horticultural Development Board (AHDB), National Farmers Union (NFU), Country, Land and Business Association (CLA) and Linking Environment and Farming (LEAF) and UK conservation organisations such as the Royal Society for the Protection of Birds (RSPB).

Policy response to climate impacts and adaptation

The Foresight project Global Food and Farming Futures (published January 2011), considers key climate impacts on the global food system up to 2050, and the related impacts on food security. This sets the context for increased worldwide food demand due to an increasing population with changing diets, against the need to adapt to climate change in order to maintain or increase production and safeguard or improve the natural environment and ecosystem services.

Domestic agricultural policy is heavily influenced by EU policy. The Common Agricultural Policy (CAP) provides support to farmers who follow good agricultural practices, and/or offer non-market benefits as well as those prepared to enter into active environmental stewardship. The current CAP (2007-2013) primarily supports adaptation through Pillar 2 funding, including agri-environment schemes and targeted capital grants. The UK Government believes that there needs to be a fundamental reform of the CAP so that it is simpler, delivers more public goods, including environmental ones, and increases the competitiveness of the EU agriculture sector over the next CAP period (2014-20). Regulatory proposals published by the commission in October list 'the sustainable management of natural resources, and climate action' as one of three objectives for rural development.

England

- The Rural Development Programme for England (RDPE) provides funding for agriculture and forestry businesses, environmental land management and wider rural development. It is jointly funded by Defra and the EU under Pillar 2 of the Common Agricultural Policy (CAP). The majority of these funds are spent on environmental land management and agri-environment schemes such as Environmental Stewardship, increasing the resilience of habitats, species and ecosystems.
- Since the CAP Health Check (2008), Defra has identified 15 RDPE measures that can be taken to adapt to climate change.

- The Soil Strategy for England, Safeguarding our Soils, was published in September 2009 and sets out the vision to tackle the degradation of soils in England within the next 20 years.
- Building the resilience of our soils to a changing climate is a key priority, so Defra are developing an evidence base on the impact of climate change on soils and ensuring that farmers and other land managers have the information and guidance necessary to be able to secure the resilience of their soils.

Scotland

- Scottish Government's Climate Change Adaptation Framework was published in 2009 and has been further developed with a series of accompanying Sector Action Plans. The Agriculture Action Plan (http://www.scotland.gov.uk/Topics/Environment/climatechange/scotlands-action/adaptation/AdaptationFramework/SAP/Agriculture) focuses on developing a solid evidence base in relation to the impacts and consequences of climate change on Scottish agriculture and also on enhancing existing advice and guidance to land managers on adaptation issues.
- As well as supporting essential research, Scottish Government funds targeted advice and guidance on climate change adaptation issues through the Scotland Rural Development Programme (SRDP) Skills Development Scheme and the Public Good Advisory Contract which operates between Scottish Government and Scottish Agricultural College. Against stated criteria, financial support is also available through SRDP to support climate change related activities on farm.

Wales

- Set within the *Rural Development Plan for Wales, 2007-2013*, the *Glastir* agri-environment scheme is a 5-year, whole farm sustainable land management scheme available to farmers and land managers. It is designed to draw together the Welsh Government's commitment to sustainable agricultural development in the context of climate change and is part-funded by the EU. Expected outcomes include improved water management, reduced flood risk, and conserved and enhanced biodiversity. *Glastir* features a grant for woodland creation, to help improve local resilience to the impacts of climate change.
- The *Adaptation Delivery Plan* published alongside the *Climate Change Strategy for Wales* (2010) includes specific action to "support and encourage land managers to adapt to the effects of climate change". In addition, the Farming Connect Programme is helping land managers to improve their understanding and capacity to manage climate change impacts and possibilities for adaptation through knowledge transfer, advice and skills development. The *Adaptation Delivery Plan* also contains an action to "improve woodland resilience to climate change" and aims to ensure that the impacts of a changing climate are fully considered in the management of farm woodlands in Wales.

Northern Ireland

- In Northern Ireland the Executive has established a Cross Departmental Working Group on Climate Change. Key aims of the Group include; to evaluate the climate change risks and opportunities for Northern Ireland; prepare and deliver a cross-departmental adaptation programme on climate change; review cross-departmental action on adaptation on an annual basis and report to the Northern Ireland Executive on progress; and make recommendations and/or decisions on wider climate change adaptation issues as appropriate.

1.6 Structure of report

This report for the Agriculture Sector is one of 11 commissioned as part of the CCRA contract with HRW, and is a key step in the process of developing the evidence base required to deliver the UK CCRA to Parliament by January 2012, as required by the Climate Change Act.

The aim of this report is to provide a detailed synthesis of the potential risks of climate change and other exogenous factors on UK agriculture, including the most important environmental, economic, technological and societal impacts, both negative and positive.

For the purposes of this assessment, agriculture is defined to include both outdoor cropping (comprising arable and field scale horticulture), livestock and dairy farming (principally milk, beef and sheep) and housed livestock (poultry) production. The 'non-food' production component of UK agriculture, including forestry, fibre and bio-fuels are excluded from this report, but readers interested in these sectors are referred to assessments by Reed *et al.* (2009) and the Forestry Sector report.

This report provides a brief introduction to UK agriculture and climate change including the policy context, the methods used to assess and quantify the identified risks (using risk metrics and response functions) and a summary of the projected estimates of change based on UKCP09 climatology. The outputs from the analyses are compared against the findings from the peer review literature on climate impacts on agriculture, and a discussion and critique of the potential socio-economic impacts, costs and need for building adaptive capacity are then provided. The report structure broadly follows the risk assessment steps described in detail in the CCRA Method Report (Defra, 2010c). A comprehensive list of references is included for additional information.

2 Methods

2.1 Introduction: CCRA Framework

The overall aim of the CCRA is to inform UK adaptation policy, by assessing the main current and future risks (threats and opportunities) posed by the current climate and future climate change for the UK to the year 2100. The overall approach to the risk assessment and subsequent adaptation plan is based on the UK Climate Impacts Programme (UKCIP) Risk and Uncertainty Framework (UKCIP, 2003). The framework comprises eight stages as shown in Figure 2.1. The CCRA has undertaken the Stages 1, 2 and 3 as outlined below. Stages 4 and 5 will be addressed as part of a separate economic assessment, entitled the 'Economics of Climate Resilience', and the remaining stages will be implemented by the UK Government and Devolved Administrations. The framework presents a continual process that can adapt as new evidence and policy emerges; in the case of the CCRA the process will be revisited every five years.

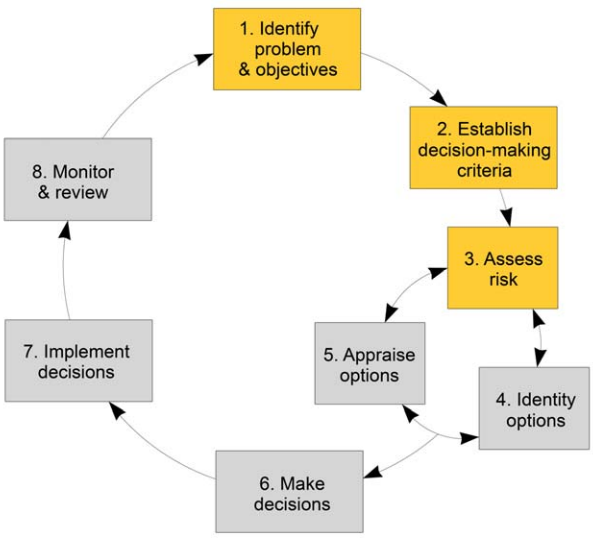


Figure 2.1 Stages of the CCRA (yellow) and other actions for Government (grey)
Adapted from UKCIP (2003)

- Stage 1 is defined by the aim of the CCRA project, to undertake an assessment of the main risks (including both threats and opportunities) posed by climate change that will have social, environmental and economic consequences for the UK.
- Stage 2 established decision-making criteria for the study, which were used to inform the selection of impacts for analysis in Stage 3. These criteria are the social, environmental and economic magnitude of consequences and the urgency of taking adaptation action for UK society as a whole.
- Stage 3 covers the risk assessment process. This involved a tiered assessment of risks with Tier 1 (broad level) identifying a broad range of potential impacts and Tier 2 (detailed level) providing a more detailed analysis including quantification and monetisation of some impacts. A list of climate change impacts was developed based on eleven sectors with further impacts added to cover cross-cutting issues and impacts which fell

between sectors. This list of climate change impacts is referred to as the **'Tier 1' list of impacts**. This list contained over 700 impacts – too many to analyse in detail as part of this first CCRA. A consolidated list of the highest priority climate change impacts for analysis was developed and referred to as the **'Tier 2 list of impacts'**. This report presents the risk assessment for Tier 2 impacts.

The background to the framework and the approach used for each of the first three stages is set out in more detail in the CCRA Method Report (Defra, 2010). This chapter aims to summarise the CCRA method for the risk assessment stage (Stage 3 in the framework above) because this includes the specific steps for which results are presented in this report.

2.2 Outline of the method used to assess impacts, consequences and risks

The risk assessment presented in this report is the focus of Stage 3 in the CCRA Framework (see Figure 2.1). This was done through a series of steps as set out in Figure 2.2. These steps are explained in Sections 2.3 - 2.7 below and are discussed in more detail in the CCRA Method report (Defra, 2010).

The components of the assessment sought to:

- **Identify and characterise the impacts** of climate change

  This was achieved by developing the Tier 1 list of impacts, which included impacts across eleven sectors as well as impacts not covered by the sectors and arising from cross sector links (see Chapter 3 of this report).

- **Identify the main risks** for closer analysis

  This involved the selection of Tier 2 impacts for further analysis from the long list of impacts in Tier 1. Higher priority impacts were selected by stakeholder groups based on the social, environmental and economic magnitude of impacts and the urgency of taking action (see Chapter 3 of this report and Section 2.5 below).

- **Assess current and future risk**, using climate projections and considering socio-economic factors.

  The risk assessment was done by developing 'response functions' that provide a relationship between changes in climate with specific consequences based on analysis of historic data, the use of models or expert elicitation. In some cases this was not possible, and a narrative approach was taken instead. The UKCP09 climate projections and other climate models were then applied to assess future risks. The potential impact of changes in future society and the economy was also considered to understand the combined effects for future scenarios. (See Chapter 4 of this report and Section 2.6 below.)

- **Assess vulnerability** of the UK as a whole

  This involved:

  i. a high level review of Government policy on climate change in the eleven sectors (see Chapter 1 of this report)

ii. a high level assessment of social vulnerability to the climate change impacts

iii. a high level assessment of the adaptive capacity of the sectors (see Chapter 8 of this report and Section 2.4 for an overview of the approach, below).

- **Report on risks** to inform action

  This report presents the results of the risk assessment for the agriculture sector. The results for the other ten sectors are presented in similar reports and the CCRA Evidence Report (CCRA, 2012) draws together the main findings from the whole project, including consideration of cross-linkages, and outlines the risks to the UK as a whole.

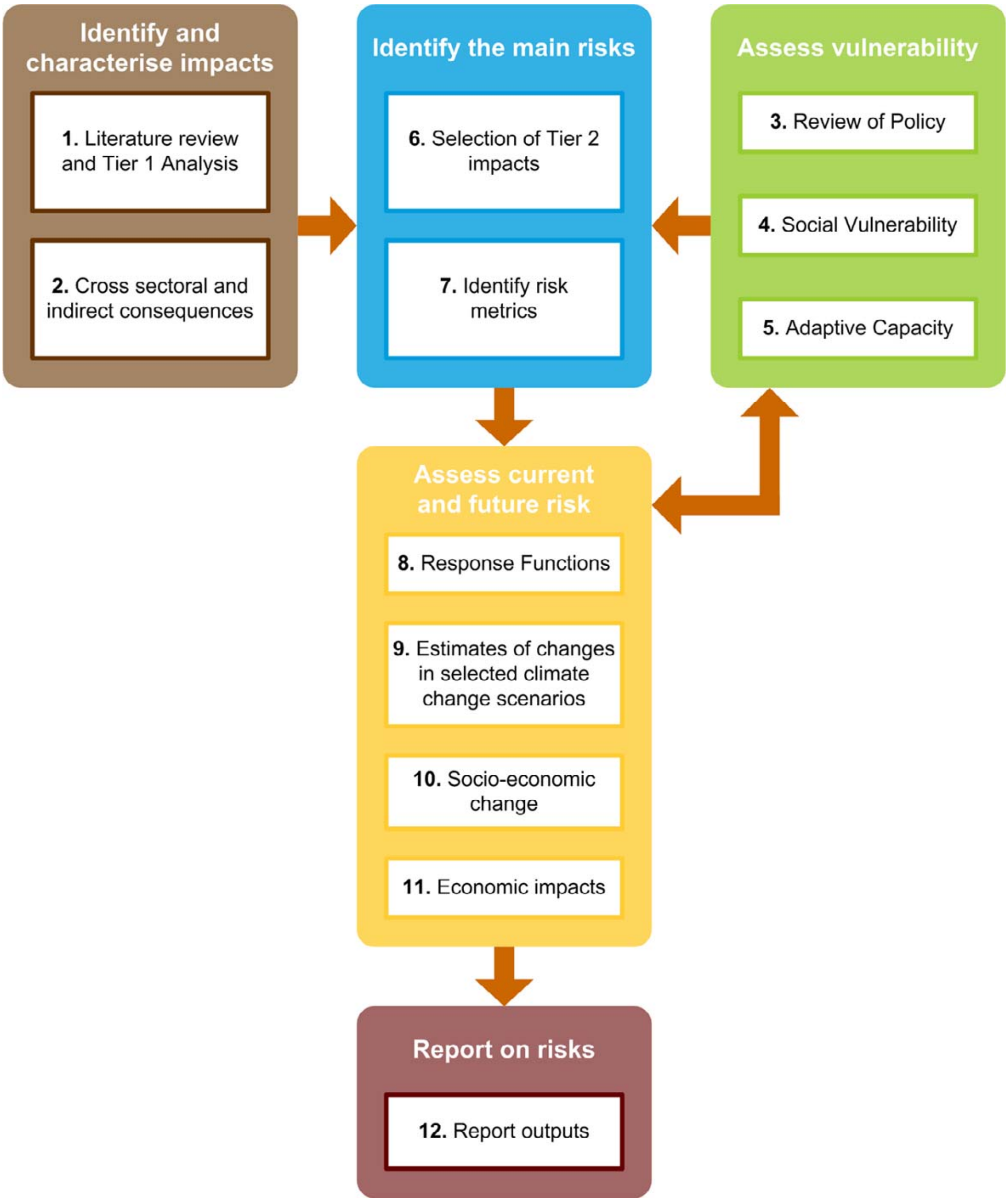


Figure 2.2 Steps of the CCRA Method (that cover Stage 3 of the CCRA Framework: Assess risks)

2.3 Identify and characterise the impacts

Step 1 – Literature review and Tier 1 analysis

This step scoped the potential impacts of climate change on the UK based on existing evidence and collating the findings from literature reviews, stakeholder participation through workshops, correspondence with wider stakeholders and soliciting expert opinion. This work developed the Tier 1 list of impacts (see Appendix 3). The Tier 1 impacts have not been analysed in detail; high level discussion of these impacts is provided in Chapter 3 of this report.

Step 2 – Cross sectoral and indirect impacts

The Tier 1 lists for the eleven sectors in CCRA were compared and developed further to include cross-sectoral and indirect impacts. This was done by 'Systematic Mapping', which sets out a flow chart to link causes and effects in a logical process. The impacts that were identified in this step were added to the Tier 1 list of impacts.

2.4 Assess vulnerability

Step 3 – Review of Policy

Government policy on climate change develops and changes rapidly to keep pace with emerging science and understanding of how to respond through mitigation and adaptation. This report includes an overview of selected relevant policy in Chapter 1 as this provides important context for understanding how risks that are influenced by climate relate to existing policies. This information will be expanded in the Economics of Climate Resilience project and the National Adaptation Programme.

Step 4 – Social Vulnerability

The vulnerability of different groups in society to the climate change risks for each sector was considered at a high level through a check list. Note that this step is different from Step 10, which considers how future changes in society may affect the risks.

Step 5 – Adaptive Capacity

The adaptive capacity of a sector is the ability of the sector as a whole, including the organisations involved in working in the sector, to devise and implement effective adaptation strategies in response to information about potential future climate impacts. An overview of the adaptive capacity of the agriculture sector is provided in Chapter 8.

2.5 Identify the main risks

Step 6 – Selection of Tier 2 impacts

The Tier 1 list of impacts for each sector that resulted from Step 2 (see above) was consolidated to select the higher priority impacts for analysis in Tier 2. Firstly, similar or overlapping impacts were grouped where possible in a simple cluster analysis, which is provided in Chapter 3. Secondly, the Tier 2 impacts were selected using a simple multi-criteria assessment based on the following criteria:

- the social, economic and environmental magnitude of impacts
- overall confidence in the available evidence

- the urgency with which adaptation decisions needs to be taken.

Each of these criteria were allocated a score of 1 (low), 2 (medium) or 3 (high) and the impacts with highest scores over all criteria were selected for Tier 2 analysis. The scoring for each sector was carried out based on expert judgement and feedback from expert consultation workshops (or telephone interviews). Checks were carried out to ensure that a consistent approach was taken across all the sectors. The results of the scoring process are provided in Appendix 3.

Step 7 – Identifying risk metrics

For each impact in the Tier 2 list, one or more risk metrics were identified. Risk metrics provide a measure of the impacts or consequences of climate change, related to specific climate variables or biophysical impacts. For example, in the agriculture sector report, one of the impacts identified is a 'reduction in crop yield' due to changes in precipitation and temperature. The risk metrics were developed to provide a spread of information about economic, environmental and social consequences. The metrics have been referenced using the sector acronym and a number; the agriculture sector metrics are referenced as AG1 to AG10.

2.6 Assess current and future risk

Step 8 – Response functions

This step established how each risk metric varied with one or more climate variables using available data or previous modelling work. This step was only possible where evidence existed to relate metrics to specific climate drivers, and has not been possible for all of the tier 2 impacts. This step was carried out by developing a 'response function', which is a relationship to show how the risk metric varies with change in climate variables. Some of the response functions were qualitative, based on expert elicitation, whereas others were quantitative.

Step 9 – Estimates of changes in selected climate change scenarios

The response functions were used to assess the magnitude of consequences the UK could face due to climate change by making use of the UKCP09 climate projections. This step used the response functions to provide estimates of future risk under three different emissions scenarios (High carbon emissions, A1FI; Medium emissions, A1B; Low emissions, B1; see http://ukclimateprojections.defra.gov.uk/content/view/1367/687/ for further details), three future 30-year time periods (centred on the 2020s, 2050s and 2080s) and for three probability levels (10, 50 and 90 percent; see http://ukclimateprojections.defra.gov.uk/content/view/1277/500/ for further details), associated with single or combined climate variables. The probability levels are cumulative and denote the degree of confidence in the change given; for example 90% suggests that it is thought very unlikely that the change will be higher than this; 50% suggests that it is thought equally likely that the change will be higher or lower than this; and 10% suggests that it is thought very unlikely that the change will be lower than this. 90% does not mean that the change is 90% likely to occur, for example.

All of the changes given in the UKCP09 projections are from a 1961-1990 baseline.

The purpose of this step is to provide the estimates for the level of future risk (threat or opportunity), as measured by each risk metric.

Step 10 – Socio-economic change

It is recognised that many of the risk metrics in the CCRA are influenced by a wide range of drivers, not just by climate change. The way in which the social and economic future of the UK develops will influence the risk metrics. Growth in population is one of the major drivers in influencing risk metrics and may result in much larger changes than if the present day population is assumed. For some of the sectors where this driver is particularly important, future projections for change in population have been considered to adjust the magnitude of the estimated risks derived in Step 9. Other sectors have also considered anticipated adaptation, where future risks may be moderated by the actions taken to adapt to future conditions.

For all of the sectors, a broad consideration has been made of how different changes in our society and economy may influence future risks and opportunities. The dimensions of socio-economic change that were considered are:

- Population needs/demands (high/low)
- Global stability (high/low)
- Distribution of wealth (even/uneven)
- Consumer driven values and wealth (sustainable/unsustainable)
- Level of Government decision making (local/national)
- Land use change/management (high/low Government input).

The full details of these dimensions and the assessment of the influence they have on the agriculture sector is provided in Chapter 5. Note that this step is different from Step 4, which considers how the risks may affect society; whereas this step considers how changes in society may affect the risks.

Step 11 – Economic impacts

Based on standard investment appraisal approaches (HM Treasury, 2003) and existing evidence, some of the risks were expressed as monetary values. This provides a broad estimate of the costs associated with the risks and is presented in Chapter 6 of this report. A more detailed analysis of the costs of climate change will be carried out in a study on the Economics of Climate Resilience[10].

2.7 Report on risks

Step 12 – Report outputs

The main report outputs from the work carried out for the CCRA are:

- The eleven sector reports (this is the sector report for the agriculture sector), which present the overview of impacts developed from Tier 1 and the detailed risk analysis carried out in Tier 2.
- The Evidence Report, which draws together the main findings from all the sectors into a smaller number of overarching themes.
- Reports for the Devolved Administrations for Scotland, Wales and Northern Ireland to provide conclusions that are relevant to their country.

[10] http://www.defra.gov.uk/environment/climate/government/

3 Impacts and Risk Metrics

3.1 Identifying impacts and consequences

A wide range of impacts and potential consequences were identified for agriculture in the Tier 1 analysis. A summary of Tier 1 risks is given in the Appendix. For simplicity and due to the significant overlap, the arable and horticulture and livestock sub-sectors were combined and a single ‘cluster diagram’ produced (Figure 3.1). Four themes were identified:

1. Environment (relating to impacts on farmland biodiversity, bird populations, water resources and air quality).
2. Soil (relating to run-off and leaching risks, water logging, drought risk, biological activity).
3. Crops and livestock (relating to crop development, yield and quality, pests, diseases and weeds, storage and stress for crops; and nutritional demands, animal stress, product yield and quality and death for livestock).
4. Land (relating to land suitability, subsidence and flooding risks and trafficability).

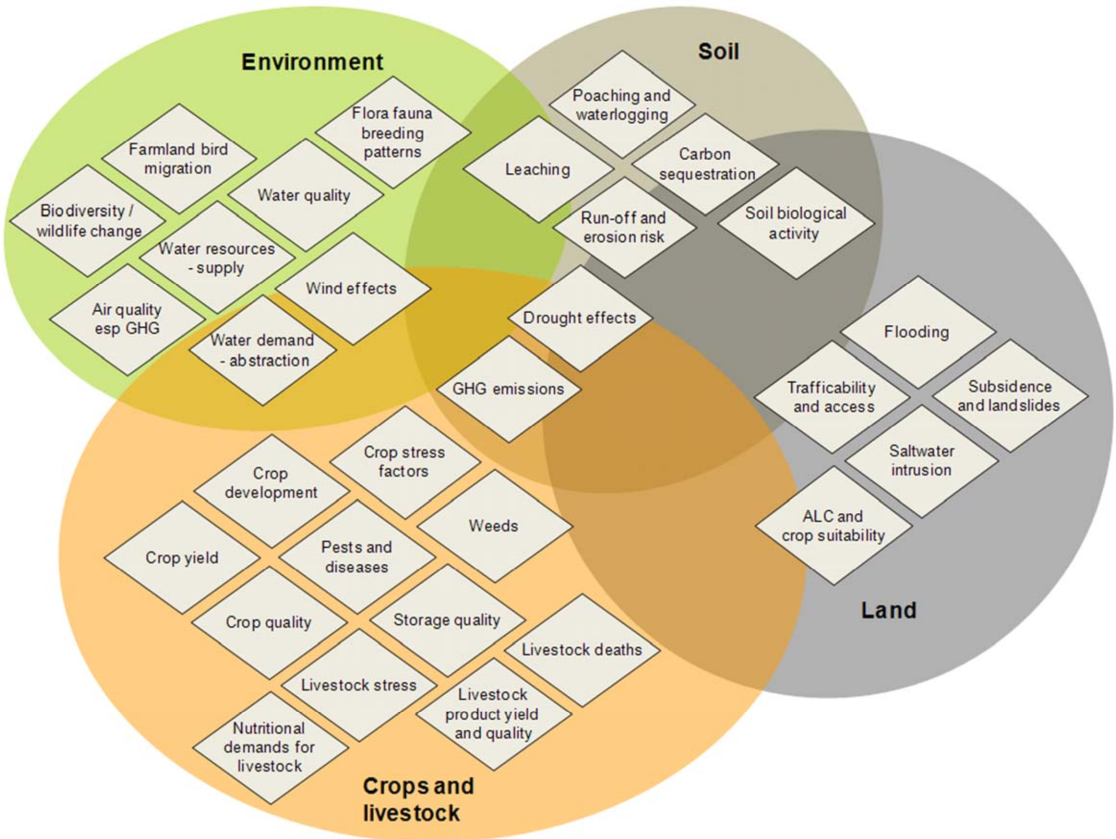


Figure 3.1 Summary of the identified impact clusters for agriculture

With the time and resources available for the CCRA, it simply would not have been possible to have undertaken a detailed analysis of all of the Tier 1 risks, and so a selection process was carried out. The CCRA pilot study involved work with Defra experts and consultation with the CCRA Forum and Project Steering Group on a simple selection process to identify the impacts that appear to be the most important for detailed assessment in the CCRA. These impacts are referred to as the Tier 2 list, and the detailed assessment is referred to as the Tier 2 assessment.

In the Tier 2 assessment, following the disaggregation of the agriculture sector into three sub sectors (arable, horticulture and livestock), the impacts were reassessed and a revised list produced containing approximately 35 impacts. For each sub-sector a lead co-ordinator with an in-depth knowledge of that industry was appointed, and asked to identify 6-8 key informants to support the risk assessment and metric analysis. A simple selection process was then carried out to identify impacts, from those listed in Tier 1, for further assessment in Tier 2. The criteria agreed by the technical advisory group to the CCRA (In House Experts Group) to be used to prioritise the consequences were:

- Magnitude of the consequence (economic, social and environmental)
- Likelihood of the consequence occurring
- Urgency with which a decision needs to be made.

Each criterion was weighted and scores derived according to standard descriptions in the methodology report (Defra, 2010c). The scoring is primarily based on qualitative information and attempts to record ‘orders of magnitude’ rather than offering a precision at this early stage of the study.

3.1.1 Consultation feedback

Selected key informants in each sub-sector were identified and then asked to prioritise the impacts identified in each sub-sector based on these criteria. For the agriculture and horticulture sub-sectors, approximately 6 key informants were identified, representing 2 academics/researchers, 2 growers and 2 industry representatives. An email pro-forma was then sent to each informant listing the impacts for a specific sub-sector together with guidance of the definitions and scoring of magnitude, likelihood and urgency. On completion, the proformas were analysed and scored to prioritise the impacts.

3.1.2 Scoring of impacts

Impacts were scored according to the project methodology that considered magnitude of the potential impacts, their likelihood and urgency criteria. Further details and a full list of scores are provided in Appendix 3.

3.1.3 Impacts below the assessment threshold

In the Tier 1 analysis a significant number (89) of potential climate impacts to agriculture were identified, and subjected to a pedigree scoring and confidence assessment. Following consultation and discussion with key informants, these were then shortlisted; 32 impacts were selected for arable, 32 for horticulture and 54 for livestock. These were then reviewed and scored individually by a group of key informants for magnitude, urgency and confidence. The output being a weighted list of impacts, priority ranked. A large number of impacts were therefore potentially excluded from the subsequent risk metric analysis.

The purpose of this section is to briefly review those excluded impacts and discuss how these relate to climate change risk, as well as any socio economic implications, where evidence is reported. Given the large number of impacts excluded, many were observed to actually have an overlapping climate impact or duplicative effect, so it is reasonable to group them according to the areas of agriculture in which they have relevance (Table 3.1). For each area (crop and soil related impacts, etc) a brief narrative is then provided, drawing on evidence in the scientific literature.

Table 3.1 Summary of selected Tier 1 and 2 key impacts excluded from the risk metric analysis

<table>
<tr><th>Crop and soil related impacts</th><th>Animal related impacts</th></tr>
<tr><td>• Changes in crop development
• Changes in crop rotation
• Changes in weed spectrums
• Crop quality
• Crop stress factors – frost damage, drought and water logging
• Water quality – frequent low flows could increase micro-biological risks of abstraction
• Trafficability issues
• Water logging effects on crops
• Increase in soil biological activity, including increased GHG emissions
• Subsidence/landslides</td><td>• Livestock pests and diseases
• Increasing water use by animals in dry periods
• Ability to provide resources for animals during extreme events
• Land salinity impacts on livestock farming
• Impact on ability to transport animals under extreme conditions due to regulations
• Water logging effects on livestock</td></tr>
<tr><th colspan="2">Environmental impacts</th></tr>
<tr><td colspan="2">• Biodiversity/wildlife changes
• Migration patterns of farmland birds
• Breeding habits/reproductive behaviour of species
• Loss of particular landscapes and communities
• Loss of native breeds in favour of those more resistant to new conditions
• Impact on Protected Areas and landscape conservation measures within the agricultural landscape (e.g. SSSIs)</td></tr>
<tr><th colspan="2">Other impacts</th></tr>
<tr><td colspan="2">• Human food supply/security
• Heat stress on workers – e.g. changing work patterns/labour costs
• Subsidence/landslides
• Air quality – especially GHG levels – CO_2 levels good for crops but bad for warming</td></tr>
</table>

Crop and soil related impacts

Over half (54%) the total number of impacts (n = 89) identified in the Tier 1 analysis related to crop and soil related impacts. The main climate effects were changes in atmospheric CO_2 concentration, rainfall, temperature, and extreme events. One of the problems with identifying the potential climate impacts on crops, however, is that the approach used in CCRA assumed that all other factors remained constant; in reality, of course, climate change will result in a combined set of climate changes with some parameters increasing, whilst others might remain unchanged or even decline. The impacts listed in Tier 1 all assumed a single climate impact with no direct links to other climate parameters and no feedbacks, which is unrealistic. Therefore, whilst many of the climate effects identified are important, the priority ranking for Tier 2 selected impacts which reflected the combined effects of a change in climate (e.g. yield).

It is also important to stress that the evidence from the Tier 1 analysis for most of the excluded impacts was considered to be of lower pedigree and confidence, so whilst there might be a climate effect, the quality of the evidence to support the impact was either lacking or of low confidence. Generally, the studies using bio-physical crop modelling approaches where the combined effects of changes in CO_2, temperature and rainfall (and for specific emissions scenario) were taken into account to assess crop response (yield and quality) were considered to be most robust (e.g. Richter and Semenov, 2005; Daccache *et al.*, 2011a), whilst studies based on a sensitivity analysis of the crop to a changing climate factor (e.g. +/- 10% rainfall or temperature etc) were considered to be of a much lower pedigree.

There are also climate feedbacks which need to be taken into account when considering changes in crop development. For example, for perennial tree fruit crops, a particularly serious temperature issue is their dormancy requirement. This period inhibits growth until the plants are exposed to low 'winter' temperatures ('chilling') which induce bud break. In the absence of effective chilling, floral bud development can be hampered and flowering can fail to develop or is not synchronised with pollinators, thus having significant implications for both crop yield and quality (Else and Atkinson, 2010). For soft fruits, such as strawberry, raspberry, and blackberry, the main concern regarding increasing temperatures is the impact on evaporative demand, with increased plant transpiration rates and hence crop water use. Although the total cropped area of soft and top fruit is relatively small (c9000 ha), both sectors generate extremely high returns (£/ha), and hence the potential risks in these sectors could be significant.

Impacts relating to crop rotation and land suitability were also identified in the Tier 1 analysis, but not selected for risk metric analysis. The viability of agricultural and horticultural production is influenced by spatial and temporal variability in soils and agroclimate, and the availability of water resources where supplemental irrigation is required. Soil characteristics and agroclimatic conditions thus greatly influence land suitability, crop rotations and location of cropping. Recent research by Daccache *et al.* (2011b) on potatoes, and the agricultural land classification and crop suitability, provides new evidence on these potential climate risks. For example, using the latest (UKCP09) scenarios of climate change, Daccache *et al.* (2011b) describes a methodology using pedo-climatic functions and a GIS to model and map current and future land suitability for potato production in England and Wales. The outputs identify regions where rainfed production could become limiting and where future irrigated production will be constrained due to shortages in water availability. The results suggest that by the 2050s, the area of land that is currently well or moderately suited for rainfed production may decline by 74 and 95% under the central climate projections for the Low and High emissions scenario respectively, owing to increased droughtiness. In many areas, rainfed production may become increasingly risky. The study found that cultivation is likely to shift substantially towards irrigated production where water is available. The resulting increase in water demand is potentially very much larger than the increase in the irrigation need of the presently irrigated crops. These shifts in land-use potential will have serious implications for both strategic water and land resource planning and food security.

Current research (Jones and Keay, 2011) is also assessing the impacts of climate change on agricultural land classification and land suitability for selected crops. This work will provide an important contribution to future risk assessment work and adaptation planning in agriculture. The ALC Climate Change study for Defra (SP1104) is being undertaken by Cranfield University in collaboration with ADAS. The aim of this work is to assess how changes in climate might affect the future grading of land based on the Agricultural Land Classification (ALC) system. The study uses a historical baseline (1961-1990) to generate a reference from which relationships are then derived to be applied to selected climate change scenarios. Twelve UKCP09 scenarios were investigated focussing on the Low, Medium and High emissions scenarios and time slices for the 2030s, 2050 and 2080s. The results are due to be reported in 2012.

The range of UK pests and diseases may change significantly, dependant upon on their vectors' response to climate change, thus making any assessment of their risk very difficult. Although a range of crop pests, diseases and weed spectrums were identified, weed spectrums were not included in the metric analysis (crop specific marker diseases were used but no relationships were found between the incidence of each 'marker' disease and climate variability). For weeds, in a hotter, drier climate, more generations of weed would be expected during the growing season, increasing the rate of evolution, and potentially leading to increased herbicide tolerance. An increase in invasive species such as giant hogweed or Japanese knotweed is also reported to be more likely (MAFF, 2000). There could also be significant effects on the composition of weed communities on agricultural land. The greatest change is likely to be in arable weed communities, where rapid changes can occur in genetic constitution, with the appearance of new species (Defra, 1999). There is thus a need continue monitoring the experiences of countries that currently have pests and diseases we may encounter in the future to develop appropriate adaptation responses to potential new pest and disease outbreaks, and support existing surveillance and eradication methods.

Changes in river water quality were also cited as being a potential risk due to lower river flows (Charlton and Arnell, 2011), with more frequent low flows increasing the micro-biological risks associated with irrigation abstraction for crops which are either eaten raw or unprocessed (e.g. salads). All crops that are eaten raw present a microbiological risk to consumers, and disease outbreaks in the UK and United States have illustrated that ready-to-eat (RTE) crops can be a vehicle for the transmission of gastrointestinal disease. Irrigation water has been implicated as a possible source of microbiological contaminants since over two-thirds of irrigation water applied to UK salad crops is abstracted from rivers and streams. Many of these are subject to a continuous input of faecal contamination from sewage treatment works as well as intermittent inputs from livestock and sewer overflows (Knox *et al*., 2011a). Climate change is likely to impact on the river flows available for dilution in receiving waters from sewage treatment, the rates of pathogen die-off which are strongly linked to temperature and radiation levels, and the timing and volumes of water abstracted for irrigation (Knox *et al*., 2011a). Further work is thus required to assess these climate impacts on the water quality risks associated with irrigation abstraction.

Trafficability issues, waterlogging effects on crops, water and wind erosion and increased risks associated with subsidence/landslides were also identified. These are all addressed in detail by recent Defra funded research on the impacts of climate change on UK soils (SP0571) using various models and UKCP09 data (Cooper *et al*., 2011).

Animal related impacts

Approximately a fifth (20%) of the impacts identified in the Tier 1 analysis related to animal production (outdoor livestock and indoor reared). The main climate effects were consequences to changes in temperature and rainfall creating issues regarding housing, heat stress, disease risk, and increased need for supplemental feed due to silage and grassland productivity problems. These impacts are diverse and vary both spatially and temporally. The impacts identified in Tier 1 were consistent with those reported by Moran *et al.* (2009). As with crop production, it is possible to distinguish between the direct and indirect effects of climate change on livestock production. The direct effects include impacts on animal health, welfare, growth and reproduction, while the indirect effects will be on productivity of pastures and forage crops. A more complex indirect impact may also result from the knock on impacts via change in the cost of UK feedstock inputs.

As highlighted previously and by Moran *et al.* (2009) there exists a considerable evidence base on the impacts of climate change on plant growth and yield, both internationally for selected crop sectors in the UK. However, much less research has been carried out on the impacts of climate change on pastures and livestock – comprehensive reviews are given in Moran *et al.* (2009) and Easterling *et al.* (2007). For the risk metric analysis, an attempt was therefore made to identify key variables that adequately reflected the direct impacts of climate change on livestock productivity highlighted above - dairying livestock was chosen as an illustrative sector, and metrics relating to heat stress and milk productivity developed. Data availability was also critical – whilst metrics on, for example, animal welfare risk would be highly valuable, there is simply insufficient data available to derive robust national level metrics. As with the crop production sector, many of the potential impacts are also strongly influenced by the combination of specific climate variables, rather than the existence of a single climate causal effect relationship. However, a detailed review of a wide range of animal welfare issues relating to the impacts of climate change is given in Haskell *et al.* (2011) covering many of the risks identified in the Tier 1 analysis (e.g. livestock pests and diseases, increased water use by animals during dry periods, potential land salinity impacts on livestock farming, water logging effects on livestock, and climate impacts on animal transport) but excluded from the metric analyses (Box 1).

Box 1. Animal Welfare

The impacts of climate change on animal health and welfare can be both direct and indirect. For example, indirect impacts on animals include a reduction in feed availability and an increase in competition for land use. The evidence presented considered animals within specific agricultural sector classifications, as the environment and management systems used dictates to a large extent the exposure to the climate change effect. The indirect effects, including adaptation options, are not considered in the CCRA.

The greatest risks to animal welfare from climate change are during transport of animals due to the potential extremes of temperature experienced. Extremes of temperature, if not mitigated, can result in an increase in mortality and thermal stress. Such consequences are clearly a significant welfare issue. Animals are also directly impacted due to their on-farm environments being outside their thermal comfort zones, with young animals being at most risk. The conditions of animals reared outside can be adapted through improvements in provision of shelter and those reared inside with mechanical ventilation systems. These must be robust enough to withstand unpredictable extreme weather conditions to ensure animal welfare is maintained. The farming industry may adapt by shifts in geographical location to reduce the likelihood of animals experiencing these extremes in weather conditions on-farm.

Mitigation strategies to reduce the likelihood of climate change occurring are numerous, but the development of 'sustainable intensification' as a mitigation strategy has the potential to have both benefits and costs to animal welfare.

Overall, animal welfare is an important issue that needs to be considered and monitored when policy makers and the agriculture industry are developing and implementing adaptation and mitigation strategies to animal welfare.

Dairying. Temperature increase would have the largest impact on dairy cow welfare. Heat stress during summer months at which time the majority of the UK dairy cattle graze on pasture may be a concern as early as the 2050s in areas such as the south west of England, and of considerable concern in many dairy producing regions by the 2080s. Increasing heat stress over time would negatively affect livestock survival, impacting across all age groups. Climate related losses in production will thus be a major concern for the dairy industry (Haskell, *et al*,. 2011).

Beef cattle production. Beef cattle will be spared the major effects of heat stress, as the geographical areas in which the majority are reared (west and north UK) may not experience major temperature increases until the 2080s (High emissions scenario). Higher altitudes are less likely to experience excessive temperatures. Extreme heat-waves and cold weather may be a welfare issue.

Sheep production. There is great diversity in the management, habitats and feedstuff regarding sheep production, beneficial as an extensive environment is often synonymous with good welfare. However, merely being outside does not necessarily ensure that the environment will meet all the requirements of sheep. In the UK the most common environmental stressor is likely to be cold temperatures, often intensified by heavy precipitation and wind. Wetter winter conditions projected under climate change may increase exposure to extreme cold. Additionally, extreme snow and ice weather across the short term may have a noticeable impact.

Pig production. As most pigs produced for meat are reared intensively indoors, the direct effects of climate change are linked to the capacity and efficiency of environmental control systems. Increased average temperatures and frequency of extreme events may place great demands upon environmental control. Heat stress during heat waves or extreme events will have the greatest effects upon slaughter pigs at their highest body weights. Indoor environments or housing reduce wind, rain and solar radiation impacts although inadequate ventilation may exacerbate the risks of heat stress. Under climate change scenarios, pig houses exceeded the critical temperature 20% of the time despite the 10% increase in ventilation (Defra, 1997).

Poultry. Almost all meat poultry are produced in intensive systems thus, in indoor systems the risks to poultry are the same as those to pigs. Climate impacts are linked to environmental control systems, and it is the extreme events, both hot and cold, that pose the greatest risk to animal welfare. As for pigs, heat stress in mid-summer will have an impact on birds at their highest meat weight. When inadequate environmental control allows temperatures to fall in winter then the risk of cold stress will be greatest in young chicks or poults. Under climate change scenarios, poultry houses exceeded the critical temperature 30% of the time despite the 10% increase in ventilation (Defra, 1997).

Animal transport. Animal transportation is the component of livestock production most vulnerable to the immediate effects of climate change, and extreme weather events. Heat waves may have measurable impacts in the UK in a very short timescale (pre 2020s) and may be more apparent in southern and eastern regions in the short term. Problems associated with the internal thermal micro-environment of transport become more serious during temperatures extremes, as well as infrastructure disruption (e.g. flooding) (Haskell *et al*, 2011).

Environmental impacts

About 10% of the impacts identified in the Tier 1 list related to environmental risks to agriculture. Many of the impacts relating to agriculture's role in supporting biodiversity, environmental and landscape enhancement in Tier 1 overlap with those impacts addressed in the CCRA Biodiversity and Ecosystem Services sector report. These include biodiversity and wildlife changes, bird migration, loss of particular landscapes and communities and natural adaptive response that favour more resilient species, in the case for agriculture this equates to more resilient breeds. Impacts on protected areas and landscape conservation measures within the agricultural landscape (e.g. SSSIs) are also discussed.

Regarding biodiversity, it is important to note that even without climate change, the evolution of farming practises may impact on biodiversity and ecological systems.

Likewise, a change in policy, environmental regulation or ecosystem management may limit future agricultural practises. It is likely that change and adaptation regarding biodiversity and agriculture would occur without climate change; therefore it is very much a balancing act between the two to ensure successful and sensible land management.

Box 2. Pollination Services

Pollination is a key ecosystem service and vital to the maintenance both of wild plant communities and agricultural productivity. Insect pollination, mostly by bees, is necessary for production in 84% of all crops in Europe and 75% of the crops used globally for human consumption. In 2005, the economic value of insect pollination was estimated to be approximately £120 billion globally and £440 million per annum in the UK (equivalent to 13% of the total value of agriculture). Crop pollination services depend on both domesticated and wild pollinator populations, and both may be affected by recent and projected environmental changes, many with unknown consequences. There has thus been growing concern about the fate of both domesticated and wild pollinators, leading to special initiatives by the Convention for Biodiversity (International Initiative for the Conservation and Sustainable Use of Pollinators) and a number of continental, national and regional programmes. Clearly, insect pollination is a key agricultural input. However, scientific knowledge on the pollination requirements of crops, the pollination potential of different bees and other insects and the impact of landscape, land use and climate change on pollination services is not well understood. For these reasons, the BBSRC are funding research by Biesmeijer *et al.* (2011) to investigate the sustainability of pollination services for UK crops, including the potential impacts of climate change on future crop pollination. The study will determine whether and how climate change will affect UK crop distributions and the need for pollination services towards the 2050s using process-based and climate-envelope models. The research will report its findings in 2014.

The role of pollination services to agriculture has strong links with biodiversity and the provision of ecosystem services. Any changes in ecosystem structure from species loss could disrupt the delivery of key services such as pollination. In recent decades, the increased intensification of agricultural production systems has impacted on the biological diversity within the landscape, with potentially damaging consequences on the natural benefits obtained from ecosystems such as pollination, soil nutrients, and control of pests and diseases.

It is estimated that during the last 20 years, habitat losses and intensification of agriculture have been responsible for 54% decline in honey bee colony numbers in England. Intensification appears to have changed the community composition of bees within agricultural ecosystems by negatively impacting on the least resilient species and reducing overall diversity. When combined with the effects of climate change and pathogens, this has major implications for the stability of pollination services to both biodiversity and agriculture NEA (2011). Agri-environment schemes have helped to redress problem areas. In terms of ecosystem services, the greatest impacts from invasive species, pests and disease are likely to be where provisioning ecosystem services, such as food or fibre provision, are affected. Much of the information on the level of risk is focussed on pests and pathogens that affect agriculture, forestry and human health, including *Phytophthora ramorum*, Lyme disease (*Lyme borreliosis*) or the veroa mite that impacts on bee populations and pollination services (Biodiversity and Ecosystem Services Sector Report).

Other impacts

About 10% of the impacts identified in the Tier 1 related to 'other' factors, mainly relating to food security and food demand. Global food demand is expected to increase by 50% by 2030 and by almost 70% in 2050 (Foresight, 2011a). Energy demand too will increase, as will the demand for water for people, agriculture and the environment. Climate change will thus impact significantly on food security. It will affect food production and availability, the stability of food supplies, access to food and food utilization (Schmidhuber and Tubiello, 2007). Many of the expected impacts of climate change on crop production will put more pressure on sustainable growth. There are complex interactions with natural resources, social and political systems, economics, trade and policy and potential conflicts with the drive to boost crop production without undue depletion of the natural resource base.

This sector report focuses only on UK agriculture, and excludes the risks associated with guaranteeing overseas food supplies and national food security, although the National Adaptation Programme and future iterations of the CCRA could attempt to address this issue. Whilst not explicitly a risk to UK agriculture *per se*, it has major consequences for the way in which the impacts and risks of climate change on UK agriculture are viewed, particularly given that half (50%) of the total food consumed in the UK is imported, in many instances from regions of the world where climate change is expected to exacerbate problems of food production as discussed in the International Dimensions of Climate Change[11] (Foresight, 2011b). Responding to the climate risks for UK agriculture therefore need to be set in context with the broader risks to the UK food supply chain.

There may also be increased heat stress on agricultural farm workers due to extreme summer temperatures with changes in working patterns. Agricultural labour may also need new skills training because different crops are being grown, and work hours (labour profiling) may change due to shifting crop requirements. Changes in land suitability (Daccache *et al*., 2011b) will also have impacts on the labour requirements for agribusinesses at key periods (e.g. land preparation, irrigation) during the growing season.

3.1.4 Selected impacts

Following the scoring and ranking of potential impacts in each sub sector, 9 main areas were defined for subsequent detailed analysis (Table 3.2).

Table 3.2 Summary of Tier 2 impacts for each agricultural sub-sector

Metric No	Arable	Field Vegetable	Livestock
AG1	Crop yield	Crop yield	-
AG2	Flooding risk	Flooding risk	Flooding risk
AG3	Pests and disease	Pests and disease	-
AG4	Aridity/drought	Aridity/drought	Aridity/drought
AG5	-	Water abstraction	-
AG6	-	-	Water abstraction
AG7	-	-	Milk production
AG8	-	-	Herd fertility

Impacts were classified according to whether a risk metric is likely to be defined successfully (blue), metric attempted (yellow) or metric unlikely to be defined (clear).

Following review, three additional impacts were selected for detailed analysis, as follows: New crop opportunities (AG9), Grassland productivity (Metric AG10) and Soil erosion (Metric AG11).

[11] http://www.bis.gov.uk/assets/bispartners/foresight/docs/international-dimensions/11-1042-international-dimensions-of-climate-change

3.2 Cross sectoral and indirect consequences

Many of the risks examined for this sector are linked or interact with risks in other sectors. This means that some risks that are pertinent to the sector are not addressed in this report because they have been covered in one of the other sector reports. This section (i) explores the cross-sectoral links in more detail based on the systematic mapping of causes, processes and consequences; and (ii) identifies the risks in other sector reports that are pertinent to the sector.

3.2.1 Systematic mapping

To supplement the initial identification of risks (Tier 1 list), a more formal process was undertaken, to identify direct, indirect and 'cross-sectoral' impacts and consequences. Referred to as Systematic Mapping, this starts with changes in climate variables as the cause of direct impacts, which are largely bio-physical. These changes were then used as the causes for the next iteration to capture indirect consequences and links between sectoral sub-systems. The process was then repeated in a series of iterations as illustrated in Figure 3.2.

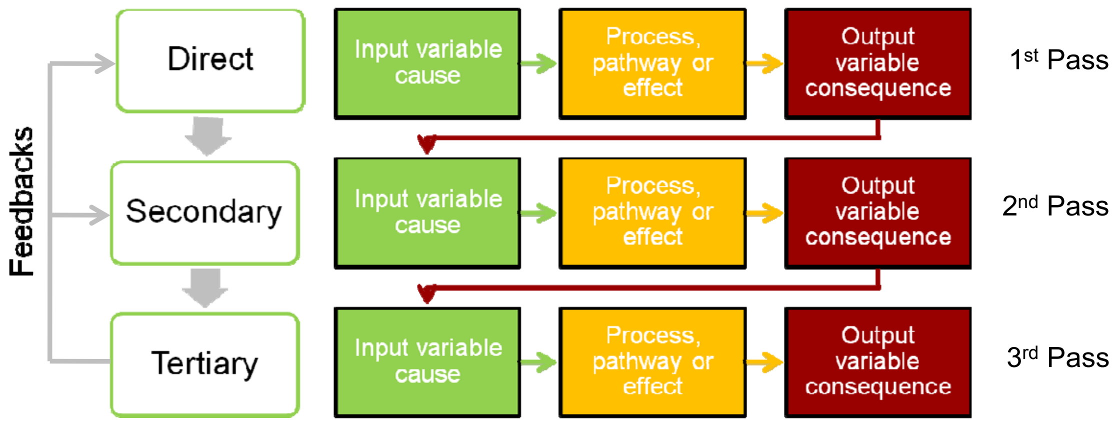


Figure 3.2 Systematic mapping of cause-consequence linkages

Outputs from the systematic mapping include diagrams showing links between climate drivers (e.g. increased precipitation), bio-physical impacts (e.g. flooding), direct consequences (e.g. property damage) and indirect consequences (e.g. health effects on people). The examples cited reveal the cross-sectoral links between Flooding, the Built Environment and Health sectors.

The systematic mapping identified a network with around 2400 consequences, of which some 1300 are unique sector based consequences (once identical consequences with different attributes have been removed). Many consequences identified within individual sectors were essentially similar to those in other sectors. For example, damage to buildings was identified in relation to hospitals under Health, commercial property under Business and all types of building under Built Environment. These were consolidated into single common consequences, with narratives that reflect the interest in the different sectors. After consolidation, the total number of impacts identified by the systematic mapping was reduced to about 240 generic consequences. These are of course much more general than the largely sector specific impacts identified in the individual sector scoping reports and this explains why there are only 240, as compared to the 720 in the Tier 1 list of impacts.

The fact that the 240 "generalised" consequences occur some 1300 times in the overall mapping reflects the occurrence of similar consequences across many sectors and the complex inter-relationships which have been captured by the systematic mapping. For example, an increased risk of fluvial flooding is linked to some 15 consequences including loss of life, damage to properties and social/community disruption.

As part of the process of populating the database, Sector Champions were asked to identify any cross sectoral impacts at each pass of the process. A number of cross sectoral impacts were identified, although the majority of these were not new, and were just existing impacts that had an effect across different sectors.

By considering the consequences for a given sector and the causes and consequences that link back to climate variables, or follow on from the given sector consequences, each sector is found to link to all other sectors in some way or other. The only exception is that transport is not linked to agriculture or forestry[12]. Some caution is needed over this interpretation, however because each entry of a sector consequence picks up on any of the available causes from earlier passes and in a few cases this will depend on which sector identified a particular impact first. This can only be investigated by considering specific instances. Nonetheless, the majority of entries do relate to sector specific consequences and this highlights the strong interaction between sectors and the complexity of some of the interactions.

Within the systematic mapping there were a number of feedbacks to earlier passes, including some climate drivers. For example, overheating of buildings has the potential to increase energy demand (for cooling), which in turn has links to water demand and a potential change in emissions. In addition, several impacts recur over several passes. The most obvious of these were the financial impacts (e.g. revenue and capital or operational expenditure), which are consequences in all passes from the second pass onwards. There are also a number of feedback loops. Most of these occur in the biodiversity sector where several impacts, e.g. population/ productivity of species, food supply and biodiversity are highly inter-dependent.

A customised web based application has been developed to enable the development and exploration of the systematic mapping. The searchable database can be used to identify linkages related to climate variables, sectors, processes or specific consequences and produces maps of the results. However, the systematic maps by sector are too large to represent in this report. The commentary that follows identifies the key links identified and discusses their relevance to the sector.

An analysis of the outputs from the systematic mapping exercise for Agriculture identified a number of cross sectoral links, with most being related to Biodiversity and Ecosystem Services, Forestry, the Built Environment, Floods and Coastal Erosion Risk Management, Business and Industrial Services and Water.

From the systematic mapping, a total of 151 cause-consequence links for Agriculture (only) were identified – this included 75 individual causes and 46 consequences. Of course, for many causes there were multiple consequences, and vice versa.

More detailed analysis showed that three quarters of all these cause-consequence links were actually focussed around only a handful of factors, including crop yield, crop development, tree/crop damage, land use, population/productivity of species, land suitability/availability, soil moisture and water availability/demand. For each of these, the potential cross-sectoral links were then identified and summarised below:

- Crop development – links with Energy (for biofuel production, increased fertiliser use) and Water (changing demand due to production switching from rain-fed to irrigated).

[12] Note that the agriculture sector work was focused on agricultural production and the forestry sector on production and biodiversity. Therefore neither of these sectors covered the supply chain aspects including the transport of agricultural or forestry products to market. These aspects, which are important, form part of the business and industry sector.

- Crop yield and crop diversification – links with Biodiversity and Ecosystem Services (changes in habitat extent and condition) and Energy (biofuels).
- Tree/crop damage – links with Energy (renewable energy potential) and Forestry (timber quality, biodiversity and species vulnerability).
- Population/production of species – links with Biodiversity and Ecosystem Services (changes biodiversity and species vulnerability) and Forestry.
- Land suitability and land use – links with Forestry, Biodiversity and Ecosystem Services, Built Environment, Flood and Coastal Risk Management. Common risk was related to impact on crop yield and hence revenue.
- Water availability – links with Water, Biodiversity and Ecosystem Services, Built Environment, Energy and Business/Industrial Services. Risks related to conflicts over supply and demand for water and impacts of changes on habitat conditions.

3.2.2 Agriculture and other cross sectoral risks

Cross-sectoral risks that have been addressed in other reports include:

- Changes in environment and habitats (Biodiversity and Ecosystem Services)
- Pest and disease vectors (Biodiversity and Ecosystem Services)
- Bird migration (Biodiversity and Ecosystem Services)
- Changes in soil organic carbon (Biodiversity and Ecosystem Services)
- Energy supply failures/outages (Energy, Flooding)
- Risks to agricultural land from flooding (Flooding)
- Changes in forestry production and agroclimate (Forestry)
- Changes in aridity (Water)
- Changes in water availability and demand (Water).

A summary of the metrics developed in other sectors and their main relevance to agriculture is given in Table 3.3. For detailed discussion of each refer to the relevant sector report.

Table 3.3 Summary of risk metrics from other sectors of relevance to agriculture

Sector	Risk metric description	Summary and relevance to agriculture sector
Biodiversity	Increased risks from invasive species, pests and diseases (BD3/4)	As low winter temperatures act as a climatic control on many pests and diseases, future projections of milder winters suggest that the risk from pests and diseases may increase, and be particularly apparent in the spread of new invasive non-native species during milder temperatures in winter. A trend towards wetter winters is also likely to increase problems from fungi and related organisms such as *Phytothphora ramorum* that thrives on high moisture levels. However, each pest and disease has its own characteristics that preclude generalisations, with the spread of diseases also determined by the population dynamics of the host organism. It is therefore important that climate change is factored into risk assessments for each organism. Invasive non-native species may become even more suited to the changed climate than native species. Similar issues apply to native pest/disease species. In some cases these may become more competitive in their particular environments due to climate change with resulting detrimental outcomes and a potential risk to ecosystem function in extreme cases. Hybridization may occur between non-native species and related native species resulting in changes to genetic constitution and in phenotype, and this hybridization may dilute the degree of local adaptations of native species to the local environment. A shift in climate can lead to changes in geographical distribution, increased overwintering, changes in population growth rates or generation number, extension of the development season and changes in the synchrony of the pest with other species (Carter *et al.*, 1992) and affect the characteristics described above. As a result of this complexity it is rarely a single variable that will cause a pest to increase in destructive ability. These compounding factors make forming generalisations about implications for biodiversity very difficult. There is LOW confidence in the assessment of this risk, due to the high variability between individual pests and diseases, and the low evidence base. However, there is a general high consensus that this risk *could* significantly increase due to climate change. Much of the risk evaluation to-date has been based related to issues of human health or productivity in forestry and agriculture, and there is therefore a strong requirement to extend this to a broader evaluation of risks to biodiversity.
	Major coastal flood/reconfiguration (BD7)	Extreme events are by definition, low frequency and high magnitude risks. When they do occur (e.g. the storm surge of 1953, Western Isles storm January 2005) they can cause major damage to both the human and natural environment. Extreme high water levels from rising sea levels combined with storm surge and large waves could lead to an increased risk of a breach in low-lying areas of the coast and reorganisation of coastal ecosystems. This risk is particularly apparent in East and South England, although other areas of the UK have also been identified as risk zones. It also possible that society in the future will decide that investment in sea

Sector	Risk metric description	Summary and relevance to agriculture sector
		defences for some sections of the coast is unsustainable and over time a large-scale realignment of the coast could occur which will also have implications for the habitats and species in that area. Note: This metric relates principally to marshlands and estuaries and not agricultural land areas; however the risks are related.
	Changes in soil organic carbon (BD8)	Despite limited evidence, climate change is considered a major threat for multiple soil processes and properties (Towers *et al*., 2006; Schils *et al*., 2008). Any threat to soils are a source of concern since soils maintain effective functioning in all terrestrial ecosystems and support the delivery of many vital ecosystem services (e.g. crop production, water regulation, carbon sequestration, water purification). Soils are also an important reserve for biodiversity, including bees which provide crucial pollination services in agriculture. The organic content of soils is a key regulator of plant nutrient cycling and water availability. Changes in the relative rates of biomass production and decomposition due to climate change (temperature, precipitation and CO_2 levels) can impact on above and below ground biota and ecosystem functioning. These changes can also lead to modification of carbon stocks held by the soil, manifest as either increased CO_2 emissions or sequestration. A qualitative risk assessment was made in the Biodiversity and Ecosystem Services Sector report using soil organic carbon as a key measure of the content of organic matter in soils. Although there is a medium evidence base much of it is contradictory, hence the level of consensus on current and future change is low. In reviewing current evidence and model predictions, Smith *et al*. (2007a) suggested that land use change and management have been significant historical drivers of change in soil organic matter while climate change is thought to become more significant over time. Soil erosion is also important (both water and wind erosion), especially during extreme events (Lilly *et al*., 2009), and may be linked to greater rainfall intensity (Jenkins *et al*., 2009a). However, increased erosion rates can also be indicative of changing land use and management practices (e.g. more autumn-sown crops). More intense and/or sustained rainfall events in combination with other factors such as land cover change (e.g. more autumn-sown crops) is thus likely to lead to changing patterns of soil formation and erosion, but interpretation is confounded by inherent climate variability and long-term lag effects from past land-use change and atmospheric pollution. A key parameter is the change in soil moisture levels, particularly through feedbacks with vegetation and CO_2, but this parameter is currently inadequately represented in climate models and future projections. Future changes in aridity (expressed as agroclimate in this sector report) and soil moisture have important implications for agricultural systems, by influencing the dependence and extent of supplemental irrigation, the viability of rainfed crop yields and modifying soil water balances and land suitability (potential for new crops).

Sector	Risk metric description	Summary and relevance to agriculture sector
	Increased risk of wildfire (BD12)	The climatic conditions that would promote an increase in wildfire risk such as higher temperatures, lower summer rainfall and drier soils (higher moisture deficits -see BD1) are projected to increase. This may result in large changes in habitat and species populations, with frequent fires associated with open habitats (grassland and heath). There may also be damage to peat and consequent release of carbon into the atmosphere (see BD8). Depending upon the scale of damage, species and habitats affected, fires have the potential to impact upon many ecosystem services. Of particular importance are the potential impacts upon carbon storage (which may be particularly severe if large-scale fire occurs on peatlands), water purification, and cultural services associated with landscape amenity, recreation and 'sense of place'. Wildfires can have a number of socioeconomic effects, including the obvious risk to human HEALTH and the impacts on FORESTRY, AGRICULTURE, and the BUILT ENVIRONMENT. Based upon recent extreme years and future projections that extreme heatwave conditions could become more normal, there is a high consensus that that large-scale fire risk is likely to increase. However, the evidence base is currently rather limited (medium level) and therefore the confidence level for this risk is overall MEDIUM.
Water	Supply-demand deficits (WA5)	The supply demand balance is calculated based on the water available in surface water and groundwater and the demand for water. In Water Resources Management Plans (WRMPs), water companies estimate the amount of water available for abstraction based on hydrological or hydrogeological conditions, licence conditions and works capacities. These calculations are combined with 25 year demand forecasts to estimate when resources zones will fall into deficit, requiring investment in demand or supply side measures. Since the Water Sector analysis looked at domestic demand only, this report cannot comment in detail on how demand for water for the public sector, industry and agriculture might change. Demand for irrigated agriculture is expected to increase significantly and this is considered later and in the Evidence Report. If supply versus demand as a simple balance of water available for use is considered, most parts of the UK currently have sufficient public water supplies and some, such as the North East, have large surpluses of available water. The largest deficits are projected to occur in the Thames river basin region, with a deficit in the 2020s -168 (range of 338 Ml/d to -712 Ml/d for Low to high p50)of around 955 Ml/d (range of -47 Ml/d to -1780 Ml/d for Low p10 to High p90) by the 2050s that increases to 1340 Ml/d (range of -277 Ml/d to -1840 Ml/d for Low p10 to High p90) by the 2080s. Although the population affected by a supply-demand deficit could be an issue for much of the country, there are variations. For example, (looking at detailed figures) while almost all of the population for the Thames, Neagh Bann and Western Wales regions is projected to be affected by supply-demand deficits by the 2080s, other river basin regions such as Clyde and North West England are less affected.

Sector	Risk metric description	Summary and relevance to agriculture sector
	Number of sites meeting WFD Environmental Flow Indicators (WA7)	Using published statistics it has been possible to determine the number of river water bodies affected by 10, 15 and 20 percent reductions in Q95 flow for England and Wales (metric WA2). This function has then been used to imply changes to the number of river sites meeting WFD Environmental Flow Indicators under a range of UKCP09 scenarios. The results of this exercise show increases under the "wet" scenarios for the 2020s. All other scenarios show decreases in the number of sites, with decreases of nearly 80% under the most extreme, 2080s scenario. The analysis highlights the need to monitor and possibly re-evaluate 'environmental flows' in rivers under a changing climate. Similar data were not available to complete the analysis for Scotland and Northern Ireland; however the latest WFD Hydrological Classification maps provide an indication as to where water quality is of most concern. If these maps are compared with this assessment estimated flow reductions and number of "hot-spots" for low flows can be identified.
	Number of sites with unsustainable abstraction (agriculture) (WA8a)	Abstraction may become unsustainable in a large proportion of UK rivers due to low summer flows. There is an urgent need to consider how to balance environmental water requirements with demands for water in a changing climate. It is important to consider agricultural abstractions as licences from unsustainable sources are likely to be limited in future with consequences for farmers who may not use licences under the current climate but could need them in the future in order to grow horticultural crops. For agriculture there are projected changes (mainly decreases) in agricultural abstractions coming from sustainable sources of -13% (i.e. a decrease) (range 8 to -18%) for the 2020s, and -21% (range -14 to -24%) for the 2080s. Therefore, in the near term (2020s) a large proportion of rivers could fail environmental flow targets if we continue to use historic climate to guide our regulatory framework. In the longer term (2050s, 2080s) changes in the way we manage water resources are likely to be needed to maintain supplies and enhance the environment. Abstractors may need to consider a more lateral-thinking approach to ensure security of supplies, for example through options for sharing resources (both within and across sectors) and forming abstractor groups.
	Water quality (WA9(a) to (b))	There is currently a lack of clear evidence on the impacts of climate change on water quality and further work in the UK is needed to assess this. As a result, there is less confidence in the assumptions and analysis for water quality than there is for water resources. Water quality is however thought to be influenced in a number of ways. A reduction in summer rainfall could lead to: • A reduction in the dilution and dispersion of contaminants as a result of low flows.

Sector	Risk metric description	Summary and relevance to agriculture sector
		• In lakes and estuaries, a reduction in flushing due to low flows could increase residence times of pollutants, exacerbating existing issues such as eutrophication[13] as well as potentially enhancing the settling rate of sediments, reducing turbidity and enhancing the conditions for algal growth through improved light penetration. • An increased risk of pollution infiltration due to lower summer groundwater tables. An increase in winter rainfall and the frequency of intense rainfall events could lead to: • More runoff, resulting in water quality problems (including groundwater) due to leaching of agricultural contaminants from surrounding land. Moreover, levels of soil erosion could increase potentially leading to greater loads of suspended solids within waters and a reduction in water clarity. • An increase in the frequency of spills from Combined Sewer Overflows (CSOs) following intense rainfall events. This might be a particular issue during the summer months when receiving waters have inadequate capacity for dilution. • Flooding, which could increase suspended solids and sediment yields as well as contaminants. • Higher flows, potentially improving water quality through increased dilution. • A change in the frequency of intense rainfall events particularly following periods of dry weather potentially leading to inflow of sediment, nutrients and pathogens. An increase in summer temperatures elevating water temperatures influences the rate of bacteriological processes and chemical reactions that occur within them. This could potentially exacerbate existing problems such as eutrophication, for example through improving conditions for algal growth as well as reducing saturation levels for oxygen concentrations. Any changes to water quality could have implications for: • Ecological status and therefore meeting WFD objectives. It should however be noted though that a deterioration in ecological status is not permitted by the WFD. • Water treatment – runoff from moorland/farmland into reservoirs and rivers used for water supply could increase requirements for water treatment processes. However, the implementation of

[13] Eutrophication is defined by the EC Urban Waste Water Treatment (UWWT) Directive (91/271/EEC) as "the enrichment of water by nutrients, especially by compounds of nitrogen and phosphorus, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable balance of organisms present in the water concerned".

Sector	Risk metric description	Summary and relevance to agriculture sector
		catchment management schemes which aim to decrease pollution from agricultural runoff could reduce the need for water treatment. • Abstractions, either directly or indirectly due to potential ecological impacts. Other uses, including: • Recreational activities due to health and safety issues, for example the accidental ingestion of contaminated surface waters. Further discussion on water borne disease is given in the Health Sector report. • Tourism, due to the detrimental impacts on the aesthetic appeal of water. • Livestock and other animals, for example if toxic blooms of blue-green algae are present. Water quality can be affected by point and diffuse sources of pollution, both of which are likely to be affected by changes in socio-economic conditions, most notably population, land use and management, water treatment technology and the cost of carbon. For example, a change in the area of agricultural land has the potential to influence the amount of diffuse pollution entering a watercourse. One of the main concerns associated with diffuse pollution in the UK is the levels of nitrate in rivers, with some of the highest concentrations in Western Europe (Burt *et al*., 2010). In England and Wales, 60% of the nitrogen which enters inland surface waters comes from agricultural land, while sewage effluent contributes only 32% (Hunt *et al*., 2004; Burt *et al*., 2010). In 2002 Nitrogen Vulnerable Zones covered 20% of Scotland, which were partly located in almost all arable land in Scotland (Maxwell, 2002). These excess nutrients come from a number of agricultural processes including the use of chemical fertilisers and animal feed supplements. Diffuse pollution can be affected by changing seasonal flow patterns and velocities, intense rainfall, drought events and temperature changes. The enrichment of water by inorganic nutrients can enhance the growth of plants such as algae which in turn affects the transparency of water, as well as the levels of dissolved oxygen concentrations and pH, potentially causing ecological disruption. This may have implications for meeting WFD objectives.
Floods	Increased flood risk for cropped areas and grazing land (tidal and river) (FL4)	This metric is based on assessing the areas of agricultural land at risk from an increased frequency of flooding. The data uses the agricultural land classification and flood frequency data from the Floods Report. The ALC classes are divided into two categories: Grades 1 to 3, and grades 4 and 5. Land use in Grades 1 to 3 is mostly arable and horticulture, whereas Grades 4 and 5 are mostly grazing land for livestock. Thus the figures provide an indication of the effects of climate change on arable/horticulture and livestock. Frequent flooding

Sector	Risk metric description	Summary and relevance to agriculture sector
		may also change land suitability for different agricultural purposes. There is also a concern that increases in flooding and waterlogging of agricultural land could affect national productivity. In the Floods sector, two metrics were developed - FL4a (area of agricultural land at 10% or greater annual probability of flooding: flood inundation depth 0.5m or greater (km^2) and FL4b (area of agricultural land at 33% or greater annual probability of flooding: flood inundation depth 0.5m or greater (km^2). Based on the risk metric, the total amount of agricultural land in England and Wales that has an annual probability of flooding of 10% (1:10) or greater from river and tidal flooding is estimated to be about 200,000 ha. It is projected that this may rise to approximately 500,000 ha by the 2080s based on the p50 Medium emissions climate change scenario. The amount of land in categories 1, 2 and 3 that could be very frequently flooded (river and tidal flooding with a frequency of 1 in 3 years on average or greater) is projected to increase from a 1961-90 baseline of about 30,000 ha to about 35,000 ha by the 2020s, reaching approximately 130,000 ha by the 2080s.. Thus the likely interference to agriculture caused by frequent flooding may increase significantly. The metric does not include surface water flooding or waterlogging, which both have a severe impact on agricultural land and production. Flood data was not available for Scotland however, it is expected that the impact of flooding could be very significant due to the importance of Agriculture for business and the economy.
	Area of agricultural land lost to coastal erosion (FL14a)	This metric was calculated assuming that existing defences will deteriorate for coastal erosion except in urban areas, where the present defence line will be maintained. This means that urban areas will not be affected by coastal erosion, and hectarage losses are limited to agricultural (and BAP habitat) land using projected future erosion rates. Coastal erosion will happen whether or not climate change occurs. Rates of erosion vary around the coast but the majority of values are in the range of 0.1 to 1m per year. The rates are projected to increase by factors of typically 2 to 5 depending on the scenarios considered. The analysis is limited to England and Wales and does not cover Scotland and Northern Ireland, in part, due to a lack of available data on coastal erosion. It is tentatively estimated that about 8,000ha of agricultural land in England and Wales could be lost to coastal erosion by the 2080s. These estimates are based on a simple analysis of old data, and therefore can only provide an indication of the magnitude of this impact. The cumulative total costs of coastal erosion was estimated based on 2010 prices to 5.44£m, 18.76 £m and 30.88£m in 2020, 2050 and 2080 respectively using the medium emission scenario.

3.3 Other impacts excluded from the risk metric analysis

Previous sections have highlighted some of the potential impacts of climate change on outdoor livestock and animal rearing and to a lesser extent on indoor housed animals. Risk metrics for livestock were provided for dairying. Provided below is a brief synthesis of the literature on the reported climate impacts on other livestock systems including beef, cattle, sheep, pigs and poultry, and a synthesis of the opportunities for new crops.

The effects of climate change on livestock sector are extremely complex and variable. Climatic variations can have a direct influence on the animal health, reproduction and appetite or indirectly by affecting the grass growth and animal feed prices.

An increased level of carbon dioxide may enhance grass production for the same amount of nitrogen fertiliser (Hopkins and Scholefield, 2004). However, CO_2 increase combined with other factors such as water availability could lead to changes in leaf/sheaf ratio, reduced nitrogen and increased fibre content affecting noticeably the dietary quality and thus lowering the liveweight gain.

Warmer winter temperature would extend the length of the growing season in upland areas resulting more grass for winter grazing and forage (CC0366). In western dairying area it was forecasted an increase in herbage production of 10-15% by the 2020's and over 20% by the 2050's (Hopkins and Scholefield, 2004). However many swards of grassland contain mixture of species making prediction of their response to climate change highly complex.

Housing period will be reduced in a milder winter with positive impact on the feed and bedding costs. On the other hand, pathogens and fly problems may increase. In hotter and drier summers grazing animals are likely to be affected by insufficient forage due to reduced grass growth especially in the south. Prolonged extreme high temperatures will also increase the risk of heat stress on animals, particularly the young. It has been calculated that the frequency of heat stress may increase in the future by 20% for ewes and 60% for lambs (Defra, 1997). Hot dry weather is not favourable to most sheep parasites and numbers of roundworms, blowflies and ticks are likely to reduce (Orson, 1999). However, warmer weather could increase the risk of fly strike and diseases currently found in warmer areas such as facial eczema (CC0366). Shearing time will also occur earlier to reduce heat stress.

A reduction in the soil moisture as a result of a warmer and drier climate may be beneficial in some areas of the country where grasslands are located on poorly drained soils leading to a reduction in such problems as poaching. In other areas, a reduction in moisture might lead to an increase in supplemental feeding needs since grass production is very sensitive to water shortage.

Extreme weather may require the farmers to increase their investments in infrastructure such as drainage systems to reduce the problem associated with water logging. Water storage, irrigation and water supply systems might also be required to satisfy the grass and livestock needs. Potential change in the agricultural building specifications or reinforcement of the existing ones might also be needed to cope with the intense weather events and increased winter rainfall and heavy rainfall days.

In additions to climate impacts on animal systems, the cultivation of new crops might be encouraged by changes in land suitability due to modified soil and agroclimate conditions. For example, changes in the spatial and temporal patterns of rainfall and temperature are likely to lead to the introduction of new crops in some regions and/or relocation of existing crops into new regions. New plant breeding coupled with investment in farming technologies (e.g. irrigation) might also lead to the introduction of new crops. Since agriculture is no longer viewed as being solely a provider of food crops – its multifunctional role will inevitably lead to a much broader range of crops being grown. New crops can be classified into 'food' and 'non-food' crops. The latter includes crops with alternative end uses such as for drugs and cosmetics development, for industrial feedstock, for renewable energy (biomass, biofuel or biogas), ornamental use, and for brewing, distillation or wine production. A crop can be considered 'new' in two situations; firstly, if it has not been cultivated before (e.g. as a result of a breeding programme or domestication process), and secondly, if it has not been grown in a certain region before (e.g. due to shifting agro-ecological zones).

The CCRA assessment of opportunities for new crops was limited to a review and assessment of existing literature, although it is stressed that the feasibility of new crops being introduced into UK agriculture is dependent on a much wider range of factors (economic, technical, market), than solely suitable agroclimate and soil conditions. It was not possible to define any risk metrics that might provide an insight into which new crops might be more feasible than others.

4 Response Functions

A risk metric is a measure of the consequences of climate change, change in frequency of specific events or a combination of the both, for example the annual average expected crop damage due to flooding. For national risk assessment, ‘good’ metrics are likely to have a number of criteria, i.e. they:

- Are sensitive to climate but also allow the disaggregation of climate and socio-economic effects.
- Provide a measure of changing probability or consequences relevant to a baseline, so historical data are required to establish the current situation.
- Can be presented at the national and regional scales, based on high quality data that are collected and held by Government departments, agencies or research institutes. The use of Government data should provide consistency between sectors and allow the metrics to be repeatable in subsequent CCRA cycles.
- Reflect economic, environmental and social consequences of climate change; some metrics may be monetised but others may simply indicate the areas affected or consequences for vulnerable groups of society.
- Are relevant/have legitimacy to the relevant Government policy.

The CCRA method highlights the difference between impacts, which are direct bio-physical effects arising from climate change, and consequences, which are the effects on society, the economy and the environment. Risk metrics aim to quantify impacts and consequences arising from climate change. For each Agriculture sub-sector, a set of risk metrics were defined and developed to reflect the range of biophysical impacts and social, economic and environmental consequences that were previously identified from a combination of the Tier 1 (review impacts) and Tier 2 (magnitude selection) phases. The risk metrics were defined taking into account their likely scale of application (whether regional or national) and the data availability needs required to compute them.

4.1 Selected risk metrics

The Tier 2 analysis identified 9 main areas for which risk metrics would need to be defined. Following an assessment of the links between climate variability and each identified impact, the potential descriptors for each risk metric and importantly the data required to quantify each metric and response function, the following metrics were defined (Table 4.1).

Table 4.1 Proposed risk metrics for each agricultural sub-sector

Metric No.	Metric description
AG1	Mean yield variability with climate
AG1a	Crop yield using sugar beet as a reference ‘arable’ crop
AG1b	Crop yield using wheat as a reference ‘arable’ crop
AG1c	Crop yield using potato as a reference ‘Field Vegetable’ crop
AG2	Agricultural areas at risk from flooding
AG2a	Flood risk to classified ‘arable’ land (ALC2/3)
AG2b	Flood risk to classified ‘horticulture’ land (ALC 1/2)

Metric No.	Metric description
AG2c	Flood risk to classified livestock ‘grassland’ (ALC 4/5)
AG3	Pest incidence with climate using 'marker' diseases
AG3a	Crop disease using ‘virus yellows’ as marker for sugar beet
AG3b	Crop disease using ‘rust’ as marker for wheat
AG3c	Crop disease using ‘blight’ as marker for potato
AG4	Agroclimate
AG4	Aridity index using PSMD as an agroclimate indicator
AG5	Water abstraction for crops
AG5	Volumes abstracted for irrigation correlated against agroclimate
AG6	Livestock water abstraction
AG6	Volumes of water abstracted for livestock
AG7	Climate impact on livestock production
AG7a	Heat stress impact on dairy milk production
AG7b	Heat stress impact on loss of dairy fertility
AG8	Climate impact on livestock health
AG8a	Duration of heat stress in dairy cows
AG8b	Dairy livestock deaths due to heat stress

Additional metrics relating to new crop opportunities (AG9), grassland productivity based on yield (AG10) and soil erosion based on ‘erosivity’ (AG11) were subsequently included.

4.1.1 Assumptions and uncertainties

The development and application of the risk metrics included a number of assumptions, particularly regarding future impacts on crop production which need to be recognised. The relationships between climate variability and yield were considered through the use of simple regressions between mean yield and specific climate variables (e.g. rainfall, temperature). In reality, crop yield is a function of a large inter-related number of climate, soil and crop management factors, many of which cannot be captured through the use of a simple metric. For example, the impacts of changes in CO_2 concentration on crop growth and consequent impacts on yield and water use were ignored. Future changes in preferred cultivars, improved pest and disease management, and changing patterns in fertiliser use were also ignored. The yield metrics also assumed trends in historical yield could be used by project future yield – this excludes the impact that any improved farm management or autonomous adaptation to climate change may have on yield potential.

The water use metric assumed the main climate drivers of irrigation (rainfall and evapotranspiration (ET) impact on soil moisture and hence the demand for irrigation abstraction. However, irrigation abstractions in dry years are constrained by water availability, hence actual reported abstractions may be much lower than theoretical demand. The agroclimate based metric also excludes the importance of irrigation in maximising crop quality – however, on many high value crops, schedules to maximise quality (as opposed to yield) are not directly climate related. The methodology also assumed that the metrics could be calculated using the UKCP09 climatology. A brief description of each metric, in terms of its rationale, data needs and application is summarised below.

In order to not overstate the potential changes in yield and productivity, it is important to consider that water and nutrient availability are major constraints regarding any potential increases. For the simple yield projections based on response functions, it has been assumed that these factors are non-limiting, but in reality they may be. In these cases the combined effects should be considered before the findings are used to inform any decisions related to adaptation policy.

4.1.2 Mean yield variability with climate (AG1)

In general terms, crop yields are sensitive to a range of climate variables (solar radiation, temperature, rainfall and relative humidity) and non-climate factors, such as fertiliser application rates, choice of crop variety, land management practices and the introduction of new technology. These factors are closely monitored and land management controlled at experimental research centres, however, relationships developed at these sites may not be scalable to UK regions and suitable for national assessments (Hermans *et al.*, 2010). Similarly, comparison of regional crop yield data with climate is difficult because variation across many farms may be primarily due to non-climate factors. This study used evidence from experimental sites and national statistics with the overall aim of understanding broad sensitivity of crops to climate and reconciling any differences between experimental data, national statistics and deductive models.

Reference crops were selected for the arable and horticulture sub-sectors. Wheat and sugar beet were chosen for the arable sub-sector and potatoes for field vegetables (horticulture). Of the 5 million hectares of agricultural land used in the UK for food crop production, cereals (wheat, barley and oilseeds) constitute almost 80% of land use. Other arable crops, such as proteins and sugar beet make up 13%, and horticulture (fruit, vegetables and ornamentals) and potatoes account for 4% and 3%, respectively.

The UK is the 4th largest producer of cereals and oilseed crops in the EU, accounting for around 8% of total EU production. It is the fourth largest EU producer of sugar beet, with around 4500 growers contracted to supply British Sugar. Wheat constitutes the most important cereal crop grown in the UK both in terms of cropped area and value. Sugar beet is also an important break crop in arable rotations throughout the major growing regions of the UK. National beet production provides over half the sugar consumed in the UK, the balance coming from sugar cane imports (British Sugar, 2011). Both sugar beet and sugar cane are high value commodity crops sensitive to climate change (Richter *et al.*, 2006; Knox *et al.*, 2010a).

Irrigated vegetable production represents a small but highly significant component of land use in the UK, in terms of production, value and rural employment (Leathes *et al.*, 2008). For the field vegetable sub-sector, potatoes were chosen as they are the most important irrigated field crop in terms of cropped area and water use (Weatherhead, 2006). Of course, horticulture comprises a large number of other crop types and production systems. Knox *et al*. (2009) estimated that within the horticulture sector, field vegetables account for 63% of total water use, soft fruit (15%), hardy nursery stock (10%), bulbs and outdoor flowers (5%) and protected crops (4%). For other vegetables, such as brassicas, irrigation is important but not so extensive, since these are grown on more moisture retentive soils, less prone to drought stress, and have quality criteria that are less sensitive to water stress. Potatoes were thus considered a suitable 'representative' crop, due to their extensive production, importance to UK consumption (84% used for human consumption) and high susceptibility (yield and quality) to climate variability. In 2009, more than 80 varieties of commercially grown potatoes in England produced 4.6 million tonnes with an average yield of 48 t ha^{-1}. During that year, over half (56%) the cropped area was irrigated, mainly by hose reels fitted with rain guns or booms. Some of the implications on potatoes can be partially transferred to other field-scale vegetable crops, recognising of course the different physiological characteristics and impacts that climate change might have on crop growth and development.

The approaches to developing response functions were similar in each crop, but these are described individually below.

4.1.3 Crop yield using sugar beet as a reference ‘arable’ crop (AG1a)

For each ‘reference’ crop (i.e. sugar beet, wheat and potatoes) national average yield data were correlated against ‘nationally’ available climate data. Mean annual yields were plotted against observations of mean monthly rainfall, temperature and global radiation, for seasonal periods (i.e. spring, summer, autumn, and annual). The regressions with the strongest statistical correlation (r^2) were selected and used for metric analysis. For sugar beet the strongest relationship was found between beet yield and the spring, summer and autumn average temperature, which equates to the average growing season temperature.

Brooms Barn experimental sugar beet annual yield data (white sugar rather than field yield) were obtained for 1980-2009. These were plotted against observations of mean monthly rainfall, temperature and global radiation. For each variable the time period over which the climate data were averaged was also varied to investigate whether a stronger correlation was obtained depending on the period, i.e. summer, spring and summer, or spring, summer and autumn. The strongest relationship was found between yield and the spring, summer and autumn average temperature, which equates to the average growing season temperature (Figure 4.1). In general, yield was higher in warmer years although there was considerable scatter in the data and the goodness of the fit is poor. This may be related to conditions at key growth stages or non-climate factors, however the overall trend is clearly upwards. The potential yield, with all other factors being non-limiting, is expected to be higher in warmer years with climate change. The linear regression equation of this relationship is considered to be the response function for metric AG1a (crop yield using sugar beet as a reference ‘arable’ crop). Since climate (X) is likely to cause changes in yield (Y), linear regression analysis was chosen. For the analyses, Spring was defined as being the period from 01 March to 31 May, Summer as 01 June to 31 August, and Autumn as 01 Sept to 30 November, respectively.

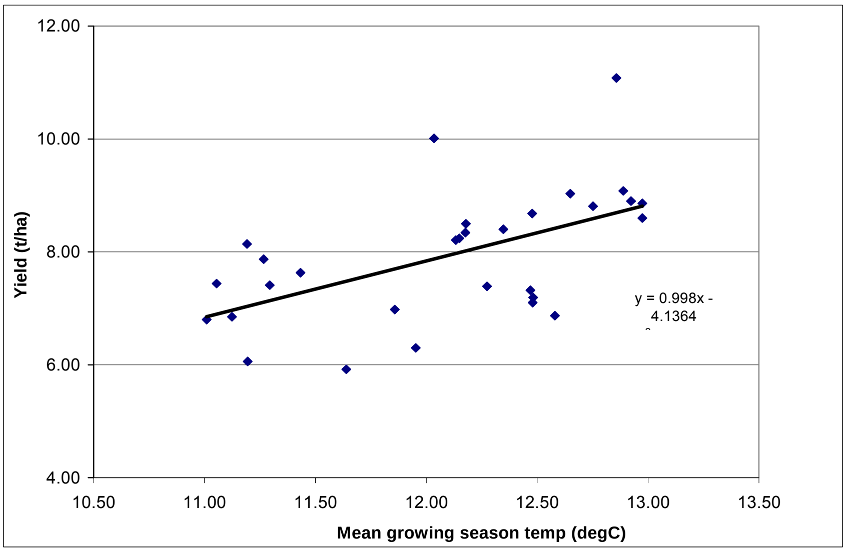


Figure 4.1 Response function for AG1a – using sugar beet yield (white sugar t/ha) as a reference crop

4.1.4 Crop yield using wheat as a reference ‘arable’ crop (AG1b)

Defra reported annual wheat yield data were obtained for 1960-2007. These were plotted against observations of monthly mean rainfall, temperature and sunshine hours.

For each variable, the time period over which the climate data were averaged was also varied to investigate whether a stronger correlation was obtained with the summer period alone, with spring and summer together or with spring, summer and autumn.

For wheat, the strongest relationship was found between mean wheat yield and spring, summer and autumn average temperature, which equates to the average growing season temperature (Figure 4.2). In general, yield was higher in warmer years although there was considerable scatter in the data, including the highest yields in a year with average temperatures. The scatter in the data (and therefore low goodness of fit) is most likely due to non-climate factors. Whilst the data fit is poor, the overall trend is clearly upwards. The potential yield, with all other factors being non-limiting, is expected to be higher in warmer years with climate change. The linear regression equation of this relationship is considered the response function for AG1b (Crop yield using wheat as a reference crop).

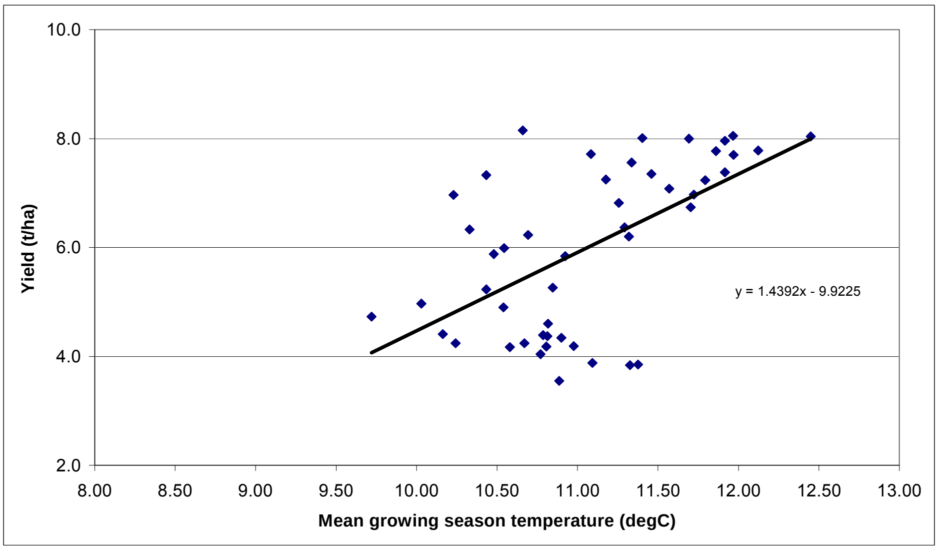


Figure 4.2 Response function for AG1b - crop yield (t/ha) using wheat as a reference crop

4.1.5 Crop yield using potato as a reference 'field vegetable' crop (AG1c)

Early UK modelling studies indicated potential yield increases in potato (Davis *et al.*, 1997). European studies and sensitivity analyses have shown that tuber yields of rain-fed potato (cv. Bintje) are slightly decreased with temperature rise and with increasing radiation (except for northern EU) and considerably increased with increasing rainfall and CO_2 (Wolf, 2002).

For this metric, national (GB) yield data were obtained from the UK Potato Council (PCL), which established a baseline figure of 31.6 t/ha. For potatoes, the strongest relationship was found between mean potato yield and summer rainfall. The yield data used in the risk metric analysis were those considering yield as a proportion of expected yield, i.e. %yield. This metric is only able to relate rain-fed yield to climate, as irrigated production is deliberately used to offset any impact of climate variability (drought) on both yield and quality. Approximately 60-65% of the UK potato crop is rain-fed, making this a potential useful indicator of the impacts of climate change. Rainfall data for the summer growth period (June, July and August) were taken from the Met Office's data archive and plotted against annual % yield (Figure 4.3). The power regression equation represents the response function for this metric.

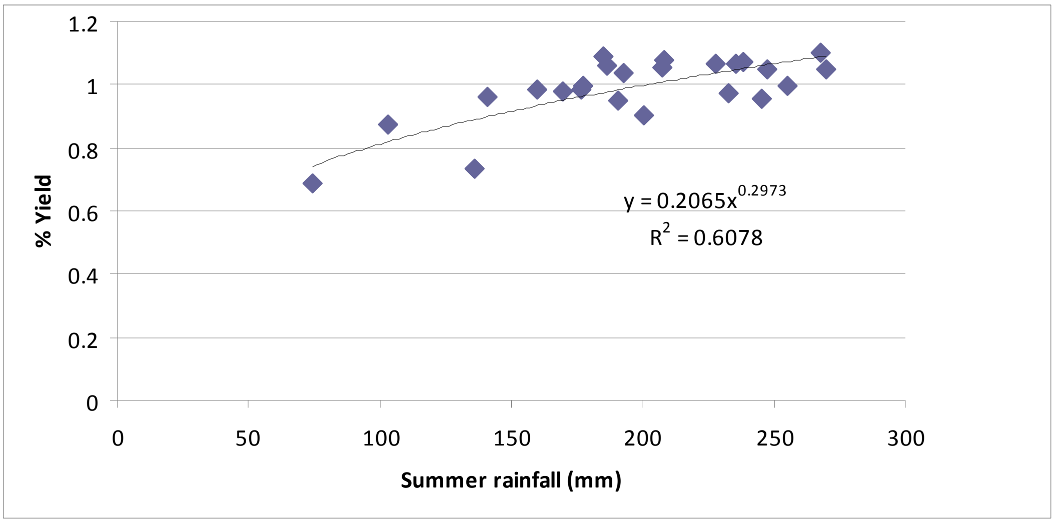


Figure 4.3 Observed rain-fed potato yields (% of target yield) against mean summer rainfall

4.1.6 Agricultural areas at risk from frequent flooding (AG2)

Agricultural land is at risk from flooding from rivers, coasts and estuaries and groundwater. Floods can destroy damage or contaminate crops and soils, harm farm animals and prevent access to land during and following flood conditions. The average flood damage cost was reported to be £1150 per hectare (Posthumus *et al.*, 2008; 2009) and the overall costs of the 2007 flooding have been estimated at approximately £49 million (Chatterton *et al.*, 2009; ADAS, 2007). This metric is related to river and tidal flooding in England and Wales; the data are also available from the Floods and Coastal Erosion Sector report. River and tidal flooding together are estimated to potentially affect over 500,000 hectares of agricultural land (Floods and Coastal Erosion Sector Report). The current risk of river and tidal flooding is that about 200,000 ha of land are at risk of flooding at frequencies of greater or equal to one in ten years (>10% risk in any year).

As arable and horticulture occupy the highest quality land and livestock more marginal land it is possible to consider a series of metrics:

- Flood risk to classified 'arable' land (ALC2/3)
- Flood risk to classified 'horticulture' land (ALC 1/2)
- Flood risk to classified livestock 'grassland' (ALC 4/5).

However, it is difficult to determine the split of arable and horticultural land in ALC class 2 so these were combined into a single analysis of flood risk to higher quality arable and horticultural land.

Table 4.2 Summary of Agricultural Land Classification for England and Wales

Grade	Description
Grade 1 - excellent quality agricultural land	Land with no or very minor limitations to agricultural use. A very wide range of agricultural and horticultural crops can be grown and commonly includes top fruit, soft fruit, salad crops and winter harvested vegetables. Yields are high and less variable than on land of lower quality.
Grade 2 - very good quality agricultural land	Land with minor limitations which affect crop yield, cultivations or harvesting. A wide range of agricultural and horticultural crops can usually be grown but on some land in the grade there may be reduced flexibility due to difficulties with the production of the more demanding crops such as winter harvested vegetables and arable root crops. The level of yield is generally high but may be lower or more variable than Grade 1.
Grade 3 - good to moderate quality agricultural land	Land with moderate limitations which affect the choice of crops, timing and type of cultivation, harvesting or the level of yield. Where more demanding crops are grown yields are generally lower or more variable than on land in Grades 1 and 2.
Grade 4 - poor quality agricultural land	Land with severe limitations which significantly restrict the range of crops and/or level of yields. It is mainly suited to grass with occasional arable crops (e.g. cereals and forage crops) the yields of which are variable. In moist climates, yields of grass may be moderate to high but there may be difficulties in utilisation. The grade also includes very droughty arable land.
Grade 5 - very poor quality agricultural land	Land with very severe limitations which restrict use to permanent pasture or rough grazing, except for occasional pioneer forage crops.
Urban	Built-up or 'hard' uses with relatively little potential for a return to agriculture including: housing, industry, commerce, education, transport, religious buildings, and cemeteries. Also, hard-surfaced sports facilities, permanent caravan sites and vacant land; all types of derelict land, including mineral workings which are only likely to be reclaimed using derelict land grants.
Non-agricultural	'Soft' uses where most of the land could be returned relatively easily to agriculture, including: golf courses, private parkland, public open spaces, sports fields, allotments and soft-surfaced areas on airports/ airfields. Also active mineral workings and refuse tips where restoration conditions to 'soft' after-uses may apply.

4.1.7 Pest incidence with climate using marker diseases (AG3)

The rationale of pest incidence as a metric was to try and evaluate observed changes in disease patterns using marker diseases for which historic data were available for at least the last 20 years and on a UK regional basis.

We know that the performance of crop plants is affected by a wide range of pest and disease organisms. Many of these are host or environment specific, attacking only a single species or even a single variety within a species. Others are more ubiquitous, tolerating a wide spectrum of environments in which they can survive. We also know that weather patterns and different climates influence the importance of particular damaging organisms to crop plants. Warmer, wetter growing seasons will, for example, favour those fungal pathogens more successful in humid environments, or which rely on moisture to move around. Winters which are less cold might result in higher survival rates of pathogens, reducing winter kill and increasing immune levels in following seasons.

The severity of the pest and disease depends upon many interacting variables which cautions against over-generalisation. Examples of such variables include:

- Land-use and land management
- Host/vector interactions
- Population dynamics (birth/death rates, immigration/emigration) of pest or disease as well as host
- Dispersal ability (by vector either vertebrate or invertebrate, wind or water borne)
- Predator/prey dynamics
- Interspecific competition and interaction with similar species
- Life cycle complexities (seasonal development and requirements of different life stages) (Biodiversity and Ecosystem Services Sector Report).

The discussion on changes in incidence of crop pests and diseases does not cover potential changes in risks from fungal toxins such as mycotoxins in wheat and other crops, which may be of increasing importance for UK agriculture. Mycotoxins are produced by fungi and can cause serious health problems if contaminated food is ingested. These toxins are principally controlled by climate with their production favouring warmer temperatures. For many Mycotoxins the optimum temperature in which they form at is 33°C which is within the range of the projected temperature increases (Russell *et al.*, 2010). This could have an affect on both the agriculture and health sectors.

4.1.8 Crop disease using 'virus yellows' as a marker for sugar beet (AG3a)

Climate change has the potential to impact on disease sources and pathways directly; for example, by changing the range of vector species or increasing disturbance events that facilitate disease. Habitats and communities of hosts may also be modified with changes in climate, thus influencing the diseases that can occur (Biodiversity and Ecosystem Services Sector Report).

Beet Mild Yellowing Virus (BMYV) is a widespread virus affecting beet crops in the UK. It is spread by aphid vectors, especially *Myzus persicae*, the Peach Potato aphid. The virus causes a yellowing symptom on expanded leaves of infected plants which become thickened and brittle. It was considered that incidence of the disease would be a good indicator of aphid activity. Aphid activity is strongly linked to weather patterns and climate. Brooms Barn Experimental Farm data for this disease from 1980 to 2009 were provided and tested against a range of climate parameters using simple linear regression analyses.

Unfortunately it was not possible to find a correlation with an acceptable degree of statistical confidence. The main reason for this was possibly the improvement in beet crop agronomy in recent years, resulting in crop treatments which have greatly reduced the significance of the disease. This has the effect of 'buffering' any impact that changes in climate has on the prevalence of the disease from year to year, so in recent years the impact of the disease on the crop is gradually being reduced.

There is anecdotal evidence of other diseases of sugar beet, for example, cercospora, which are becoming more prevalent in the UK, perhaps influenced by recent changes in weather patterns. At present, there is unfortunately insufficient historical data on these new diseases for them to be used in a metric exercise. As such, the conclusion of the analysis on this metric indicate that the specific threat of BMYV has been significantly reduced, which may be regarded as a form of autonomous adaptation in the sector. There may be other diseases that we know little about that could become more prevalent in a changing climate so ongoing surveillance is prudent.

4.1.9 Crop disease using 'rust' as a marker for wheat (AG3b)

Yellow rust (*Puccinia striiformis*) is a common foliar disease of wheat in cool climates, thriving in the temperature range 2 – 15 degrees Celsius. High humidity and rainfall aid transmission and infection. Brown rust (*Puccinia recondita / P. triticana*) is another foliar disease of wheat in the UK but favouring slightly warmer conditions. Both diseases attack leaf tissue and if uncontrolled can have a severe effect on crop yield and grain quality. The success of rust pathogens is weather dependant.

In this study, it was expected that a relationship between recorded incidence of the disease and prevailing weather could be derived. For this, annual data collected by Defra were used and a correlation between observed infection and climate (rainfall/temp) undertaken. As with the virus yellows marker disease for sugar beet, it was not possible to derive a statistically significant correlation. It is likely that the development and use of fungicide treatments across the UK cereal area has significantly reduced disease expression.

4.1.10 Crop disease using 'blight' as a marker for potatoes (AG3c)

Potato blight is caused by the fungus *Phytophthora infestans* and constitutes a major risk to UK potato production each year. It spreads through the air and develops when local weather conditions are warm and humid. The spores of this water mould over-winter on infected tubers, particularly those left in the ground after the previous year's harvest, or in soil or infected volunteer plants and are spread rapidly in warm and wet conditions. This can have devastating effects by destroying entire crops. Spores develop on the leaves, spreading through the crop when temperatures are above 10 C and humidity is over 75% for 2 days or more and there has been recent rain leaving wet foliage. Rain can wash spores into the soil where they infect young tubers. Seemingly healthy tubers may subsequently rot later in store. Blight forecasting has often been based on the occurrence of "Smith periods". Potato blight fungus is generally killed by cold weather, although there are some rare resistant crossbred strains that overwinter.

In the UK, the Potato Council has offered a blight incident reporting service to growers for the past 7 years. This information is collected on a voluntary basis by 300 blight scouts drawn from members of the industry who routinely walk potato fields during the season. Maps and data are then disseminated to the grower base to alert them of potential blight risks and how other crop husbandry practices (e.g. irrigation, spraying) might need to be modified. For this study, it was hoped that a long term historical spatial dataset on the number of confirmed blight cases across the UK would have been available from the PCL for correlation against local weather conditions, but unfortunately that data is not currently available in a format suitable for risk metric analysis.

4.1.11 Agroclimate (AG4)

The main variables that directly influence soil moisture and hence the need for supplemental irrigation are rainfall and reference evapotranspiration (ETo). To assess the aridity impacts of climate variability on crop production, previous research has shown that a strong relationship exists between irrigation need and potential soil moisture deficit (PSMD) across a range of crops and climates de Silva *et al.*, 2007; Rodríguez Díaz al., 2007; Knox *et al.*, 2010b). The advantage of this index over others such as the Wetness Index (ratio of total annual rainfall and total annual evapotranspiration) is that the distribution of rainfall and ET throughout the year is taken into account. In this study, PSMD was used as an aridity metric to assess the impacts of climate change on crop production and specifically the impact on the likely future need for supplemental irrigation.

In this study, the variable potential soil moisture deficit (PSMD) was used as an agroclimatic indicator, in preference to temperature, because it reflects the balance between rainfall and crop water use in the irrigation season. It has been applied to quantify the irrigation needs at national scales in different countries (Knox *et al.*, 2010a; De Silva *et al.*, 2007; Rodríguez Díaz *et al.*, 2007; Knox *et al.*, 1997). It is also used by the regulatory authority in England and Wales for setting licences (permits) for irrigation water withdrawal (abstraction). A simple monthly water balance model was used to estimate the potential soil moisture deficit (PSMD) for each grid pixel. The PSMD in each month is calculated from:

$$PSMD_i = PSMD_{i-1} + ET_i - P_i$$

Where:
$PSMD_i$: potential soil moisture deficit in month i, mm
ET_i : potential evapotranspiration of short grass in month i, mm
P_i : rainfall in month i, mm

In months where $P_i > (PSMD_{i-1} + ET_i)$, no soil moisture deficit is assumed to occur and $PSMD_i = 0$. In the UK, soil moisture deficits typically start to build up in early spring as ET > P, peak in midsummer (July-August) and then decline through autumn and winter as P > ET. Therefore in the UK, the estimation of PSMD can start with January as month i = 1. The maximum PSMD of the 12 months of the year is the PSMD for that grid pixel.

A computer model was developed to calculate from the baseline and future UKCP09 datasets the monthly values of reference evapotranspiration (Eto) and PSMDmax to produce an agroclimatic database for England and Wales. Results were integrated into a GIS to represent the spatial and temporal variation of $PSMD_{max}$ both nationally and spatially across England and Wales. Further information on the calculation of this metric is given in Appendix 4.

4.1.12 Water abstraction for crops (AG5)

Data relating to total abstractions for spray irrigation (agriculture) from surface water, ground water and tidal waters were obtained from the Environment Agency (EA), at region level, for the period 1990-2003. Unfortunately equivalent data are not available for Scotland or Northern Ireland.

The EA data were correlated against the $PSMD_{max}$ for each year (1990-2003), choosing a representative point within each EA Region (Figure 4.4) for the PSMD calculation. The linear regressions were then used to develop the response functions for this metric. Further information on the calculation of this metric is given in Appendix 4.

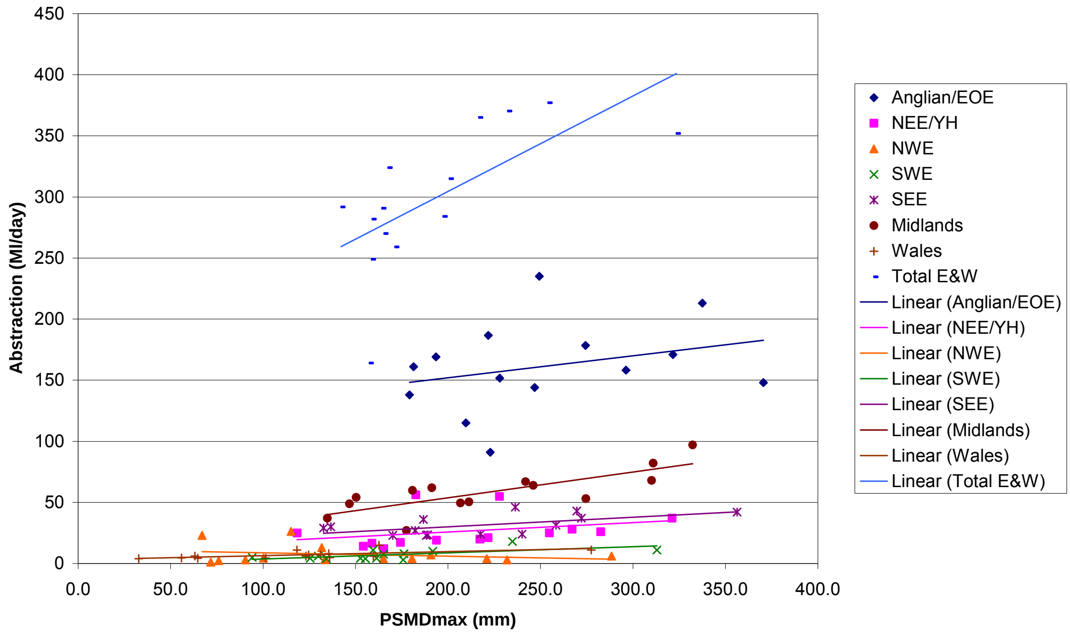


Figure 4.4 Linear regressions of EA reported spray irrigation abstraction (Ml/day) against agroclimate (PSMD/mm)

4.1.13 Livestock water abstraction (AG6)

Currently water abstraction for utilisation by livestock agriculture is small and is predominantly related to watering and washing of livestock and their production systems (e.g. housing). Whitehead *et al.* (2008) showed that approximately half the agricultural water abstractions in England and Wales were related to livestock systems. It should also be noted that some of the irrigation of crops could also be related to livestock systems as these crops (grass and cereals) are a component of livestock diets. However, details of the exact use of water in all these circumstances and therefore our ability to proportion them to livestock directly, is limited. Furthermore, no data exists for water abstraction in Scotland and Northern Ireland. Therefore it is not possible to develop a specific response function for water abstraction for livestock. This should be considered alongside the agricultural water abstraction (Water Sector Report).

It is likely that the major water abstraction issue for livestock is the need for access to drinking water for livestock and the potential need to use more water in the system for cooling animals and cooling plant mechanisms (e.g. milking parlours). To examine the potential impact of climate change on the abstraction of water for these livestock system purposes it would be necessary to monitor each category of water utilisation in the system (drinking, animal cooling, plant cooling) and link to biological models of water requirements by animals. The requirement for cooling is linked with heat stress, which is covered in Section 4.1.14 / 4.1.15 (response function) and 5.7 (assessment).

4.1.14 Climate impact on livestock production (AG7)

The metrics for which it has been possible to analyse impacts on livestock are based on heat stress. Heat stress itself is immeasurable but can be represented by thermal humidity index (THI). The THI is calculated as a function of both air temperature and relative humidity – humidity affecting the extent to which temperature is experienced by both humans and animals. The limit for heat stress in cows is considered to be about 72 (Pusta *et al.*, 2011) but this will vary depending on breed of cow. There are a number of equations for thermal humidity, but one of the most commonly used is:

THI = ((1.8)*TEMP(°C) +32)-(0.55-0.55*(Relative Humidity))*((1.8)*TEMP(°C) -26)

Where:

THI is Thermal humidity index

Temperature (TEMP) is in expressed in degrees Celsius

Relative Humidity is expressed as a proportion.

Extensive work by St-Pierre *et al.* (2003) studied the impacts of heat stress on United States livestock industries and the approaches used in this work have been verified by Wall *et al.* (2010) for application to the UK livestock industry, showing that UK dairy was likely to be affected by the UKCIP02 climate scenarios. In this study a modelling approach previously developed by Wall *et al.* (2010) to calculate the impacts of heat stress on dairy cows with UKCIP02 data was re-run using the equivalent UKCP09 data for future absolute temperatures and relative humidity. In this study a category of animal (e.g. milking dairy cow, growing calf) was assigned a THI value (based on experimental literature data) above which it was then assumed they began to feel discomfort/heat stress and that their physiology may be affected. Where the results were expressed per animal, then the 2009 Defra dairy cow population for each region was used to convert the results to actual numbers assuming that the future population would remain unchanged.

The following results were generated:

- Duration of heat stress – expressed in days or proportions of days when heat stress is experienced
- Impacts of heat stress on milk production – expressed in kilograms per day per animal
- Impacts of heat stress on 'days open' – the number of days when cows are not 'in calf', expressed as increase in the number of days open
- Deaths due to heat stress – expressed as number of deaths in 1000 animals.

The duration of heat stress is similar, in its characteristics as a metric, to the aridity (water sector) and PSMDmax (agriculture sector) metrics in that it is a derived climate variable in itself and can then be used built upon for other metrics (e.g. PSMDmax is used to assess water demand, see Section 4.1.12. All of these metrics are relevant to livestock production in terms of loss of income (milk production, fertility) and animal welfare. At a national scale, sustainable livestock production is important for the economy, food security and landscape. Although a proportion of dairy cows are housed inside year-round, the outdoor dairy systems is seen as being the best representation for this metric.

Heat stress impact on dairy milk production (AG7a)

The response function for loss of milk production as a function of THI load is shown in Figure 4.5. The THI combines temperature and humidity and is a measure of the degree of discomfort experienced by an individual in warm weather, and is calculated using daily weather data. An animal has an index value threshold, above which they begin to experience discomfort. The THI load is the integral of the daily THI sine curve above the THI threshold, which is the THI above which heat stress occurs. The data is derived from St-Pierre *et al.* (2003).

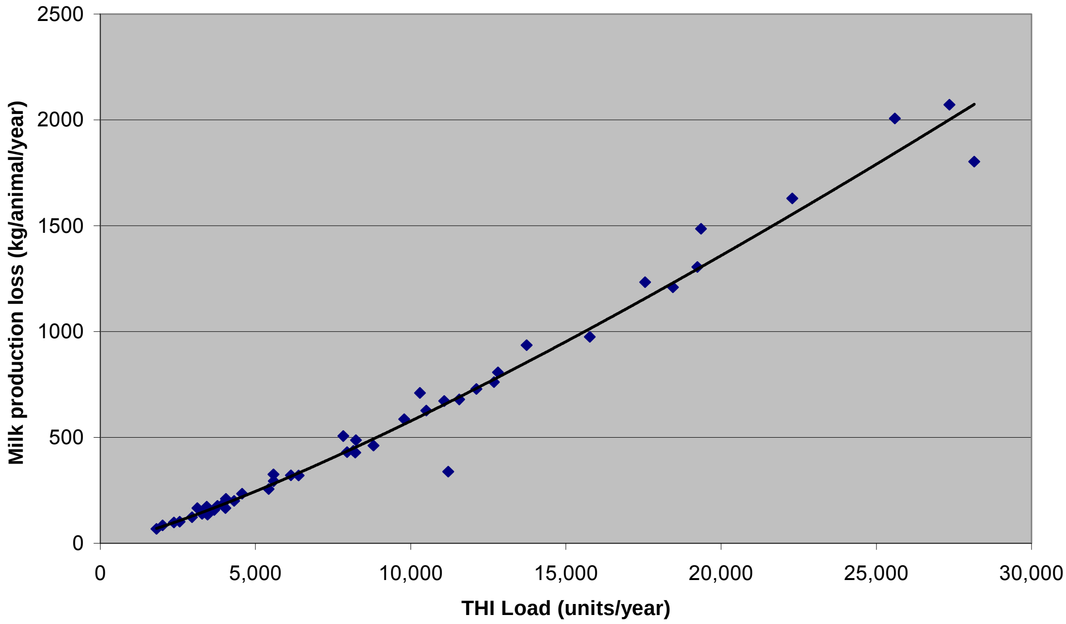


Figure 4.5 Response function for loss of dairy milk production (kg/animal/year) as a function of THI

In order to provide some context for this function:

- The THI loads presented are the range experienced in the US under current climate, so cover the range experienced in the UK but extend to much higher loads.
- The average yield for a cow is the UK is about 7500 kg per annum (Defra, 2010d) so THI loads of about 15,000 would result in loss of yield of 1000 kg or about 13 percent.
- With a milk price of approximately 25 pence per kilo in 2010 (1 litre of milk weighs 1.03 Kg) this equates to a loss of income of about £250 per cow per year.

Heat stress impact on loss of dairy fertility (AG7b)

The response function for loss of fertility in dairy cows measured as the increase in ‘days open’ as a function of thermal humidity index (THI) load is shown in Figure 4.6. Days open refers to the number of days that a dairy cow is not with calf, following a calving event and is the number of days between calving and subsequent conception. The THI load is the integral of the daily THI sine curve above the THI threshold, which is the THI above which heat stress occurs. The data is derived from St-Pierre *et al.* (2003).

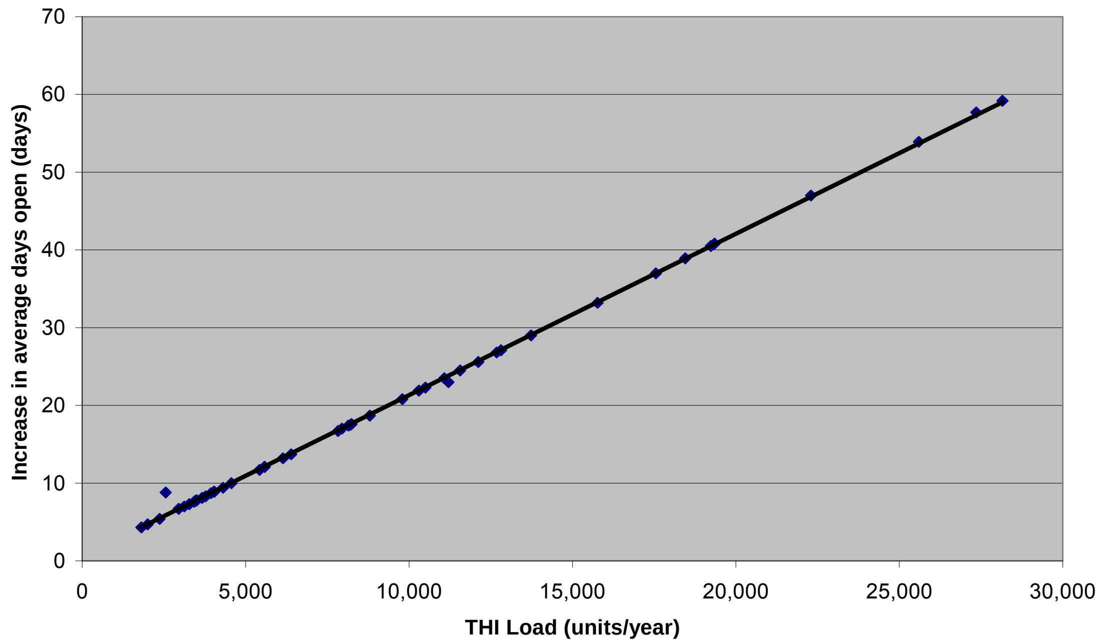


Figure 4.6 Response function for the increase in days open per year as a function of THI

4.1.15 Duration of heat stress in dairy cows (AG8a)

The response function for duration of heat stress as a function of thermal humidity index (THI) load is shown in Figure 4.7. THI load is the integral of the daily THI sine curve above the THI threshold, which is the THI above which heat stress occurs. The data is derived from St-Pierre *et al.* (2003).

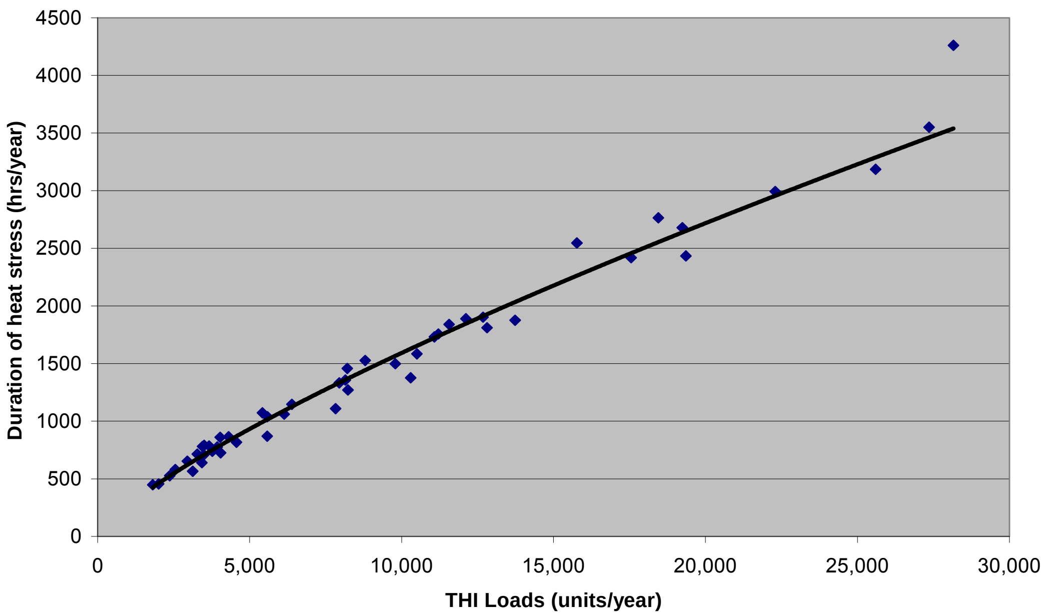


Figure 4.7 Response function for duration of heat stress a function of THI for dairy cows

4.1.16 Dairy livestock deaths due to heat stress (AG8b)

The response function for dairy livestock deaths due to heat stress as a function of thermal humidity index (THI) load, as per the above metric and is shown in Figure 4.8. Overall fatality rates are low, less than 2 percent at very high loads, but are still significant at the farm level and are indicative of much larger livestock numbers that would be affected, and potentially, harmed by heat stress.

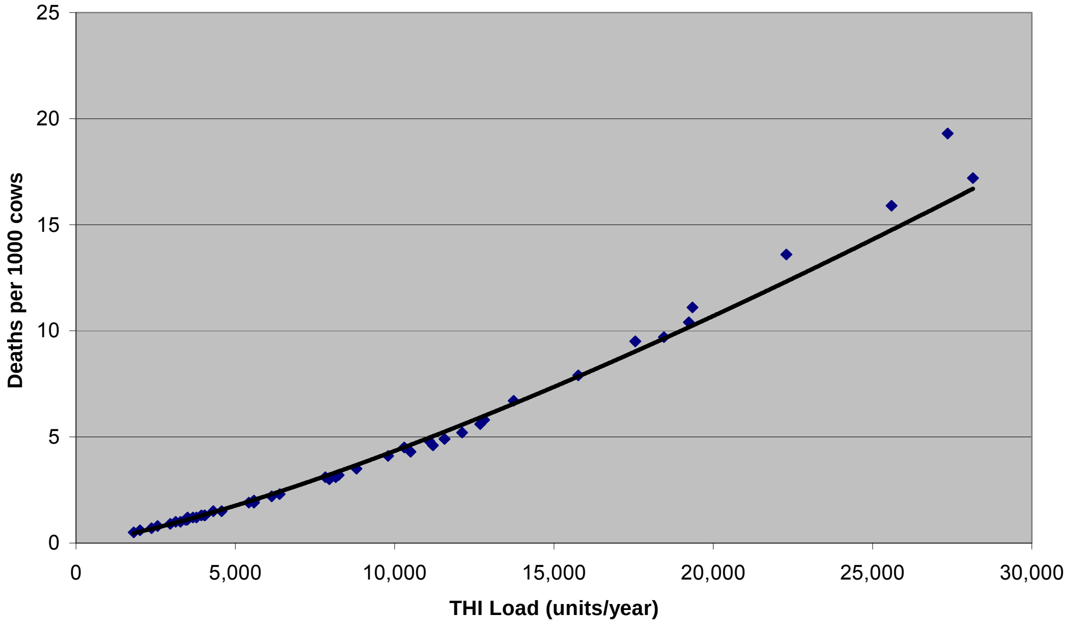


Figure 4.8 Response function for animal deaths as a function of THI load for dairy cows

4.1.17 New crops (AG9)

An assessment of potential crop opportunities has been made and reported in Section 5.9.3, 5.9.4 and 5.9.5. Whilst some information on increases in yield is presented, there are no formal response functions in the analysis.

4.1.18 Grassland productivity (AG10)

Response functions were developed for four UK sites (West Wales, Central Devon, Gloucestershire and Cumbria). These are presented in Section 5.10.

4.1.19 Soil erosion (AG11)

A response function was not developed for soil erosion. A direct calculation of soil erosivity was made using UKCP09 rainfall projections. This was used to calculate projections of erosivity as an indicator of soil erosion (Section 5.11).

5 Sector Risk Analysis

5.1 Cross sectoral and indirect consequences

The following sections describe the effects of climate projections on crop yield, flood risk, agro-climate and livestock metrics described in the previous section. In some cases the results are based on relatively simple application of empirical relationships between climate variables and metrics, however for agro-climate, flood risk and livestock the results are based on detailed modelling studies. Where simple empirical analysis was used this was compared with results from the research literature to understand key differences and relative effects of climate and other factors, including the effects of elevated CO_2 concentrations on crop growth.

More detailed results including regional projections for some metrics are given in Appendix 5.

For each metric a scorecard is given at the start of each section to indicate the confidence in the estimates given and the level of risk or opportunity. Confidence is assessed as high (H), medium (M) or low (L). Risks and opportunities are scored either high (3) medium (2) or low (1) (shown to the right). These are given for the lower (l), central (c) and upper (u) estimates for the 2020s, 2050s and 2080s. Further information is provided in Appendix 4. Where estimates are uncertain, or no data is available, this is stated in the scorecard.	M	Confidence assessment from very high (VL) to very low (VH)
	3	High consequences (positive)
	2	Medium consequences (positive)
	1	Low consequences (positive)
	1	Low consequences (negative)
	2	Medium consequences (negative)
	3	High consequences (negative)

5.2 UKCP09 climatology

The UKCP09 dataset for the 2020s, 2050s and 2080s for the Low, Medium and High emissions scenarios was used, and datasets for the following variables prepared:

- Change in mean annual temperature (degrees Celsius) (change in future 30-year average of annual average air temperature at 1.5m above ground level, from the baseline climate (1961-90) long term average)
- Change in annual average precipitation (%) (change in future annual average precipitation from the baseline climate (1961-90) long term average)
- Change in total cloud cover (monthly data for 25km grid of the UK)
- Change in relative humidity (monthly data for 25km grid of the UK)
- Change in daily minimum temperature (monthly data for 25km grid of the UK)
- Change in daily maximum temperature (monthly data for 25km grid of the UK)
- Change in precipitation (monthly data for 25km grid of the UK).

For each metric the p10, p50 and p90 (10%, 50%, 90% respectively) probability levels are provided. The p50 equates to the median probability ('central projection') and the p10 and p90 represent smaller and larger projections for a specific emissions scenario.

The UKCP09 emissions scenarios are based on those developed by the IPCC (Nakicenovic *et al*., 2000), known as SRES (Special Report on Emissions Scenarios), each of which represents a different scenario combining two sets of divergent tendencies; one set varying between strong economic values and strong environmental values, the other set varying between increasing globalisation and increasing regionalisation (IPCC-TGCIA, 1999). In the UKCP09 dataset, only the A1FI, A1B and B1 scenarios are available, renamed for simplicity as High, Medium and Low emissions respectively.

The A1 scenarios characterise alternative developments of energy technologies, with A1FI being fossil fuel intensive (with an assumed atmospheric CO_2 concentration of 593 ppmv by the 2050s) and A1B being balanced between fossil and non-fossil fuel. Conversely, the B1 scenario has the lowest atmospheric CO_2 concentration (489 ppmv by the 2050s), reflecting efforts to control CO_2 emissions principally through the introduction of clean and resource-efficient technologies.

In this study, the High (A1FI) and Low (B1) scenarios for the 2050s were used. The assumed atmospheric CO_2 concentration for the baseline (1961-90) was 330 ppmv based on data presented by the IPPC SRES (Nakicenovic *et al*., 2000). Further details on the emissions scenarios in UKCP09 are given in Jenkins *et al.* (2009b).

A brief description of the application of the data for assessing the impacts of climate change on the response function for each metric is given below.

5.3 Mean yield variability with climate (AG1)

Metric number	Risk metric	Confidence	Summary Class								
			2020s			2050s			2080s		
			l	c	u	l	c	u	l	c	u
AG1a	Crop yield (sugar beet)	M	1	1	2	1	2	3	2	3	3
AG1b	Crop yield (wheat)	M	1	2	2	2	2	3	2	3	3
AG1c	Crop yield (potato)	L	1	1	2	1	1	2	1	1	2

Yield variability with climate has been assessed for sugar beet (reference arable crop), wheat (reference arable crop), potatoes (reference field vegetable/horticulture crop) and grass (covered in Section 6.8).

Yield variability has been calculated based on change in particular climate variables but has not taken all factors into account. For example, changes in yield for sugar beet and wheat are based on temperature but changes in rainfall and nutrient availability are not covered. This therefore provides a partial view of projected changes in yield.

5.3.1 Crop yield using sugar beet as a reference ‘arable’ crop (AG1a)

The projections suggest that yields of sugar beet in the UK would increase in warmer conditions. Taking the p50 medium emissions scenario, yields are projected to increase from the baseline by 23% by the 2020s (range 11% to 37% for p10 to p90), rising to 39% by the 2050s (range 18% to 68% for Low p10 to High p90) and 55% by 2080s (range 23% to 105% for Low p10 to High p90).

For 1961-90 baseline data, the yield is approximately 6 t/ha of white sugar; UK yield increases in the years since 1961/90 have already outstripped the projections. UK average sugar yields per hectare have increased steadily since 1990. They exceeded 10 t/ha in both 2008 and 2009 and have only fallen below 8 t/ha once in the last 14 years. Sugar yields of 16 t/ha are now not unusual.

It is probable that UK average yields have already reached the projected level for the p50 medium emissions scenario for the 2020s, indicating that factors other than temperature increase have influenced crop performance. Factors cited include improvements in genetics (higher performing varieties), pest and disease control and management of the harvest and post harvest periods.

The 2080 yield level of base yield plus 55% (p50 medium emissions scenario) indicates a sugar output of just under 9.5 t/ha. This is way below peak yield today of 16 t/ha. This suggests that whilst the increase in yield attributable to climate change might be 55%, the effect of better exploitation of other components of yield would take yield improvement way above that figure, i.e. technological developments are already having a greater effect than future climate change.

Water is an important yield component and as yields increase, the ability of the crop to exploit the available water resource would become a major determinant of final yield in future and this is addressed under other metrics.

Table 5.1 shows national values for percentage change in yield for sugar beet (regional data are given in the Appendices).

Table 5.1 UKCP09 percentage change in yield for sugar beet due to climate change

	Low			Medium			High		
	P10	p50	p90	p10	p50	p90	p10	p50	p90
2020s				11	23	37			
2050s	18	35	55	21	39	61	24	44	68
2080s	23	43	68	31	55	85	40	68	105

(turquoise)	0-25% increase
(green)	25-50% increase
(yellow)	>50% increase

In 2009 the value of sugar beet production was £241 million based on a production area of 116,470 hectares, located predominantly in the East of England, followed by the East Midlands and to a lesser extent Yorkshire and Humberside. UK farms provided 64 percent of UK’s refined sugar for food production. As such large increases in sugar yield (>50%) due to technological change and climate change are of significant to the national agricultural economy as well as parts of the UK and individual agri-businesses and growers.

The results indicate gains in yield based on temperature increases but these potential yields may only be realised as long as other constraints do not have negative impacts over the same time periods.

Recent research (Richter *et al.*, 2006) suggests that potential growth rates due to increased CO_2 levels and higher temperatures could result in average sugar yields rising by 1.4 and 2 t ha^{-1} (2050LO and 2050HI), although soil variability would have a major impact on yield variations regionally. In future, sugar yields on sandy soils (8 t ha^{-1}) are likely to increase only slightly (by 0.5 to 1.5 t ha^{-1}), but on loamy soils yields are likely to increase from 11 t ha^{-1} to between 13 t ha^{-1} and 15 t ha^{-1} (2050HI and 2080HI). Earlier sowing and later harvest dates could potentially compensate for any drought-related losses on sandy soils (Richter *et al.*, 2006).

The risks to sugar beet production were also investigated as part of a recent Defra funded project (AC0301). For sugar beet, simulations using temperature and rainfall predicted that sowing dates would become earlier and vary by a similar number of days as today. The research suggested that this would tend to increase yield, so too would warmer early summer weather, while the foliage canopy is developing. However, hotter and drier summers would increase the risk of drought, and there is little prospect that valuable irrigation water resources would be used to overcome this.

The consequence of these changes, plus the change in CO_2 concentration would be an increase in the national mean sugar yield in 2050, by an average of 3.5 t/ha (i.e. 35%). However there would also be an increase in yield range from one year to the next. The difference between the 5 and 95 percentiles for the national mean sugar yield would increase from 5.4t/ha to 7.9t/ha by 2050. Because beet is a perishable crop that cannot be stored from one season to the next, this increase would be very difficult for farmers and processors to manage.

However, the economic assessment showed that for U.K. sugar beet, extreme events due to future climate change do not lead to adverse effects in terms of higher relative yield variability or an increased probability of very low yields. The probability of very low yield levels for sugar beet (as measured by the Value at Risk, VaR) is reduced with the subsequent climate scenarios for all locations and types of soil.

5.3.2 Crop yield using wheat as a reference 'arable' crop (AG1b)

Average wheat yields in the UK have shown very little increase over the past decade. At around 8 t/ha they have failed to increase in line with genetic improvement, suggesting that the benefits from plant breeding are being given away elsewhere in the production cycle. This might be related to soil degradation, poorer crop nutrition, or failure to control weeds, pests and diseases, or a combination of these factors.

It is projected that yield increases due to a warmer agroclimate would take yields up by 47% by the 2020s (p50 Medium, range 22% to 76% for p10 to p90), 79% by the 2050s (range 36% to 137% for Low p10 to High p90) and 111% by the 2080s (range 46% to 212% for Low p10 to High p90) (Table 5.2). If the baseline yield is approximately 5 t/ha, then an uplift of 47% by the 2020s indicates a yield of 7.4 t/ha, lower than the current average yield and way below that of the upper quartile of producers. Even the 2080s yield projection is only 12.7 t/ha, a figure regularly achieved by some UK growers.

All of this would suggest that the yield increases projected are defendable and that improvements in other yield components, especially plant genetics, may well lead to actual yields exceeding them. As with sugar beet, water is an important yield component and as yields increase the ability of the crop to exploit the available water resource would become a major determinant of final yield.

Recent research (Semenov, 2009) suggests that despite higher temperatures and lower summer precipitation, the impact of drought stress on wheat yield is anticipated to be smaller than that at present, because wheat would mature earlier in a warmer climate and avoid severe summer drought. However, the probability of heat stress occurring around flowering which could result in considerable yield losses could increase significantly. Breeding strategies might thus need to focus on varieties tolerant to high temperature rather than drought (Semenov, 2009).

In 2005 the Arable Area Payments Scheme (AAPS) was among several crop and livestock payments replaced by the Single Payment Scheme (SPS). This de-coupled grant payments from production. The Single Farm Payment aims to protect environmental, public, animal and plant health and animal welfare standards to keep land in good agricultural and environmental condition (GAEC). In 2009 the value of wheat production including area payments was £1754 million with largest area of production in the East of England, East Midlands, South East and Yorkshire and Humberside. As such, improvements in production due to technological change and climate change are very important for national as well as regional economies. The UK already produces more wheat than is consumed so increased production would depend on export opportunities and the relative competitiveness of UK businesses compared to those in other major European production regions, such as Northern France, Denmark and the Czech Republic.

On low available water capacity soils (sandy and shallow soils) it is water supply during April and May that has the biggest impact on wheat yield – this is why not so long ago farmers with ‘spare’ irrigation capacity on sandy soils would irrigate their wheat crops during this period, but not in summer (i.e. in June/July). Notably, in this context - the highest yielding wheat crops are generally produced on soils with the highest available water capacity (all other factors being even) and this is where many of the 12 t/ha plus wheat crops are grown. Drought within the report is acknowledged as yield limiting for non-irrigated potatoes and sugar beet on sandy soils, and increases are projected in PSMD.

Table 5.2 UKCP09 percentage change in yield for wheat due to climate change

	Low			Med			High		
	p10	p50	p90	p10	p50	p90	p10	p50	p90
2020s				22	47	76			
2050s	36	71	111	42	79	124	47	88	137
2080s	46	87	138	62	111	172	79	138	212

5.3.3 Crop yield using potatoes as a reference ‘field vegetable’ crop (AG1c)

The response function for rain-fed potato yields was based on the sensitivity of yields to summer rainfall, a relationship that has been used as a climate indicator by Defra in previous studies (Defra, 2005). However, potato yields are expected to particularly sensitive to increases in CO_2 concentrations, for example European studies have indicated yield increases of 28% due to CO_2 increases alone (Kimball *et al.*, 2002; Wolf and Van Oijen, 2003; Hermans, 2010). Therefore this metric was considered alongside more detailed biophysical modelling studies that account for climate, atmospheric carbon, nutrient balance and other factors to estimate future yields.

For the simple CCRA analysis, baseline average summer rainfall measurements for each of the CCRA admin regions were used in conjunction with the response function to calculate a baseline yield for each region (Table 5.3). Immediately it is clear that the yield factors in Table 5.2 are lower than factors used for atmospheric carbon (1.28) and are also be lower than the influence of technological developments on potato production.

Table 5.3 Baseline rain-fed potato crop yields by region

Admin Region	Summer rainfall (mm average values 1961-90)	% of expected yield
East Midlands	171	0.95
East of England	152	0.92
Eastern Scotland	227	1.04
London	153	0.92
North East England	200	1.00
Northern Scotland	289	1.11
North West England	265	1.08
Northern Ireland	237	1.05
South East England	159	0.93
South West England	195	0.99
Wales	259	1.08
West Midlands	173	0.96
Western Scotland	317	1.14
Yorkshire and Humberside	193	0.99

UKCP09 projected regional changes in rainfall for the summer period for all CCRA time horizons, emissions scenarios and high/low probabilities were applied to baseline summer rainfall to give absolute projected summer rainfall depths. The response function was then applied to these rainfall depths to suggest future % yields and compare these to the baseline to estimate percentage changes.

Table 5.4 shows national values for percentage change in % yield for rain-fed potato crops compared with a 1961-90 baseline of 31.6 t/ha. Regional data are given in Appendix 5. Therefore the CCRA analysis shows that lower summer precipitation is likely to result in downward pressure on yields of rain-fed potatoes and that the changes in yield (for p50 and p90) are small, within the range of natural variability and less than the effects of CO_2 fertilisation.

Table 5.4 UKCP09 percentage change in %yield for rain-fed potato crops

	Low			Medium			High		
	p10	p50	p90	p10	p50	p90	p10	p50	p90
2020s				-7	-2	3			
2050s	-10	-4	3	-12	-5	1	-12	-5	2
2080s	-11	-4	2	-15	-6	1	-18	-8	1

	Positive percentage change
	Negative percentage change

The analyses based on the metric using national historical rain-fed yields suggest future average projected changes in maincrop potato yield of approximately -2% (i.e. a reduction) by the 2020s for the Medium emissions scenario, central estimate (range -7% to +3%), -5% by the 2050s for the Medium emissions scenario, central estimate (range -12% to +3%), and -6% by the 2080s for the Medium emissions scenario, central estimate (range -18% to +2%)[14]. These data relate to rain-fed yield, which account for less than half the total production area (Daccache *et al.*, 2011b).

However, these data are not consistent with more detailed biophysical crop modelling studies which considered the impacts of climate change on crop growth and yield including CO_2 fertilisation effects. For example, Daccache *et al.* (2011b) studied the impacts of climate change on maincrop potatoes (cv Maris Piper) in England by combining the downscaled outputs from an ensemble of GCMs with a potato crop growth model (SUBSTOR–Potato) to simulate the baseline and future irrigation needs (mm) and yield (t ha^{-1}) for selected emissions scenario (SRES A1FI and B1) for the 2050s.

Assuming crop husbandry factors remained unchanged, farm yields showed only marginal increases (3-6%) due to climate change owing to limitations in nitrogen availability. In contrast, future potential yields, without restrictions in water or fertiliser availability, were reported to increase by 13-16%. These increases are principally due to increased radiation and temperature levels and elevated CO_2 concentration effects.

Similarly, Wolf and van Oijen (2003) reported that irrigated tuber yields (cv. Bintje) would increase in the 2050's by between 2000 and 4000 kg ha^{-1} dry matter for most regions of Europe, largely due to the positive response to increased levels of CO_2 concentration. In Ireland, Holden *et al.* (2003) showed that an increase in drought potential resulting from climate change would threaten the viability of non-irrigated potato production.

These studies highlight the complexities of projecting future yields that are affected by climate, atmospheric CO_2 and technological changes. A simple metric based on nationally published yield data to estimate future yields indicates a reduction in yield, whereas site specific studies using parameterised crop models suggest marginal increases in yield. Whilst the data from site studies cannot be extrapolated nationally to other potato growing regions, it is preferable and more robust to rely on biophysical modelling approaches to assess potential yield impacts and consequent production risks. However, because of the structure of the industry and the high health status required for seed potato crops, the majority of seed potatoes are produced in Scotland. These crops are not usually irrigated but plant health considerations are of greater consequence.

The potential impacts of climate change on water availability for rain-fed potato production and the potential benefits of supplemental irrigation are discussed in Section 5.6.

[14] Note that the lowest to the highest projected change to this metric do not result from the Low emissions p10 and the High emissions p90 scenarios. See Table 5.4 for results for each scenario.

5.4 Flood risk to crops and grazing land (AG2)

Metric code	Metric name	Confidence	Summary Class								
			2020s			2050s			2080s		
			l	c	u	l	c	u	l	c	u
AG2a; AG2b;	Flood risk to classified 'arable' land; Flood risk to classified 'horticulture' land; flood risk for cropped areas (tidal and river)	H	1	1	2	1	2	2	2	3	3
AG2c	Flood risk to classified livestock 'grassland'; flood risk for grazing land (tidal and river)	H	1	1	1	1	1	1	1	1	2

The results for this metric are summarised in Figure 5.1 and Table 5.5. The results are presented for both groups of agricultural land grades, (a) grades 1 to 3, arable and horticultural land and (b) grades 4 and 5, grassland and rough grazing. They are also split into frequency classes to show areas of land flooded more than once in every three years, three to five and five to ten years.

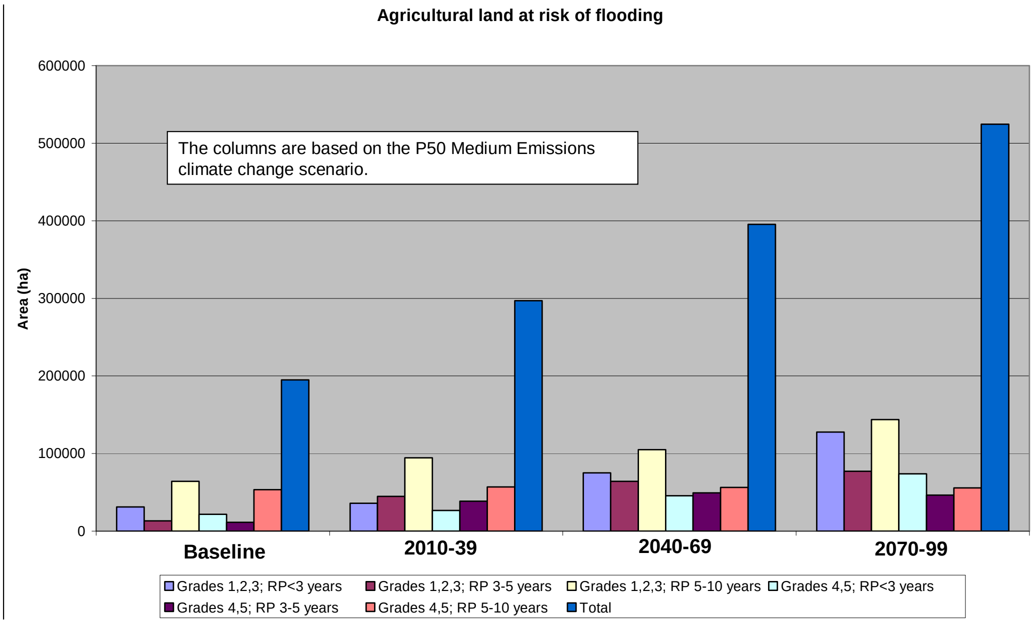


Figure 5.1 Areas of agricultural land at risk from river or tidal flooding

Flood frequencies of less than 1 in 3 years, 3-5 years and 5-10 years shown for agricultural land classification grades 1 to 3 (horticulture/arable – left frame) and 4 and 5 (grassland/grazing – right frame), for selected 2020s, 2050s and 2080s scenarios. This assessment was based on the possible scenario in England and Wales as equivalent data from Scotland and Northern Ireland was not available.

In the near term (2020s) small increases in the area at risk of frequent flooding (1 in 3 years (33%) or greater) but a larger increases in area is projected for flood frequencies of 1 in 10 years (10%) or greater. The area of Grade 1, 2 and 3 land flooded by frequent events from rivers and the sea could increase from a baseline of about 30,000ha to about 35,000ha by the 2020s. Furthermore, this could double to about 75,000ha by the 2050s and reach nearly 130,000ha by the 2080s, about four times the present day area. As this represents high quality horticultural and arable land (grades 1-3), the impact on the sector and businesses could be substantial.

In the longer term (2050s, 2080s) large increases are projected in the areas of agricultural land that would be at flood risk from the sea on a regular basis (almost every other year). Under the highest rates of relative sea level rise for the 2080s High emissions scenario (average sea level rise about 57 cm), there is a ten fold increase in the amount of good quality agricultural land that would be at risk of regular flooding from the sea, making it untenable for normal agricultural use. There are also large increases projected in the amount of grassland and rough grazing at risk of frequent flooding from the sea, although some of this land may still be used for grazing.

A sense of the short term costs of flooding on agriculture can be gained from work following the 2007 floods (Box 4.1) but this only includes direct damage. Much of land flooded on the coast would lose its value due to the loss of quality associated with frequent inundation. Even considering the high quality land in the 'frequent flooding' class alone, annual costs in the 2080s High emissions scenario would be greater than £60 million every year.

Table 5.5 Areas of agricultural land flooded from rivers and the sea (ha)

Frequencies of less than 1 in 3 years, 3-5 years and 5-10 years for agricultural land classification grades 1 to 3 (horticulture/arable) and 4 and 5 (grassland/grazing), for selected 2020s, 2050s and 2080s scenarios, for England and Wales.

River	Grades 1,2,3			Grades 4,5			Total
Scenario	<3	3 to 5	5 to 10	<3	3 to 5	5 to 10	
1961-1990	24,300	9,900	44,400	15,100	8,300	43,400	145,300
2020s	28,900	32,400	50,700	19,600	33,600	40,200	205,400
2050s	40,100	38,600	68,500	32,000	35,600	47,400	262,200
2080s	54,400	42,900	79,400	43,000	38,700	47,100	305,400

Tidal	Grades 1,2,3			Grades 4,5			Total
Scenario	<3	3 to 5	5 to 10	<3	3 to 5	5 to 10	
2008	5,200	2,000	10,100	3,400	1,300	5,200	27,300
2020s	5,200	5,100	26,700	3,500	2,100	9,700	52,100
2050s	17,400	17,400	25,200	6,400	7,800	5,400	79,600
2080s	42,700	23,800	41,000	16,200	4,700	4,800	133,200

River and Tidal	Grades 1,2,3			Grades 4,5			Total
Scenario	<3	3 to 5	5 to 10	<3	3 to 5	5 to 10	
1961-1990	1,700	1,400	9,500	3,300	1,700	4,800	22,400
2020s	1,800	7,200	17,100	3,500	2,800	7,000	39,400
2050s	17,600	8,000	11,300	7,300	5,900	3,500	53,600
2080s	30,600	10,600	23,400	14,600	3,000	3,700	85,900

Total	Grades 1,2,3			Grades 4,5			Total
Scenario	<3	3 to 5	5 to 10	<3	3 to 5	5 to 10	
1961-1990	31,200	13,300	64,000	21,800	11,300	53,400	195,000
2020s	35,900	44,700	94,500	26,600	38,500	56,900	296,900
2050s	75,100	64,000	105,000	45,700	49,300	56,300	395,400
2080s	127,700	77,300	143,800	73,800	46,400	55,600	524,500

The total area of agricultural land in England and Wales is about 4.1 million hectares of arable land and 6.1 million hectares of grassland. If arable land is assumed to correspond to grades 1 – 3, and grassland to grades 4 and 5, these results indicate the following:

- About 200,000 hectares of agricultural land has a 10% or greater annual probability of flooding from rivers and the sea (about 2% of the total area of agricultural land in England and Wales).
- It is projected that this total may rise to more than 500,000 ha by the 2080s based on the p50 Medium Emissions climate change scenario. This corresponds to an increase from 2% to about 5% of the total area of agricultural land in England and Wales (Floods and Coastal Erosion Sector Report).

Box 4.1 Economic impacts of the summer 2007 floods on agriculture

During the summer in 2007, a series of exceptional rainfall events caused extensive flooding in South and East Yorkshire, Worcestershire, Gloucestershire and Oxfordshire. ADAS (2007) estimated 42,000 ha of agricultural land were flooded. As part of a broader assessment of the impacts of these floods on the economy and environment, Chatterton *et al.* (2009) estimated the total agricultural damage cost due to these summer floods to be £50 million. This was based on analyses from farm visits and interviews with 78 flooded farms in the regions affected.

The average flood damage cost was reported to be £1150 per flooded hectare when weighted by land use (Posthumus *et al*., 2008, 2009). Their estimate was higher than that derived by ADAS (2007) because more detailed and comprehensive estimation methods were used. Chatterton *et al* (2009) reported regional differences in flood damage costs per hectare, depending on land use and dominant farm type, but these were not statistically significant given the considerable variation within regions. The average cost per hectare of flooding was multiplied by the total flooded area of 42,000 ha reported by the Environment Agency, allowing for regional distribution of land use and farming systems. A mean estimate of £48.6 million was derived, with a 95% confidence interval between £31 -66 million.

Taking into account regional differences in the areas flooded and the composition of land use, about 50% of total damage costs were reported to be borne by farms in Yorkshire and Humberside, 28% in Worcestershire and Gloucestershire and 22% in Oxfordshire. The analysis reported that >90% of flood damage costs were associated with losses of farm output and additional production costs. The remainder involved damage to farm assets such as machinery, property and infrastructure. Only about 5% of costs (excluding damage to household property) were insured. The floods did not have a major impact on food supply, but probably contributed to further price increases during a year of general commodity deficit at the global scale.

Estimated economic costs to agriculture of the summer 2007 flood (based on Chatterton *et al*., 2009)

Sector	Area flooded (ha)*	Loss (£ million)**	Average loss (£/ha flooded) **
Arable	26,500	34.3 (±9.2)	1,293 (±347)
Grassland and livestock	15,600	10.1 (±6.5)	647 (±416)
Other costs		4.2 (±2.0)	100 (±48)
Total	**42,100**	**48.6 (±17.7)**	**2040 (±811)**

* Based on ADAS (2007) using EA sources; ** 95% confidence interval.

5.5 Agroclimate (AG4)

Metric number	Risk metric	Confidence	Summary Class								
			2020s			2050s			2080s		
			l	c	u	l	c	u	l	c	u
AG4	Agroclimate	M	1	2	2	1	2	3	1	2	3

The national assessment of potential changes in aridity using the variable PSMD as an agroclimate index (Table 5.6) suggest potential increases in PSMD of 38% for the 2020s Medium emissions scenario (range of -33% to 116%), rising to 86% (range of -7% to 183%) by the 2050s and 118% (range of 4% to 277%). The data represent a nationally averaged assessment but mask significant spatial variability.

Table 5.6 National percentage change in PSMDmax

(Regional values in Appendix 5)

	Low			Medium			High		
	p10	p50	p90	p10	p50	p90	p10	p50	p90
2020s				-33	38	116			
2050s	-7	67	152	8	86	177	15	93	183
2080s	4	83	177	32	118	223	58	156	277

(blue)	Positive percentage change
(purple)	Negative percentage change

To illustrate the spatial impacts of climate change on aridity, changes in agroclimate from the baseline for selected future UKCIP02 scenarios have been modelled and mapped for the UK using a similar procedure to that described in Section 6.7, but working at a 5km^2 grid resolution. For this, the variable, potential soil moisture deficit (PSMD), was used as an agroclimatic indicator. This combines data on rainfall and reference evapotranspiration (ETo) the two variables that directly influence soil moisture and hence irrigation needs. It is important to recognise that PSMD is quite different to soil moisture deficit (SMD). The PSMD only considers the climate impact (i.e. rainfall and ET), whereas the SMD relates to the actual (estimated) deficit taking into account local soil characteristics and the actual crop type. Previous research has shown that a strong relationship exists between irrigation need and PSMD for a wide range of cropping systems and agroclimates (de Silva *et al*., 2007; Rodriguez Diaz *et al*., 2007; Knox *et al*., 1996, 1997). The advantage of this 'aridity' index over others such as the Wetness Index (ratio of total annual rainfall and total annual evapotranspiration) is that the distribution of rainfall and ET throughout the year is taken into account.

The long term average PSMD for each grid pixel was estimated using a water balance model, then classified into agroclimatic zones (where zone 1 represents the lowest aridity and zone 9 the highest). The agroclimatic map for the baseline (1961-90) is shown in Figure 5.2. Equivalent maps for selected UKCP09 scenarios are shown in Figure 5.3.

The maps show how climate change might impact spatially and temporally on the agroclimatic conditions under which agriculture is dependent. They are also useful for identifying regions or catchments where future water resource problems might arise in the future.

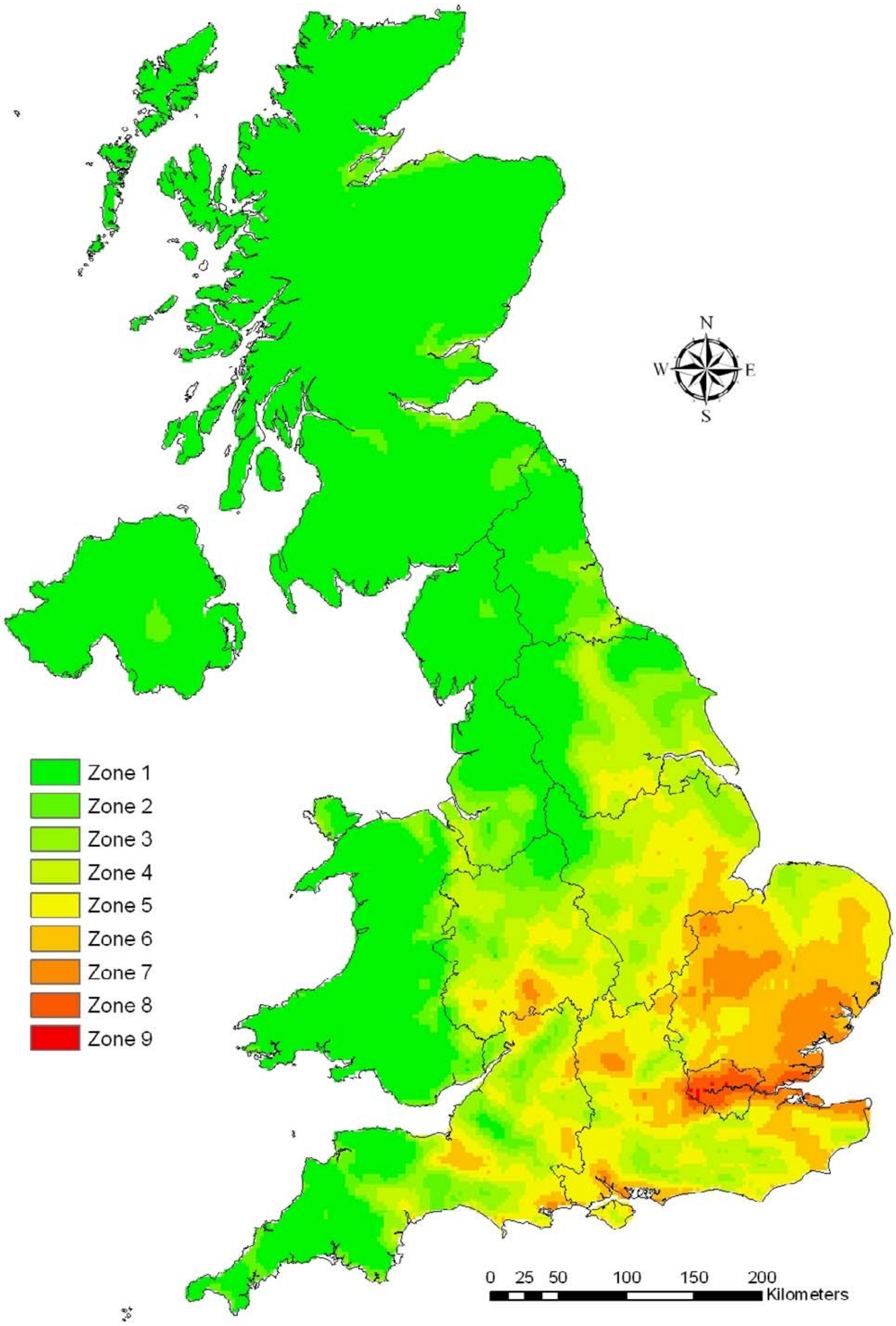


Figure 5.2 Spatial variability in agroclimate ($PSMD_{max}$) for the UKCP09 long-term average baseline (1961-90) in England and Wales
Source: Weatherhead *et al.*, 2011

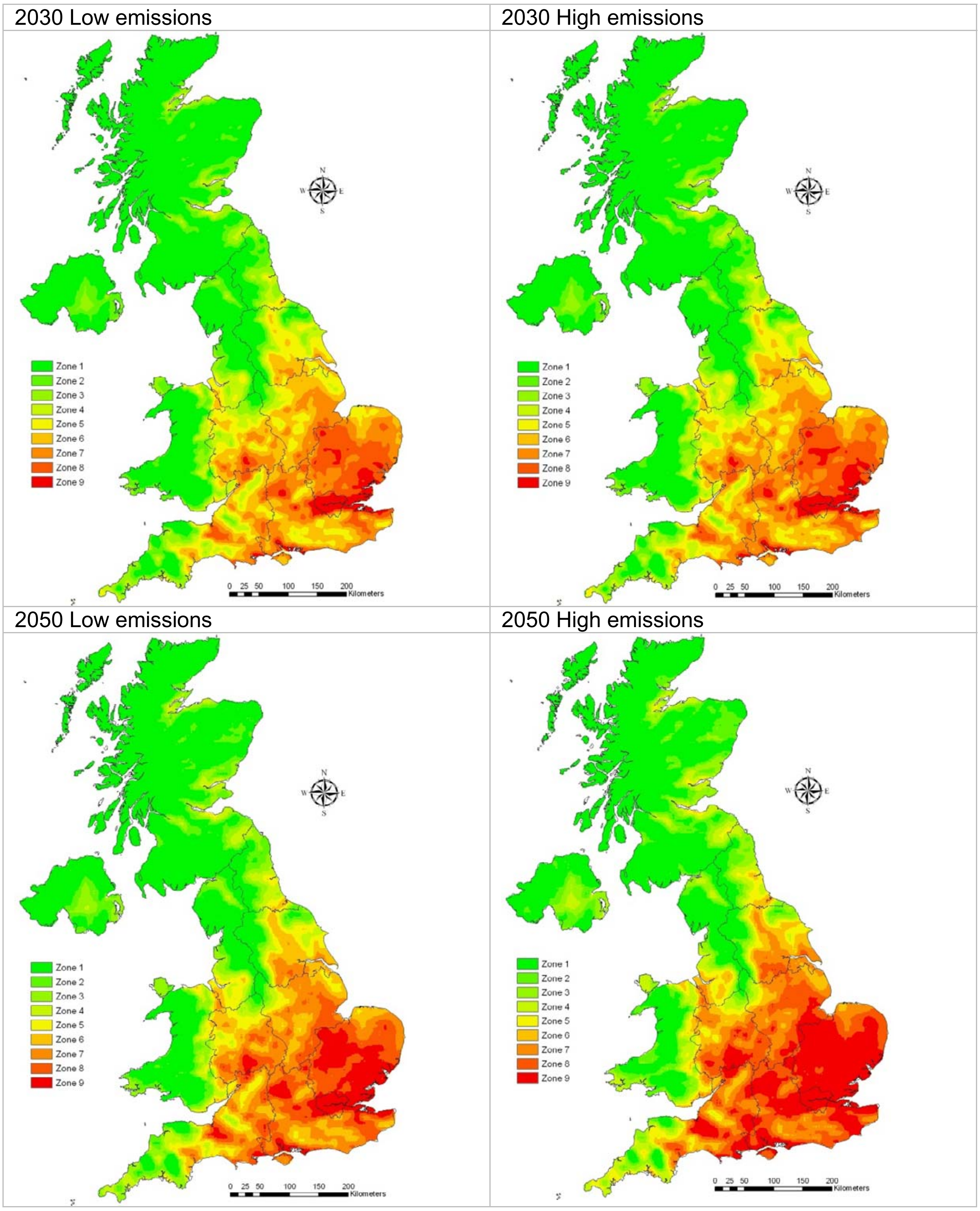


Figure 5.3 Projected changes in agroclimate ($PSMD_{max}$) in the UK for selected UKCP09 emissions scenarios (low, high) for the 2030s and 2080s

Source: Source: Weatherhead *et al.*, 2011

For the baseline, the agroclimatic zones with the highest $PSMD_{max}$ are currently located in the eastern and south eastern parts of the country, notably in Norfolk, Suffolk, Essex and Kent. These correspond to parts of the country where irrigation is most concentrated (Knox *et al.,* 1997; 2010b) and where the reliability and availability of water resources for agriculture are under severe pressure. In contrast, zones with the lowest $PSMD_{max}$ (< 75 mm) extend across much of Scotland, Wales, the south west and north-west of England.

In the future, the drier agroclimatic zones generally increase in area and magnitude spreading from the south and east towards the north and west. The analyses suggests that by the 2030s, the irrigation needs of central England would be similar to that currently experienced in eastern England, and by the 2050s eastern, southern, and central England would have irrigation needs greater than those currently experienced anywhere in England.

Changes in agroclimate would also affect land suitability and the viability of rainfed cropping. Soil characteristics and agroclimatic conditions greatly influence crop choice, agronomic husbandry practices and the economics of production. Changes in land suitability due to agroclimate would thus impact on the sustainability of existing cropping and opportunities for new crops. For example, using selected UKCP09 scenarios, Daccache *et al.* (2011b) developed a methodology using pedo-climatic functions and a GIS to model and map current and future land suitability for potato production in England and Wales. The outputs identified regions where rain-fed production would become limiting and where future irrigated production would be constrained due to shortages in water availability. The results suggested that by the 2050s, the area of land that is currently well or moderately suited for rain-fed production would decline by 74 and 95% under the "most likely" climate projections for the Low and High emissions scenario respectively, owing to increased droughtiness. In many areas, rain-fed production would become increasingly risky. However, with supplemental irrigation, around 85% of the total arable land in central and eastern England would remain suitable for production, although most is in catchments where water resources are already over-licensed and/or over-abstracted; the expansion of irrigated cropping is thus likely to be constrained by water availability.

Unfortunately it is not possible to accurately consider the change in farming systems due to climate change. The evidence on potential changes in farming systems is highly complex and in many cases actually driven more by externalities linked to agro-economic policy and changes in the profitability of particular farming systems, rather than a direct response to a change in climate. The Foresight 2011 Land Use Futures Report discusses the difficulties in projecting changes in land use because of the multifunctional nature of agriculture. Changes in land use will be more influenced by population growth, competition for natural resources (land/water etc) and demands for food versus environmental protection (Foresight, 2011a).

Their research concluded that the growth in water demand due to the switch from rain-fed to irrigated cropping is likely to be much larger than the increase in need of the irrigated crops. In Scotland, Brown *et al.* (2009) demonstrated the importance of soil moisture on land-use options, and how shifts in land-use potential have implications for both strategic resource planning and for adaptation actions. Their assessment highlighted not only potential changes in agriculture and other productive land uses, but also repercussions for biodiversity and terrestrial carbon stocks.

5.6 Water abstraction for crops (AG5)

Metric number	Risk metric	Confidence	Summary Class								
			2020s			2050s			2080s		
			l	c	u	l	c	u	l	c	u
AG5	Water Abstraction	M	1	2	3	1	2	3	2	2	3

The CCRA outputs based on the metric using EA historical abstraction data for England and Wales alone due to a lack of data for Scotland and Northern Ireland, combined with an agroclimate index (AG4) project increases in agricultural water demand for spray irrigation of approximately 15% for the 2020s Medium emission scenario, central estimate (range -20% to +52%), rising to 34% for the 2050s Medium emission scenario, central estimate (range -9% to +76%) and 45% for the 2080s Medium emission scenario, central estimate (range -4% to +108%). In the near term (2020s) this indicates upward pressure on water resources for agriculture for the p50 and p90 medium emissions scenarios. In the longer term (2050s, 2080s), it is projected that there would be significant increases in water abstraction for crops.[15]

Water availability is already affecting crop production in England, therefore the projections can be seen as a continuation of a problem that is already impacting the sector. An earlier onset of hot and dry weather can cause drought effects to occur earlier in the year. In 2011, an exceptionally dry spring reduced the yields of many crops.[16]

Table 5.7 National percentage change in water abstracted for spray irrigation

	Low			Medium			High		
	P10	p50	p90	p10	p50	p90	p10	p50	p90
2020s				-20	15	52			
2050s	-9	25	65	-2	34	76	1	36	75
2080s	-4	32	74	7	45	91	17	58	108

(blue)	Positive percentage change
(purple)	Negative percentage change

As with the crop yield metrics (AG1) the impacts of climate change on water abstraction for crops can be compared against other more detailed studies reported in the literature. For example, Weatherhead and Knox (2008) developed a set of demand forecasts for irrigated agriculture in England and Wales. This considered three time periods, (i) the short-term, 2008 to 2020, for 'business as usual' (baseline), (ii) the medium term, 2025 to 2035, for four EA marker scenarios; and (iii) the longer term, 2050s, for four extended EA scenarios. All forecasts were for "unconstrained demand in a dry year", i.e. what the volume abstractors would abstract in a dry year assuming water is made available under conditions similar to the 2005 baseline.

Actual future water use is likely to be constrained by future water availability and allocation policy, which may also lead to a relocation of demand. Due to the enormous

[15] These projections do not consider advancement in irrigation technology or improvements in efficiency as such changes are out with the scope of this report.
[16] http://www.telegraph.co.uk/earth/agriculture/farming/8517376/Lack-of-rain-already-causing-crop-failures-Defra-warns.html

uncertainty, the demand forecasts were not meant to be taken as predicted values, but rather to show the effects of the assumptions on trends in the crops and locations of the demand.

The ‘Alchemy’ scenario resulted in around a 150% increase in irrigation water demand by 2050, abstracted within environmental constraints, split roughly a quarter each between potatoes, horticulture and arable, with new food and non-food crops increasing in importance as the fourth quarter. ‘Jeopardy’ resulted in the largest increase in water demand, about 180% by 2050. Potatoes remain the largest user, but there is major growth for vegetable and arable irrigation to meet the increased population food requirements under climate change.

‘Restoration’ resulted in a continuing growth in irrigation demand, 80 to 90% higher by 2050 than today, concentrated on potatoes and vegetables, with slightly larger depths being applied to significantly larger areas, despite the emphasis on efficiency. Finally, in the ‘Survivor’ scenario, there was only a slight increase in irrigation water demand (+22% by 2050) due to population growth and climate change, as people become prepared to accept lower quality and local produce.

Taking these four scenarios into account that considered a full range of socio-economic factors, the reported range was +22% to +180%, clearly significantly higher than the projections produced from the CCRA analysis using climate effects alone. Therefore the conclusions from this analysis are that warmer conditions are very likely to increase the demand for water for crops by the 2050s and socio-economic changes would add further pressures, potentially more than doubling the increase in demand due to climate change.

These increases in demand would occur at the same time as reductions in water availability from rivers and within a regulatory framework that already indicates that that there is no additional water available for abstraction across much of England and Wales (Water Sector Report). As such farmers and agri-businesses would need to continue to adapt to water scarcity in a numbers of ways, including better on-farm water management and moving production to where water is available.

5.7 Climate impact on livestock production (AG7)

Metric number	Risk metric	Confidence	Summary Class								
			2020s			2050s			2080s		
			l	c	u	l	c	u	l	c	u
AG7a	Reduction in milk production due to heat stress	L	1	1	1	1	1	1	1	1	3
AG7b	Reduction in dairy herd fertility due to heat stress	L	1	1	2	1	1	2	1	1	2

The following livestock analysis was based on modelling the production system, including the effects of thermal humidity and heat stress on dairy production. It is important to note that the losses defined here after are related to the average change in climate or baseline and do not include additional extreme weather events that may result in higher numbers of heat stress losses (e.g. heat wave, drought). Dairy was selected as previous Defra reports show that it was likely to be affected by the UKCIP02 scenario and subsequently this was extrapolated further using the UKCP09 scenarios.

Overall, the current UK climate does not result in losses from dairy system or pose a major risk to dairy production and this is likely to continue to be the case in the near term (0% change across all scenarios for the 2020s). The projections going forward suggest that losses to heat stress only begin to become relevant in the 2050s. For example, for THI loads indicate a loss of 3 million kg/year (range of 0 to £100 million for Low p10 to High p90) in the 2050s up to 14 million kg/year (range of 0 to 549 million for Low p10 to High p90) for the 2080s. The percentage loss of national milk production in the 2050s, equates to only 0.03% (range 0% to 1.13% Low p10 to High p90), financially less than £0.15 million, for UK milk production, but there would be costs related to declines in herd fertility. In the longer term consequences become significant under some scenarios with more humid and hotter conditions to the extent that they would impact on farmers operating on low margins and regional economies that rely on export of dairy products (Table 5.8 and Table 5.9); the 2080 indicated a 0.14% loss of milk production (range 0% to 5.64% for Low p10 to High p90).

The current levels of THI in many livestock species under normal scenarios tend to be comfortably within their thermal neutral zone however, certain weather (rather than climate) can temporarily push them outside that zone. Although there is a proportion of dairy herds that are kept indoors all year round, in general cows spend a proportion of the year outside grazing grass and it is this time of year that the cows is likely to be pushed to the upper level of the thermal comfort zone. The work refers to this type of scenario, common in the UK. Indoor systems for dairy (and pig and poultry) can also experience heat stress however, many building designs are developed with ventilation etc in place to help keep the animals comfortable. If these designs are not future climate proof it may be necessary to modify, however it is harder to put interventions in place for outdoor periods.

5.7.1 Heat stress impact on dairy milk production (AG7a)

Data concerning the number of dairy cows in the UK were obtained from two sources – Defra and DairyCo. The number of dairy cows in each region in 2009 was used to multiply up the results which were calculated per animal. While it requires the assumption that the population would not change over time, this method at least provides some indication of the likely impacts if the population were to remain at current levels. Any attempt to estimate the future population would be subject to a great degree of uncertainty in addition to that associated with the climate.

In September 2010 the price of milk was 25p per kilo so a loss of production by 3 million kg would be valued at less than £1 million but the worst case loss of 549 million kg would have a value of £137 million per annum. This is based on a UK milk production total of 13,151m kg/annum baseline.[17]

Table 5.8 National total loss of milk production due to heat stress (million kg/annum)

	Low			Medium			High		
	p10	**p50**	**p90**	**p10**	**P50**	**p90**	**p10**	**p50**	**p90**
2020s				0	0	0			
2050s	0	2	58	0	3	96	0	5	110
2080s	0	3	113	0	14	320	0	27	549

[17] Calculated assuming an average yield of 19.4kg/day/cow with a UK cow population of 1,857,364 in 2009.

Table 5.9 National percentage (%) loss of milk production due to heat stress

	Low			Medium			High		
	p10	**p50**	**p90**	**p10**	**p50**	**p90**	**p10**	**p50**	**p90**
2020s				0.00	0.00	0.00			
2050s	0.00	0.02	0.60	0.00	0.03	0.98	0.00	0.05	1.13
2080s	0.00	0.03	1.16	0.00	0.14	3.29	0.00	0.28	5.64

5.7.2 Heat stress impact on loss of dairy fertility (AG7b)

The analysis on loss of dairy fertility indicates further pressures on dairy production and that there would be additional costs over and above lost milk production. The amount of 'days open' indicates periods when dairy are not producing but still require costs in terms of feeding and maintaining the herd. In Table 5.10 the 'days open' metric is converted into an annual costs (assuming a value of £2.50 per day open per cow (Hudson *et al*, 2010)), indicating significant costs in the longer term under the hot and humid scenarios (2050s and 2080s, p90 Medium and p90 High emissions scenarios). For the medium 2020s scenario costs are projected to be approximately 1 million/year (range of £0mill to £3 million p10 to p90), for the 2050s and 2080s the projections are of £1 million/year (range of £0 to £23million for Low p10 to High p90) and £4 million/year (range of £0 to £51 million/year Low p10 to High p90) respectively.

Reduced fertility in dairy cows due to a changing climate may not initially appear to have post-farm gate impacts. However, poor fertility does have an unfavourable impact on the overall profit of the farm business. If the costs of producing milk at a farm level increases then it will eventually have a downstream effect on milk prices. Also, if there are regional differences in the extent of climate impacts on cow fertility it may be that milk supply is not evenly distributed across the country, causing a need for increased milk transportation around the country. As a diet staple, post farm gate and distribution transport costs would increase and this and this could be reflected in milk prices if processors and retailers decide not to absorb the costs.

Table 5.10 Estimated costs (£million/annum) of decline in fertility of UK dairy herd

	Low			Medium			High		
	P10	p50	p90	p10	p50	p90	p10	p50	p90
2020s				0	1	3			
2050s	0	1	14	0	1	17	0	2	23
2080s	0	1	23	0	4	39	0	9	51

5.8 Climate impact on livestock health (AG8)

Metric number	Risk metric	Confidence	Summary Class								
			2020s			2050s			2080s		
			l	c	u	l	c	u	l	c	u
AG8a	Longer periods of heat stress in dairy cows	H	1	1	1	1	1	2	1	1	2
AG8b	Dairy livestock deaths due to heat stress	L	1	1	2	1	1	2	1	1	2

The livestock production model indicates small but largely insignificant increases in the number of days of heat stress for the dairy herd. For example, in the highest scenario considered (p90 High emissions in the 2080s) the model indicates a maximum of just 3 days per annum where livestock would be classified as stressed. Consequently the expected number of deaths from heat stress is negligible and the overall risk for the production system is related to the previous metrics on the decline in milk production and fertility. The full results of the livestock health metrics are summarised in the Appendix 5.

Livestock farmers also face a range of disease risks, both endemic (present in the UK e.g. Bovine TB), exotic (not usually present in the UK, except during outbreaks e.g. Foot and Mouth Disease) and new and emerging diseases, which have the potential to cause significant economic damage and threat to food production for the UK as a whole, the agriculture sector and individual farms (e.g. Bluetongue virus).

Bluetongue virus

An example of a disease that may have future consequences for UK agriculture is bluetongue, caused by bluetongue virus (BTV). BTV infects all ruminants and causes serious disease, and sometimes death, in improved breeds of sheep, certain species of deer (specifically White Tailed deer in North America) and (less frequently) in cattle and goats. BTV is spread by *Culicoides* midges and in the Old World the principal vector is the species *Culicoides imicola* which is limited to Africa, Asia and the Mediterranean. However, some strains of BTV can also be transmitted by other species of *Culicoides* common throughout Europe and this has been a key factor in the recent northward spread of BTV. It has been suggested that the northward spread is partly driven by changes in the European climate, such as ambient temperature and milder winters, that have allowed the principal vector to extend its range northward and the virus to increasingly persist during winter months (Purse *et al,* 2006). Different *Culicoides* species have different moisture and temperature requirements depending on their ecology. *C. imicola* occurs in warm habitats with low to medium levels of precipitation, although other factors such as vegetation type also appear to be important. Other European *Culicoides* species occur in areas with higher precipitation and lower temperature. Ambient temperature also affects the ability of a species to transmit BTV; a higher proportion of adults which experience high temperatures at the larval stages are capable of being vectors. The Foresight project, Infectious Diseases: Preparing for the Future (2006) project projected the broad distribution of BTV to 2030 in Europe[18].

[18] Based upon the UKCIP02 climate projections and the statistical pattern-matching approach modelling they had developed in previous work (Purse *et al.* 2005)

The authors consider that it is possible for BTV to extend into areas with an average temperature of 10°C and annual precipitation level up to 1,200 mm.

Despite the fact that BTV is one of a few relatively well studied diseases that suggest a link to climate factors, there are still knowledge gaps regarding the indirect effects of climate change (social, economical, political and land-use changes) and non-climatic drivers (livestock density and control tools). The UK experienced its first outbreak in 2007, which was caused by BTV-8 and linked to the windborne transmission of the vector across the English Channel from Europe[19]. No cases of BTV-infected animals (except among imported animals) have been recorded in the UK since 2007, and there were no recorded cases of infection of deer in the UK. Changes in climatic conditions may have provided a favourable environment in which the disease was able to spread which, together with a susceptible livestock population, resulted in the widespread outbreak of BTV-8. However, its emergence in northern Europe is not explained entirely by climate change but by a complex combination of drivers, and factors such as increased international transport are likely to have increased the frequency with which BTV is introduced to areas beyond its current distribution. Whilst safe effective vaccines against some serotypes are already commercially available and those against others are in development, there is no cure for bluetongue and the cost of vaccination is relatively high when the low per-animal profit margins in sectors such as sheep farming are considered.

5.9 New crops (AG9)

Metric number	Risk metric	Confidence	Summary Class								
			2020s			2050s			2080s		
			l	c	u	l	c	u	l	c	u
AG9	New crop opportunities	H	1	1	1	2	2	2	3	3	3

A summary of new crops that could potentially be grown in the UK and their geographical suitability is provided. The list is non exhaustive and identifies crops which may have greater potential under climate change conditions, however local markets, trading opportunities and local variations may affect the commercial viability of such crops. The list includes over 30 food crops, about 20 'pharmaceutical' and 'industrial' crops, and 5 energy crops (for potential energy production). Some information is also provided on potential yields.

The cultivation of new crops might be encouraged by changes in land suitability due to modified soil and agroclimate conditions. For example, changes in the spatial and temporal patterns of rainfall and temperature are likely to lead to the introduction of new crops in some regions and/or relocation of existing crops into new regions. New plant breeding coupled with investment in farming technologies (e.g. irrigation) might also lead to the introduction of new crops. Since agriculture is no longer viewed as being solely a provider of food crops – its multifunctional role will inevitably lead to a much broader range of crops being grown.

New crops can be classified into 'food' and 'non-food' crops. The latter includes crops with alternative end uses such as for drugs and cosmetics development, for industrial feedstock, for renewable energy (biomass, biofuel or biogas), ornamental use, and for brewing, distillation or wine production. A crop can be considered 'new' in two

[19] Defra, *Bluetongue Epidemiology Report*, 19th October 2007. Available from http://www.defra.gov.uk/foodfarm/farmanimal/diseases/atoz/bluetongue/publications/index.htm

situations; firstly, if it has not been cultivated before (e.g. as a result of a breeding programme or domestication process), and secondly, if it has not been grown in a certain region before (e.g. due to shifting agro-ecological zones). This report considers the impact of both changes in agro-ecological zones on shifting crop cultivation and the introduction of new crop genotypes. For all the crops identified, it is important to stress that assessing their potential for production in the UK under a changing climate would need detailed biophysical modelling to assess yield potential under the changed soil and agroclimatic conditions, coupled with economic modelling to assess their financial viability from a farming perspective. This report highlights the potential new crops that might be suitable, rather than quantifying specifically which new crops would be most/least likely from an agronomic/agroclimatic/economic perspective.

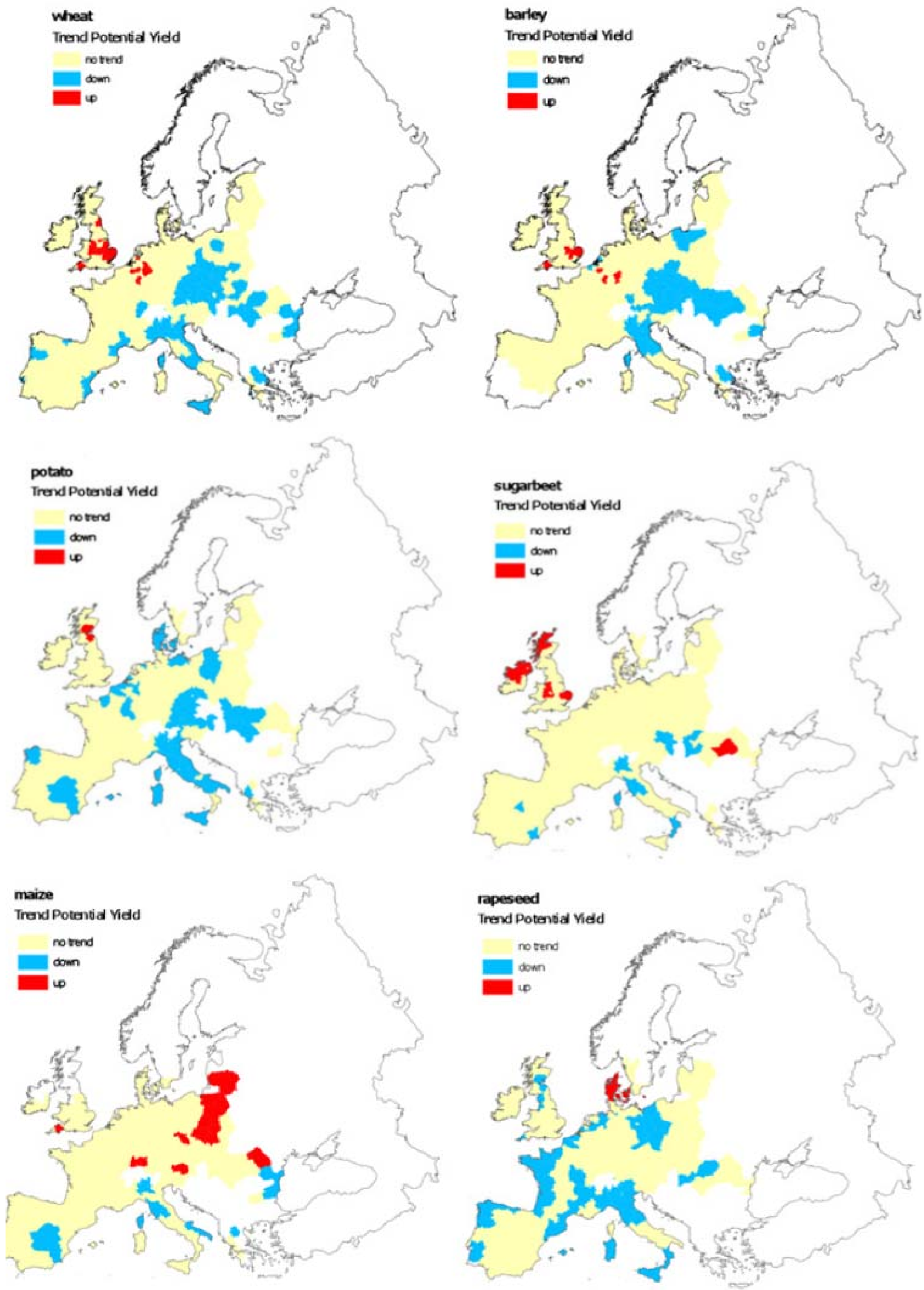
5.9.1 Changing European climate – impacts on UK crops

In considering what new crops might emerge in the UK agricultural landscape, it is useful to consider what the reported potential impacts of climate change on cropping are in Europe, as changes in climate there will inevitably influence the transition of new crops in the UK. Due to projected temperature and rainfall changes, crop production would need to adapt to maintain existing productivity levels. Various studies suggest that the overall area of land suitable for agricultural cropping in Europe will move northwards (Olesen and Bindi, 2002). For example, Carter *et al.* (1992) estimate that the northern limit for land suitable for maize cropping could shift by around 190 km per decade from the 1990s to the 2050s. It is also expected that the length of the growing season would change – for some crops such as cereals it is expected to decline, but for others, such as vegetable and root crops, it is expected to increase (Olesen and Bindi, 2002).

For crop production, the consequences of climate change could be either positive or negative, depending on location and crop type. There are some advantages such as the introduction of new crops, and increase in the amount of species and varieties; higher crop productivity, and the expansion of cultivation areas. However, plant protection needs are likely to increase; and there would be an increased risk of nutrient leaching, and turnover of soil organic matter (Olesen and Bindi, 2002). For example, for perennial crops such as vineyards and olive trees, there would be major changes in land suitability. Energy crops such as willow and Miscanthus could become more suitable and potentially more profitable; forage maize would increasingly be grown in northern European countries. However, the effects in northern and central Europe would be quite different to the consequences and adaptation measures required for agriculture in the Mediterranean areas. Supit *et al.* (2010) studied the changes in potential yield for several crops grown across Europe. The general trend was one of negative impact in southern areas and positive in northern regions (Figure 5.4).

The reported yield impact for the UK was positive for wheat (+0.06 t ha^{-1} $year^{-1}$), barley (+0.05 t ha^{-1} $year^{-1}$), maize (+0.09 t ha^{-1} $year^{-1}$), sugar beet (+0.09 t ha^{-1} $year^{-1}$), and pulses (+0.03 t ha^{-1} $year^{-1}$), but negative for rape seed (-0.04 t ha^{-1} $year^{-1}$). These results refer to potential crop production assuming optimal moisture and nutritional levels. The study was based on yield and biomass production, caused by changes in the temperature and global radiation patterns recorded over the period 1975–2005. The Crop Growth Monitoring System (CGMS) model was used as it can monitor year to year impacts of climate on yield production.

The projections for future UK climate are characterized by the risk of more frequent extreme events. Several studies identify an increasing tendency of heat waves and droughts with consequences on crop production (e.g. Beniston, 2004; Luterbacher *et al.*, 2004; Schär *et al.* 2004). Mechler *et al.* (2010) studied the impact of extreme events on crop yield in UK agricultural production since the 1970s. Whilst some crops have shown adaptation others have not. Each subsequent drought or heat wave (1975/6, 1983/4, 1992, 1995, 2003, 2006) has generally resulted in a lower impact than the previous event with potatoes and oilseed rape yield showing a gradual trend in adaptation. However, some crops such as barley do not appear to have shown any significant adaptation changes.



(a)

(b)

(c)

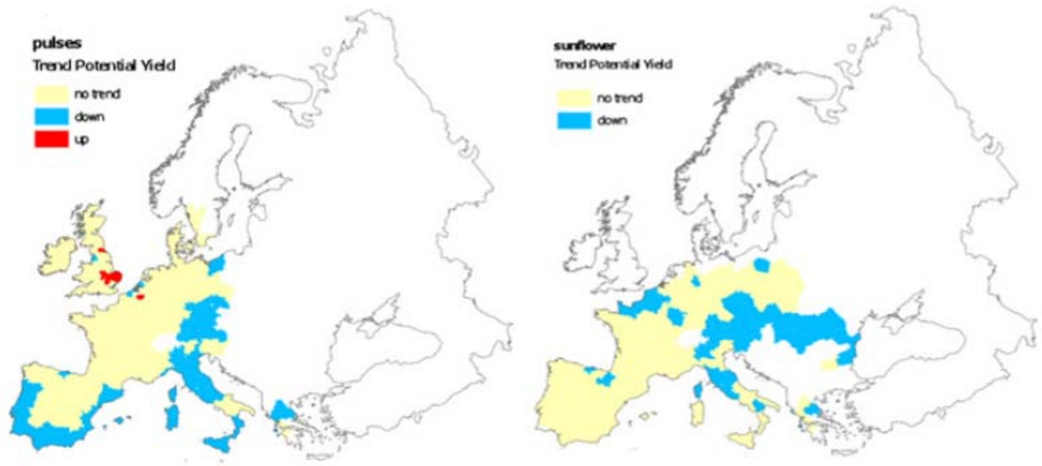
(d)


Figure 5.4 Reported trends in simulated potential yield of (a) wheat and barley, (b) potato and sugar beet, (c) maize and rapeseed, and (d) pulses and sunflower
Source: Supit *et al.*, 2010

5.9.2 New crops

With a changing climate, there are opportunities for a wide range of new crops to be potentially grown. These could be either for food production, industrial, pharmaceutical and/or energy use. Table 5.11 summarises the key groupings of the potential new crops that could emerge. Note that some crops are already grown (e.g. sugar beet) but their target market/use could change.

Table 5.11 Summary of selected new crops that could be cultivated in the UK, aggregated by sector

Crop use	Sector	Selected crop type examples
Food	Animal feed	Amaranth, Jerusalem artichoke, canary seed, millet
	Food processing	Chamomile, coriander, dill
	Fresh human consumption	Globe artichoke, blueberries, maize, grapes, pumpkin, lupin
Energy	Biofuel	Canary seed, crambe, Gold of pleasure
	Biomass	Miscanthus, reed canary grass
Pharmaceutical	Drugs	Caper spurge, celery, daffodil, echium, fennel, garlic, poppy, yew
	Cosmetics	Bog-myrtle, chamomille, lavender, nettle, peppermint, sea buckthorn
Industrial	Biolubricants	Caper spurge
	Oil	Sunflower, linseed, soya bean
	Fibre	Hemp, linseed (fibre flax), nettle, switch grass
	Paper and pulp	Reed canary grass, switch grass
	Dye	Madder, safflower, St Johns Wort, woad
	Brewing, distillation	Grapes
Ornamental		Mistletoe, yarrow

A brief overview of individual crops within each sector, their agronomic requirements and potential for future cultivation in the UK are summarised below.

5.9.3 New 'food' crops

This category includes crops grown for both human consumption and animal nutrition. Some crops could be grown for both purposes or animals could be fed with secondary yield products. Crops grown for human consumption can either be eaten fresh (e.g. garlic) or require processing (the case for many cereal and herb species that are processed such as flours, pasta, and breakfast cereals, or dried and then prepared for infusions or as culinary complements). There is potential for many new crops to be introduced into the UK, depending on suitable soil and agroclimatic conditions. There are also other crops whose end use is expected to change, but these are not strictly considered as being 'new'. In assessing the potential for new crops and their agronomic suitability, the UK has been divided into eight main regions (Figure 5.5).

Figure 5.5 UK defined areas for new crop suitability

A summary of the new food crops that could potentially be grown in the UK and their geographical suitability is given below.

Amaranth (*Amaranthus hybridus* and *A.caudatus*) is mainly aimed at the food industry for its seeds and flour which are low in gluten, which makes it appropriate for gluten intolerants. Its seeds are rich in oil used for cosmetic use and as a cholesterol level reducer. Due to its protein high content it is used as animal forage. It could also be used as an ornamental plant. It is a warm-season crop, which would tolerate some drought and salinity levels. Suitable areas for amaranth cropping would be in the East, South and Heart of England.

Globe artichoke (*Cynara scolymus*) is typically grown in Mediterranean regions for its edible flower head, which can be consumed fresh or canned. This cold-season herbaceous perennial crop is productive when temperatures range from 7 to 29°C. It is also used as a source of antioxidant with pharmaceutical applications. In the UK, its cultivation would be suitable in the southern regions (East, South, Heart and West of England).

Jerusalem artichoke (*Helianthus tuberosus*) is a food crop, although it has other potential uses such as for biofuel, inulin and oligofructose feedstock, and as perennial game cover crop. Its tubers can be used for human consumption, whilst its biomass can be used as an animal feedstock. It could be grown across the UK, where temperatures range from 18 to 27°C, with 125 frost-free days and where annual rainfall is 600-1200 mm.

Blueberry (*Vaccinium spp.*) can be consumed fresh, or canned, frozen, dried or processed. The demand for blueberries has increased due to its antioxidant properties (anthocyanins). With low rainfall requirements (600-800 mm) and susceptible to late spring frost, the most suitable areas for its cultivation are the East and Southern England.

Canary seed *(Phalaris canariensis)* is mainly grown as bird feed, although it can also be used in some food preparations and may have potential as a biofuel source due to its high starch content. It could be grown across the UK.

Catmint (*Nepeta cataria*) contains essential oils in flowers, leaves and stems, which are rich in nepetalactone, nepetalic acid, epinepetalactone, camphor and other substances - it is used as source of insect behaviour-modifying chemicals. Although less common, it could also be used in the food and drink industry (tea, salads). Catmint is most suitable for the South, East, Southwest and Heart of England.

Chamomile (*Chamaemelum nobile, Matricaria chamomilla)* is mainly grown for its use as a herbal tea, for food flavouring, herbal remedies and aromatherapy. Essential oils are extracted from the flowers. This crop prefers relatively warm, dry winters and sunny conditions, which makes it most suitable for cultivation in the southern regions (East, South, Heart and West of England).

Chicory (*Cichorium intybus*) has edible leaves and a taproot. The leaves are used mainly as salad and a coffee substitute can be made from its roots. It is a rich source of inulin and fructose, and can also be used as forage for pigs and cattle. Although sensitive in some development stages, it is generally frost tolerant, and the deep taproot improves its drought tolerance. It could be grown in Scotland, the East and South West England. Inulin is a polysaccharide used by the food industry as a sugar and fat substitute in light, diet and low-fat products. Inulin does not produce any caloric contribution during digestion (Toneli *et al.*, 2008) and contributes to increase the beneficial bifido bacteria in the system (Silva, 1996). This crop is currently being grown in Belgium, France and Holland as a commercial source of inulin (Toneli *et al.*, 2008).

Chilli (*Capsicum* spp.) and aubergine production have been included in the Defra statistics since 2000 as “other crops”, together with courgettes (1995) and cold tolerant tomatoes (named tomatoes cold) (since 2004). Chilli can be grown in the warmer regions of the country but requires a high degree of management. There is very limited published evidence on chill production and currently only 10 registered growers in the UK. With climate change and higher summer temperatures, this could become a more widespread crop grown outdoors and with seasonal protection (polytunnels).

Coriander *(Coriandrum sativum)* products are the seeds and dried leaves which are used as culinary compliments. This crop requires cool springs and hot summers, not exceeding 21°C, which would lead to a decrease in the oil concentration. Coriander is already grown in East England but could also be grown in Southern England.

Dill *(Anethum graveolens)* is grown for its seeds and leaves which are used for flavouring; its oil can be used in cosmetics and it has some medicinal properties. It cannot tolerate temperatures above 30°C or below -4°C, and has rainfall minimum requirements of 500 mm. Dill farming would be suitable in the southern regions including East, South, South West and Heart of England.

Elder *(Sambucus nigra)* is a tree which flowers and its berries used for drink and food preparation. It is also used to enrich certain food products with vitamins A and C (jellies, jams, pies). Infused berries and flowers are used as traditional remedies to some ailments such as colds, coughs, constipation, and colic. It is already grown in the UK, but could become much more widespread.

Ethiopian mustard (*Brassica carinata*) can be grown either as a food crop (its seeds and leaves can be used as raw material for spices and cooking oils) or as an energy crop (discussed later). This crop is highly adaptable to different soil types, and is drought and heat tolerant. It could be grown in the East, Southern and Heart of England.

Fennel (*Foeniculum vulgare)* is an herbaceous perennial crop grown for its leaves and seeds as culinary spices. It has also some medicinal and alcoholic beverage uses. It would be suitable in the southern regions of UK (East, South, South West and heart of England), as it grows best in cool to warm climates. However, the plants could die over winter due to persistent low temperatures.

Garlic (*Allium sativum)* is grown for its bulbs, and used as a food, in the nutritional supplements' sector and pharmaceutical industry. Garlic prefers warm summers and tolerates cold winters; however it is sensitive to dry soil conditions. The best regions in the UK for its cultivation would be in the East, Southern, Heart of England, English Midlands and Wales.

Gold of Pleasure (*Camelina sativa*) is an oilseed crop which has multiple uses including a food crop. It is a low-input hardy crop. In the UK it is generally grown as a cover crop for game. Due to its agronomic characteristics, it is suitable for cultivation in the southern regions (East, South, South West and Heart of England).

Grapes (*Vitis vitifera*) can be grown for use as either table grapes, raisins and juice production, or for wine processing. The importance of this crop in the UK has increased in the last few decades with the vine production area increasing from 325 ha in 1984 to almost 1000 ha in 2009 (Figure 5.6).

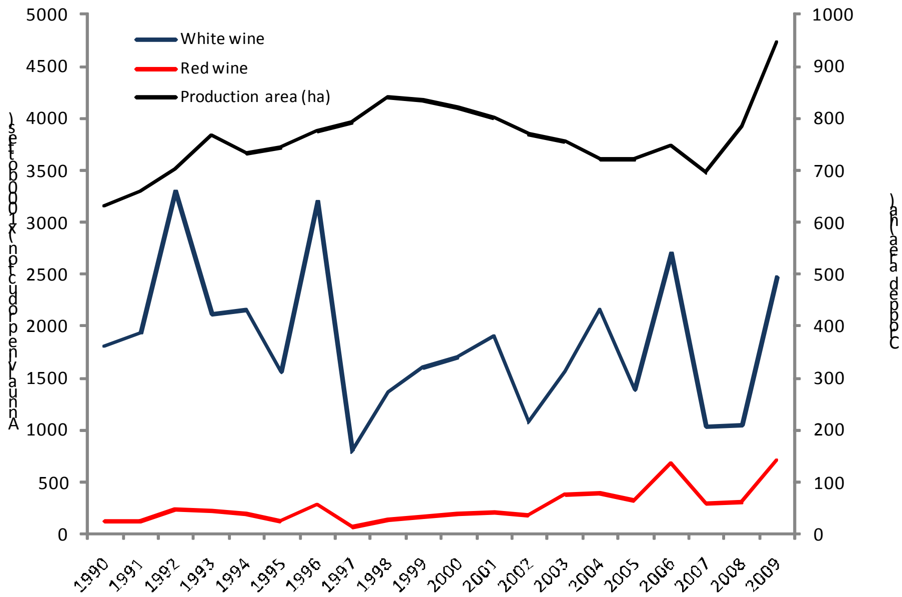


Figure 5.6 Reported trend in UK vine cropped area (ha) and production (x1000 bottles) from 1990-2009

Source data: English Wine Producers[20]

According to Bisgrove and Hadley (2002) grapes would be suitable for cultivation across most of England except in the Midlands. However, some studies have focussed on the effects of climate change on grape production. For example, Olesen *et al.* (2011) identified current limiting factors, adaptation measures and yield trends in winter wheat, spring barley, grain maize, grapevine, and grassland in each environmental zone in Europe. In that study, the UK corresponds to the zones ATN (Atlantic North) and ATC (Atlantic Central). Large to extreme damages on grapevine in the ATN were identified due to the consequences of changes in the length of the growing season and the damage caused during winter. Other important limitations in this agro-ecological zone were problems related with rainfall during harvesting and the occurrence of late/early frosts. This crop may also be affected by the effects of hail and droughts (Olesen *et al.*, 2011). In the ATC zone, the limiting factors were less important. Moderate problems could occur due to changes in the length of the growing season, and rainfall during the harvesting period (Olesen *et al.*, 2011). Climate change was reported to positively impact on UK grapevine production, as winter and frost damages would be reduced in the ATN and ATC areas. According to Olesen *et al.* (2011), the growing period would increase in the ATN, as well as the risk of hail and diseases.

Simulations for future scenarios HCGG and HCGS showed that the date of maturity would occur earlier (25-50 days / 20-40 days with HCGG and HCGS, respectively) and the bud burst and flowering would take place earlier (10-25 days). Potential yield increases with both scenarios due to the positive effect of CO_2 would outweigh the negative impacts of any increase in temperature. Mean yield increases ranged from 10-25% (Butterfield *et al.*, 1995).

Juniper (*Juniperus communis*) berries are used principally for flavouring drinks (gin) and food, but its oil also has medical properties. This conifer would be suitable for cultivation across much of the UK.

Linseed (*Linum usitatissimum)* has several uses. The seeds, which are rich in oil (30-35% of seed weight) are used to make flour and the oil has health attributes. The by-products of linseed processing can be used in the pharmaceutical and cosmetics sector. Frost can affect the plant at seedling establishment and flowering, but linseed is

[20] http://www.englishwineproducers.com/stats.htm#top

suitable for cultivation in cool and humid climates, making it appropriate for England and Northern Ireland.

Lupin (*Lupinus albus, L.angustifolius, L. luteus*) is a herbaceous crop which is very high in protein and therefore suitable for animal (fresh or after silage) and human consumption. Lupin is suitable for most UK soils and has soil nitrogen enrichment potential.

Maize (*Zea mays)* can be grown for grain, as a forage crop for animal feed, or as feedstock for several industrial sectors and for energy. There are also many products used for human consumption that can be derived from maize grain such as thickening agents (cornflour), cereal products (tortilla, polenta), or components of products such as noodles. Several studies have focused on maize cropping in Europe and its potential to move to new areas of production (e.g. Carter *et al.*, 1992 Olesen *et al.*, 2011). According to these studies, forage maize could be grown in more northern latitudes than maize grown for grain. This is due to crop temperature requirements - maize for forage use has a lower temperature requirement than grain maize. In grain maize, the grain has to reach a fully ripened and dried stage before it can be harvested (Carter *et al.,* 1992).

Current limiting factors on maize cropping were identified in the ATN and ATC regions by Olesen *et al.* (2011). In the ATN region major damages due to early/late frosts, while moderate problems affect the length of the growing season and rainfall occurred during the harvesting/sowing period. Smaller problems caused by hail and floods might limit maize growth in the ATN. The length of the growing season would be positively affected on this C4 crop by temperature increase in the ATN. In ATC zones, maize limiting factors are identified as the moderate problems caused by the length of the growing season, early/late frosts, rainfall during harvesting/sowing period, and drought. Smaller or rare problems are caused by floods and hail (Olesen *et al.,* 2011). In southern Scotland 2000ha of forage maize is currently grown, as cattle feed, and it is becoming one of Southern Scotland's traditional crops[21]. Forage maize is drought tolerant and thrives in warmer soils. Current climate projections suggest that for Southern Scotland, increased summer temperatures and aridity may provide an expanding opportunity for maize crops (Davies *et al.*, 2007).

Marigold (*Calendula officinalis*) is an oilseed crop, which has multiple uses including food, industrial feedstock, cosmetics and pharmaceutical uses. It has a high tolerance to poor soils, is hardy and well adapted to northern and western European conditions, which make this crop well suited to Southern and South West England and the Heart of England.

Marjoram (*Origanum majorana*) is a small perennial bush and used for its aromatic leaves as a culinary flavouring and medical use. It would be possible to grow marjoram across much of the UK.

Millet (*Panicum miliaceum*), used as a crop for animal feed (and seed for birdfeed), it could be introduced into the UK and grown in the warmer regions of southern England (East, South, West and heart of England). Millet is suitable for cultivation on most soils, however, it is not frost tolerant and cannot be sown before May.

Nettle (*Urtica dioica*) typically grown for food and medicine purposes has shown to be a source of industrial feedstock and fibre. Nettle is a very tolerant species that could also be grown across much of the UK. It has potential to be grown commercially for producing chlorophyll (colouring agent for food and pharmaceutical products).

Peppermint *(Mentha piperita)* is an essential oil used widely in food products, and as a nutritional supplement in the pharmacological and cosmetic sectors. There is currently

[21] http://www.sac.ac.uk/news/currentnews/11n13maize

no UK market for this product as the country is a net importer; however a new market could appear. This crop could be grown widely across the UK.

Pumpkin *(Cucurbita pepo)* has a wide range of varieties used as edible fruits or as decoration (Halloween pumpkins). This annual crop is not frost-tolerant and requires warm conditions; therefore, the only appropriate areas would be the South, the West, the heart of England and its Midlands.

Quinoa (*Chenopodium quinoa*) seeds are rich in protein and oil. Its flour is used instead of wheat flour in some South American countries. Some medical properties are link to this plant. However in the UK it is only used as game cover. It would be possible to grow Quinoa in Southern and Eastern England.

Rocket (*Eruca vesicaria subsp. sativa)* is an herbaceous crop from which only the young leaves are harvested and then used in salads. The optimum temperature for growing conditions is around 20°C and it needs to be well watered, but once established is relatively drought-resistant. Cultivation would be possible across most of England and Wales.

Sea buckthorn (*Hippophae rhamnoides*) is a perennial bush considered to have a high economic potential. From its berries, leaves, and bark it has uses in the pharmaceutical, cosmetic, food and drink (teas, juices, sport and health drinks, jam), textile (dyes) sectors. Cultivation would be possible across England and Wales.

Soya bean (*Glycine max)* has recently been introduced into the UK as an animal feed crop, it is grown for its seeds. These are very rich in protein and oil content; therefore employed in the development of many food products and oil. Soya oil is one of the most consumed vegetable oils. Currently it is acquiring importance as biofuel. The UK imported 3,300 mt of soya meal in 2010 (WWF, 2011), whose principal markets are for animal feed and human food consumption. Contrary to imported soya, UK soya could guarantee GM-free production. New varieties adapted to UK conditions are being introduced. The most important areas for this crop would be in the East, South, South West and Heart of England.

Sunflower (*Helianthus annuus*) is grown for its seeds and seed oil. The seeds can either be eaten cooked, raw or processed into flour. The oil also has non-food uses. The UK currently annually imports approximately 400,000 t of sunflower, mainly as oil. It is estimated that 400-600 ha of sunflowers are currently grown in the UK producing about 1000 tons of seed. Given suitable agroclimatic and soil conditions, this area could increase up to 60,000 ha in Eastern, Southern, South West and Heart of England.

The principle factor determining the rate of physiological development in sunflower is the accumulated air temperature (mean daily air temperature over a 6°C). The projections from UKCIP02 data indicate that the area suitable for sunflower production could increase to approximately 79% of the land area of England by 2050. There will be a substantial increase in the number of varieties that will be suitable for use in the UK.[22] Additional factors include rainfall and soil temperature, with analysis of these indicating an opportunity for sunflower production extends north to the Humber River and includes parts of Wales (Cook, 2009).

Sainfoin (*Onobrychis viciifolia*) is a perennial plant cultivated for animal feed, due to its high protein (20%) content. It can be silaged or used as hay or fodder for ruminants as well as for horses. It is considered to be highly palatable and very nutritious for livestock. Sainfoin has the advantage of fixing nitrogen in the soil, which makes it a good choice for crop rotations. Sainfoin is more tolerant to drought than lucerne, but it

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22 http://www.hgca.com/content.output/3750/3750/Crop%20Research/Sunflowers/Sunflowers%20and%20climate%20change.mspx

does not tolerate wet or compacted soils, and prefers warm temperatures, which makes its optimum growing areas in the South, East, and South West of England.

In summary, for new ‘food crops’ three main regions across UK are considered most suitable:

- Southern region (East, South, West and Heart of England) could provide the most suitable agronomic conditions for the cultivation amaranth, globe artichoke, chamomile, dill, Ethiopian mustard, fennel, gold of pleasure, soya bean, sunflower, and thyme.
- Central region (East, West, Heart of England, English Midlands and Wales) would be suitable for garlic, grapes and rocket, with the exception of grapes in the Midlands and garlic in western areas. All these crops would also be suitable in the southern region.
- Northern region of Scotland and Northern Ireland. This corresponds to the coldest areas. No new food crops are considered to be explicitly suitable to these areas.
- There are of course other crops that could be grown across the UK. These are food crops such as elder, juniper, lupin, marjoram, nettle, peppermint, sea buckhorn, and yarrow. No data on their current or future suitability was identified.

5.9.4 New ‘energy’ crops

This group includes crops that are cultivated for energy production, including biomass, biofuel and/or biogas. The importance of these crops is likely to increase in the future with a changing climate, as successive governments seem to be committed to increasing the proportion of UK electricity generated from renewable sources.

Miscanthus (*Miscanthus x giganteus)* is a high biomass generating herbaceous species, which reaches maximum productivity approximately 5 years after its establishment. It can be grown continuously for 10-20 years on the same soil. There is currently a high level of interest in this crop as it is considered to be a suitable energy source for medium-scale applications such as schools and hospitals. Its use at this scale is being promoted by the *Bio-Energy Capital Grant Scheme*[23] as part of the *UK Environmental Transformation Fund (Department of Energy and Climate Change)*. UK production of miscanthus has increased over the last decade, with the cropped area increasing from 52 ha in 1998 to 12000 ha in 2009. Miscanthus is characterized by having a very high yield and low moisture content at harvest. Despite its high efficiency in water use, it does not tolerate drought, thus supplemental irrigation may be required in dry years to achieve maximum productivity. Spring frosts can also cause some damage. The most suitable areas in the UK would be the warmer areas of the South, East, West and Heart of England.

Oilseed rape (*Brassica napus*) is one of the most important arable crops grown in the UK after barley and wheat in term of generated income (Defra, 2010) and second in sown area (Defra, 2011). Its oil is used in many food products; however, there is an increasing interest in its use for non-food purposes (notably bioenergy and industrial feedstock). It has been grown in the UK for many years and is likely to continue to be cultivated widely. Oilseed rape varieties can be classified as 00 (double low content in erucic acid and glucosinolates), High Erucic Acid Rape (HEAR) and High Oleic and

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23 http://www.decc.gov.uk/en/content/cms/what_we_do/lc_uk/lc_business/lc_economy/env_trans_fund/bio_grants/bio_grants.aspx

Low Linolenic (HOLL). The 00 varieties are used for animal feed and human oil consumption. The HEAR varieties are used to produce biodiesel and lubricants, and the HOLL varieties for food (frying oil). The latest Defra cropping census on 'non-food' crops shows that the area cultivated has increased rapidly. For example, in 2001, 47343 ha were cultivated in the UK - by 2009 this had increased up to 85711 ha. However, during this time the cultivated area showed significant fluctuations, peaking in 2007, and then declining rapidly.

Reed canary grass (*Phalaris arundinacea)* is a perennial grass indigenous to the UK. It is grown as a bio-energy crop, and as a fibre source for paper and pulp production.

Switch grass (*Panicum virgatum*) is a low input crop with a reliable yield production (Wright and Turhollow, 2010), considered as a biomass source for energy production as well as pulp, paper and other fibre products. It is a very efficient crop in terms of its water use and biomass production as it is a C4 crop. It would be most suitable for cultivation in Southern, South West, Eastern and the Heart of England.

Willow *(Saliz spp.)* is a short rotation coppice (SRC) crop which is cut and burned to produce energy as heat or electricity. It can produce up to 10-12 t dry matter ha^{-1} $year^{-1}$, which would produce energy equivalent to 5000 litres of oil. It can be harvested 3 years after planting. The SRC cultivated area in the UK has increased from 200 ha in 1998 up to 6444 ha in 2009 (Figure 5.7). The most significant planting occurred between 2006 and 2007 with 1474 and 1513 ha of new willow and poplar (SRC) being planted, respectively. For cultivation, very humid soils should be avoided; it can tolerate low temperatures during the winter, but frost in spring and autumn can damage its shoots. It could be grown across much of the UK. Studies regarding climate change impacts on willow (Evans *et al.*, 1995) predicted an increase in mean yield (total dry matter) of 9.4t/ha to 32.2 t/ha (baseline mean of 22.8 t/ha) and a reduction in the variability of predicted yield (coefficient of variation from 14 to 9%). Eckersten *et al.* (1985) predicted that large areas of land would be converted to willow for energy production in the future.

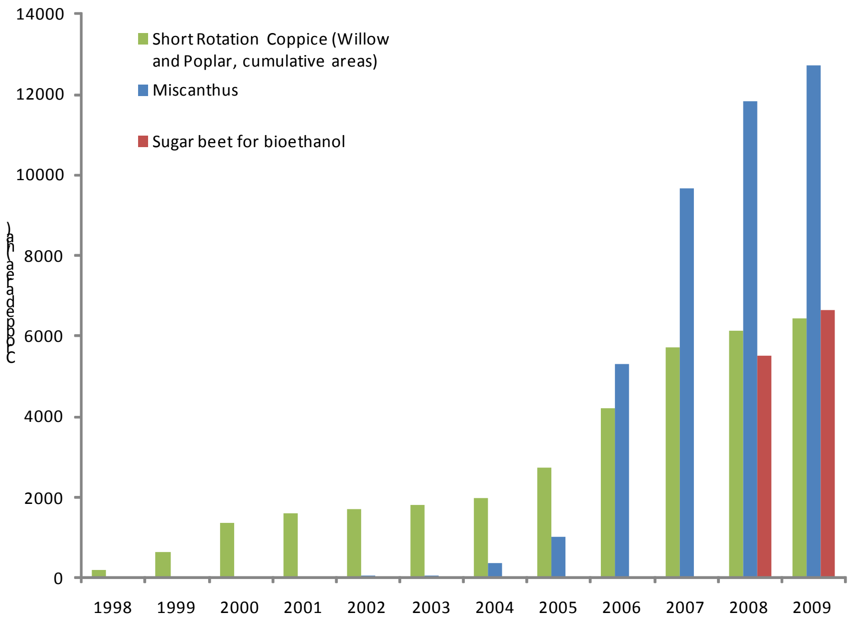

Figure 5.7 Reported UK cropped area (ha) for short rotation coppice (SRC), miscanthus and sugar beet grown for bioethanol production between 1998 to 2009
(Source: Defra, 2009).

There are also a few other crops that could be used for energy production although this is not generally its primary target: these include, for example, the Jerusalem artichoke (*Helianthus tuberosus)*, Crambe (*Crambe abyssinica)*, Ethiopian mustard (*Brassica carinata)*, Gold of Pleasure (*Camelia sativa*), maize (*Zea mays*), and soya bean (*Glycine max*). Traditional crops such as wheat (*Triticum aestivum)* and sugar beet (*Beta vulgaris)* are also increasingly being grown for biofuel purposes.

5.9.5 New ‘pharmaceutical and industrial’ crops

The following crops have been identified as being potentially valuable for their future pharmaceutical and industrial use.

Bog-myrtle (*Myrica gale*) is used by the brewing industry to add flavour to beer, but has other uses in the pharmaceutical and cosmetics industries. It requires peaty wetlands and warm temperatures and is therefore most suitable for Scotland.

Borage (*Borago officinalis)* is grown as a source of gamma linolenic acid, which is used in the health and nutritional supplements sector. It has been grown as a very minor crop in the UK, but the market for its produce is expected to increase. It would be most suitable in the southern region of UK.

Caper spurge (*Euphorbia lathyris)* seeds are rich in oil and have a high content in oleic, palmitic, linoleic, and linolenic acids, as well as a toxic diterpene, which makes it unsuitable for human consumption. However it can be used as feedstock for bio-lubricants, plastics, paints, soaps, detergents, and cosmetics. Recent research has shown that this crop has potential for biodiesel production (Wang *et al.* 2010). It would be suitable for cultivation under most UK climatic conditions.

Crambe (*Crambe abyssinica)* has a high potential to become a competitor to non-food oilseed rape due to its high content of erucic acid. Research is underway to genetically modify this crop (e.g. Li *et al.*, 2010). Contrary to other oilseed crops, crambe is a crucifer and therefore the risk of an outcross does not exist. This means there is no risk of contaminating other edible oilseeds. Due to its oil composition it is suitable to be used as a biofuel and to become the raw material of long chain wax and polymers. It requires temperature from 15-25 ^{o}C which would make the South, East, South West and heart of England the most suitable regions for its cultivation.

Hemp (*Cannabis sativa*) has plenty of applications as demonstrated by Hemp Technology Limited (http://www.hemcore.co.uk/). Traditionally used as a source of fibre, many other products can be manufactured from this crop, including industrial textiles and other construction and insulation materials, animal bedding, energy, and edible oil. However, the cultivated area in the UK has declined since 2003 (Figure 5.8). The most suitable areas for cultivation are in the South, East, South West and heart of England.

Fibre flax (*Linum usitatissimum*) was traditionally grown for fibre and oil production**.** With moderate rainfall requirements and being sensitive to frost, it is suitable for cultivation across most regions of the UK excluding Wales and Scotland. The current cropped area (ha) is unknown but in recent years it cultivation has been declining rapidly (Figure 5.8).

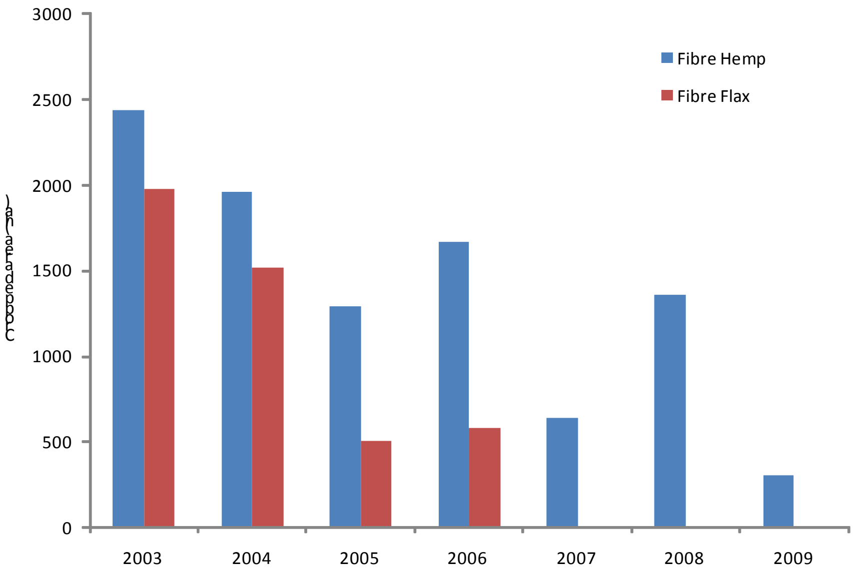

Figure 5.8 **Reported cropped area (ha) in the UK for fibre hemp and fibre flax from 2003 to 2009**
(Source: Defra, 2009).

Lunaria (*Lunaria annua*) oilseeds are rich in long-chain fatty acids and used in the pharmaceutical industry, cosmetics, nutritional supplement sector, as well as for industrial feedstock. Its characteristically high content in nervoric acid makes it useful as a gene source in some breeding programs (Guo *et al.*, 2009). It would be a suitable crop for most future climate conditions in England.

Madder (*Rubia tinctorun*) is grown for the red dye colour it produces and is used mainly in the food industry as a natural colorant for drinks and food preparation. It is most suitable for cultivation in the South, and South West of England, Wales and Northern Ireland.

Meadowfoam (*Limnanthes alba*) has a potential use as an oilseed crop with applications as an industrial feedstock and for the cosmetics and personal care sectors. It is frost tolerant and grows well in most soil types, even those with a low nutrient content. For cultivation, the most suitable areas are in the warmer regions of England.

Safflower (*Carthamus tinctorius*) is grown for its oil, which contains a large amount of linoleic acid (75% of oil). It has applications as an industrial feedstock, in the pharmaceutical industry and personal care sector. Safflower protein can be used as an ingredient in several food products ranging from salad dressing to meat products and ice creams. This crops seed ripening requires long and hot summers; therefore it would be most suitable for cultivation in the East, South and West of England.

St John's wort (*Hypericum perforatum*) is a perennial herb used to obtain dye for wool and silk, and for its range of applications to treat problems related to depression, sleep and anxiety. It would be suitable for most areas of the UK excluding Scotland.

Woad (*Isatis tinctoria*) grown as source of indigo (blue dye) used for textiles, it is also used in the pharmaceutical industry for its benefits for health. It has been grown in the some regions in the UK and could continue being farmed in the warmer areas of Southern, Eastern and Heart of England.

Hop (*Humulus lupulus*) is not strictly a new crop but as it has been grown for many years for the brewing industry, but it does have emerging uses in the health and pharmaceutical industry. However, the cropped area (ha) has dropped from 5000 ha in

1985 down to 1500 ha in 2005 (Defra, Annual reports 1985-2005), so production is now only a third of the former area, which could have a serious knock on the UK beer industry.

There are also a small number of other crops which have only pharmaceutical applications, and which could be cultivated in a future warmer climate.

Echium (*Echium plantagineum*) is principally grown for its fatty acids (omega-6, omega-3, gamma-linolenic acid), health food ingredient and for the nutritional supplements sector. This herbaceous annual crop requires sunny warm locations, and has some frost and drought tolerance. It is suitable for most regions of Eastern and Southern UK.

Evening primrose (*Oenothera biennis)* is an established oilseed crop used for as source of gamma linolenic acid (GLA). The cropped area has declined in the UK since borage is now grown as an alternative source of GLA. However, it would be suitable for cultivation in the East, South and heart of England.

Lavender (*Lavandula officinalis, L. Latifolia, L. x intermedia*) is a perennial shrub grown for its essential oils which are used in the pharmaceutical industry, for cosmetics and personal care products and sometimes for decorative purposes. For cultivation, it requires light soils and warm temperatures for growing, but it can tolerate cold conditions as well as drought. It could be grown in the warmer regions of England including the East, South and heart of England.

Poppy (*Papaver somniferum)* is an annual crop mainly used as pharmaceutical drug source, (e.g. morphine and codeine), but it can also be used in some food preparation. The crop is generally frost tolerant, and requires between 600 and 1200 mm of annual rainfall. The most suitable areas for poppy farming would be Northern Ireland and the South, Eastern and Heart of England.

Yew (*Taxus baccata*) is a coniferous crop grown for the pharmaceutical industry as it contains anti-cancer substances (taxol). Generally, yew is considered a hardy tree, and could be grown more extensively across the UK.

There is a small group of aromatic crops, which have medical, culinary, and cosmetic uses:

Rosemary (*Rosmarinus officinalis)* is an aromatic herb used in the pharmaceutical industry for its antioxidant properties, for the development of cosmetics and as culinary condiment. A significant cost in its production is its drying. Rosemary prefers light alkaline well drained soils, does not have large water requirements, and grows better in warmer climate although it is frost tolerant. This crop would be suitable for more widespread cultivation in the South, West and Eastern areas of England.

Thyme (*Thymus vulgaris*) is an aromatic herb which grows in a wide range of soils apart from wet heavy soils, and is considered to be a low input crop, adapted to any climate. It is suitable for cultivation in the warmer regions of southern UK (South, East, and Heart of England).

Yarrow (*Achillea millefolium)* is a perennial herbaceous crop grown for its leaves and flowers from which oil is extracted. It used in about 20 pharmaceutical products due to its effectiveness against disorders such as gastrointestinal, high blood pressure, and nervousness. It can also be used for ornamental or decorative purposes and in the development of cosmetics. It could be suitable for cultivation in most areas of the UK, as it can be grown a wide range of soils and temperature regimes, and is frost and drought tolerant.

There are traditional crops with new industrial applications such as Barley, Maize, and Potato as sources of bioethanol, starch, etc.

5.9.6 New ‘other’ crops

These include crops which have other uses not mentioned above, including for example, mistletoe, which is used for ornamental purposes. Mistletoe (*Viscum album*) is used for decorative purposes but also has properties which could be used for medical applications. It is very hardy in terms of temperature and drought conditions and could be grown across the UK.

5.10 Grassland productivity (AG10)

Metric number	Risk metric	Confidence	Summary Class								
			2020s			2050s			2080s		
			l	c	u	l	c	u	l	c	u
AG10	Grassland productivity	M	1	1	1	1	2	2	1	2	2

Since the submission of Release 1 of the Agriculture Sector Report, HR Wallingford agreed with Defra to complete some limited further work on livestock which included presenting a ‘risk metric’ on grassland production which is relevant to different livestock systems, and some expert high level interpretation of what this may mean for UK agriculture and livestock farmers. The approach taken was to review and update (through simple scaling and interpretation) existing Defra research completed with previous climate change projections.

An assessment of increases in grassland productivity is presented based on four experimental UK sites (West Wales, Central Devon, Gloucestershire and Cumbria). However, a regional projection of potential changes in grassland productivity is provided to indicate possible future changes (Table 5.12) throughout the UK. These results provide an indication of the sensitivity of different systems to warmer conditions and suggest a 15 percent increase in yield per degree of warming for conditions with adequate water and nitrogen.

This relationship can be used, within reason, to scale and estimate possible outcomes for UKCP09 projections. On this basis average grass yields in the UK are projected to increase by about 20% for the 2020s medium emission scenario, central estimate (range 11% to 31%) rising to 35% (range 18%to 53%) for the 2050s and 49% (range 24% to 54%) for the 2080s[24] (Table 5.13). Changes of this magnitude are likely in Scotland and Northern Ireland and increases in yield may exceed those of England and Wales as water stress is likely to be less limiting.

[24] The 2080s data should be treated with caution as, due to there being no modelled outputs from UKCIP98 data, the projections have been extrapolated based on temperature, CO_2 and precipitation, from the 2050 figures. All ranges provided for this metric are for the lowest to the highest projected results, which may not necessarily be the Low p10 to the High p90.

Table 5.12 Percentage change in grass-clover sward for UK countries

	2020s			2050s			2080s			Emission Scenario
Admin Region	p10	p50	p90	p10	p50	p90	p10	p50	p90	
Northern Ireland				17	28	41	22	36	52	Low
Scotland				16	29	43	22	36	53	
England				19	32	48	25	41	54	
Wales				19	32	47	24	41	54	
Northern Ireland	10	19	28	20	32	46	29	45	54	Medium
Scotland	10	19	29	19	32	47	27	44	54	
England	11	22	33	24	38	54	33	54	54	
Wales	11	20	31	22	36	54	32	51	54	
Northern Ireland				23	35	51	38	54	54	High
Scotland				21	35	52	34	52	54	
England				26	41	54	41	54	54	
Wales				25	40	54	41	54	54	

Table 5.13 Average UK increases in grass-clover yield (%)

	Low			Medium			High		
	p10	p50	p90	p10	p50	p90	p10	p50	p90
2020s				11	20	31			
2050s	18	31	47	22	35	51	25	39	53
2080s	24	40	54	31	49	54	40	54	54

Experimental evidence shows that grass production can increase in response to higher temperatures and CO_2 concentrations, both singly and especially in combination, as long as other factors affecting grass growth are not limiting. Projected increases in temperature and elevated levels of CO_2 are likely to lead to increased grass growth, but only under conditions where water and nutrient supply, particularly nitrogen availability, are non-limiting.

The principle risk metric for grassland-based livestock production is herbage dry matter (DM) yield. (The term herbage refers principally to grasses, of sown and unsown species, together with non-grass forage species of grassland, such as clovers and other legumes as well as any other non-grass species in the sward). There are some trade-offs between herbage DM yield and its feeding value for livestock, as increasing maturity increases the proportion of non-digestible material; however, for the present analysis total DM yield can be considered as the simplest metric that determines grassland productivity as a feed for livestock. Grassland yield is strongly influenced by temperature and soil moisture availability (which is partly determined by rainfall amount and distribution). These determine the number of grass-growing days (GGD) per year. The number of GGD is greatest in oceanic western areas on soils with good soil moisture conditions, and least in the upland areas and in areas with a more ‘continental’ climate (with low temperatures in spring plus dry periods in summer, as in eastern Britain).

Average ‘baseline’ values of DM yields from grassland exist for a range of sites and growing conditions. These are based on reliable results of field experiments from the 1970s-1990s, including research on commercial farms. Improvements in grassland productivity have been made in recent decades largely through better understanding of the rates and timing of fertilizer applications, improved plant genetics and better on-farm utilization, although agricultural productivity of UK grasslands is generally below its potential. This partly reflects the need to farm within environmental constraints. Many grassland areas, particularly in upland and marginal areas, and in situations such as lowland meadows and wetlands, are of high conservation value and contribute to ecosystem services, and are managed under agri-environmental management agreements (ELS/HLS etc). In many cases this multi-functional role also affects the productivity and method of utilization. These functions may also be affected by future climate change.

In the UK, grassland is the largest agricultural land-use category (7 m ha, plus a further 5 m ha of rough grazing). Grassland-based livestock farming predominates in western and northern areas of the UK, although it is also important in the mixed-farming areas of central and southern England, as well as on limited areas of eastern lowland Britain (e.g. wetlands and land in grass-arable rotations). Dairying (based on grazed grass plus grass silage and concentrate supplements) is mainly confined to lowland western areas where topography, soil and climate conditions are most suitable for sustaining and utilizing high yields of high quality forage production. Beef and sheep production is generally more reliant on grass (typically supplying >70% feed requirements). Beef cattle are widespread in their distribution, including farms on areas with relatively marginal conditions for forage production engaged in calf rearing by suckler cows, producing weaned calves for sale as store cattle for fattening on lowland farms. Sheep are also widely distributed; in hill and moorland areas they are often the main, or only, livestock, but elsewhere they may be integrated with other ruminant enterprises. Sheep and many beef cattle are kept outdoors for all or most of the year, or housed in the winter months when grazed forage is unavailable or weather conditions present animal welfare or pasture management problems.

Several key features of grassland production in the UK are pertinent to considerations of climate change on grass production and its utilization by livestock:

First*, grassland has greater management flexibility compared with the main arable crops* that have critical annual production cycles involving cultivation, sowing and harvesting dates. The start and end of grazing season, stock numbers per hectare, the relative areas mown or grazed, and even cutting dates for silage or hay can, to some extent, be changed in response to seasonal variability and inter-annual variations, in weather and growing conditions.

Secondly, *forage yields per hectare vary considerably between sites and between years*. In general, production is greatest in the areas that have the highest mean temperatures. Low temperatures in the spring reduce early season production and therefore the total annual production. In areas most suited to grass growth, such as lowland western Britain on soils with a good depth, structure and soil available water capacity, annual DM production of 15-20 t/ha is achievable under silage cutting, given adequate supplies of nitrogen and supporting nutrients. In contrast, upland pastures in northern Britain, where there is a short growing season due to low temperatures in spring and autumn, with leached and shallow soils on slopes, typically provide around 2-5 t/ha of forage mainly for grazing, sometimes of low feed value. Between these extremes lie a range of grassland production levels, but UK average forage yields under moderate total nitrogen inputs (100-150 kg N/ha/year) are typically 6-8 t DM/ha under grazing, and 8-10 t under management with less-frequent defoliation with cutting for silage and some subsequent grazing.

Thirdly, *grassland production follows an uneven seasonal distribution*. In lowland areas it peaks in late spring/ early summer necessitating cutting and conservation (mostly as silage) to meet feed demands in winter (or other times of feed deficit). As most grassland farms have a year-round feed requirement, the area available for silage and its potential production is a key determinant of farm output. Therefore, any climate-change implications for silage production from grassland require particular consideration to local and seasonal variations in grass growth.

Potential impact of climate change in term of impacts on herbage yield for a subset of sites, mainly in the context of beef and sheep production.

Further grassland analysis has been undertaken for the CCRA for four experimental sites in England and Wales. The influences of future climate change on the sustainability of grassland systems were investigated through a combination of modelling and experimentation in Defra Project CC0359 in which eight model areas were identified to represent a range of grassland environments and grassland-based livestock enterprises. Further consideration is here reported based mainly on a subset of four sites and the livestock systems appropriate for those sites.

1. Lowland west Wales (Carmarthen area). Representative of the most productive grassland in the UK, with a long grass-growing season and oceanic conditions.
2. Lowland south-west England (central Devon). Representative of a major UK livestock area, with a relatively long grass-growing season. The main livestock systems are beef and dairy cattle for milk production, often combined with sheep, particularly the finishing of store lambs.
3. South-central/western England (example area around Cirencester, Glos). Representative of a mixed-farming area in which grass and forage crops support a range of livestock enterprises including beef finishing, lamb production (both lamb rearing and lamb finishing), and to a lesser extent, dairying.
4. North-west England uplands (central Cumbria) Representative of a large area in northern England used for rearing of lambs and suckler-beef calves for sale mainly as store lambs and store cattle for finishing elsewhere. The growing season is short due to low temperatures.

Site 1. Lowland west Wales (modelled area Carmarthen/ Dyfed) is representative of some the most productive grassland in the UK, with a long grass-growing season and oceanic conditions. Historically, this is an important dairying area, with milk production often combined with beef finishing of dairy- or suckler-bred store cattle, and/or finishing of store lambs. Impacts of climate change are considered with reference to (i) a high fertilizer N improved ryegrass mainly for silage, and (ii) red clover ley mainly for silage.

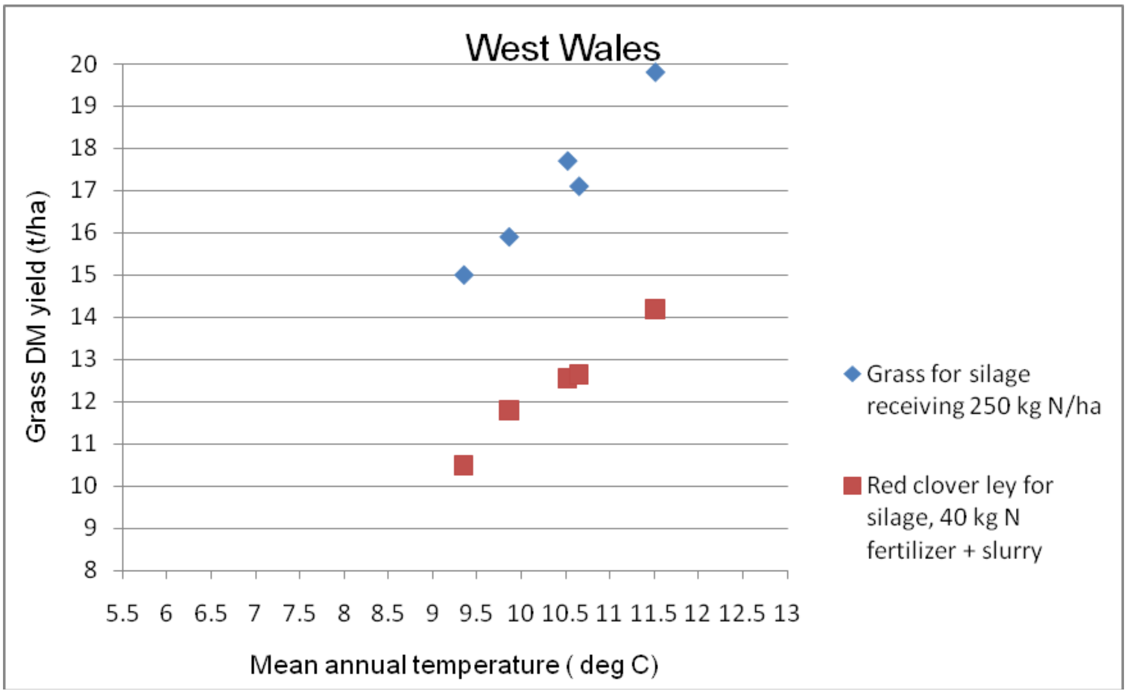

Figure 5.9 Response function for herbage yield metric based on observed and modelled projections, for high-N grass and low-input red clover swards under silage cutting, for west Wales

Intensive management of sown or improved ryegrass-based grassland, with high N inputs (250 kg N/ha) used mainly for silage, has a baseline herbage DM yield potential, as recorded experimentally during recent years, of ca. 15 t /ha. Modelled outcomes based on UKCIP98 estimate increased production by +32% to 19.8 t DM/ha (2050s High emission scenario). This is close to maximum ceiling yield. There is a theoretical potential for a small increase under 2080s scenarios, but more realistic is the potential to maintain high outputs with lower N inputs. An alternative system based on frequently resown red clover-based leys, receiving organic N inputs mainly as slurry N plus biologically fixed clover N, and low fertilizer inputs of 40 kg N/ha, have a lower baseline yield of 10.5 t/ha. Projected responses to climate changes under UKCIP98 show a greater percentage increase than for the high-N ryegrass, by +35% to 14.2 t DM/ha (2050s High emission scenario), and the advantages of red clover to warmer temperatures (deep rooting and N fixation) suggest than higher yields may be possible under the conditions representing the 2080s scenarios.

Table 5.14 Intensive management (250 kg N/ha) mainly for silage based on ryegrass ley / improved permanent pasture % change in harvested DM yield relative to baseline 1990s and yield in t/ha

Baseline yield	**15.0 t/ha**		
UKCIP98	**Low**	**Med-High**	**High**
2020s	+6% (15.9 t/ha)	+18% (17.7 t/ha)	+14% (17.1 t/ha)
2050s	+10% (16.5 t/ha)	+25% (18.75 t/ha)	+32% (19.8 t/ha)
2080s *	+14% (17.1 t/ha)	+32% (19.8 t/ha)	+32% (19.8 t/ha)

**No modelled outputs for 2080s with UKCIP98 data; values in cells extrapolated based on summer temperatures and CO_2, modified by summer precipitation.*

Table 5.15 Grassland herbage yield changes based on management for lowland beef/ dairy system with red clover-based ley, receiving organic N inputs mainly as slurry N plus biologically fixed clover N, and additional 40 kg fertilizer N/ha (and resown after 2 years)

Baseline yield	**10.5 t/ha**		
UKCIP98	**Low**	**Med-High**	**High**
2020s	+12.5% (11.8 t/ha)	+20% (12.6 t/ha)	+20% (12.6 t/ha)
2050s	+15% (12.1 t/ha)	+27% (13.3 t/ha)	+35% (14.2 t/ha)
2080s*	+20% (12.6 t/ha)	+40% (14.7 t/ha)	35% (14.2 t/ha)

**No modelled outputs for 2080s with UKCIP98 data; values in cells extrapolated based on summer temperatures and CO_2, modified by summer precipitation.*

Table 5.16 Projected changes in mean annual temperatures 2020s/ 2050s/ 2080s based on UKCIP98 GB10km scale

1961-90 Baseline mean temp	**9.35**		
UKCIP98	**Low**	**Med-High**	**High**
2020s	9.86	10.52	10.65
2050s	10.14	11.22	11.51
2080s	10.4	11.99	12.30

Site 2. Lowland south-west England (modelled area in central Devon north of Okehampton) is representative of one of the major UK livestock areas, and is characterized by a relatively long grass-growing season and a predominance of soils having good soil moisture retention. The main livestock systems are beef and dairy cattle for milk production, often combined with sheep, particularly the finishing of store lambs. Impacts of climate change are considered with reference to three systems (i) high fertilizer N on an improved ryegrass sward mainly for silage, (ii) a moderate input

system using grass-white clover swards mainly for grazing, and (iii) improved ryegrass system used for integrated cutting and grazing.

For system (i) a baseline yield of 10.0 t DM/ha under N inputs of 180 kg/ha was assumed, and management of 2 silage cuts plus grazing (lowland beef/ dairy) on a ryegrass ley / improved permanent pasture. Modelled outcomes based on UKCIP98 project increased production by +38% to 13.8 t DM/ha (2050s High emission scenario). An alternative outcome might be to maintain baseline production with reduced N inputs. For the moderate input system on a sward containing white clover (ii) a baseline yield of 9.3 t DM/ha is assumed and modelled outcomes based on UKCIP98 project increased production by +22% to 12.2 t DM/ha (2020s High emission scenario) and by +38% to 13.8 t/ha (2050s High emission scenario).

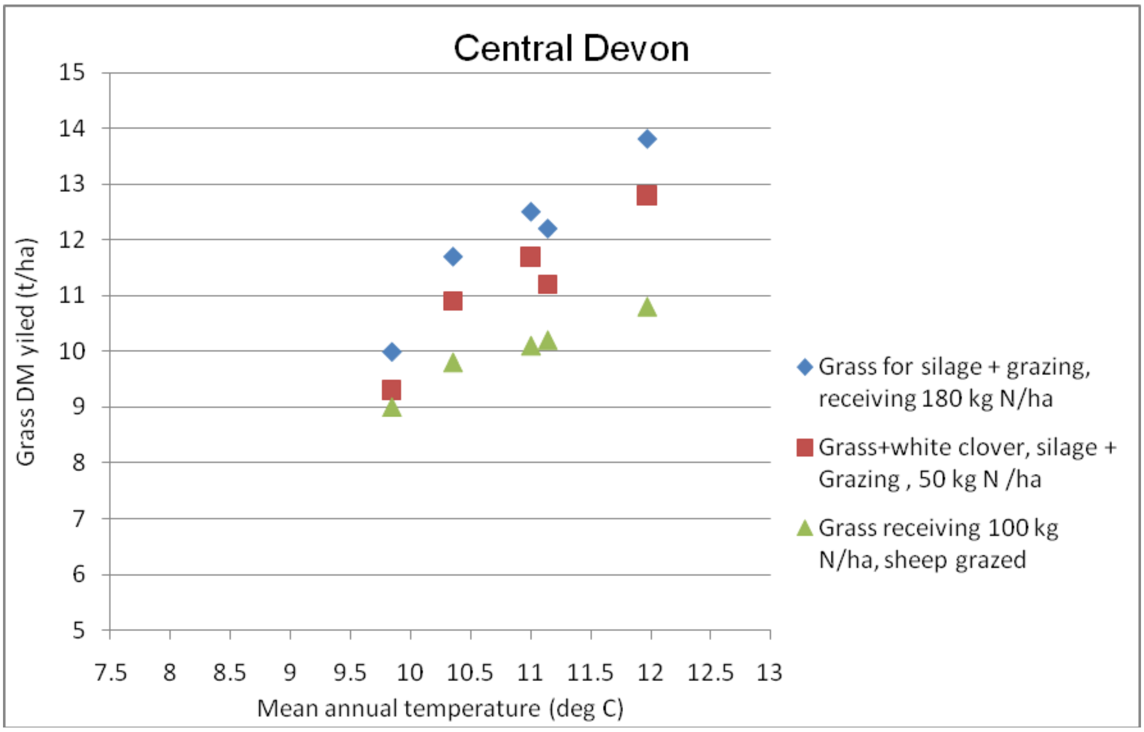

Figure 5.10 Response function for herbage yield metric based on observed and modelled projections for three grassland systems, site in central Devon

The third system, based on using 100 kg N/ha for grazing (e.g. finishing of store lambs) a baseline yield of 9.0 t DM/ha was assumed. Modelled outcomes based on UKCIP98 estimate increased production by +12% to 10.1 t DM/ha (2020s High emission scenario) and by +20% to 10.8 t/ha (2050s High emission scenario), with the theoretical potential for greater increases under 2080s scenarios (including increased spring production due to higher temperatures in the early part of the growing season).

Table 5.17 Grassland herbage yield changes based on grassland management for lowland beef/ dairy system with ryegrass ley / improved permanent pasture, receiving total N inputs of about 180 kg N/ha, with 2 silage cuts plus grazing

Baseline yield	**10.0 t/ha**		
UKCIP98	**Low**	**Med-High**	**High**
2020s	+17% (11.7 t/ha)	+25% (12.5 t/ha)	+22% (12.2 t/ha)
2050s	+20% (12.0 t/ha)	+30% (13.0 t/ha)	+38% (13.8 t/ha)
2080s*	+30% (13.0 t/ha)	+38% (13.8 t/ha)	+30% (13.0 t/ha)

**No modelled outputs for 2080s with UKCIP98 data; values in cells extrapolated based on summer temperatures and CO_2, modified by summer precipitation.*

Table 5.18 Grassland herbage yield changes based on management for lowland beef/ dairy system with sown grass sward containing white clover, receiving organic N inputs mainly as slurry N plus biologically fixed clover N, and additional 50 kg fertilizer N/ha, silage plus grazing

Baseline yield	**9.3 t/ha**		
UKCIP98	**Low**	**Med-High**	**High**
2020s	+17% (10.9 t/ha)	+26% (11.7 t/ha)	+21% (11.2 t/ha)
2050s	+26% (11.7 t/ha)	+32% (12.3 t/ha)	+38% (12.8 t/ha)
2080s*	+32% (12.3 t/ha)	+38% (12.8 t/ha)	*Uncertainty too high*

**No modelled outputs for 2080s with UKCIP98 data; values in cells extrapolated based on summer temperatures and CO_2, modified by summer precipitation.*

Table 5.19 Grassland herbage yield changes predominantly under grazing for a store lamb finishing system; 100 kg fertilizer N/ha

Baseline yield	**9.0 t/ha**		
UKCIP98	**Low**	**Med-High**	**High**
2020s	+9% (9.8 t/ha)	+12% (10.1 t/ha)	+12% (10.1 t/ha)
2050s	+12% (10.1 t/ha)	+15% (10.3 t/ha)	+20% (10.8 t/ha)
2080s*	+20% (10.8 t/ha)	+24% (11.2 t/ha)	+20% (10.8 t/ha)

**No modelled outputs for 2080s with UKCIP98 data; values in cells extrapolated based on summer temperatures and CO_2, modified by summer precipitation.*

Table 5.20 Projected changes in mean annual temperatures 2020s/ 2050s/ 2080s based on UKCIP98 GB10km scale

1961-90 Baseline mean temp	**9.84**		
UKCIP98	**Low**	**Med-High**	**High**
2020s	10.35	11.0	11.14
2050s	10.64	11.68	11.97
2080s	10.89	12.47	12.78

Site 3. South-central England /western England (modelled area around Cirencester, Glos) is representative of a mixed-farming area in which grass and forage crops support a range of livestock enterprises including beef finishing, lamb production (both lamb rearing and lamb finishing), and to a lesser extent, dairying. Soils that are often stony and have low moisture retention are widespread and the climate is less oceanic than sites 1 and 2. Impacts of climate change are considered with reference to (i) semi-improved permanent pasture receiving moderate fertilizer N and (ii) low-input sown ryegrass-white clover sward that receives no artificial N fertilizer.

For system (i) a baseline yield of 6.5 t DM/ha under N inputs of 100 kg/ha was assumed, (based on local experimental results) and management of one silage cut plus grazing (lowland beef/ store lamb finishing) on a ryegrass ley / improved permanent pasture. Modelled outcomes based on UKCIP98 estimate increased production by +9% to 7.1 t DM/ha (2020s High emission scenario) and by +17% to 7.6 t/ha (2050s High emission scenario). This low response to higher temperatures partly reflects the site conditions, notably limitations due to reduced summer rainfall combined with soil characteristics.

For system (ii) a similar baseline yield of 6.5 t DM/ha was assumed, (again based on evidence from grass-white clover on similar sites). Modelled outcomes based on UKCIP98 estimate increased production by +13.5% to 7.4 t DM/ha (2020s High emission scenario) and by +25% to 8.2 t/ha (2050s High emission scenario). This better response to higher temperatures reflects advantages of white clover including better root development and improved N fixation in spring due to warmer soil conditions.

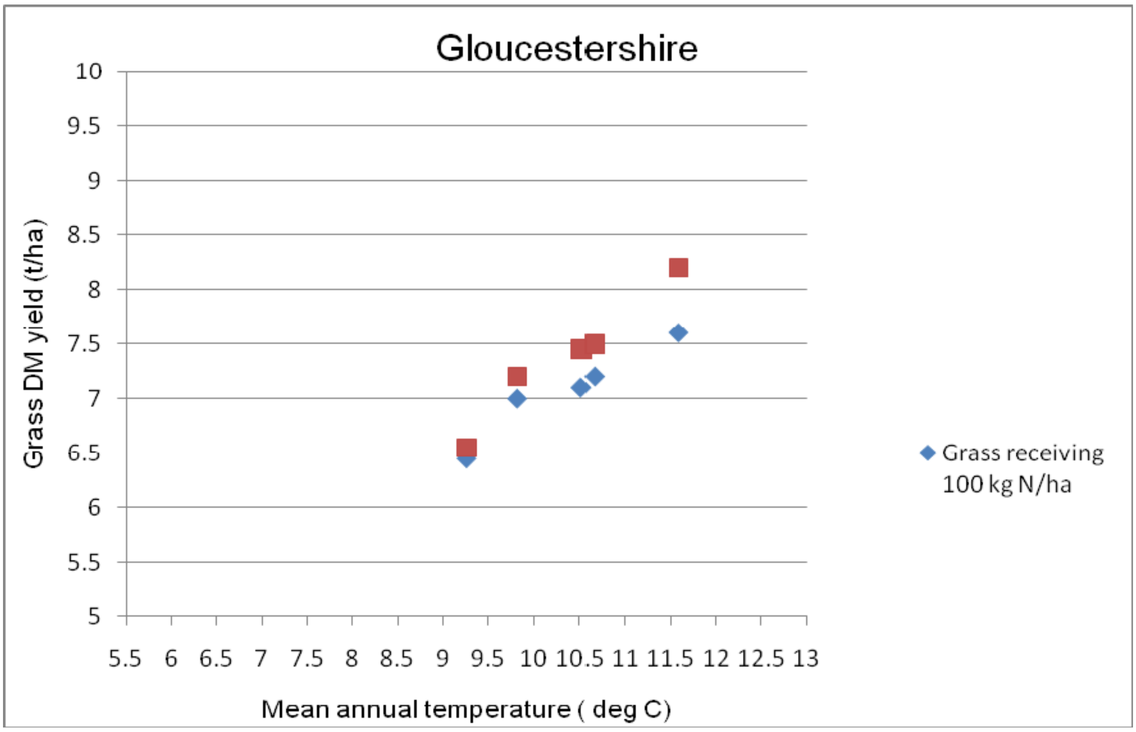

Figure 5.11 Response function for herbage yield metric based on observed and modelled projections N-fertilized grass and nil-N grass-white clover systems, site in Gloucestershire

Table 5.21 Grassland herbage yield changes for a ryegrass ley or improved permanent 1 silage cut plus grazing beef or store lamb finishing; 100 kg fertilizer N/ha

Baseline yield	**6.5 t/ha**		
UKCIP98	**Low**	**Med-High**	**High**
2020s	+7.5% (7.0 t/ha)	+9% (7.1 t/ha)	+9% (7.1 t/ha)
2050s	+9% (7.1 t/ha)	+12% (7.3 t/ha)	+17% (7.6 t/ha)
2080s*	+12% (7.3 t/ha)	+17% (7.6 t/ha)	+17% (7.6 t/ha)

**No modelled outputs for 2080s with UKCIP98 data; values in cells extrapolated based on summer temperatures and CO_2, modified by summer precipitation.*

Table 5.22 Grassland herbage yield changes based on management for lowland sheep/ beef systems with sown grass sward containing white clover, receiving organic N inputs mainly as returns under grazing plus biologically fixed clover N, with no additional fertilizer N

Baseline yield	**6.5 t/ha**		
UKCIP98	**Low**	**Med-High**	**High**
2020s	+10.5% (7.2 t/ha)	+13.5% (7.4 t/ha)	+13.5% (7.4 t/ha)
2050s	+13.5% (7.4 t/ha)	+18% (7.7 t/ha)	+25% (8.2 t/ha)
2080s*	+18% (7.7 t/ha)	+25% (8.2 t/ha)	*Uncertainty too high*

**No modelled outputs for 2080s with UKCIP98 data; values in cells extrapolated based on summer temperatures and CO_2, modified by summer precipitation.*

Table 5.23 Projected changes in mean annual temperatures 2020s/ 2050s/ 2080s based on UKCIP98 GB10km scale

1961-90 Baseline mean temp	**9.26**		
UKCIP98	**Low**	**Med-High**	**High**
2020s	9.82	10.52	10.67
2050s	10.11	11.27	11.59
2080s	10.39	12.10	12.43

Site 4. North-west uplands (central Cumbria; ca. 300 m elevation). The site is representative of a large area in northern England used for rearing of lambs and suckler-beef calves for sale mainly as store lambs and store cattle for finishing elsewhere. The growing season is short due to low temperatures, and there are few opportunities for crops other than grass. Climate change impacts are considered with reference to (i) semi-improved permanent pasture and (ii) a low-input grass-white clover sward.

For system (i) a baseline yield of 6.1 t DM/ha under N inputs of 100 kg/ha was assumed, (based on local experimental results) and management of mainly grazing for upland suckler beef on an improved permanent pasture. Modelled outcomes based on UKCIP98 estimate increased production by +8% to 6.6 t DM/ha (2020s High emission scenario) and by +14% to 7.0 t/ha (2050s High emission scenario). For system (ii) a similar baseline yield of 6.1 t DM/ha was assumed and modelled outcomes based on UKCIP98 estimate increased production by +21% to 7.4 t DM/ha (2020s High emission scenario) and by +32% to 8.1 t/ha (2050s High emission scenario). These responses though lower than in the better lowland sites are particularly important in the context of marginal upland farms where there are several limitations for grass production. Mean ‘baseline’ temperatures for the site during spring (March-May) are 5.4°C, which implies many days too cold for grass growth, but temperatures are projected to rise to 9.3°C under UKCIP98 2050 High emission projections. Although lower summer rainfall is projected under future climate change, reductions of about 5% in daily summer rainfall under 2050 High emissions scenario, compared with 1961-1990 baseline, are insufficient to impact on summer grass growth.

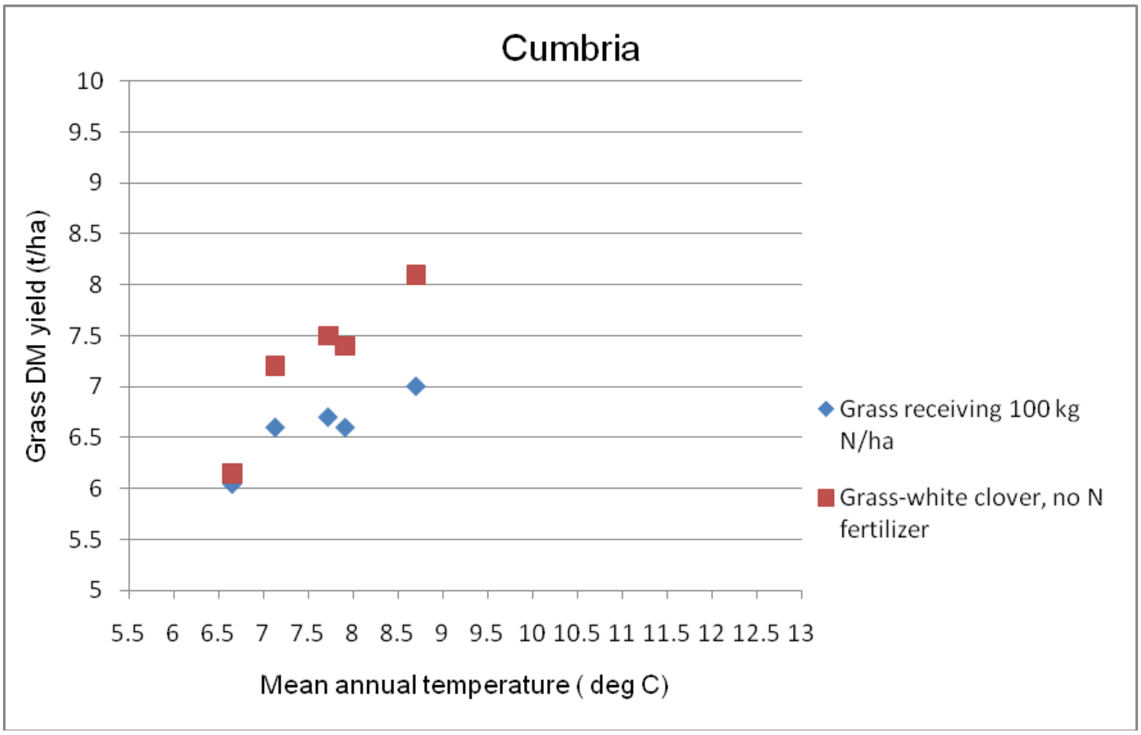

Figure 5.12 Response function for herbage yield metric based on observed and modelled projections N-fertilized grass and nil-N grass-white clover systems, upland site in Cumbria

Table 5.24 Grassland herbage yield changes based on grassland management for upland suckler beef system from improved permanent pasture receiving total N inputs of about 100 kg N/ha

Baseline yield	**6.1 t/ha**		
UKCIP98	**Low**	**Med-High**	**High**
2020s	+8% (6.6 t/ha)	+10% (6.7 t/ha)	+8% (6.6 t/ha)
2050s	+10% (6.7 t/ha)	+12% (6.8 t/ha)	+14% (7.0 t/ha)
2080s	+12% (6.8 t/ha)	+16% (7.1 t/ha)	+20% (7.3 t/ha)

**No modelled outputs for 2080s with UKCIP98 data; values in cells extrapolated based on summer temperatures and CO_2, modified by summer precipitation.*

Table 5.25 Grassland herbage yield changes based on grassland management for upland sheep (lamb rearing) system with sown grass sward containing white clover, receiving recycled organic N inputs and biologically fixed clover N, but no additional fertilizer N

Baseline yield	**6.1 t/ha**		
UKCIP98	**Low**	**Med-High**	**High**
2020s	+18% (7.2 t/ha)	+24% (7.5 t/ha)	+21% (7.4 t/ha)
2050s	+20% (7.3 t/ha)	+27% (7.75 t/ha)	+32% (8.1 t/ha)
2080s*	+25% (7.6 t/ha)	+32% (8.1 t/ha)	+36% (8.3 t/ha)

**No modelled outputs for 2080s with UKCIP98 data; values in cells extrapolated based on summer temperatures and CO_2, modified by summer precipitation.*

Table 5.26 Projected changes in mean annual temperatures 2020s/ 2050s/ 2080s based on UKCIP98 GB10km scale (°C)

1961-90 Baseline mean temp	**6.65**		
UKCIP98	**Low**	**Med-High**	**High**
2020s	7.13	7.72	7.91
2050s	7.41	8.42	8.7
2080s	7.63	9.16	9.45

5.10.1 Scaling of results from UKCIP98 projections to take account of revised projections based on UKCP09

The analyses described above are based mainly on modelled outcomes as described by Doyle and Topp (2004), further details of which were given in the reports to Defra on project CC0359. Baseline grass production values for selected sites are based on recent (1980s-1990s field experiments, mainly conducted by IGER). Temperature and rainfall data for the UKCIP98 scenarios are taken from the GB10KM scales for each scenario considered. Modelled outcomes were not provided for the 2080s in project CC0359.

The effects of climate change on grassland production for the four sites representative of some important grassland areas of England and Wales described here are generally positive: i.e. increased temperatures in spring and autumn plus increased CO_2 concentrations are beneficial for grass growth. However, under the conditions described for the most extreme UKCP09 projections, notably for the 2050s High, and the 2080s Medium and High scenarios, consideration needs to be given to negative impacts and whether, and in what situations, future climate changes might have a negative net impact on grass yield.

South-west England: Under UKCP09 2050 high and 2080s Medium and High emission scenarios with 50% probability, mean summer temperatures are projected to increase by 3-5 °C in the eastern parts of the region, though by less than this in most of Devon and Cornwall. Combined with reduced summer rainfall by between 20 and 40% of ‘baseline’ amounts, this would inevitably lead to greatly reduced soil moisture and reduced grass growth during summer. Effects would be greatest on soils with low soil moisture retention (over chalk, limestone, sandstone; stony soils and shallow soils). There is evidence from field experiments of reduced grass growth in dry summers. Some farm management adaptations can help overcome short-term reduction or cessation of grass growth in summer, especially if increased grass growth in spring or autumn has enabled additional surplus forage to be conserved. Although growth in the autumn following a dry summer may compensate, this could be lost if increased rainfall in autumn meant that ground conditions prevented harvesting of grass by machinery or grazing.

West Wales: Under UKCP09 2050s High and 2080s Medium and High emission scenarios with 50% probability, mean summer temperatures are projected to increase by 2-4 °C, with reduced summer rainfall by between 10 and 25% of ‘baseline’ amounts. These effects might be expected to lead to some short term reductions in grass growth, especially on sites with shallow soils, but the likelihood that any short-term loss would be offset by growth in spring and autumn.

North-west England uplands: Mean annual temperatures in the northern uplands are, at present, relatively low (baseline of 6.65°C) and the summer (June-Aug) value of 12.2 °C is at least 2 °C lower than that for west Wales and central Devon. Under UKCP09 2050s High and 2080s Medium and High emission scenarios with 50% probability, mean summer temperatures are projected to increase by 3-4 °C (from

12.1 °C to about 15 °C), with reduced summer rainfall of between 10 and 25% of the 'baseline' value (320mm). However, these effects would not be expected to lead to net negative impacts; earlier spring growth would compensate for reduced summer growth, but locally there could be reduced grazing availability especially on shallow soils on slopes.

Other areas of England: It has been noted that grassland is widely distributed in the UK, including in areas of central, eastern and southern England where arable and mixed-farming predominates. In the South-east of England, under UKCP09 2050s High and 2080s Medium and High emission scenarios at 50% probability, mean summer temperatures are projected to increase by 3-5 °C (with an uncertainty range of 1.4 to 8.1 °C). This, combined with reduced summer rainfall by between 20 and 30% of 'baseline' amounts, would increase evapotranspiration, and thus greatly reduce summer grassland production to unsustainable levels. However, even under such extreme scenarios there are farm-level adaptations including the use of lucerne and other legumes which develop deep rooting systems; greater use of forage maize and early cut whole-crop silage; summer feeding of silage or grazing of designated fodder banks sown with drought resistant species.

Modelled responses of grass productivity in Ireland show increases of production in response to climate change impacts, including CO_2 fertilization, show a maximum average increase of 34% by the 2080s, indicating a lesser impact than suggested by CCRA analysis. Seasonality of grassland productivity indicates an early start for grazing with a seasonal peak occurring in early-April. Modelled results show low productivity mid-summer due to the effect of water deficits indicating a potential need to house cows indoors to allow the grass to recover for late-season grazing (Fitzgerald, 2008). Therefore there is evidence to suggest that, for dairy grazing throughout Ireland, and therefore potentially the UK, climate change may increase production, but increased seasonality will result in low productivity mid summer.

5.10.2 Qualitative consideration of socio-economic change

Farm-scale adaptations with the potential to reduce the risks of climate change are listed below:

- Improved water management (e.g. use of boreholes or on-farm storage of excess winter rain from roof run-offs) to enable a supply irrigation water for dry spells.
- Improvements in soil structure to reduce effects of summer drought and to improve percolation and reduced run-off during intense rain, thereby minimizing some of the adverse impacts of climate change.
- Changes in grassland species composition, e.g. with deep-rooting or drought-tolerant species, and greater use of clovers and other N-fixing legumes that respond well to greater springtime temperatures.
- Changes in on-farm allocation of grassland resources in response to changes in seasonal demands for forage, e.g. with deferred grazing to cover dry periods, use of fodder banks (stockpiling) of dedicated grazing blocks with sown species adapted to seasonal drought, and changes in the proportions of grazed and mown (conserved) forage.
- Replacement of grass swards with alternative forages, e.g. greater use of maize (for silage or cutting for 'zero grazing'), and of forage brassica crops such as stubble turnip to extend the grazing season into the winter.

- Changes in livestock breeds and production cycles (e.g. autumn lambing and calving to enable greater use of grazed grass in spring).
- Greater use of tree planting and shelter belts can provide shade and windbreaks.

Other socioeconomic effects

Globally it is anticipated that livestock supplementary feeds are likely to be in short supply (due to combination of increased demand and reduced unreliable production in some parts of the world). UK ruminant livestock thus needs to adapt to production based predominantly on home-produced forages with legumes supplying more of the protein requirement of livestock diets.

The dietary preferences of UK consumers may also change in future, partly in direct response to a changing climate but also in response to societal factors, including changing dietary preferences towards healthy eating via for example, the Food Standards Agency 'Eatwell Plate' campaign and increasing demand for year-round fresh supplies favouring food imports – both impacting on demand for meat and livestock products.

Incentives for grassland farmers to produce grass and other crops for biofuels could result in a reduction in UK ruminant livestock numbers. There is scope for integrated use for forage and biomass, e.g. double-cut lucerne with a large first cut of low feeding value harvested for biomass, followed by cuts later in the season to provide high feed value forage.

Plant breeding: further production potential of grass and legume varieties is possible, and considerable opportunities exist for improvement in forage quality, including polyunsaturated fatty acids that can translate into high value end products, as well as in feed digestibility and protein quality. The application of new technological approaches provides the means to improve varieties for a range of nutritional and other targets such as rumen efficiency, lipid composition and drought tolerance. There may be an increased role for many of the lesser used grassland species for particular environments.

There is considerable scope for agri-environmental payments (e.g. through Pillar 2) to be adapted to reward farming systems that incorporate measures to reduce net GHG emissions and/or that lead to climate change mitigation (e.g. soil C sequestration; improved management to reduce N_2O and CH_4 emissions).

Net risks after anticipated adaptations

Capacity for ruminant livestock based on grass and forage diets is potentially greater than in the cropping and horticulture sectors because of flexibility in the production system (dates of harvesting of forages less critical than crops; also capacity for carrying over stocks of hay/ silage between seasons). Thus, although anticipated adaptations can reduce net risks (and there is evidence that this has already occurred through extended grazing seasons) an increased incidence of extreme events can only be partly addressed through adaptations.

5.10.3 Interpretation of the outputs and consideration of some key issues

There is the potential for the effects of future climate change and higher atmospheric CO_2 to lead to generally favourable outcomes for grassland-based livestock production. However, there are some exceptions; at some sites, and under some of the more extreme probabilities of summer rainfall reduction and summer temperature increases, benefits for grass growth due to warmer temperatures and enhanced CO_2 could be more than offset by the effects of summer drought.

In the lowland areas of western Britain, where grass growing conditions are favourable due to the effects of oceanic climatic and adequate soil moisture conditions, increased annual herbage DM yield, of up to 20-30%, are considered as a possible effect of higher temperatures and CO_2. This assessment is based on production (relative to baseline values that were typically recorded in the 1980s-1990s) for the 2050s high emission scenario (at the 50% probability). Alternatively, the outcome may be one in which existing production is maintained while reducing fertilizer N inputs. Increased production may be exploited through extending the grazing season into early spring or late autumn; however, more frequent intense rainfall events may affect ease of utilization under grazing. On grassland that has good machinery access any additional grass production may be best utilized by making additional silage, including provisions for carry over of feed between production years and for feeding during other periods of feed deficit. The effects of the more extreme probabilities, especially as projected under the 2080s High emissions scenarios, are considered likely to present grassland producers, even in the most favourable grass-growing areas, with some management problems. For example, in response to summer rainfall reductions of 30-50% combined with greatly increased evapotranspiration from mean summer temperature increases of >5°C, grass growth might temporarily cease, thus requiring new approaches to feed budgeting.

In the drier, relatively 'continental climate' areas of lowland Britain, particularly on soils with low soil moisture retention, the likely outcomes for grassland production are less favourable. Warmer temperatures would be beneficial to grass growth in spring and early summer, and also in autumn. The negative effects of summer drought and high temperatures, especially on shallow and free-draining soils, are likely to be greater than in much of western Britain. There are opportunities to manage for this, particularly through using better adapted species and varieties, most notably lucerne and red clover for silage crops. The opportunities to extend the grazing season also, theoretically, enable reduced demand for silage for winter feeding, thus enabling some of the silage made in late spring / early summer to be used to maintain grass-based feed during summer droughts. However, under the most extreme conditions as presented under the 2080s High emissions scenarios, the effects of summer rainfall reductions of 30-50% plus >5 °C summer increases would likely lead to prolonged periods of feed deficit.

In the uplands, where at present there are few opportunities for agriculture other than grass-based cattle and sheep farming, the effects of higher temperatures and CO_2 are anticipated to lead to a net improvement in forage production on most sites. At present, temperatures in spring and autumn limit the grass production potential, even in situations where management options exist to raise it (as through improvement in soil nutrient supply or sward improvement through reseeding). Increased forage DM production of 10-25% of recent baseline production values is an estimate consistent with the temperature, rainfall and CO_2 changes for the 2050s High emission scenarios (at the 50% probability). Areas in the uplands that are suitable for mowing for crops of silage or hay are likely to benefit the most from warmer and drier conditions, due to earlier spring growth and better weather conditions in summer for wilting and harvesting. Secondly, the benefits of warmer temperatures for grassland containing legumes, especially white clover, are particularly appropriate in the low-input systems associated with upland beef and sheep production. As most upland areas currently experience relatively high precipitation, reductions of 20-30% in summer rainfall would have less impact on grass growth than would be the case in the drier lowlands. However, there are many upland pastures on shallow soils overlying igneous and metamorphic rocks and have limited soil moisture retention: such pastures, especially when on south-facing slopes, are already prone to droughtiness and this might become a serious issue, especially under the more extreme probabilities of the 2080s scenarios. One limiting factor for some locations may be the topography. In many areas it may be difficult to convert upland areas to arable land due to hill slopes and possible field sizes, however, this would be unlikely to prevent a shift to grazing on upland areas.

5.10.4 Resilience of grassland systems to climate change, particularly to the impacts of drier conditions

The above analysis suggests that the grassland sector in many areas of the UK has a high degree of resilience to the impacts of future climate change. This arises partly from some inherent flexibility in the annual production and utilization cycles, which apply particularly for sheep and beef production; for example, by changing the times of calving and lambing to better match feed availability, using livestock breeds more suited to changes in climate. Increased opportunities for early season silage making, and of extended grazing seasons, and the use of forage legumes including white clover in pastures and red clover and lucerne in silage crops, are examples of grassland systems that are likely to be most resilient to the effects of climate change consistent with the medium emissions (50% probability) scenarios. Systems that are likely to show least resilience are those exposed to summer droughts. These include lowland grasslands in drier areas on soils with low soil moisture, and some upland sites on thin soils, as well as any systems that are based on frequent reseeding, as newly-sown swards are most vulnerable to the effects of drought or intense rainfall during their establishment phase. In addition there are a number of uncertainties including the direct effects on livestock of higher temperatures and more frequent extreme weather events, water supplies for livestock, and problems of utilization under grazing caused by increased winter rainfall.

Soil nutrient supplies are key determinants of grassland production. One consequence of reduced grass growth during dry summer conditions is the accumulation of soil N reserves (from soil N mineralization and from legume N fixation, as well as from urine patches under grazing). Intense rainfall in late summer does have the potential to lead to N leaching, especially during autumn, the importance of which will vary with soil texture and structure, and there are some management options to limit this. Intense rainfall events also have the potential to lead to increased losses of phosphorus from grassland soils through surface run off.

5.10.5 The implications for Wales, Northern Ireland and Scotland

The above analysis has been based largely on the modelled outcomes for lowland and upland sites in England, and in lowland Wales, and their wider extrapolation. The proportion of agricultural land that is grassland or enclosed rough grazing is higher in Wales (at 95%) and Northern Ireland (>80%) than the UK average, while Scotland has a particularly high proportion of rough grazing land. The implications noted for upland sheep and beef systems apply similarly for all parts of the UK, although the changes in rainfall and temperature for Scotland and Northern Ireland under UKCP09 are less than the equivalent scenarios for southern Britain. These 'devolved regions' of the UK are particularly important in terms of the high proportions of UK sheep and beef cattle that they support, a situation likely to continue as there are only limited opportunities for land-use change, especially on upland and sloping sites.

5.11 Soil erosion (AG11)

Metric number	Risk metric	Confidence	Summary Class								
			2020s			2050s			2080s		
			l	c	u	l	c	u	l	c	u
AG11	Soil erosivity	L	1	2	2	1	2	3	1	3	3

Soil erosivity is related to kinetic energy of rainfall which in turn is related to the duration and intensity of rainfall (figure 5.13). The results show increases in soil erosivity throughout the UK. However this parameter must be considered alongside other factors such as soil type and vulnerability before an assessment of soil erosion can be made.

The results show the following projected increases in soil erosivity for the medium emissions climate change scenario by the 2080s:

- Between 8% and 23% for p10 (with the exception of south east and eastern basins in England, where a value of -18% is projected).
- Between 50% and 60% for p50 (with the exception of south east and eastern basins in England, where a value of 3% is projected).
- Between 36% and 71% for p90.

Soils are an important and irreplaceable resource that provide a range of functions or 'ecosystem services' that are essential for growing food, supporting biodiversity and providing an essential part of carbon and nutrient cycles (Defra, 2009).

Soils may be eroded by wind or heavy precipitation and, in the context of a changing climate, increased rainfall intensities are a potential threat that may increase erosion rates. Previous reviews have also raised concerns related to increases in summer drought, which may damage soil structure and subsequently influence erosion (CCIRG, 1996). The interaction of many climate, soil, hydrological, landscape and land use factors have the potential to cause greater rates of soil erosion and long term soil degradation. Current erosion rates are low, compared to other parts of the world, but there are problems in parts of the UK related to specific uses of land, e.g. high grazing densities of livestock or deer in Scotland (Lilly *et al*, 2009) or arable and horticultural production on steep slopes or on highly erodible soils on the east and south-east of England (Simmons and Rickson, pers. comm.).

The concept of 'rainfall erosivity' describes the energy in rain drops and its potential for soil erosion. It is highly correlated with rainfall intensity and any increase in intensity or the number of intense storms per year is likely to increase erosion rates. Severe erosion episodes may cause significant damage to soils, agricultural production and water quality, potentially contribute to loss of carbon and increase sediment loads in rivers that may affect river ecology and sedimentation of water intakes and reservoirs. Some of these consequences are discussed further in Chapter 4 on the natural environment and biodiversity. This section summarises the potential biophysical impact of changes in rainfall erosivity and potential erosion rates.

Evidence on current rates of erosion come from field scale studies, monitoring of suspended sediment in rivers and detailed modelling studies. Recent research in Northern Ireland and Scotland has modelled soil loss due to grazing and climate change (figure 5.14). This is particularly important in these countries as their peaty soils account for approximately 50 percent of the UK's soil carbon (Lilly *et al*., 2010).

Rainfall erosivity

The kinetic energy of the raindrop is the parameter most correlated to soil erosion rates. Morgan (1979) stated that the most suitable expression of the erosivity of rainfall is an index based on the kinetic energy of the rain, and the erosivity of a storm is a function of the rainfall intensity and duration. The following equation (Hudson, 1965) for the calculation of KE from hourly rainfall intensity has been taken from Soil Erosion and Conservation (Morgan 1979):

$$KE\ (J\ m^{-2}\ mm^{-1}) = 29.8 - (127.5 / I)$$

Where I is the rainfall intensity (mm hr^{-1})

This equation reaches a limit of KE of around 28 J m^{-2} mm^{-1}.

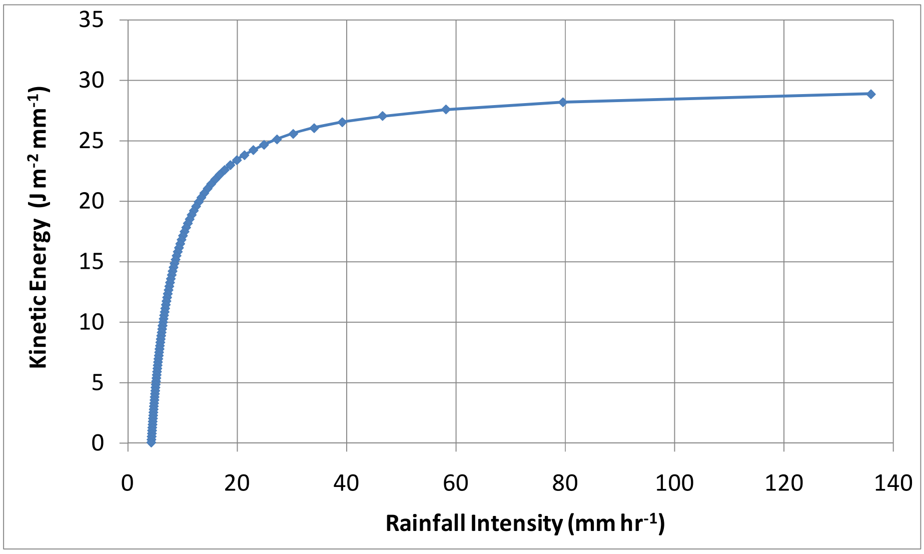

Figure 5.13 The relationship between kinetic energy and rainfall intensity (response function)
Adapted from Morgan, 1979

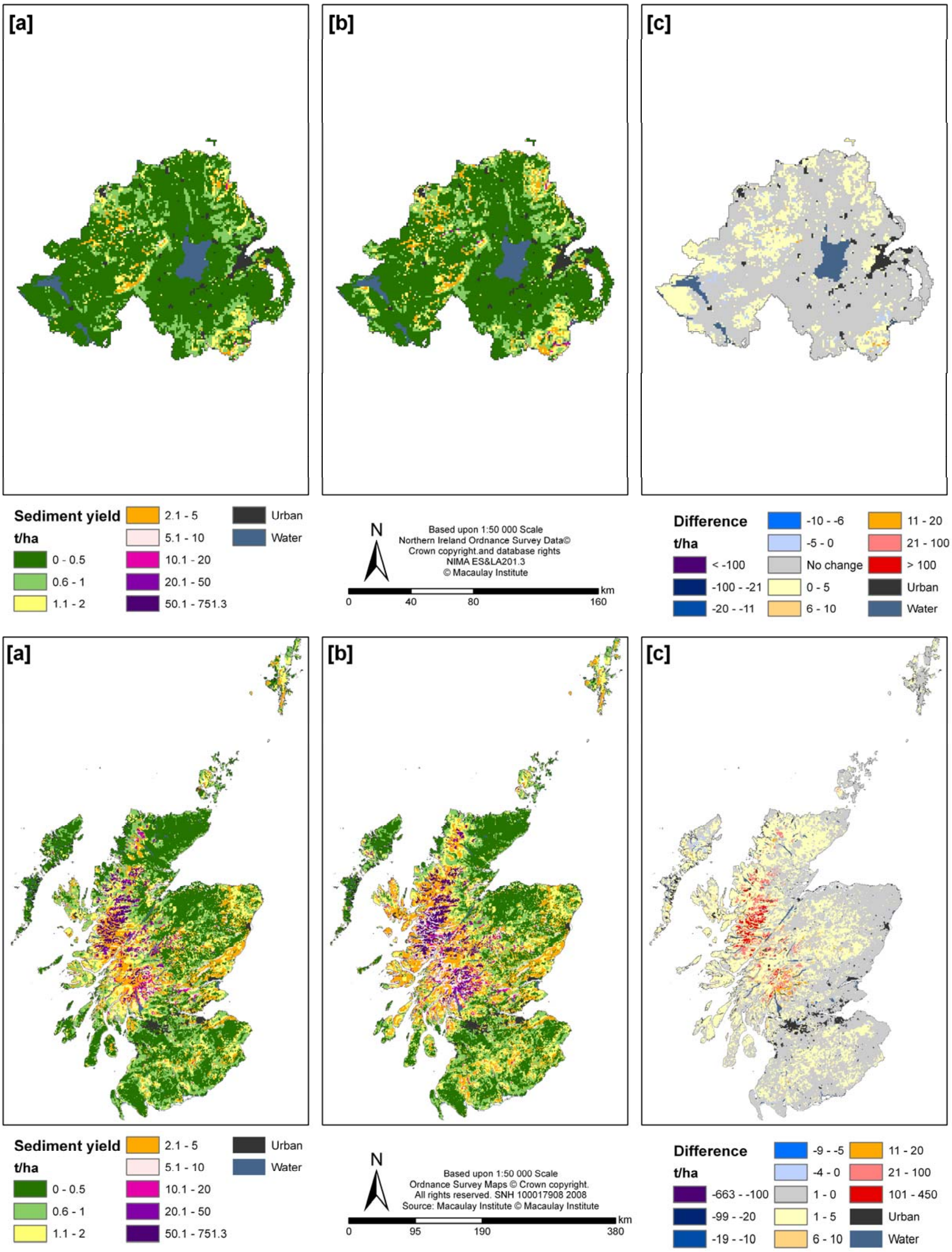

Figure 5.14 Modelled estimated of annual sediment yields in Northern Ireland and Scotland for different levels of dwarf shrub cover (a. 100% cover, b. 80% reduction in cover, c. difference attributable to heavy grazing

Source: Lilly *et al*., 2009

Rainfall erosivity calculation under future climate change scenarios

For the UK, changes in rainfall intensity can be estimated using data from Regional Climate Models, the UKCP09 Weather Generator or UKCP09 sampled data on 'rainfall depths' on the wettest day of the year. Some illustrative calculations are summarised below. Further research outputs for England and Wales are expected in 2011 (Defra, pers. comm).

Calculations for four sites across the UK, using the UKCP09 Weather Generator and medium emissions scenario for the 2080s, indicate that it is likely that rainfall erosivity would only increase in areas that receive greater annual precipitation at intensities above 10 mm hr^{-1}:

- In the East of England rainfall erosivity may decrease or increase; the mid estimate (p50) is just a 3% increase[25] (range -18% to 36% for p10 to p90)
- In Scotland rainfall erosivity may increase by 56% (23% to 58% for p10 to p90)
- In Wales rainfall erosivity may increase by 55% (21% to 69% for p10 to p90)
- In Northern Ireland rainfall erosivity may increase by 49% (8% to 71% for p10 to p90).

Increases in annual average rainfall erosivity are related to the number of days with heavy rainfall and the rainfall intensity on these days. As the site calculations demonstrated that erosivity increases (almost at unity) with rainfall intensity, the latter can be used to scale the results using the UKCP09 sampled data. The UKCP09 variable *"winter precipitation on the wettest day of the winter season*" was used to provide a first order and broad scale estimate of changes in erosivity at the scale of UKCP09 river basins. These figures cover a similar range to the site figures with the greatest increases in the north and west including south west England and the north of England as well as Wales, Northern Ireland and Scotland. Overall we have very low confidence in these figures as an indicator of actual erosion as this depends on other characteristics but if the figures in Table 5.28 are considered alongside soil maps that indicate vulnerability to erosion, this provides an indication of areas at risk.

[25] This is likely to be within the range of natural variability

Table 5.28 Increase in rainfall erosivity for selected locations in England, Wales, Northern Ireland and Scotland for the 2080s medium emissions scenario based on Weather Generator analyses

		Annual precipitation (mm) above 10 mm/hr			Kinetic Energy ($J\ m^{-2}\ mm^{-1}$)		
Location	**Probability level (from 100 WG runs)**	**Control (61-90)**	**Future Scenario**	**Factor**	**Control (61-90)**	**Future Scenario**	**Factor**
Peterborough	10	147	119	0.8	228	186	0.8
	50	253	265	1.1	396	409	1.0
	90	369	533	1.5	587	799	1.4
Inverlochy, Scotland	10	297	373	1.3	477	587	1.2
	50	405	627	1.6	645	1006	1.6
	90	561	905	1.6	907	1430	1.6
Kilcoo, Northern Ireland	10	238	381	1.1	257	410	1.1
	50	347	548	1.5	512	818	1.5
	90	473	753	1.8	828	1285	1.7
Abergavenny, Wales	10	224	353	1.2	265	427	1.2
	50	312	496	1.5	477	766	1.6
	90	471	738	1.7	797	1249	1.7

Key;

High Low

Table 5.29 Estimates of changes in rainfall erosivity (%) for UKCP09 river basins and the 2080s medium emissions scenario

* Note south and eastern basins have been estimated using the Peterborough sites results and UKCP09 sampled data.

	2080s Medium Emissions (probability levels associated with changes in precipitation on the "wettest day of the winter season")		
River Basin	p10	p50	p90
Anglian*	-18	3	36
Argyll	23	56	58
Clyde	23	56	58
Dee	21	55	69
Forth	23	56	58
Humber*	-18	3	36
Neagh Bann	23	56	58
North East Ireland	8	49	71
North East Scotland	23	56	58
North Highland	23	56	58
North West England	23	56	58
North West Ireland	8	49	71
Northumbria	23	56	58
Orkney and Shetland	23	56	58
Severn	23	56	58
Solway	23	56	58
South East England*	-18	3	36
South West England	21	55	69
Tay	23	56	58
Thames*	-18	3	36
Tweed	23	56	58
West Highland	23	56	58
Western Wales	21	55	69

Key.

-20% - -1%	(light blue)
0% – 19%	(pale orange)
20% – 39%	(light orange)
40% – 59%	(orange)
60% – 79%	(brown)

The key findings for each metric are summarised in Table 5.30 overleaf.

Table 5.30 Summary findings for each metric (Includes qualitative assessment of the strength of evidence to support the key findings)

Metric	Qualitative assessment of evidence	Metric description	Key findings
AG1a	Weak	Crop yield using sugar beet as reference 'arable' crop	Higher mean growing season temperatures could benefit yields but technological developments in the sugar beet industry are more significant; yields have already outstripped the gains expected due to climate change. In future water availability may become a limiting factor.
AG1b	Credible	Crop yield using wheat as reference 'arable' crop	There is an opportunity for greater wheat yields resulting from increases in mean growing season temperature, assuming other factors do not become limiting. Yields may increase even further with improvements in wheat varieties and some gains due to higher CO_2 concentrations. The CCRA results are robust (in comparison to the broader research literature). The results indicate opportunities for the UK if it retains or improves its relative competitiveness in Europe.
AG1c	Credible	Crop yield using potato as reference 'field vegetable' crop	The CCRA analysis indicates a risk of a downward pressure on potato yields due to lower summer rainfall but biophysical modelling indicates yield gains due to higher CO_2 concentrations. Considering all the available evidence, it is possible that yields would be maintained or improved in future; there would be an increase the requirements for water abstraction for irrigation and potential northwards movement in production if more water is available in these regions.
AG2a	Strong	Flood risk to classified 'arable' land	There is a risk of increased flooding of all grades of agricultural land from the river and the sea. For higher quality land saltwater flooding could make its use untenable in the longer term. The CCRA analysis is based on detailed modelling for England and Wales with updated estimates of sea level rise from UKCP09.
AG2b	Strong	Flood risk to classified 'horticulture' land	
AG2c	Strong	Flood risk to classified livestock 'grassland'	
AG4	Very strong	Agroclimate	There is a risk of large changes in soil moisture balances projected for the longer term. This would affect cropping patterns in the UK, and/or place increasing pressure on water abstractions for irrigation; the CCRA analysis is based on detailed modelling of the soil moisture balance that updates research already published in the peer reviewed literature.
AG5	Strong	Water abstraction for crops	The risk of increased water abstraction for irrigation may increase in line with decreases in soil moisture availability with the largest percentage increases in wetter areas such as Wales where irrigation is not so prevalent at present. The CCRA analysis compares well with other published literature but the impacts may be far greater and even double under some future socio-economic scenarios.

Metric	Qualitative assessment of evidence	Metric description	Key findings
AG7a	Strong	Heat stress impact on dairy milk production	Whilst there is a risk millions of litres of milk are projected be lost to heat stress (assuming no heat abatement measures are taken), in most regions these represent a very small proportion of the total national present day production and therefore represents a small impact. Projections indicated that production may be significantly impacted for high emissions scenarios by the 2050s and medium/high emissions scenarios by the 2080s. The CCRA analysis is based on applying UKCP09 to a livestock production model that is published in the peer reviewed literature.
AG7b	Strong	Heat stress impact on loss of diary fertility	The risk associated with the cost of reduced fertility in the dairy herd may become significant at the regional scale and could be absorbed or passing on, potentially increasing costs to consumers. There may be a point at which heat abatement measures become financially viable, especially if other impacts of heat stress are also taken into account.
AG8a	Weak	Duration of heat stress in dairy cows	The risk of heat stress is projected to increase, although the risks appear to be negligible. The existing model does not take full account of extreme events and is based on a changing baseline condition.
AG9a	Weak	Dairy livestock deaths due o heat stress	The risk of deaths in dairy livestock is projected to be low as numbers are negligible, but this does not take extreme events into account.
AG10	Credible	Grass yield	The opportunity for increases in grass yields are projected to result from increases in mean growing season temperature, assuming other factors do not become limiting.
AG11	Weak	Soil erosion	The risk of soil erosion as a result of projected increases in winter rainfall and rainfall intensity is projected to increase. The analysis provides an indication of the direction of change but does not provide estimates of erosion volumes.

6 Socioeconomic Changes

Discussion in previous sections highlighted the importance of technology in agriculture, for example, the impacts of better seeds and crop management on yield increases, the role of integrated crop management in reducing pests and diseases incidence and the impacts of better soil and water management on crop productivity. When considering the impacts of socio economic policy changes on agriculture, the situation is more complex – for example, the recent Foresight (2010) study explored past trends and likely future socio-economic drivers but did not attempt to produce a coherent set of land use futures for UK agriculture. This was due to the complex interactions and uncertainties associated with possible impacts of national global population increases, changes in per capita food demand, governance of national and global food systems, climate change and competition for natural resources. Collectively, these create large uncertainties in projecting future national and global food supply and demand.

For the CCRA, six socio-economic dimensions have been devised to represent a broad range of socio-economic factors that have the potential to have a significant impact on the UK agricultural sector, in terms of both its contribution to food security and ecosystem services. The dimensions are:

Population needs/demands (high/low) This dimension is intended to encapsulate drivers of population size and distribution (geographically and demographically) and the pressure the population places onto the country in terms of housing, infrastructure, education and development. One extreme is that there is a high degree of demand on natural, economic and social resources (demand exceeds supply and more people are exposed to risk); the other is that demand is very low (supply exceeds demand and people are less exposed to risk).

Global stability (high/low) This dimension describes drivers based on world events that would increase or decrease global stability (e.g. war, natural disasters, economic instability). The extremes are higher global stability (with little pressure on Government and people) compared to today, and lower global stability (with a high degree of pressure on Government and people that outweigh other priorities) compared to today.

Distribution of wealth (even/uneven) This dimension considers the distribution of wealth amongst the British population, measured in terms of the Geni coefficient; the extremes being whether it is more even compared to today; or more uneven (with a strong gradient between the rich and poor) compared to today.

Consumer driven values and wealth (sustainable/unsustainable) Globalisation and consumerism are the primary drivers, specifically movement towards or away from consumerism values. The extremes are that consumers prioritise their time for working and the generation of wealth, with a greater focus on the consumption of material market goods and services compared to today; and consumers reduce the importance of work and wealth generation in favour of leisure and non material quality of life, with a focus on the consumption of non-market goods and services such as conservation and recreational activities in green spaces.

Level of Government decision making (local/national) This relates to how centralised policy making is on adaptation; the extremes being whether there is a greater centralisation of policy compared to today; or whether there is a very small central Government input and high degree of localism in decision making compared to today.

Land use change/management (high/low Government input) These dimensions relate to aspects of urbanisation versus rural development. The extremes are that looser planning restrictions might increase development in rural areas (e.g. building on the green belt, power stations) compared to today, versus tighter planning which might constrain urban development within existing boundaries (e.g. more brown field sites) compared to today.

6.1 Influence of socio-economic futures on agriculture sector risk metrics

The influence of the socio-economic dimensions described above on the projected changes of each risk metric for agriculture has been assessed from a broad perspective, assuming a time horizon of the 2050s. The qualitative results are given in Tables 6.1 and 6.2. The main sensitivities of selected agriculture sector risk metrics to these various socio-economic dimensions are summarised below:

Population demographics will strongly influence crop production and food security. Local food production will help sustain rural economies and reduce dependence on food imports.

Flooding of agricultural land can have significant socio-economic impacts (Posthumus *et al*., 2010) with consequences on the sustainability of rural economies. It also has knock on impacts on land management practices including cropping, fertility and ecosystem services (biodiversity).

Socio economic futures will have minimal direct influence on agroclimate conditions, but changes in agroclimate due to climate change will alter cropping systems and land productivity. Choices regarding future cropping will depend on consumer demands, markets, competition and availability of natural resources (e.g. water).

Adaptation strategies to cope with new biotic (pests and diseases) and abiotic (heat stress, drought) stresses associated with changes in aridity will be needed. New pests and diseases might emerge due to globalisation of agriculture.

Demand for water for agriculture is likely to increase in response to population growth, increased consumer wealth, and consumer demands for greater product choice.

Livestock production is likely to increase in response to population growth, increased consumer wealth, changing diets and changing consumer demands for meat products.

Table 6.1 below summarises whether the dimensions are relevant or not for the agriculture metrics, and Table 6.2 provides commentary on each dimension/metric combination.

Table 6.1 Relevance of socio-economic dimensions to agriculture risk metrics

Agriculture risk metric	Population needs/ demands	Global stability	Distribution of wealth	Consumer driven values and wealth	Govern-ment decision making	Land use change / manage-ment
AG1 Crop yield variability	✓	✓	✓	✓	✓	✓
AG2 Flood risk to agriculture	✓	✓	✓	×	✓	✓
AG3 Pest incidence	✓	✓	✓	✓	×	✓
AG4 Changes in agroclimate	×	✓	✓	×	✓	✓
AG5 Irrigation abstraction	✓	✓	✓	✓	✓	✓
AG6 Livestock water use	✓	✓	✓	✓	✓	✓
AG7 Livestock production	✓	×	✓	✓	✓	✓
AG8 Livestock health impact	×	✓	✓	✓	✓	✓

✓ Relevant × Not relevant

Table 6.2 Commentary on each socio-economic dimension and agriculture metric

Population needs / demands (high / low)	The impact of population needs/demands on agriculture relate mainly to (i) the requirement for additional land for housing development, (ii) increased demand for affordable food supplies, (iii) access to green spaces for leisure, (iv) demands on land use/agriculture for other ecosystem services beyond food production, and (v) competition for natural resources (land, water, energy). Over the last 50 years, demand across many land use sectors in the UK has intensified in response population change and rising incomes – which themselves have fuelled increased expectations. But over the next 50 years even greater pressure on land is expected – a consequence of continued growth in population and incomes, the impact of climate change, new technologies, and changing public attitudes and values (Foresight, 2010), but note that higher yields have potential to reduce some land demand. In the UK, agriculture is the largest single type of land use, representing 77% of the total land area (Angus *et al*., 2009). demographic change will create significant challenges in how to manage the associated significant increases in the demand for land for housing, recreation, transport, water, food and energy in the face of an uncertain climate, and how to manage the potential for uneven distribution of demographic change across the UK. As the UK population grows, so will our demand for food and water. With rising incomes and continuing urbanisation, food habits change towards higher consumption and more varied diets. For example, global annual milk consumption per person is expected to increase from 78 kg (2000) to 100 kg (2050) and that of meat from 37 kg (2000) to 52 kg (2050) (FAO, 2006). This has major impacts on agricultural production since every 1 kg increase

	in milk or meat requires an addition 5 to 8 kg of animal feed. Population needs/demands are also closely tied with national food security. The UK government seeks to achieve 'food security' by guaranteeing households access to affordable, nutritious food (Defra, 2010). UK agriculture, along with the food industry as a whole, is charged with 'ensuring food security through a strong UK agriculture and international trade links with EU and global partners which support developing economies'. Climate change could affect the relative productivity of UK agriculture and its competitive position in international markets (Knox *et al*., 2010c).
Global stability (high / low)	Global stability could affect the UK agriculture sector via (i) changes in international trade agreements and price volatility in global food markets, (ii) international currency fluctuations and foreign exchange rates, especially £:Euro and £:US$ ratios (iii) energy prices, (iv) natural disasters (e.g. drought) impacting on food supplies and UK imports, (v) water shortages affecting international crop productivity, and (vi) national policies to cope with increasing food security risks impacting on other ecosystems services for agriculture. High levels of volatility in global food markets are important because of the adverse side effects they can have on producers and consumers, the disruption they can cause to the global food system, and the general economic and political instability that can then ensue. Food security is the cornerstone of a stable society. The peak in food prices in 2008 and the riots that occurred in many developing countries is a clear example of how food insecurity can destabilise national economies. However, the effects of global instability are most severe for low income countries and the rural poor – food spikes can be a major cause of increased hunger in these regions (Foresight, 2011a). Instability in developing countries (e.g. civil wars, conflict, drought) will also add pressure on developed nations to provide support for food security programmes to cope with rising hunger levels. Increased levels of immigration can be an indirect impact of low global stability. Global stability is also closely aligned with food markets, but predicting their future volatility is difficult. Volatility is expected to increase in the future, due to a wide range of drivers including: • non-economic factors such as armed conflict, civil wars,/unrest • breakdown of regional or national governance • globalisation and international trade, and shocks in other commodity sectors • increasing and volatile energy prices • levels of food stocks held by private and public sector agencies • market regulation • improvements in crop protection and biotechnology • subsidies or incentives for biofuel production • cultural importance of certain foodstuffs as this can lead to government interventions to reduce price volatility. (Foresight, 2010, 201a) Global conflicts for water (the major driving force for a secure and productive agricultural sector in many countries) are also likely to increase significantly in the future, due to rising demand for water to meet population growth and food production, increased competition between sectors (e.g. urban v agriculture) , trans boundary water conflicts and climate change.

Distribution of wealth (even / uneven)	Agriculture is central to the food security and economic growth of developing countries and the main source of livelihood for three out of four of the world's poor (Wheeler and Kay, 2010). However, in EU and OECD countries, the importance of agriculture and its share of national economic output are markedly different. UK agriculture contributes <1% of total GDP and provides employment for about 2% of the labour force (Angus *et al*., 2009). These figures do mask the high economic importance of agriculture to the sustainability and fabric of rural communities in parts of the UK. For example, , it was estimated that irrigated agriculture in East Anglia supports over 50,000 jobs and contributes £3billion to the rural economy (Knox *et al*., 2009). The impacts of wealth distribution on agriculture therefore mainly relate to rising incomes and the consequent impacts changing food habits with higher levels of consumption and more varied diets. This is important because dietary changes are very significant because, per calorie, some food items (such as grain-fed meat) require considerably more resources to produce than others. However, predicting patterns of dietary change is complex because of the way pervasive cultural, social and religious influences interact with economic drivers (Foresight, 2011a). For example, studies have predicted the increases in UK meat per capita consumption (kg/capita/annum) from 37 kg today to 52 kg by the middle of the century. In high-income countries, consumption is nearing a plateau. Whether meat consumption in economies such as Brazil and China will stabilise at levels similar to the UK, or whether they will rise further to reach levels similar to the USA is uncertain. However, major increases in meat consumption, particularly grain-fed meat, will have serious implications for competition for land, water and other inputs, and will affect the sustainability of food production (Foresight, 2011a). There are also uncertainties regarding the extent to which wealth distribution will impact on agriculture and future per capita consumption, including the degree to which consumption will rise in Africa, whether diets will converge on those typical of high-income countries today, whether regional differences in diet (particularly in India) persist into the future, and the extent to which increased GDP is correlated with reduced population growth and increased per capita demand – how these different trade-offs develop will have a major effects on gross food demand, both nationally (UK) and internationally.
Consumer driven values and wealth (sustainable / unsustainable)	Globalisation and consumerism values exert major impacts on agriculture and food supply chains. Rising incomes and greater environmental awareness in particular are strong drivers for influencing UK consumer food choice. Some of the factors that also influence consumer driven values include: • The importance of locally produced food and its contribution to environmental sustainability • Supporting fair trade from developing countries to achieve sustainable development and concerns regarding 'food miles' • The increasing role of assurance schemes (e.g. Field to Fork, Nature's Choice) for providing consumer confidence, product traceability and quality control • Corporate, ethical and environmental benchmarking and food labelling (e.g. water and carbon footprinting) • Perceptions of food safety and organics • Diets, healthy eating and the 'Eat Well Plate'. Previous research (Weatherhead *et al*., 2008) investigated the impacts of contrasting socio economic scenarios and climate change on future irrigation demand. This highlighted the sensitivity of the assumptions

	regarding consumer driven values, wealth and population growth. For example, under one highly technology and knowledge-led UK scenario ('Alchemy') future consumers were happy to accept intensive production methods, high fertiliser use, GM and other new technologies. In contrast, the 'Restoration' scenario featured a society more concerned with the environment than increased consumption, where consumers wanted naturally grown, sustainable food. But farming became extensive, non-organic fertilisers were too expensive and yields dropped. In another scenario ('Survivor'), low resource consumption and local food production using green or traditional technologies were dominant, but led to lower yields and less emphasis on food quality. Each of these scenarios led to very different forecasts of future water demand, which is not surprising, but did highlight the sensitivity of the socio economic scenarios to quantifying the impacts of climate change in a specific sector of UK agriculture.
Level of Government decision making (local / national)	Centralised policy making would facilitate adaptation policies regarding emissions targets, and the pivotal role that agricultural land plays in climate change mitigation (recognising the complex interaction between the effect of climate change on land itself, and the use of land to reduce greenhouse gas emissions) (Foresight, 2011a). Because of the scale of the potential climate change impact, together with the diversity and interaction of conflicting interests on agricultural land (crop production, ecosystem services, etc), centralised policy making could promote an integrated and coherent climate change adaptation and mitigation strategy which recognises the multifunctional nature of agriculture. Centralised policy making would also support adaptations required to cope with global food security. Conversely, a high degree of localism in adaptation decision making would facilitate the creation of local solutions to local issues such as water management (e.g. catchment scale initiatives to resolve water shortages/re-allocation), supporting local farm businesses to adapt, and fostering greater engagement between local communities and their food producers.
Land use change / management (high/low Government input).	Increasing urbanisation would (i) impact on the area of land available for food and biofuel production, (ii) intensify pressures on water resources for agriculture particularly in regions where development are planned (south East England), (iii) increase competition for natural resources, (iv) create conflicts between rural communities and urban developments, and (v) increase flood risks due to climate change with implications for building on agricultural flood plains and vulnerable coastal areas. Increasing land productivity using technological innovations could release some proportion of agricultural land for delivering other ecosystem services such as habitat conservation and opportunities for recreation and carbon sequestration. Conversely, increased food demands and lower levels of productivity (via land degradation, climate change, water restrictions) could lead to the transformation of previously unfarmed land into agricultural production, with environmental consequences.

7 Costs

7.1 Summary

Climate change adaptation decisions that are designed to reduce climate change risks inevitably involved making trade-offs concerning the use of scarce economic resources. To the extent that economic efficiency is an important criterion in informing such decision-making, it is useful to express climate change risks in monetary terms, so that they can be:

- Assessed and compared directly (using £ as a common metric) and
- Compared against the costs of reducing such risks by adaptation.

For the CCRA, a monetisation exercise has been undertaken to allow an initial comparison of the relative importance of different risks within and between sectors. Since money is a metric with which people are familiar, it may also serve as an effective way of communicating the possible extent of climate change risks in the UK and help raise awareness.

Where possible, an attempt has been made to express the size of individual risks (as described in this report) in monetary terms (cost per year) however, due to a lack of available data it has sometimes been necessary to use alternative costs (repair or adaption) to provide an estimate. A summary of the results are provided in Table 7.1.

A variety of methods have been used to determine the costs. In broad terms, these methods can be categorised according to whether they are based on:

- Market prices (MP)
- Non-market values (NMV) or
- Informed judgement (IJ)
- Informed judgement has been used where there is no quantitative evidence and was based on extrapolation and/or interpretation of existing data.

In general terms, these three categories of method have differing degrees of uncertainty attached to them, with market prices being the most certain and informed judgement being the least certain. It is important to stress that the confidence and uncertainty of consequences differs. Therefore, care must be taken in directly comparing the results. Whilst we attempt to use the best monetary valuation data available, the matching-up of physical and monetary data is to be understood as an approximation only.

Further, it is important to highlight that some results are presented for a scenario of future climate change only, whilst others include climate change under assumptions of future socio-economic change[26]. The approach used, and the relative baseline, is stated in the table below. There are also some important cross-sectoral links, or areas where there is the risk of double counting impacts: these are highlighted on the table.

Market prices, with adjustment for gross margins, were used where possible. Medium and high benefits are shown for sugar beet and wheat. Uncertainty is highest for flood

[26] The combined effects of socio-economic and climate change together provides the total risks faced, but care should be taken when attributing the relative (or marginal) risk due to climate change specifically, as this only includes the climate related element.

risk in this case, due to the difficulties in valuation. Whilst the uncertainty attached to future agricultural prices is sizeable, and primarily driven by population and technology (rather than subsidies) that attached to non-market values is likely to be greater. It also appears to be the case that uncertainties in climate sensitivities dwarves these uncertainties.

Some caveats are useful to make with regard to the monetised results. First, it is emphasised that the metrics included in this risk assessment only address a subset of those that may be thought potentially important for the agricultural sector in the future. Second, it is clear from the risk assessment above that the relationships between climatic variables, agricultural productivity and socio-economic change are not well-established under climatic conditions, let alone under future scenarios. This complexity ensures that the quantitative results presented here have to be viewed as highly uncertain and indicative at best. What does seem clear, however, is that climate change is unlikely to be the most important driver of future change in the sector; socio-economic change appear likely to be dominant.

Table 7.1 Summary of results in £million per annum

(2010 prices, no uplift or discounting) – climate change signal with adjustment for socioeconomic change on land use and prices – relative change from baseline period. Medium emission, p50 unless stated

Risk metrics	2020s	2050s	2080s	Estimation Method	Confidence ranking	Notes
AG1a; Mean yield variability with summer rainfall, using sugar beet as a 'reference' crops.	+ M	+ M	+ M	Market Prices	M	Includes land use and price scenarios
AG1b; Mean yield variability with summer rainfall, using wheat as a 'reference' crops.	+ H	+ H	+ H	Market Prices	M	Includes land use and price scenarios
AG1c; Mean yield variability with summer rainfall, using potatoes as a 'reference' crops.	Neg.	Neg.	Neg.	Market Prices	M	
AG2; Flooding risk to crop and pasture land	- M	- H	- H		L	
AG3; Crop diseases	?	?	?	Informed Judgement	L	
AG4; Agroclimate	- H	- H	- H	Informed Judgement	L	
AG5; Water Abstraction for crops	-	-	-	-		Not assessed
AG6; Livestock water abstraction	Neg.	Neg.	Neg.	Informed Judgement		
AG7a; Loss of milk production due to heat stress	- L	- L	- L	Market Prices	M	Includes price scenarios
AG7b; Loss of fertility due to heat stress in dairy cows	- L	- L	- L	Market Prices	M	Includes price scenarios
AG8; Increased duration of heat stress: Livestock	Neg.	Neg.	Neg.	Market Prices	M	

Risk metrics	2020s	2050s	2080s	Estimation Method	Confidence ranking	Notes
AG9: New crop opportunities	-	-	-	-		Not assessed
AG10: Grassland productivity	+H	+H	+H	Market Prices	H	Assumes hay/silage use, and constant grass price.

Note: - signifies a negative impact or loss; + signifies benefits or cost reductions**.**

Impact Cost Ranking: L = £1-9m/pa M = £10-99m, H = £100-999m, Neg.: Negligible (<£1mn), ? = not possible to assess.

Monetisation Confidence Ranking:

Ranking	Description	Colour code
High	Indicates significant confidence in the data, models and assumptions used in monetisation and their applicability to the current assessment.	
Medium	Implies that there are some limitations regarding consistency and completeness of the data, models and assumptions used in monetisation.	
Low	Indicates that the knowledge base used for monetisation is extremely limited.	

7.1.1 Introduction to Monetisation

The overall aim of the monetisation is to advance knowledge of the costs of climate change in the UK, by generating initial estimates of the welfare effects.

The basic approach to the costing analysis is, for each impact category considered, to multiply relevant unit values (market prices or non-market prices) by the physical impacts identified in earlier sections of this sector report. The total value to society of any risk is taken to be the sum of the values of the different individuals affected. This distinguishes this system of values from one based on 'expert' preferences, or on the preferences of political leaders. However, due to the availability of data, it has sometimes been necessary to use alternative approaches (e.g. repair or adaptation costs) to provide indicative estimates.

There are a number of methodological issues that have to be addressed in making this conversion (Metroeconomica/UKCIP, 2004) including the compatibility between physical units and monetary units and the selection of unit values that address market and non-market impacts. As far as possible, physical and monetary units have been reconciled. The selection of unit values is justified in the explanation of the method used to monetise each risk metric. The aim is to express the risk in terms of its effects on social welfare, as measured by the preferences of individuals in the affected population. Individual preferences are expressed in two, theoretically equivalent, ways. These are:

- The minimum payment an individual is willing to accept (WTA) for bearing the risk or
- The maximum amount an individual is willing to pay (WTP) to avoid the risk.

There are also other issues (beyond this scoping analysis) in terms of impacts that have non-marginal effects on the UK economy, the treatment of distributional variations in impacts, and the aggregation of impact cost estimates over sectors and time.

7.1.2 Methodology

Crop impacts

For crop impacts, the methodology employed to value the impact was based on the use of market prices. The change in total yield under climate change is estimated first as follows:

$$Y = (yc - yb)*A$$

Where:

Y is total yield in the region or country (in tonnes)

yc is the yield per hectare under the climate change scenario

yb is baseline yield (1961-90)

A is the area cultivated in 2009

This is clearly a very rough approximation of the change in yield, which can be multiplied by the prices of crops. Crop prices were extracted from the FAO-STAT database and an average of the most recent 5 years taken – to minimise the impact of annual variations in prices. FAO-STAT presents producer prices in £/tonne.

Here it is also possible to account for some socioeconomic change, building on past studies socioeconomic change can be accounted for in terms of land use for agriculture and in terms of changes in real prices that may arise as a result of e.g. changing world market structures. Changes in crop productivity as a result of technological change cannot be accounted for (e.g. enhanced GM cropping, changes in crop type) – this would require a more detailed study.

The potential need to account for socioeconomic change is illustrated in Figure 7.1. Here the future impacts of climate change are given by the projected losses/gains with climate change compared to a projected reference scenario. Because agriculture is particularly affected by factors such as land use change and price changes driven by wider socioeconomic issues, the influence of such factors has been included. This differs from some of the other sectoral reports. The case where no socioeconomic change is taken into account is also presented for comparative purposes.

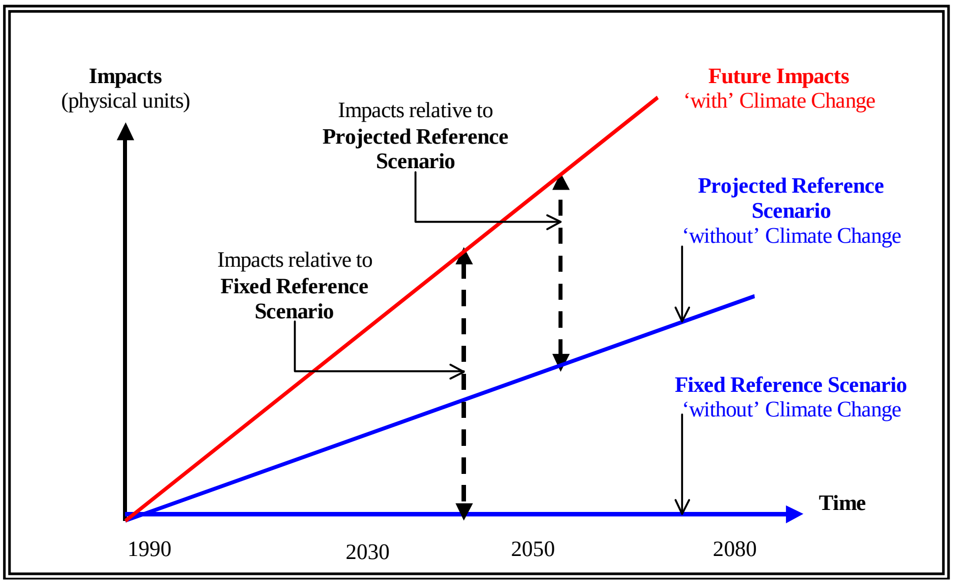

Figure 7.1 Costing climate change with socioeconomic change
Source: Metroeconomica (2004), adapted from Parry and Carter (1998)

Hence to obtain estimates including the impact of socioeconomic change, the socioeconomic scenarios from the REGIS project (Holman and Loveland, 2001) and the UKCIP Socioeconomic Scenarios have been built on.

To translate the scenarios to the emissions scenarios, the Global Sustainability is linked to the low emissions scenario, the National or Regional Enterprise to the Medium emissions scenario and for the High emissions scenario the World/Global Markets Scenario is used. There are obviously issues with doing this – because of the potential inconsistencies inherent in transferring scenarios, but to get an approximate estimate of the costs this exercise is necessary – as will become apparent the impacts may be significantly reduced or increased under different scenarios of socioeconomic change[27].

Changes in agricultural land use under the different scenarios were also taken into account from the REGIS study (using the same translation of scenarios as above). This reflects the proposition that it is likely that in the period to 2080 the extent of agricultural land could fall as land moves out of agricultural use and into alternative uses (e.g. forestry, urban development). The change in area coverage is considered uniform across the UK, an unlikely pattern. To get a true picture of the distributional effects across the regions in terms of land use change would require complex modelling beyond the scope of this project.

Hence, the change in total yield under climate change is estimated as follows:

$$Y = (yc - yb)*A*LU$$

Where:

Y is total yield in the region or country (in tonnes)

yc is the yield per hectare under the climate change scenario

yb is baseline yield (1961-90)

A is the area cultivated in 2009

[27] It should be noted that this report differs from other reports for the CCRA in that it integrates such socioeconomic scenarios into the analysis explicitly. This is because of the availability of a significant body of research in this area, including the Foresight analysis.

LU is a multiplier to take into account the change in land use under the relevant socioeconomic scenario.

The Land Use multiplier (LU) represents the change in land use projected under future socio-economic scenarios. Thus, if there is a projection of an increase of, say, 15% in the area devoted to wheat production in a future time period, the LU multiplier would be 1.15. If the LU multiplier is lower than 1, this denotes a decrease in the area projected to be devoted to agricultural activity. The socio-economic data are derived from the REGIS study which developed detailed story lines for the agricultural sector.

The prices were extracted from the FAO-STAT database and an average of the most recent 5 years taken – to minimise the impact of annual variations in prices. FAO-STAT presents producer prices in £/tonne. These were then adjusted to take into account the REGIS socioeconomic scenarios.

A number of issues are highlighted in the use of this approach.

First, UK production cannot be seen in isolation of global food production and prices – this is one area where the UK boundary for the CCRA needs to be extended. The autonomous response at the local - national scale will depend on what is expected to happen to prices of agricultural commodities in local national and global markets. To properly assess this, effects have to be analysed in the wider context of what will be happening to the prices of agricultural commodities as a result of changes in yields worldwide. The use of REGIS scenarios helps to integrate some of these wider issues in the context of food prices.

Second, future prices will change significantly, as result of global production trends, socio-economic drivers (population, food production levels, biofuel use, etc.) and from the effects of climate change on production. This is important because price levels would be very different between the UKCP Low and UKCP High scenarios, consistent with the underlying socio-economic scenarios and level of climate change associated with these. Again, the use of REGIS and UKCIP socioeconomic scenarios allow some of these factors to be taken into account, albeit crudely.

Presentation of results, uplifts and discounting

Consistent with other sectors, the indicative results below are presented in terms of constant (2010 prices) for the three time periods considered in the CCRA i.e. the 2020s, 2050s and 2080s. The results are presented in this way to facilitate direct comparison.

At this stage, the values below have not been presented as a present value or equivalent annual cost. However, the use of the values in subsequent analysis, for example in looking at the costs and benefits of adaptation options to reduce these impacts, would need to work with present values. For this, the values below would need to be adjusted and discounted. For discounting, the Green Book recommends 3.5% discount rates/factors (HM Treasury, 2007).

7.2 Crop yield using sugar beet as a reference 'arable' crop (AG1a)

7.2.1 Outputs from the Risk Assessment

The baseline data for sugar beet is presented in Appendix 5. The overall area cultivated is estimated at 116,470 hectares. The baseline (1961-90) refers to white sugar yield and this is the focus of the valuation as a consequence. The world sugar price in 2009 was approximately 15 cents per pound, or £203.86 per tonne.

A national average yield change[28] was used to estimate the change in value of crops. First, a weighted average needed to be constructed. This is shown in Table 7.2. Note these may differ from the percentage changes reported earlier, as there is a need to account for the regional variation in cropping patterns. Table 7.2 also assumes that the distribution of crop land will be the same as the present in future time periods.

Table 7.2 Weighted average yield by scenario: UK Sugar (t/ha)

	Low			Medium			High		
	p10	p50	p90	p10	p50	p90	p10	p50	p90
2020				7.66	8.39	9.24			
2050	8.11	9.13	10.34	8.34	9.42	10.74	8.49	9.68	11.11
2080	8.45	9.63	11.13	8.95	10.36	12.16	11.11	9.51	11.22

The baseline average sugar production per hectare can be estimated as 6.99 t/ha based on the area and production figures above. Taking this as the non-climate change case[29], the increases in sugar production due to climate change can then be estimated by multiplying by the area of production. This gives us the results as shown in Table 7.3.

Table 7.3 Change in yield under different scenarios (no socioeconomic change) (t/annum)

	Low			Medium			High		
	p10	p50	p90	p10	p50	p90	p10	p50	p90
2020				77199	163201	261676			
2050	129625	248671	389954	157072	282407	436117	174474	313160	480067
2080	169271	307591	482332	227831	392223	602003	293259	491917	743340

Building in an adjustment to the area cultivated drawing on land use change scenarios, changes in productivity can be estimated as shown in Table 7.4. It can be seen that yield may increase by between 158,000 and 743,000 tonnes by the 2080s relative to the non-climate change case[30]. Note that for some cases, there is likely to be no change in area under crops, hence for example for the High emissions scenarios there is no change, whether socioeconomic change is considered or not.

Table 7.4 Change in yield under different scenarios (with socioeconomic change) (t)

	Low			Medium			High		
	p10	p50	p90	p10	p50	p90	p10	p50	p90
2020				75141	158849	254698			
2050	120983	232093	363957	146601	263580	407043	174474	313160	480067
2080	157986	287085	450177	212643	366075	561869	293259	491917	743340

[28] Assuming water and nutrient availability are non-limiting.
[29] Noting that an increasing baseline could potentially be included in this case due to technical change – one would anticipate production to rise in the non-CC case.
[30] Note that for the baseline current production is estimated on the basis of regional land use for production of the crops, multiplied by the 1961-1990 baseline. This is then adjusted to take into account land use change when considering socioeconomic scenarios.

7.2.2 Methodology and unit values to be adopted

To value this, the market value in 2009 of £204 per tonne is taken, and multipliers from the REGIS study[31] applied to account for the effect of socioeconomic change on prices. The prices applied are as shown in Table 7.5. It is clear in both AG1a and AG1b that the prices are dependent on the emission scenarios which are, themselves, linked to socio-economic scenarios. Thus, a principal reason why prices are lower under High emission scenarios is that these scenarios assume a greater rate of growth in global trade and therefore more possibilities for comparative advantage to be exploited. This trend is exacerbated by the higher degree of technological change. It is acknowledged, however, that other factors such as population growth and international climate change may not be accounted for fully.

Table 7.5 Sugar prices under different emissions scenarios (£/t)

2020s			2050s			2080s (as 2050s)		
Low	Medium	High	Low	Medium	High	Low	Medium	High
214	183	173	224	163	143	224	163	143

7.2.3 Results and discussion

Multiplying prices by the tonnes leads to the estimate of the impact on sugar revenues.

The results are shown in Table 7.6 to Table 7.9. Under the case where socioeconomic change is ignored the benefits are projected to be between £15.7m and £53.3m for the 2020s, whilst for the 2080s the benefits are projected to be between £34.5m and £151.5m.

When adjustments are made for socioeconomic scenarios, the projected benefits in terms of revenues for the 2020s are between £13.8m and £46.7m and for the 2080s between £34.7m and £106.1m. In the Low climate scenario for the 2050s it is apparent that the effects of lower prices outweigh the effects of higher yields.

Table 7.6 Marginal change in sugar revenues per annum due to climate change
Results for the 2020s, 2050s and 2080s, compared to 1961-1990 climate. (£ million per year, 2010 prices, with no adjustment for socioeconomic change or discounting)

	Low			Medium			High		
	p10	p50	p90	p10	p50	p90	p10	p50	p90
2020				15.7	33.3	53.3			
2050	26.4	26.4	26.4	32.0	57.6	88.9	35.6	63.8	97.9
2080	34.5	62.7	98.3	46.4	80.0	122.7	59.8	100.3	151.5

Table 7.7 Marginal change in sugar revenues per annum due to climate change
Results for the 2020s, 2050s and 2080s, compared to 1961-1990 climate. (£ million per year, 2010 prices, with adjustments to prices and land use, but no discounting)

	Low			Medium			High		
	p10	p50	p90	p10	p50	p90	p10	p50	p90
2020				13.8	29.1	46.7			
2050	27.1	19.7	17.3	23.9	43.0	66.4	24.9	44.7	68.5
2080	35.4	64.4	101.0	34.7	59.7	91.6	41.8	70.2	106.1

Note that in the estimation of benefits, it would be better to use the “gross margin” – i.e. the margin over costs. To come to an estimate of this, a multiplier of 0.7 is applied,

[31] Note that it is assumed that sugar yields vary as do sugar beet prices – as this is the focus of REGIS. Here again compatible socioeconomic scenarios are linked to emissions scenarios.

estimated on market data for 2003[32]. This gives impacts on gross margins as in the tables below. The influence of considering socioeconomics can be seen, with reductions of £21.5m for the p50 case under the High scenario, for example. It should also be noted that price rises higher than those adopted here will exacerbate the size of these impact estimates.

Table 7.8 Impact on Gross Margins for Sugar, per annum due to climate change
Results for the 2020s, 2050s and 2080s, compared to 1961-1990 climate. (£ million per year, 2010 prices, with no adjustment for socioeconomic change or discounting)

	Low			Medium			High		
	p10	p50	p90	p10	p50	p90	p10	p50	p90
2020				11.2	23.8	38.1			
2050	18.9	18.9	18.9	22.9	41.1	63.5	25.4	45.6	69.9
2080	24.6	44.8	70.2	33.2	57.1	87.7	42.7	71.6	108.2

Table 7.9 Impact on Gross Margins for Sugar, per annum due to climate change
Results for the 2020s, 2050s and 2080s, compared to 1961-1990 climate. (£ million per year, 2010 prices, with adjustments to prices and land use, but no discounting)

	Low			Medium			High		
	p10	p50	p90	p10	p50	p90	p10	p50	p90
2020				9.8	20.8	33.4			
2050	19.4	14.1	12.3	17.1	30.7	47.4	17.8	31.9	48.9
2080	25.3	46.0	72.1	24.8	42.6	65.5	29.9	50.1	75.8

7.3 Crop yield using wheat as a reference 'arable' crop (AG1b)

7.3.1 Outputs from the Risk Assessment

The baseline data for wheat is presented in Appendix 5. The data show the regional variation in the yield and in hectares cultivated[33]. For some regions no data are available. Table 7.10 shows the projected total wheat yield by region. This shows that there are potentially significant gains in yield of wheat in most regions of the UK, with some experiencing over a 100% gain in the 2080s relative to the 1961-90 baseline.

Table 7.12 presents the potential total wheat yield changes, taking into account land use change. This shows that in general, the greatest gains in terms of tonnes produced would be for the High emissions scenario.

[32] Comparing the gross margins in Nix Farm Management Pocketbook, 29th – 32nd Edition with FAOSTAT data on producer prices for sugar beet gives a ratio of 0.71
[33] Assuming water and nutrient availability are non-limiting.

Table 7.10 Yield projections under emissions scenarios (t/ha) by region

	2020			2050			2080			
Region	p10	p50	p90	p10	p50	p90	p10	p50	p90	Emission Scenario
East Midlands				7.2	8.7	10.4	7.7	9.4	11.5	
East of England				8.1	9.6	11.4	8.6	10.3	12.5	
Eastern Scotland				3.6	5.0	6.7	3.9	5.7	7.8	
London				9.4	10.9	12.8	9.9	11.7	14.0	
North East England				5.1	6.5	8.1	5.5	7.2	9.3	
North West England				6.3	7.7	9.3	6.7	8.4	10.5	
Northern Ireland				5.7	7.0	8.4	6.2	7.6	9.4	Low
Northern Scotland				3.0	4.3	5.9	3.3	4.9	6.9	
South East England				8.3	9.8	11.7	8.8	10.6	12.9	
South West England				7.9	9.4	11.2	8.4	10.2	12.4	
Wales				6.4	7.8	9.4	6.8	8.5	10.6	
West Midlands				7.2	8.7	10.5	7.7	9.5	11.6	
Western Scotland				4.7	6.1	7.7	5.2	6.8	8.8	
Yorkshire and Humberside				6.3	7.7	9.4	6.7	8.4	10.4	
East Midlands	6.6	7.6	8.8	7.6	9.1	11.0	8.4	10.4	13.0	
East of England	7.5	8.6	9.8	8.5	10.0	12.0	9.4	11.4	14.0	
Eastern Scotland	3.1	4.1	5.3	3.7	5.3	7.2	4.3	6.5	9.1	
London	8.7	9.8	11.1	9.7	11.4	13.4	10.7	12.8	15.6	
North East England	4.4	5.4	6.6	5.3	6.8	8.6	6.2	8.2	10.7	
North West England	5.6	6.7	7.8	6.5	8.0	9.8	7.4	9.4	11.9	
Northern Ireland	5.2	6.1	7.2	6.0	7.4	9.0	6.9	8.6	10.8	Medium
Northern Scotland	2.5	3.5	4.6	3.1	4.6	6.3	3.7	5.6	8.1	
South East England	7.6	8.7	10.0	8.6	10.3	12.3	9.6	11.7	14.5	
South West England	7.2	8.3	9.6	8.3	9.9	11.9	9.2	11.3	14.0	
Wales	5.7	6.8	8.0	6.7	8.2	10.1	7.6	9.6	12.1	
West Midlands	6.6	7.7	8.9	7.6	9.2	11.1	8.5	10.6	13.3	
Western Scotland	4.1	5.1	6.2	5.0	6.4	8.2	5.8	7.8	10.1	
Yorkshire and Humberside	5.7	6.7	7.8	6.6	8.1	9.9	7.5	9.4	11.9	
East Midlands				7.8	9.5	11.5	9.2	11.6	14.7	
East of England				8.7	10.4	12.5	10.2	12.7	15.8	
Eastern Scotland				3.9	5.6	7.7	4.9	7.4	10.6	
London				9.9	11.8	14.0	11.5	14.1	17.4	
North East England				5.6	7.3	9.3	7.0	9.4	12.4	
North West England				6.8	8.4	10.5	8.2	10.6	13.6	
Northern Ireland				6.2	7.7	9.4	7.5	9.7	12.3	High
Northern Scotland				3.3	4.9	6.8	4.2	6.5	9.4	
South East England				8.9	10.7	12.9	10.4	13.0	16.3	
South West England				8.5	10.3	12.4	10.0	12.6	15.9	
Wales				6.9	8.6	10.6	8.4	10.8	13.8	
West Midlands				7.8	9.6	11.7	9.4	11.9	15.1	
Western Scotland				5.2	6.8	8.8	6.6	8.9	11.8	
Yorkshire and Humberside				6.8	8.4	10.4	8.2	10.6	13.5	

Table 7.11 Yield change (t) under emissions scenarios with no adjustment for socioeconomic change

Projections compared to no climate change case (1961-90 baseline)

	2020			2050			2080			
	p10	p50	p90	p10	p50	p90	p10	p50	p90	Emission Scenario
Region										
East Midlands				543304	1043862	1641234	709692	1295741	2028324	
East of England				770316	1477122	2314368	1005424	1823514	2861889	
Eastern Scotland				0	0	0	0	0	0	
London				0	0	0	0	0	0	
North East England				107485	199065	306736	135381	245150	380516	
North West England				0	0	0	0	0	0	
Northern Ireland				34680	73342	117235	47973	93384	148506	Low
Northern Scotland				0	0	0	0	0	0	
South East England				387840	744732	1168678	501317	917910	1442054	
South West England				275668	523294	824026	357338	651955	1024943	
Wales				0	0	0	0	0	0	
West Midlands				250293	475862	747453	326252	594827	932213	
Western Scotland				0	0	0	0	0	0	
Yorkshire and Humberside				347369	667959	1046026	455357	827111	1294007	
East Midlands	325392	685324	1101376	663582	1185144	1830431	955007	1644352	2526339	
East of England	458586	968710	1551805	930399	1675858	2588242	1350903	2327252	3570862	
Eastern Scotland	0	0	0	0	0	0	0	0	0	
London	0	0	0	0	0	0	0	0	0	
North East England	65392	132213	206800	123825	221447	338019	179711	311334	471412	
North West England	0	0	0	0	0	0	0	0	0	
Northern Ireland	17748	46757	79126	43640	85131	133445	69532	124154	189695	Medium
Northern Scotland	0	0	0	0	0	0	0	0	0	
South East England	230575	486885	783252	467186	841472	1303226	679763	1168020	1800921	
South West England	156823	345751	557290	333440	604361	935548	490586	845630	1302301	
Wales	0	0	0	0	0	0	0	0	0	
West Midlands	144099	315007	507810	303539	549587	852009	446819	770167	1183027	
Western Scotland	0	0	0	0	0	0	0	0	0	
Yorkshire and Humberside	208247	439028	702249	422699	758965	1168275	615815	1052449	1614270	
East Midlands				734470	1314530	2020119	1231828	2063521	3119527	
East of England				1035297	1858632	2846154	1738797	2917759	4408906	
Eastern Scotland				0	0	0	0	0	0	
London				0	0	0	0	0	0	
North East England				139731	249297	379366	230037	386946	584271	
North West England				0	0	0	0	0	0	
Northern Ireland				49211	94784	148624	90090	155926	237766	High
Northern Scotland				0	0	0	0	0	0	
South East England				519754	933384	1438871	874451	1466966	2224099	
South West England				368603	668933	1029771	632603	1063203	1609671	
Wales				0	0	0	0	0	0	
West Midlands				335933	607525	937277	578705	966804	1464821	
Western Scotland				0	0	0	0	0	0	
Yorkshire and Humberside				468094	841153	1287475	785962	1320895	1991140	

Table 7.12 Yield change (t) under emissions scenarios with adjustment for land use related to socioeconomic change

Projections compared to no climate change case (1961-90 baseline)

	2020			2050			2080			
	p10	p50	p90	p10	p50	p90	p10	p50	p90	Emission Scenario
Region										
East Midlands				507084	974272	1531819	662379	1209359	1893102	
East of England				718961	1378648	2160076	938396	1701946	2671097	
Eastern Scotland				0	0	0	0	0	0	
London				0	0	0	0	0	0	
North East England				100319	185794	286287	126356	228806	355148	
North West England				0	0	0	0	0	0	
Northern Ireland				32368	68452	109419	44774	87158	138606	Low
Northern Scotland				0	0	0	0	0	0	
South East England				361984	695083	1090766	467896	856716	1345917	
South West England				257290	488408	769091	333516	608491	956614	
Wales				0	0	0	0	0	0	
West Midlands				233607	444138	697623	304502	555172	870065	
Western Scotland				0	0	0	0	0	0	
Yorkshire and Humberside				324211	623428	976291	425000	771970	1207740	
East Midlands	316715	667049	1072006	619344	1106135	1708402	891340	1534729	2357916	
East of England	446357	942877	1510424	868372	1564135	2415693	1260843	2172102	3332805	
Eastern Scotland	0	0	0	0	0	0	0	0	0	
London	0	0	0	0	0	0	0	0	0	
North East England	63648	128687	201285	115570	206684	315484	167731	290578	439985	
North West England	0	0	0	0	0	0	0	0	0	
Northern Ireland	17275	45510	77016	40731	79456	124549	64897	115877	177049	Medium
Northern Scotland	0	0	0	0	0	0	0	0	0	
South East England	224426	473902	762366	436040	785374	1216344	634445	1090152	1680859	
South West England	152641	336531	542429	311211	564070	873178	457880	789255	1215480	
Wales	0	0	0	0	0	0	0	0	0	
West Midlands	140256	306607	494268	283303	512948	795208	417031	718822	1104159	
Western Scotland	0	0	0	0	0	0	0	0	0	
Yorkshire and Humberside	202694	427321	683523	394519	708367	1090390	574761	982285	1506652	
East Midlands				734470	1314530	2020119	1231828	2063521	3119527	
East of England				1035297	1858632	2846154	1738797	2917759	4408906	
Eastern Scotland				0	0	0	0	0	0	
London				0	0	0	0	0	0	
North East England				139731	249297	379366	230037	386946	584271	
North West England				0	0	0	0	0	0	
Northern Ireland				49211	94784	148624	90090	155926	237766	High
Northern Scotland				0	0	0	0	0	0	
South East England				519754	933384	1438871	874451	1466966	2224099	
South West England				368603	668933	1029771	632603	1063203	1609671	
Wales				0	0	0	0	0	0	
West Midlands				335933	607525	937277	578705	966804	1464821	
Western Scotland				0	0	0	0	0	0	
Yorkshire and Humberside				468094	841153	1287475	785962	1320895	1991140	

7.3.2 Methodology and unit values to be adopted

To value these impacts, the five year median price from FAOSTAT of £86 per tonne for wheat is used. This reflects price data for 2004 to 2008. Adjusting for price changes under socioeconomic scenarios likely to be linked to the emissions scenarios leads to the prices shown in Table 7.13. It should be noted that REGIS provides socioeconomic projections to 2050, so that prices for 2080 are assumed to be as in 2050. This shows that under low emissions scenarios, prices are likely to be higher than under High emissions scenarios – reflecting factors such as world trade.

Table 7.13 Prices of wheat under different scenarios (£/t)

2020			2050			2080 (as 2050)		
Low	Medium	High	Low	Medium	High	Low	Medium	High
94.6	77.4	73.1	86	77.4	60.2	86	77.4	60.2

7.3.3 Results and discussion

Multiplying the change in total yields by the relevant price gives the results as shown in the tables below for the regions. The impacts vary significantly by region, depending on the extent of coverage and the variation in yield projected.

Table 7.14 Marginal change in Revenues of wheat (£million/year) due to climate change

Results for the 2020s, 2050s and 2080s, compared to 1961-1990 climate (no socio-economic change, 2010 prices, but no discounting)

	2020			2050			2080			
	p10	p50	p90	p10	p50	p90	p10	p50	p90	Emission Scenario
Region										
East Midlands				46.7	89.8	141.1	61.0	111.4	174.4	
East of England				66.2	127.0	199.0	86.5	156.8	246.1	
Eastern Scotland				0.0	0.0	0.0	0.0	0.0	0.0	
London				0.0	0.0	0.0	0.0	0.0	0.0	
North East England				9.2	17.1	26.4	11.6	21.1	32.7	
North West England				0.0	0.0	0.0	0.0	0.0	0.0	
Northern Ireland				3.0	6.3	10.1	4.1	8.0	12.8	Low
Northern Scotland				0.0	0.0	0.0	0.0	0.0	0.0	
South East England				33.4	64.0	100.5	43.1	78.9	124.0	
South West England				23.7	45.0	70.9	30.7	56.1	88.1	
Wales				0.0	0.0	0.0	0.0	0.0	0.0	
West Midlands				21.5	40.9	64.3	28.1	51.2	80.2	
Western Scotland				0.0	0.0	0.0	0.0	0.0	0.0	
Yorkshire and Humberside				29.9	57.4	90.0	39.2	71.1	111.3	
East Midlands	28.0	58.9	94.7	57.1	101.9	157.4	82.1	141.4	217.3	
East of England	39.4	83.3	133.5	80.0	144.1	222.6	116.2	200.1	307.1	
Eastern Scotland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
London	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
North East England	5.6	11.4	17.8	10.6	19.0	29.1	15.5	26.8	40.5	
North West England	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Northern Ireland	1.5	4.0	6.8	3.8	7.3	11.5	6.0	10.7	16.3	Medium
Northern Scotland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
South East England	19.8	41.9	67.4	40.2	72.4	112.1	58.5	100.4	154.9	
South West England	13.5	29.7	47.9	28.7	52.0	80.5	42.2	72.7	112.0	
Wales	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
West Midlands	12.4	27.1	43.7	26.1	47.3	73.3	38.4	66.2	101.7	
Western Scotland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Yorkshire and Humberside	17.9	37.8	60.4	36.4	65.3	100.5	53.0	90.5	138.8	
East Midlands				63.2	113.0	173.7	105.9	177.5	268.3	
East of England				89.0	159.8	244.8	149.5	250.9	379.2	
Eastern Scotland				0.0	0.0	0.0	0.0	0.0	0.0	
London				0.0	0.0	0.0	0.0	0.0	0.0	
North East England				12.0	21.4	32.6	19.8	33.3	50.2	
North West England				0.0	0.0	0.0	0.0	0.0	0.0	
Northern Ireland				4.2	8.2	12.8	7.7	13.4	20.4	High
Northern Scotland				0.0	0.0	0.0	0.0	0.0	0.0	
South East England				44.7	80.3	123.7	75.2	126.2	191.3	
South West England				31.7	57.5	88.6	54.4	91.4	138.4	
Wales				0.0	0.0	0.0	0.0	0.0	0.0	
West Midlands				28.9	52.2	80.6	49.8	83.1	126.0	
Western Scotland				0.0	0.0	0.0	0.0	0.0	0.0	
Yorkshire and Humberside				40.3	72.3	110.7	67.6	113.6	171.2	

Table 7.15 Marginal change in Revenues of wheat (£million/year) due to climate change

Results for the 2020s, 2050s and 2080s, compared to 1961-1990 climate 2010 prices, including socioeconomic change for prices and land use (no discounting)

	2020			2050			2080			
	p10	p50	p90	p10	p50	p90	p10	p50	p90	Emission Scenario
Region										
East Midlands				43.6	83.8	131.7	57.0	104.0	162.8	
East of England				61.8	118.6	185.8	80.7	146.4	229.7	
Eastern Scotland				0.0	0.0	0.0	0.0	0.0	0.0	
London				0.0	0.0	0.0	0.0	0.0	0.0	
North East England				8.6	16.0	24.6	10.9	19.7	30.5	
North West England				0.0	0.0	0.0	0.0	0.0	0.0	
Northern Ireland				2.8	5.9	9.4	3.9	7.5	11.9	
Northern Scotland				0.0	0.0	0.0	0.0	0.0	0.0	Low
South East England				31.1	59.8	93.8	40.2	73.7	115.7	
South West England				22.1	42.0	66.1	28.7	52.3	82.3	
Wales				0.0	0.0	0.0	0.0	0.0	0.0	
West Midlands				20.1	38.2	60.0	26.2	47.7	74.8	
Western Scotland				0.0	0.0	0.0	0.0	0.0	0.0	
Yorkshire and Humberside				27.9	53.6	84.0	36.5	66.4	103.9	
East Midlands	24.5	51.6	83.0	47.9	85.6	132.2	69.0	118.8	182.5	
East of England	34.5	73.0	116.9	67.2	121.1	187.0	97.6	168.1	258.0	
Eastern Scotland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
London	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
North East England	4.9	10.0	15.6	8.9	16.0	24.4	13.0	22.5	34.1	
North West England	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Northern Ireland	1.3	3.5	6.0	3.2	6.1	9.6	5.0	9.0	13.7	
Northern Scotland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Medium
South East England	17.4	36.7	59.0	33.7	60.8	94.1	49.1	84.4	130.1	
South West England	11.8	26.0	42.0	24.1	43.7	67.6	35.4	61.1	94.1	
Wales	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
West Midlands	10.9	23.7	38.3	21.9	39.7	61.5	32.3	55.6	85.5	
Western Scotland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Yorkshire and Humberside	15.7	33.1	52.9	30.5	54.8	84.4	44.5	76.0	116.6	
East Midlands				44.2	79.1	121.6	74.2	124.2	187.8	
East of England				62.3	111.9	171.3	104.7	175.6	265.4	
Eastern Scotland				0.0	0.0	0.0	0.0	0.0	0.0	
London				0.0	0.0	0.0	0.0	0.0	0.0	
North East England				8.4	15.0	22.8	13.8	23.3	35.2	
North West England				0.0	0.0	0.0	0.0	0.0	0.0	
Northern Ireland				3.0	5.7	8.9	5.4	9.4	14.3	
Northern Scotland				0.0	0.0	0.0	0.0	0.0	0.0	High
South East England				31.3	56.2	86.6	52.6	88.3	133.9	
South West England				22.2	40.3	62.0	38.1	64.0	96.9	
Wales				0.0	0.0	0.0	0.0	0.0	0.0	
West Midlands				20.2	36.6	56.4	34.8	58.2	88.2	
Western Scotland				0.0	0.0	0.0	0.0	0.0	0.0	
Yorkshire and Humberside				28.2	50.6	77.5	47.3	79.5	119.9	

The overall impacts for the UK in terms of increased revenues for wheat are shown in Table 7.16 and Table 7.17. It can be seen that much of the variation in benefits by yield changes may be smoothed by the price variations from the socioeconomic scenarios. For the 2020s, projected benefits for wheat may amount to between £121.1m to £413.6m, with the projected benefit by the 2080s being between £284m to £812m for the low emissions scenario and between £371m to £942m for the High emissions scenario.

Table 7.16 Revenue benefits – wheat - total UK with no adjustment for socioeconomic change (£m)

2020			2050			2080			
p10	p50	p90	p10	p50	p90	p10	p50	p90	Emission Scenario
			233.7	447.7	702.3	304.3	554.7	869.7	Low
138.2	294.1	472.1	282.8	509.3	786.8	411.8	708.9	1088.7	Medium
			314.0	564.9	867.5	530.0	889.4	1345.1	High

Table 7.17 Revenue benefits – wheat - total UK with adjustment for socioeconomic change for land use and prices (£m)

2020			2050			2080			
p10	p50	p90	p10	p50	p90	p10	p50	p90	Emission Scenario
			218.1	417.8	655.4	284.0	517.7	811.7	Low
121.1	257.6	413.6	237.5	427.8	660.9	345.9	595.5	914.5	Medium
			219.8	395.4	607.3	371.0	622.6	941.5	High

Taking the gross margin to be approximately 75% of the revenue[34], this leads to estimated impacts on gross margins as shown below. These indicate benefits of £446m by the 2080s under the medium emissions scenario.

Table 7.18 Gross margin benefits – wheat – total UK with no adjustment for socioeconomic change (£m)

2020			2050			2080			
p10	p50	p90	p10	p50	p90	p10	p50	p90	Emission Scenario
			175.2	335.7	526.7	228.2	416.0	652.3	Low
103.6	220.6	354.1	212.1	382.0	590.1	308.8	531.7	816.5	Medium
			235.5	423.7	650.7	397.5	667.1	1008.8	High

Table 7.19 Gross margin benefits – wheat – total UK with adjustment for socioeconomic change for land use and prices (£m)

2020			2050			2080			
p10	p50	p90	p10	p50	p90	p10	p50	p90	Emission Scenario
			163.6	313.4	491.6	213.0	388.3	608.8	Low
90.8	193.2	310.2	178.2	320.9	495.7	259.4	446.6	685.9	Medium
			164.8	296.6	455.5	278.2	466.9	706.2	High

7.4 Crop yield using potato as a reference ‘field vegetable’ crop (AG1c)

7.4.1 Outputs from the Risk Assessment

For potatoes, the indicator shows the percentage change in average yield from summer rainfall for rain-fed potatoes. Rain-fed potatoes make up approximately 60% of maincrop potatoes in the UK. The projected changes are relatively small (see Table 7.20). The analysis shows that lower summer precipitation is likely to result in downward pressure on yields of rain-fed potatoes and that the changes in yield (for p50 and p90) are small, within the range of natural variability and less than the effects of CO_2 fertilisation. As such, this impact can be considered negligible in terms of economic value.

[34] Comparing the gross margins in Nix Farm Management Pocketbook, 29th – 32nd Edition with FAOSTAT data on producer prices gives a ratio of 0.77.

Table 7.20 UKCP09 percentage change in %yield for rain-fed potato crops compared to 1961-90 baseline

	Low			Medium			High		
	p10	**p50**	**p90**	**p10**	**p50**	**p90**	**p10**	**p50**	**p90**
2020s				-7	-2	3			
2050s	-10	-4	3	-12	-5	1	-12	-5	2
2080s	-11	-4	2	-15	-6	1	-18	-8	1

(blue)	Positive percentage change
(purple)	Negative percentage change

7.5 Flood risks to crops and grazing land (AG2)

7.5.1 Outputs from the Risk Assessment

Section 5.4 analyses the areas of agricultural land at risk from riverine and tidal flooding in England and Wales. This gives the projected areas of land at flood risk for different return periods (Table 7.21).

Table 7.21 Areas at risk of river and tidal flooding at different return periods (ha)

Total	Grades 1,2,3			Grades 4,5			Total
Scenario	<3	3 to 5	5 to 10	<3	3 to 5	5 to 10	
1961-1990	31,200	13,300	64,000	21,800	11,300	53,400	195,000
2020s	35,900	44,700	94,500	26,600	38,500	56,900	296,900
2050s	75,100	64,000	105,000	45,700	49,300	56,300	395,400
2080s	127,700	77,300	143,800	73,800	46,400	55,600	524,500

Baseline is 1961-90 (river flooding) and 2008 (tidal flooding).

7.5.2 Methodology and unit values to be adopted

To estimate the impact on agricultural production, a study on the crop impacts of the Summer 2007 floods on agriculture has been used. The estimates given by Chatterton *et al.* (2009) are perhaps most useful as they divide the damages by type of land (Table 7.22). These estimates are used as a proxy for flood damage arising from all floods[35]. This historical analogue approach has a number of caveats, but provides some broad estimates.

An expected value approach is used, using the mid point of the annual return to reflect the probability. This means the probability is taken as being 1 in 2 for floods less than 3 years, 1 in 4 for 3 to 5 years and 1 in 7.5 for 5 to 10 years. The average annual damage costs under the different scenarios can be estimated, using 2010 damages as the base.

In this case, only the results for the medium emissions scenario are reported. The sectoral analysis above only reports the results for the High emissions scenario and low emissions scenario for the 2080s.

[35] Noting that the damages from river water are likely to be different, and that depths of water and different contamination issues may affect the true values, this is a rather crude assumption.

Table 7.22 Estimated economic costs to agriculture of the summer 2007 flood

Sector	Area flooded (ha)*	Loss (£ million)**	Average loss (£/ha flooded) **
Arable	26,500	34.3 (±9.2)	1,293 (±347)
Grassland and livestock	15,600	10.1 (±6.5)	647 (±416)
Other costs		4.2 (±2.0)	100 (±48)
Total	**42,100**	**48.6 (±17.7)**	**2040 (±811)**

Source: based on Chatterton et al. (2009)

7.5.3 Results and discussion

The estimated annual damages are reported in Table 7.23. The total projected costs for the medium emissions scenario range from £24.7m to £119.5m.

Table 7.23 Estimated annual damages due to climate change induced flooding to agricultural land (£m)

	Grade 1, 2, 3			Grade 4, 5			
Return period (years):	**<3**	**3 to 5**	**5 to 10**	**<3**	**3 to 5**	**5 to 10**	**Total**
2020s Medium p50	3.0	10.2	5.3	1.6	4.4	0.3	24.7
2050s Medium p50	28.4	16.4	7.1	7.7	6.1	0.3	66.0
2080s Medium p50	62.4	20.7	13.8	16.8	5.7	0.2	119.5

The assumption that costs for the summer 2007 flood is similar to that of all floods is questionable, particularly as winter floods will have differential impacts to those occurring in the summer. The assumption that coastal flooding has similar impacts is also questionable, with more work is needed on this issue.

7.6 Crop disease (AG3 indicators)

7.6.1 Outputs from the Risk Assessment

For the indicators of crop disease, no discernible quantitative impact of climate could be identified. This is likely due to increased use of chemicals (e.g. pesticides) to reduce the impact (autonomous adaptation). As a consequence, no quantitative valuation of impacts could be undertaken.

7.6.2 Methodology and unit values to be adopted

The outputs from the previous sections are presented in qualitative terms. Consequently, it is not possible to apply unit values to quantitative risk estimates to derive monetary results using the conventional approach. Instead we are obliged to provide an informed judgement on the possible order of magnitude of these risks, expressed as a monetary metric. However, it is possible to identify the types of economic impacts that may be associated with the climate change risks described above. For example, the pests identified above are closely related to the risk of lost agricultural and/or forestry production, with corresponding losses in human welfare as a consequence of higher food prices.

An important knowledge gap for pests and diseases is a lack of robust computer models which can quantitatively analyses the future risk of pests and diseases. The situation involving pests and diseases is likely to be complex and may have a significant effect on how farmers respond to pests and diseases, and indeed, how effective their current methods will become.

7.6.3 Results and discussion

It seems as though there are potentially significant welfare impacts but we can find no empirical basis to substantiate this. However, as identified in BD3, initial estimates of the total costs of invasive species have been made for the UK (Williams *et al.,* 2010). This study estimates that the annual cost associated with yield loss and control costs of plant pathogens is £400 million in Great Britain. A total cost for all invasive species is estimated to be £1.7 billion. Whilst we have no substantive way to estimate to what extent this latter total may change as a result of climate change, it is clear that even a small percentage change would be significant. On that basis we judge that the cost ranking could be Medium (£10-99 million) in the 2020s, rising to a high cost in subsequent time periods.

7.7 Agroclimate (AG4)

7.7.1 Outputs from the Risk Assessment

Possible changes in the agro-climate are described in Section 5.5. A strong relationship exists between irrigation need and potential soil moisture deficit (PSMD) and this is used to estimate the change in total irrigation needs in parts of the UK.

The modelling suggests that by the 2020s, the irrigation needs of central England would be similar to that experienced now in eastern England, and by the 2050s eastern, southern, and central England would have irrigation needs greater than those currently experienced anywhere in England. Changes in climate would also affect land suitability and the viability of cropping, since production is influenced by spatial and temporal variability in soils and agroclimate, and the availability of water resources where supplemental irrigation is required. Soil characteristics and agroclimatic conditions thus greatly influence the crop choice, agronomic husbandry practices and the economics of production.

Changes in land suitability would thus impact on the sustainability of existing cropping and opportunities for new crops. The results suggested that by the 2050s, the area of land that is currently well or moderately suited for rain-fed production would decline by 74 and 95% under the “most likely” climate projections for the Low and High emissions scenario respectively, owing to increased drought risk. In many areas, rain-fed production would become increasingly risky. However, with supplemental irrigation, around 85% of the total arable land in central and eastern England would remain suitable for production, although most of this is in catchments where water resources are already over-licensed and/or over-abstracted; the expansion of irrigated cropping is thus likely to be constrained by water availability.

Their research concluded that the growth in water demand due to the switch from rain-fed to irrigated cropping is likely to be much larger than the increase in need of the irrigated crops. In Scotland, Brown *et al.* (2009) demonstrated the importance of soil moisture on land-use options, and how shifts in land-use potential have implications for both strategic resource planning and for adaptation actions. Their assessment highlighted not only potential changes in agriculture and other productive land uses, but also repercussions for biodiversity and terrestrial carbon stocks.

It is important to remember that effects such as drought can occur as a short-term severe weather episode and as a long-term climate change. Climate change projections indicate and increase in severe weather episodes; therefore the incidences of summer “droughts” may increase. However a simultaneous change of climate experiencing warmer temperatures and less rainfall may result in a droughtier climate in certain parts of the country.

7.7.2 Methodology and unit values to be adopted

No qualitative data is available to express these modelled findings in terms of changes in agricultural production. In order to make any estimation we are therefore required to undertake an informed judgement.

7.7.3 Results and discussion

In 1995, the value of the main crops in England and Wales totalled £12,500 million.[36] Whilst we would expect this agricultural value to be preserved either through crop switching, technological improvements or greater irrigation, the estimates above of land areas affected are very significant (up to 95%) suggesting that the cost to consumers in terms of higher prices and reduced availability could be very important. As a consequence, we make a cautious judgement that the cost ranking is high. Further research is, however, needed to validate this.

7.8 Water abstraction for crops (AG5)

7.8.1 Outputs from the Risk Assessment

Section 5.6 describes the change in agricultural abstraction under different scenarios. It should be noted that the Water Sector report considers agricultural abstractions based on a reduction of river flows whilst the agriculture report discussion focuses around an increase in demand and abstractions.

Metric WA8 monetised the risk of the agricultural sector paying to ensure continued water resource use to meet requirements. This is equivalent to the increase in demand from the agricultural sector, as in AG5. For completeness, therefore, the results from the Water Sector report, regarding agriculture are show below.

7.8.2 Methodology and unit values to be adopted

To approximate the WTP of the sectoral users, abstraction charges may be used. However, it should be borne in mind that it is likely that the charges are set at below WTP levels (e.g. see RPA (1999) who undertake an informal survey of a number of sectoral users).

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[36] http://www.ecn.ac.uk/iccuk/indicators/19.htm

Table 7.24 Current abstraction charges by use sector and indicative WTP
(pence/m3, 2010 prices)

		Spray Irrigation from agriculture
Abstraction Charge (National Average)	Minimum	0.012
	Central (Median)	1.6
	Maximum	13
WTP (Indicative)		1.3 (0.13-13)

Source: Based on data in RPA (1999)

7.8.3 Results and discussion

Using the WTP unit values from Table 7.24, Tables 7.25 to 7.26 present estimates of the total value of abstractions that would be lost to the three groups of users if catchments switch from being designated "sustainable" to being "unsustainable". Table 7.X presents results for abstraction from local catchments whilst Table 7.X presents results for abstraction from downstream catchments. The results in these tables show that the economic cost of lost abstraction attributable to climate change from agriculture. As might be expected, the costs increase between Low and Medium, and Medium to High emissions scenarios, across time periods to the end of the century.

Table 7.25 Value of Change in Agricultural Abstraction from Sustainable Catchments (Local) in England and Wales
(£ million/annum, 2010 prices)

	Low Emissions			Medium Emissions			High Emissions		
	p10 (wet)	p50 (mid)	p90 (dry)	p10 (wet)	p50 (mid)	p90 (dry)	p10 (wet)	p50 (mid)	p90 (dry)
2020s	(0.18)	0.28	0.38	(0.18)	0.29	0.38	(0.15)	0.28	0.38
2050s	0.19	0.38	0.44	0.29	0.40	0.46	0.33	0.42	0.47
2080s	0.31	0.42	0.47	0.38	0.45	0.50	0.41	0.48	0.53

Notes: Climate Change impacts only considered (i.e. no socio-economics), no uplift or discounting included. Brackets imply cost savings or benefits.

Table 7.26 Value of Change in Agricultural Abstraction from Sustainable Catchments (Downstream) in England and Wales
(£ million/annum, 2010 prices)

	Low Emissions			Medium Emissions			High Emissions		
	p10 (wet)	p50 (mid)	p90 (dry)	p10 (wet)	p50 (mid)	p90 (dry)	p10 (wet)	p50 (mid)	p90 (dry)
2020s	(0.09)	0.12	0.21	(0.09)	0.12	0.21	(0.08)	0.12	0.21
2050s	0.08	0.21	0.24	0.13	0.22	0.24	0.15	0.23	0.25
2080s	0.14	0.23	0.25	0.20	0.24	0.26	0.23	0.25	0.26

Notes: Climate Change impacts only considered (i.e. no socio-economics), no uplift or discounting included. Brackets imply cost savings or benefits.

7.9 Livestock water abstraction (AG6)

7.9.1 Outputs from the Risk Assessment

As discussed in Section 4.1.13, it was not possible to develop a specific response function for water abstraction for livestock. Hence, there is no attempt to monetise this impact using quantitative data. The likely consequences may not be that significant unless livestock fatality occurs, so it is surmised that this is likely to be a negligible impact.

7.10 Heat stress impact on dairy milk production (AG7a)

7.10.1 Outputs from the Risk Assessment

The estimated impact on milk production of heat stress under different emissions scenarios is shown in Table 7.27. The impacts range from 0 to 549m kg per annum. Note that these estimates do not account for the effects of adaptation.

Table 7.27 National total loss of milk production due to heat stress (million kg/annum)

	Low			**Medium**			**High**		
	p10	**p50**	**p90**	**p10**	**P50**	**p90**	**p10**	**p50**	**p90**
2020s				0	0	0			
2050s	0	2	58	0	3	96	0	5	110
2080s	0	3	113	0	14	320	0	27	549

7.10.2 Methodology and unit values to be adopted

To value this, the farm-gate price is used as shown in Table 7.28. Taking the mean value of the last 5 years data available, the estimated current price is 21.3 pence per litre.

Table 7.28 Farm-gate price (pence per litre)

	UK	**GB**	**NI**
2005	18.46	18.55	17.89
2006	17.94	18.13	16.75
2007	20.66	20.47	21.78
2008	25.91	26.43	22.92
2009	23.71	24.39	19.46

Source: http://www.dairyco.org.uk/

In terms of projected values in the 2020s, 2050s and 2080s the REGIS study provides scenarios for prices of milk[37]. Applying these values to the appropriate emissions scenario gives the values in pence per litre as shown in Table 7.29.

Table 7.29 Scenarios for milk prices (pence per litre)

2020s			2050s			2080s		
Low	**Medium**	**High**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
22	18	15	23	15	13	23	15	13

7.10.3 Results and discussion

The damages can be costed as shown in Table 7.30. Damages in the 2020s are projected to be low at between zero and £70,000, whilst by the 2080s the projected costs could reach up to £66m, depending on the climate and socio-economic scenario. Note again the significant influence of the socioeconomic scenarios – if the median 2005-2009 price is simply applied to the 2080s estimated milk impact, the projected High p90 value would rise to £110m.

Clearly, the price range used to express socio-economic scenario uncertainty could be broader; however, here consistency with the method used for other estimates in the CCRA for agriculture is maintained by not implementing SES outside the REGIS scenarios. Further sensitivity analysis could be conducted - the current estimates may be overly cautious in this regard.

Table 7.30 Marginal damage from heat stress on milk production (£million/year) due to climate change

Results for the 2020s, 2050s and 2080s, compared to 1961-1990 climate. 2010 prices, with socioeconomic change on prices, with no discounting.

	Low			Medium			High		
	p10	p50	p90	p10	p50	p90	p10	p50	p90
2020	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00
2050	0.00	0.34	12.85	0.00	0.45	13.43	0.00	0.56	13.19
2080	0.00	0.60	24.88	0.00	1.94	44.87	0.00	3.29	66.04

7.11 Heat stress impact on loss of dairy fertility (AG7b)

7.11.1 Outputs from the Risk Assessment

The impact of the loss of dairy fertility as a result of heat stress was first estimated in terms of “days open” and then the total impact valued assuming a cost of £2.50 per cow per day. The derived impacts ranged from between zero and £51m for heat stress on dairy fertility.

[37] Note that although the REGIS study is now rather dated, the sections dealing with socioeconomic scenarios would not be likely to be impacted by time – they show % changes in prices due to different scenarios. Effects of changes in subsidies are assumed to be unimportant compared to the other climate and socio-economic drivers.

7.11.2 Results and discussion

Taking the scenarios for milk prices changes in Table 7.31, and weighting the £2.50 cost by these over the scenarios leads to a revised estimate of cost as shown in Table 7.28. Costs range from zero to £21m depending on the scenario. Effects of changes in subsidies are assumed to be unimportant compared to the other climate and socio-economic drivers.

Table 7.31 Marginal damage from loss of dairy fertility (£million/year) due to climate change

Results for the 2020s, 2050s and 2080s, compared to 1961-1990 climate. 2010 prices, adjusted for socioeconomic change in prices, with no discounting)

	Low			Medium			High		
	p10	p50	p90	p10	p50	p90	p10	p50	p90
2020	0	0	0	0	0	3	0	0	0
2050	0	1	15	0	1	14	0	1	14
2080	0	2	25	0	3	28	0	5	31

7.12 Climate impact on livestock health (AG8)

7.12.1 Outputs from the Risk Assessment

The projected impact of heat stress on livestock populations was estimated to be small, with the modelling work indicating that there would be only 3 days per annum when livestock would be considered stressed under the worst-case scenario, with a negligible effect on mortality. This relates to a change in average temperature and not to extremes such as heatwaves – where mortality rates could be much higher.

The negligible impact means we expect a negligible economic cost for this climate change impact.

7.13 Grassland Productivity (AG10)

This report looks at the economic impact of climate change on grassland yields in the UK. The impacts on yields are expressed in monetary terms as this is a common metric that allows the direct comparison of climate change impacts against other agricultural impacts, as well as other impacts in different sectors.

The paper is set out as follows. First, the outputs from the risk assessment are presented and discussed, including a discussion of the nature of these results and assumptions. Following this, the methodology and the unit values employed to estimate the impacts in monetary terms are outlined. Finally the monetisation results are presented.

Consistent with other sectors, the indicative results below are presented in terms of constant (2010 prices) for two of the three time periods considered in the CCRA i.e. the 2020s and the 2050s. The results are presented in this way to facilitate direct comparison.

At this stage, we have not presented the values below as a present value or equivalent annual cost. However, the use of the values in subsequent analysis, for example in looking at the costs and benefits of adaptation options to reduce these impacts, would need to work with present values. For this, the values below would need to be adjusted and discounted.

7.13.1 Outputs from the Risk Assessment

The output from the physical risk assessment is the percentage change in the yield of grass due to climate change based on the UKCP09 projections. On this basis, the report notes that grass yields in England and Wales are projected to increase by about 11 percent to 31 percent for the 2020s medium emissions scenario and 22 percent to 51 percent for the 2050s medium emissions scenario. The report also notes that similar changes are likely in Scotland and Northern Ireland but increases in yield may exceed those of England as water stress is likely to be less limiting in these countries. Based on the above outputs from the risk assessment, we use the percentage change in yields projected for England and Wales for the 2020s and the 2050s for the whole of the UK.

The physical risk assessment also provides the percentage change in grass yields based on the UKCIP98 projections for the 2020s, 2050s and 2080s for four sites in England and Wales, namely, lowland west Wales, lowland south-west England, south-central/western England and north-west England uplands. The percentage changes in grass yields reported in the four sites were based on different levels of management (i.e. amount of fertiliser input) and are for different types of grass (e.g. ryegrass ley, red clover-based ley and white clover-based ley etc.). In order to value these yield changes we would have needed information on the total number of hectares that is under cultivation for each of these types of grasses and the respective prices of these grasses. We were unable to source this information from publicly available government records, thus we were unable to proceed with this analysis. Moreover these yield changes are based on UKCIP98 projections whereas all the other metrics are based on the UKCP09 projections. Therefore in order to maintain consistency with the monetisation of other metrics, we value the changes in grass yields based on the UKCP09 projections in this analysis.

A number of assumptions are important in interpreting these yield results, especially in the context of the subsequent monetisation exercise. These do not detract from the study, but are important in understanding what is included and excluded.

The analysis is undertaken for a scenario of future climate change only: it does not include the effects of future socio-economic change (land-use change, agricultural policy including reform, international agricultural development, mitigation policy for agriculture, etc.). It also does not include baseline productivity increases from technological advance, water and irrigation, new species (including GMOs), etc.

The analysis only considers the direct primary effect of a number of climate variables on yield, using a direct relationship. However, in practice the impact of climate on is likely to be much more complex. For example, the relationship between climate, grass growth and yield are complicated by a large number of climate, soil and crop management factors, the effects on pests and pathogens, extreme events and seasonal to daily change, etc.

The analysis assumes no adaptation, including no farm level autonomous adaptation – in practice farm responses would reduce impacts through a number of local responses (e.g. alternative cultivars, different species, etc.).

The analysis also does not consider the effects of climate change internationally, including the differences between low and high climate scenarios.

7.13.2 Methodology and Unit Values

The basic approach to the costing analysis is, for each impact category considered, to multiply relevant unit values (market prices or non-market prices) by the physical impacts identified in earlier sections of this sector report.

The first step is to establish the baseline grass production in the UK. In order to do this, we require information on the baseline grass yield in the UK and the total land area in the UK that is used for grass production.

The CCRA report provides information on the baseline grass (herbage dry matter) yields in tonnes per hectare for various sites in the UK and types of grasses based on different management practices (see above for a discussion of this). Due to the lack of other information on baseline grass yields in the UK, we use the average baseline grass yield across all sites as the baseline grass yield for all types of grasses in the UK. This is estimated to be 8.78 tonnes per hectare during the period 1970-1990. Data on the area of land classed as 'grassland' comes from the agricultural statistics for the UK published by DEFRA (2010). Land used for temporary grass under 5 years old and permanent grass over 5 years old totals 7,157 thousand hectares in 2010 in the UK. Disaggregating by country, the area of land under the sum of both temporary grass under 5 years old and permanent grass over 5 years old in England[38], Wales[39], Scotland[40] and Northern Ireland[41] is 3,875 thousand hectares, 1,021 thousand hectares, 1,377 thousand hectares and 779 thousand hectares respectively in 2010. Multiplying the baseline grass yield by the land area used for grass production gives an estimate of the baseline grass production in the UK, i.e. 62,823 thousand tonnes in 2010. Similarly, the baseline grass production in England, Wales, Scotland and Northern Ireland are estimated as 34,014 thousand tonnes, 8,962 thousand tonnes, 12,089 thousand tonnes and 6,841 thousand tonnes respectively in 2010.

The second step is to value the baseline grass production by adopting suitable market values of grass. Two prices are available:

1. Price of grassland hay – This information comes from DEFRA's feeding stuff price statistics[42]. The average price of grassland hay for the year 2010 is £95.92 per tonne.
2. Price of grass silage – This information comes from Nix (2012). Here the price of grass silage is reported as £35 per tonne[43].

Based on the above two unit values of grass, the baseline (2010) monetary value of grass production in the UK is estimated to be between £2,199m to £6,026m in 2010 prices. Disaggregating by country, the baseline monetary value of grass production is estimated to be between: £1,190m - £3,263m in England; £314m – £860m in Wales; £423m – £1,160m in Scotland; and £239m – £656m in Northern Ireland. An implicit assumption being made, therefore, is that all grass is able to be used for these purposes of grassland hay and grass silage.

The third step is to calculate the monetary value of the change in grass yields as a result of climate change in the 2020s and the 2050s. To value the changes in grass yields, the study has adopted a partial equilibrium approach. This applies direct yield prices only (see later discussion for the caveats with this approach). The percentage

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[38] See http://www.defra.gov.uk/statistics/files/defra-stats-foodfarm-landuselivestock-june-results-englandtimeseries1109151.xls
[39] This includes permanent grass only. See http://wales.gov.uk/docs/statistics/2011/110622farmfacts11en.pdf
[40] See http://www.scotland.gov.uk/Resource/Doc/358779/0121282.xls
[41] See http://www.dardni.gov.uk/june11-prelim-press-release_tables.pdf
[42] http://www.defra.gov.uk/statistics/files/defra-stats-foodfarm-farmgate-commodity-feedingstuff-110620.xls
[43] We assume this to be in 2010 prices as it is not specified what year these prices relate to in the book.

changes in grass yields projected for the 2020s and the 2050s in the risk assessment are used to do this, i.e. 11-31 percent change in the 2020s and 22-51 percent change in the 2050s. The monetary values are also reported based on the two sets of prices discussed above, i.e. price of grassland hay and price of grass silage. Note that these prices represent the current prices of grass and are not adjusted for projected price changes in future time periods. The results are reported in the next section.

7.13.3 Results and Discussion

The baseline monetary value of grassland production in the UK was estimated to be between £2,199m to £6,026m in 2010 prices (based on the grass silage price and grassland hay price respectively). Applying the percentage changes in grass yields to these baseline monetary values gives the change in monetary value of grass production in the UK due to climate change. The results are presented in Table 7.32.

Table 7.32 Change in monetary value of grass production in the UK due to climate change (£m, in 2010 prices)

	2020s	2050s
Change in monetary value based on grass silage price	242 (11%)	484 (22%)
Change in monetary value based on grassland hay price	663 (11%)	1,326 (22%)
Change in monetary value based on grass silage price	682 (31%)	1,121 (51%)
Change in monetary value based on grassland hay price	1,868 (31%)	3,073 (51%)

Note: percentages in parentheses represent projected percentage changes in grass yields in the future time periods from the baseline (1970-1990).

The change in the monetary value of grass production in the UK for an 11 percent increase in the yield of grass is estimated to be between £242m to £663m for the 2020s. This is estimated to be between £682m to £1,868m for a 31 percent increase in grass yield for the 2020s. Thus, the change in monetary value of grass production in the UK due to climate change is estimated to be between £242m to £1,868m for the 2020s.

The change in the monetary value of grass production in the UK for a 22 percent increase in the yield of grass is estimated to be between £484m to £1,326m for the 2050s. This is estimated to be between £1,121m to £3,073m for a 51 percent increase in grass yield for the 2050s. Thus, the change in monetary value of grass production in the UK due to climate change is estimated to be between £484m to £3,073m for the 2050s.

The changes in the monetary values of grass production disaggregated by the specific countries are presented in Tables 7.33, 7.34, 7.35 and 7.36 for England, Wales, Scotland and Northern Ireland respectively.

The change in monetary value of grass production in England due to climate change is estimated to be: between £131m to £1,011m for the 2020s; and between £262m to £1,664m for the 2050s.

Table 7.33 Change in monetary value of grass production in England due to climate change (£m, in 2010 prices)

	2020s	2050s
Change in monetary value based on grass silage price	131 (11%)	262 (22%)
Change in monetary value based on grassland hay price	359 (11%)	718 (22%)
Change in monetary value based on grass silage price	369 (31%)	607 (51%)
Change in monetary value based on grassland hay price	1,011 (31%)	1,664 (51%)

Note: percentages in parentheses represent projected percentage changes in grass yields in the future time periods from the baseline (1970-1990).

The change in monetary value of grass production in Wales due to climate change is estimated to be: between £35m to £266m for the 2020s; and between £69m to £438m for the 2050s.

Table 7.34 Change in monetary value of grass production in Wales due to climate change (£m, in 2010 prices)

	2020s	2050s
Change in monetary value based on grass silage price	35 (11%)	69 (22%)
Change in monetary value based on grassland hay price	95 (11%)	189 (22%)
Change in monetary value based on grass silage price	97 (31%)	160 (51%)
Change in monetary value based on grassland hay price	266 (31%)	438 (51%)

Note: percentages in parentheses represent projected percentage changes in grass yields in the future time periods from the baseline (1970-1990).

The change in monetary value of grass production in Scotland due to climate change is estimated to be: between £47m to £359m for the 2020s; and between £93m to £591m for the 2050s.

Table 7.35 Change in monetary value of grass production in Scotland due to climate change (£m, in 2010 prices)

	2020s	2050s
Change in monetary value based on grass silage price	47 (11%)	93 (22%)
Change in monetary value based on grassland hay price	128 (11%)	255 (22%)
Change in monetary value based on grass silage price	131 (31%)	216 (51%)
Change in monetary value based on grassland hay price	359 (31%)	591 (51%)

Note: percentages in parentheses represent projected percentage changes in grass yields in the future time periods from the baseline (1970-1990).

The change in monetary value of grass production in Northern Ireland due to climate change is estimated to be: between £26m to £203m for the 2020s; and between £53m to £335m for the 2050s.

Table 7.36 Change in monetary value of grass production in Northern Ireland due to climate change (£m, in 2010 prices)

	2020s	**2050s**
Change in monetary value based on grass silage price	26 (11%)	53 (22%)
Change in monetary value based on grassland hay price	72 (11%)	144 (22%)
Change in monetary value based on grass silage price	74 (31%)	122 (51%)
Change in monetary value based on grassland hay price	203 (31%)	335 (51%)

Note: percentages in parentheses represent projected percentage changes in grass yields in the future time periods from the baseline (1970-1990).

Among the four UK countries, the change in the monetary value of grass production due to climate change is the highest in England, followed by Scotland, Wales and Northern Ireland, which has the smallest change in magnitude. This of course mirrors the trends in the current area under grassland production in these countries.

It is important to note that the above projected changes do not represent welfare changes since they are not based on the 'gross margin', i.e. the revenue minus the cost. Whilst we do not have the data for gross margins for grass, cereals indicate they are typically 0.3 – 0.5 of the changes projected above (depending on the crop).

The Climate Change Risk Assessment for the agricultural cost analysis uses a ranking system for the monetary impacts of climate change. Monetary impacts are ranked as: 'Low' if the valuation falls between £1-9m per annum; 'Medium' if the valuation is between £10-99m per annum; 'High' if it is between £100-999m per annum; and 'Very High' if the valuation is £1000m or more per annum. Based on this ranking, the monetary impacts of climate change on grass production estimated above for the UK would fall into the High category, using the gross margin-adjusted totals. Disaggregating by country, the estimated monetary impacts of climate change on grass production fall predominantly into the High category for England, whereas they predominantly fall into the Medium category for Scotland, Wales and Northern Ireland, using the gross margin-adjusted totals.

It should be emphasised that several strong assumptions have been adopted in making these estimates. In particular:

- **the yield changes to grass projected under climate change are assumed to be applicable to all** temporary grass under 5 years old and permanent grass over 5 years old in the UK. No differentiation according to type of grass has been possible.

- the prices used to value the grass are informed by a range generated from the prices derived for hay and silage. It is therefore assumed that all UK grass yields affected by climate change are capable of being used for one, at least, of these purposes. Clearly, if this is not the case, the prices are likely to over-estimate the value of this grass.

7.14 Methodological limitations

The methodology adopted in this report, drawing on public domain datasets and deriving national risk metrics, has a number of inherent limitations which need to be recognised. The main limitations are summarised briefly below:

The risk metrics assumed a direct relationship between a variable and the climate, but in reality the impact of climate on an underlying change is likely to be much more complex. For example, regarding the yield metric, in reality the relationship between climate, crop growth and yield are complicated by a large number of climate, soil and crop management factors, all of which were implicitly included in the response function.

Lack of a clear agro-economic policy for the baseline and future – for example, the future changes in agricultural productivity (yield) and water use (abstraction) excluded any consideration of the underlying economic conditions under which crop production might be practiced.

There are a raft of international drivers that could affect future UK agriculture including the consequences for world trade, affecting both demand for, and supply and prices of agricultural commodities in global and regional markets and an increased volatility of market conditions. There are also the actions being taken by governments to address climate change effects – with consequences for agricultural markets, including protectionism. There is also likely to be greater instability in international food and energy prices, affecting fuel costs and fertiliser use, and greater global water scarcity with consequent impacts on food production especially in relation to food exports to the UK from Southern Europe (Yang *et al.*, 2007). Other international risks also include:

- Agri-support funds for competitors. For example, European funds for the modernisation of southern European irrigation schemes could provide competitive advantage over UK growers.
- The conversion of agricultural land from food production to production of bio fuel and raw materials. The use of agricultural food commodities (such as wheat or sugarcane) for bio fuels rather than for human consumption could impact on UK food imports and prices.
- Internationally agreed GHG mitigation policies may inadvertently affect agriculture, through for example, policies to reduce energy use which would impact on fertiliser production.
- Migration - climate change could increase the inward flux of migrants from drought affected areas in northern Africa and southern Europe northwards towards climatically 'safe havens' such as the UK, with possible impacts on local demand for land for housing, food and natural resources.

There are also likely to be societal factors, such as public and political resistance to the use of GMOs that could help to adapt to environmental change; changing dietary preferences towards healthy eating via for example, the Food Standards Agency 'Eatwell Plate' campaign; increasing demand for year-round fresh supplies favouring food imports; and competition for land and water for development and non-agricultural use, such as nature conservation and recreation. All of these socio-economic factors were excluded from the risk metric approach, but clearly impose significant impacts on the future direction and intensity of UK agriculture.

The most significant economic impacts on-farm relate to CAP reform, as it could affect farm income support, compliance requirements and incentives for environmental sensitive farming. Rising production costs for water, energy, labour and fertiliser, coupled with increasing risks associated with infrastructure damage due to flooding are other sources of economic risk. Much depends whether these increased costs are offset by higher commodity prices arising from strong global demand - the latest OECD-FAO (2010) forecast is that average crop prices over the next ten years will be 15-40% higher in real terms relative to 1997-2006. The main environmental impacts off-farm relate to changes in water availability due to low surface water flows and groundwater levels, increasing demands for water from other sectors, increasing environmental regulation and abstraction control, and the risks associated with GMO cultivation (Knox *et al*., 2010c). These factors were all excluded from the assessment, but need to be integrated into subsequent risk assessments.

The study deliberately focussed on the agronomic aspects of climate change by using the reference crops and developing yield/productivity metrics. However, it is important to stress that climate change is also likely to impact on the economics of farm management and particularly to agribusiness approaches to risk management. For example, yields will be affected by the so-called 'yield gap', where farmers do not seek to achieve the best possible yields because it is not profitable to do so or it might be environmentally undesirable.

There is thus a need to consider the business risks to agriculture, for example, how structural shifts in agro-economic policy driven by changes in global commodity markets etc might impact on agribusiness. Some of these on-farm and off-farm economic risks were identified by Knox *et al*. (2010c)and would warrant further investigation, particularly in the context of the economics of farm level adaptation.

Care is also needed in the interpretation of the results and, in particular, extrapolation to agriculture as a whole. Whilst some results, for example wheat yields, provide an indication of how yields may change for similar crops the extrapolation of other results could provide could lead to erroneous conclusions. For example, potato was selected as a reference horticultural crop but other horticultural crops are different in character and cultivated using different methods.

Finally, the assessment ignored the range of potential adaptation options and responses available, and the institutional and regulatory barriers to their uptake by farmers. There are likely to be both positive (e.g. yield gains) and negative (e.g. increased water stress) impacts. This will inevitably require new investments in adaptive management and technology, including new collaborations between the public and private sectors, to enable UK agriculture to respond to the potential effects of climate change. But it is important that policies that lead to mal-adaptation are avoided, for example, responses by the food and farming industry to changes in temperature/water quality and water supply/soil suitability might lead to significant over-abstraction and exacerbate water stressed areas, with negative impacts on the natural as well as social/economic (rural employment) environment.

Despite extensive research on climate risks and agriculture there were no suitable integrated assessment models, such as RegIS that are capable of performing integrated assessments of the effects of climate and/or socio-economic change on agriculture and natural resources (e.g. Holman *et al*., 2008) that could have been used for this study in the same way that, for example, the Environment Agency's National Assessment of Flood Risk Assessment model was used to explore future flood risks. Given the multifunctional nature of agriculture, this is an important research gap, which it is suggested should be addressed before the next CCRA.

Adaptation is to be covered in the ongoing Economics of Climate Resilience study which follows the CCRA.

8 Adaptive Capacity

8.1 Overview

Adaptive capacity considers the ability of a system to design or implement effective adaptation strategies to adjust to information about potential climate change, to moderate potential damages, to take advantage of opportunities, or to cope with the consequences (Ballard, 2009, after IPCC, 2007). This can be considered as having two components; the inherent biological and ecological adaptive capacity of ecosystems and the socio-economic factors determining the ability to implement planned adaptation measures (Lindner *et al.*, 2010). Considering adaptive capacity is essential for adaptation planning and the CCRA project has included work in this area that will contribute to the ongoing Economics of Climate Resilience study and the National Adaptation Programme. The CCRA work on adaptive capacity focuses on structural and organisational adaptive capacity and this chapter provides an overview of the assessment approach. The subsequent sections of this chapter provide an overview of the findings from other work on adaptive capacity in the agriculture sector that has been carried out.

The climate change risks for any sector can only be fully understood by taking into account that sector's level of adaptive capacity. Climate change risks can be reduced or worsened depending on how well we recognise and prepare for them. The consequences of climate change are not limited to its direct impacts. Social and physical infrastructure, the backdrop against which climate change occurs, must also be considered. Most climate impacts still lie in the future and their consequences for economic, social and environmental systems depend not only on the impacts themselves, but also on the social and physical infrastructure within which they occur. If such infrastructure is maladapted, the economic, social or environmental cost of climate impacts may be much greater; other consequences could also be considerably more detrimental than they otherwise might have been. Avoiding maladaptation is one outcome of high adaptive capacity; high adaptive capacity lowers the negative consequence of climate impacts. Conversely, low adaptive capacity increases the negative consequences.

8.2 Assessing structural and organisational adaptive capacity

The methods used for assessing structural and organisational adaptive capacity in the CCRA are based on the PACT framework[44]. The work included a preliminary literature- and expert interview-based assessment of all eleven sectors in the CCRA. This was followed by more detailed analysis for the following sectors:

- **Business, Industry and Services** (focusing on the finance sector)
- **Transport** (focusing on road and rail)
- **Built Environment** (focusing on house building)
- **Health**
- **Biodiversity and Ecosystem Services**
- **Water**

[44] PACT was developed in the UK as one of the outcomes of the ESPACE Project (European Spatial Planning: Adapting to Climate Events): http://www.pact.co/home.

Structural adaptive capacity

The extent to which a system is free of structural barriers to change that makes it hard to devise and implement effective adaptation strategies to prepare for future impacts. This covers issues such as:

> ***Decision timescales***: This considers the lifetimes of decisions, from their conception to the point when their effects are no longer felt. The longer this period is, the greater the uncertainty as to the effects of climate change impacts. Cost-effective adaptation becomes harder. Potential climate impacts also become more extreme over longer timescales. This means that a greater scale of adaptation may need to be considered, and that the barriers to adaptation resulting from 'lock-in' to maladapted processes become more pronounced (Stafford-Smith *et al.*, 2011). Adaptive capacity is therefore lower, and maladaptation more likely, when long-lasting decisions are taken.
>
> ***Activity levels***: This considers what opportunities are there for adaptation, and on what scale. The frequency with which assets are replaced or created determines how many opportunities there will be to take action which increases adaptive capacity.[45] In addition, when a lot of asset replacement and/or new investment is expected, there will be more chances to learn from experience, which increases adaptive capacity.
>
> ***Maladaptation***: This evaluates the effect of decisions already made on adaptive capacity. Long-term previous decisions which have reduced adaptive capacity are often difficult or expensive to reverse. Such decisions were made either before climate change was recognised as an issue, or more recently as a result of poor organisational capacity. Such maladaptation makes implementing effective strategies much harder.
>
> ***Sector (or industry) complexity***: This refers to the level of interaction between stakeholders within an industry, or with outside industries and groups, that is required to facilitate effective decision-making. Complexity is higher (and adaptive capacity lower) when many stakeholders are involved in decision-making and when their agendas (e.g. their financial interests) differ substantially.

Organisational adaptive capacity

Organisational adaptive capacity is the extent to which human capacity has developed to enable organisations to devise and implement effective adaptation strategies. Effective adaptation requires decision-making that takes account of an uncertain future and avoids locking-out future options that might be more cost-effective if climate impacts become more severe, or arrive more rapidly, than expected. The PACT framework used to assess this recognises different levels of adaptation. This framework is arranged in a hierarchy of 'Response Levels' ('RLs'), as set out below, of increasing capacity[46]. These levels do not supersede one another; instead, each one builds on the experiences and practices built up in the previous response level. Organisations may need to be active on all levels for an effective adaptation programme. An RL4 organisation focused on breakthrough projects still needs to be stakeholder-responsive, for example.

> ***RL1: Core Business Focused:*** At this level, organisations see no benefit from adapting; if change is required of them, it should both be very

[45]This differs from 'Decision timescales' because investment in a sector is not continuous but varies over time, with periods of high investment being followed by periods of little or no investment.
[46] The PACT framework contains six response levels: those cited are the most relevant to the adaptation field.

straightforward to implement and also incentivised, e.g. through 'carrots' and 'sticks'.

RL2: Stakeholder Responsive: At early stages of adaptation, organisations lack basic skills, information, processes and also skilled people; they need very clear advice and information plus regulations that are straightforward enough to help them get started.

RL3: Efficient Management: As organisations begin to professionalise adaptation, they become more self-directing, able to handle short term impacts up to 10 years (Stafford-Smith *et al.*, 2011). They need professional networks, best practice guidelines, management standards, etc.

RL4: Breakthrough projects: When impacts beyond 10 years need to be considered, organisations may need to consider more radical adaptation options. As well as high quality support from scientists, they may need support with the costs of innovation.

RL5: Strategic Resilience: Adapting a whole region or industry for long-term climate impacts of 30 years or more requires lead organisations to develop very advanced capacity that is able to co-ordinate and support action by a wide range of actors over programmes that are likely to last for many years.

8.3 Adaptive Capacity in the Agriculture Sector

Agricultural businesses have always faced a high degree of uncertainty; risk management is fundamental to farming sustainability, whether explicit or implicit. The main characteristics of the structural adaptive capacity of the agriculture sector can be described thus:

- Decision timescales: The time frame of climate change is beyond the normal planning horizon of much sector activity, such as crop rotations and machinery replacement cycles, hence few of the shorter-term decisions made now will become long term maladaptations. Climate change impacts from the 2030s onwards may, however, be experienced within the lifetimes of some important longer-term decisions for farmers, leaving them potentially subject to maladaption. These long-term decisions include consideration of issues such as irrigation, water storage, crop storage, land acquisition and drainage.
- Activity levels: Farmers take frequent decisions with respect to what changes may be appropriate in the management of their farms. In the context of the framework for assessing adaptive capacity set out above, this suggests that there are regular opportunities to put in place adaptation measures and learn by doing so.
- Maladaptation: As outlined in the decision timescales point above, some of the decisions that farmers take now may influence their potential for maladaptation. This is a consideration for farms in South East England, for example, where a number of river catchments are already over-licensed or over-abstracted[47]. The pressure on the system now means that if the projections for increased drought conditions are realised in the future, the impacts of droughts on agriculture may become more severe.

[47] Quoted in Weatherhead, K. (Cranfield University), Water – future availability, demand and management, Speech to Oxford Farming Conference, 2008.

- Sector complexity: There are around 300,000 farms in the UK, ranging from international agribusinesses to family farms and from outdoor cultivation to indoor livestock. Although farmers are often able to act independently to modify the management techniques implemented on their farm, collaborative action can be needed for longer term adaptation (such as large scale water supply schemes).

The organisational adaptive capacity of the agriculture sector varies significantly, since the management approach that each farmer takes varies according to size of the farm or estate, culture, focus of the business and a range of other influences.

In such a diverse sector as farming, considerable variations in capacity are to be expected. Price fluctuations for both inputs and outputs are substantial, driven by events well outside the control of the business, and annual weather variation is unavoidable. Traditionally this uncertainty was constrained by spreading risk across different crops and livestock systems in mixed farming systems, but increasingly businesses are making careful use of contracts and futures markets and/or including farming as part of a larger investment portfolio, ensuring sufficient financial resilience to survive the “bad” years.

Underlying changes in the farming systems also occur regularly. The typical arable farm of 2010 is very different from the farms of the 1970s, themselves vastly different from the farms of the 1930s. Technological developments have revolutionised farm machinery, economic developments have led to the dominance of supermarkets as buyers in many sectors, and political developments have periodically reversed the support mechanisms from Whitehall and Brussels. Potato growing, for example, has become concentrated in far fewer businesses in just a few recent years. Agricultural businesses have had to cope with change, and have generally succeeded.

Within this context of major underlying change, adapting to climate change has been described by some farmers as “just one more thing”, and has a fairly low priority for businesses in the sector. Adaptive capacity can, however, vary significantly. Many of the horticultural businesses for example are highly innovative, and can adapt quickly. Some sub-sectors are less able to adapt, or may be able to adapt to some changes but not others. Small family run units in marginal farming areas are likely to have fewer resources to draw on to implement adaptation measures. Hill farming could quickly respond to warmer temperatures and increased grass growth by increasing stocking rates; however if sheep farming becomes impractical or uneconomic due to higher rainfall, there are few or no alternative farming options available.

Support in developing capacity to adapt in the farming sector is being provided from a number of sources at present:

- The NFU and others (including the Environment Agency and Defra) has been working to promote cooperation of the type necessary to address common water issues, for example by supporting Water Abstractor Groups.
- Defra’s sub-programme ‘Climate change impacts and adaptation in agriculture’ aims to estimate the likely impacts of climate change on agriculture (both production and ecosystem services) and its ability to adapt, and thence to inform policy development on adaptation to climate change.
  - A separate research review established a register of risks of climate change to farming
  - Since 2009 the risks which require policy intervention have been prioritised in discussion with stakeholders.

- A review of research on options for adaptation to climate change by the agricultural, forestry and land management sectors was undertaken in 2007/08, which pulled together results from a long running programme on the prediction of impacts and adaptation in agriculture which ended in 2005/06, as well as more recent work on the impacts of extreme events on UK agriculture.
    - Work recently completed in this programme has assessed the potential impacts on major UK crops and livestock and looked at opportunities and knowledge transfer for innovation. An ongoing project is looking to rank the risks according to timescale for adaptation.
- Adaptive capacity will also be enhanced by government support for training, variously provided across a range of funding mechanisms.
    - Programmes such as the recently announced BBSRC Advanced Training Partnerships bring farming companies together with research and training organisations. While not yet directly related to climate change adaptation, such programmes provide a resource that can be used to assist it in the future.

9 Discussion

9.1 Outcomes for each metric

The key outcomes for each metric and its response function, the implications for assessing climate change risks to agriculture, and the strength of evidence available, are summarised in Table 9.1.

Table 9.1 Summary findings for each metric

Shows estimated magnitude of risk and mid estimate (M),upper and lower bounds (U, L) for all emissions scenarios and probability levels considered

					2020s			2050s			2080s		
Metric No.	Name	Baseline	Unit	Confidence	L	M	U	L	M	U	L	M	U
AG1a	Crop yield	1961-90	%yield	M	1	1	2	1	2	3	2	3	3
AG1b	Crop yield	1961-90	%yield	M	1	2	2	2	2	3	2	3	3
AG1c	Crop yield	1961-90	%yield	L	1	1	2	1	1	2	1	1	2
AG2a	Flooding	2008	%	H	1	1	2	1	2	2	2	3	3
AG4	Aridity/drought effects	1961-88	mm	M	1	2	2	1	2	3	1	2	3
AG5	Water Abstraction	1961-90	%abstractions	M	1	2	3	1	2	3	2	2	3
AG7a	Production (Livestock)	2010	million kg	L	1	1	1	1	1	1	1	1	3
AG7b	Production (Livestock)	1961-90	Days open	L	1	1	2	1	1	2	1	1	2
AG8a	Heat stress (Livestock)	1961-90	Days	H	1	1	1	1	1	2	1	1	2
AG8b	Heat stress (Livestock)	1961-90	Cow deaths	L	1	1	2	1	1	2	1	1	2
AG9	New crop opportunities			H	1	1	1	2	2	2	3	3	3
AG10	Grassland Productivity	1961-90	%yield	M	1	1	1	1	2	2	1	2	2
AG11	Soil Erosion	1961-90	%	L	1	2	2	1	2	3	1	3	3

Key

Positive ++	3
Positive +	2
Positive	1
Negative	1
Negative -	2
Negative --	3

Crop productivity

For the crops considered in this study, the projected increases in temperature and elevated levels of CO_2 concentration is generally likely to provide more favourable conditions for crop growth and development, but only under conditions where water and nitrogen availability are non-limiting. This is consistent with evidence from pan European studies by Wolf *et al.* (2002) for potatoes and for wheat by Supit *et al.* (2010).

Whilst the derived responses were crop specific and should not be directly transposed to other crop types, the reported impacts for wheat could be broadly applied to cereals and similarly for potatoes the potential impacts could be applied with care to field-scale vegetables - recognising of course that physiological differences will mean individual crop types respond differently to climate change. This study did not set out to assess impacts across all crop sectors, but merely to identify the scale and direction of change in crop yields for the most important cereal and field-scale crops grown in the UK.

The results for potatoes should not be directly extrapolated to other horticultural crops because of differences between crops and also growing conditions. For example, unlike potatoes some horticultural crops grow above ground, and some are grown in closed production systems.

Warmer temperatures and elevated CO_2 levels would increase growth rates for arable and horticulture crops, including grasses. This may lead to higher yields for existing crops, plus the possibility of new crops becoming more viable as the northern limit of their production range extends. However, increased growth rates do not necessarily lead to higher yields if other factors become constrained. In particular, warmer temperatures and lower summer rainfall may lead to increased heat and soil moisture stress, reducing growth unless supplemental irrigation is available. Faster rates of crop growth may also reduce crop quality, for example, with grain failing to fill properly and grass digestibility falling unless grazed or cut sooner.

The yield based metric analyses for wheat, sugar beet and potatoes established reasonable relationships between productivity and climate variability. However, using these metrics to project forward lacked sufficient integration of other climate related factors (including CO_2 fertilisation, and climate extremes) and assumed unchanged farm practices regarding crop, water and nitrogen management.

Despite this forward projections suggests that the climate effects may increase sugar beet yield by 23% by the 2020s for the Medium emissions scenario, central estimate (range 11% to 37%), rising to 39% by the 2050s for the Medium emissions scenario, central estimate (range 18% to 68%) and 55% by 2080s for the Medium emissions scenario, central estimate (range 23% to 105%) for certain parts of the UK. Increases of wheat yields by 47% by the 2020s for the Medium emissions scenario, central estimate (range 22% to 76%), increasing to 79% by the 2050s for the Medium emissions scenario, central estimate (range 36% to 137%) and 111% by the 2080s for the Medium emissions scenario, central estimate (range 46% to 212%) are also estimated. Negative effects were also considered a possibility as small changes (mostly reductions) in mean main crop potato yields were seen; -2% (i.e. a reduction) by the 2020s for the Medium emissions scenario, central estimate (range -7% to +3%), -5% by the 2050s for the Medium emissions scenario, central estimate (range -12% to +3%), and -6% by the 2080s for the Medium emissions scenario, central estimate (range -18% to +2%). Larger reductions were projected for certain regions (Appendix 5) including in the East of England (which is an important area for production) due to lower summer rainfall.[48]

Whilst the metrics provided useful data, robust estimates of the risks to productivity should be based on bio-physical (crop) modelling approaches. At present, for sugar beet, wheat and similarly for other important crops grown in the UK, such as soft fruit, there is a lack of research on the impacts of climate change using the latest UKCP09 climatology, particularly in terms of climate uncertainty and weather extremes.

Other factors that should be considered when assessing future yields include the economics and business aspects of farm management, and potential adaptation. For example, farmers may not seek to achieve the best possible yields because it is not profitable to do so or it might be environmentally undesirable.

Flood risks to agriculture

Agricultural land is at risk from flooding from rivers, coasts and estuaries and groundwater. Response functions for agricultural land at risk of frequent tidal and river flooding were based on GIS analysis of flood risk areas combined with spatial

[48] However, this finding could be contradicted by more detailed biophysical models that project an increase in yield due to CO_2 fertilisation effects.

assessments of land suitability using the Agricultural Land Classification (ALC) to estimate the areas of agricultural land flooded from the sea with return periods of less than 1 in 3 years, 3-5 years and 5-10 years, and for ALC grades 1 to 3 (horticulture/arable) and 4 and 5 (grassland/grazing), for selected 2020s, 2050s and 2080s scenarios.

In the near term (2020s) increases in risk of over 30% are projected in the area flooded at frequencies of once in ten years on average or more frequently. The largest increase in flood risk is a more than two-fold increase in the area affected for arable and horticultural land in the 3 to 5 year class. This means that that there is a large area of good quality land that could flood more frequently by the 2020s.

In the longer term (2050s, 2080s) there are large projected increases in the areas of agricultural land at risk of being flooded from rivers or the sea on a regular basis (once in three years or more frequently on average) although the range in projections for different climate change scenarios is wide. Good quality agricultural land that is flooded regularly from the sea could become untenable for normal agricultural use because of salinity effects. There are also large projected increases in the amount of grassland and rough grazing flooded regularly from the sea, although some of this land may still be used for grazing.

Surface water flooding and waterlogging are also serious problems for agriculture. However these have not been analysed because of a lack of suitable information on present day and future risk.

Crop pests and disease

For each reference crop, the most significant climate related disease was identified and a 'marker' disease defined. The following were used - yellow rust (wheat), beet mild yellow virus, BMYV (sugar beet) and blight (potatoes). Unfortunately, despite long-term historical data relating to each 'marker' disease being obtained, no significant relationships were found between incidence of each and climate variability - the underlying reason being that disease treatment methods and improved crop agronomy within each of these crop sectors has significantly reduced disease expression and buffered the effects of climate variability on disease prevalence. Based on a qualitative assessment, the evidence that climate change will increase crop pests and disease is weak. However, the interactions between crops, pests and pathogens are complex and currently poorly understood in the context of climate change (Evidence Report, 2012).

Aridity and agroclimate

National level changes in aridity using potential soil moisture deficit (PSMD) as an agroclimate index suggest mean increases of approximately 40% for the 2020s (range of -33% to 116% p10 to p90), rising to approximately 90% (range of -7% to 183% for Low p10 to High p90) in the 2050s and to 120% (range of 4% to 277% Low p10 to High p90) by the 2080s, for a p50 medium emissions scenario, but with significant variability, depending on the probability and emissions scenario. The combined changes in rainfall and evapotranspiration (ET) would increase aridity levels and hence the need for supplemental irrigation, particularly on high-value crops where premium quality production is the primary objective. Maps showing the spatial changes in agroclimate across the UK were produced and highlight areas of high aridity which generally increase in area and magnitude, spreading across England from the South and East towards the North and West.

Mechler *et al.* (2010) studied the impact of extreme events on crop yield in UK agricultural production since the 1970s.

- Some current crop production systems have shown some adaptation to these events and others have not.

- Each subsequent drought or heat wave (1975/6, 1983/4, 1992, 1995, 2003, 2006) resulted in a lower impact than the previous event on potatoes and oilseed rape yield, showing a gradual adaptation.
- Crops such as barley did not show any adaptation. However, any of the events which occurred after the first drought (1975/6) had similar consequences in terms of lost yields.
- The agricultural sector responded to the 1975/76 event by putting in place systems to avoid similar damages from possible future similar events. In potatoes for example, the installation of irrigation systems started to be popular after this drought.

Access to water resources is a key factor for adaptation in the arable and horticultural sectors. If growers can not get access to water, through storage schemes or abstraction licenses they may need to relocate to areas with water available, diversify into different crops or find other methods of adapting to greater risk of drought (Evidence Report, 2012).

However, evidence and knowledge gaps exist. The current climate models used cannot predict drought as accurately as desired. Additionally, the crop adaption to change is not fully understood as Semenov (2009) suggests that wheat may mature earlier in a warmer climate, avoiding severe summer droughts, resulting in lower yield losses than projected.

Agricultural water demand

By combining historical irrigation abstraction data from the Environment Agency with data on agroclimatic variability (PSMD), future average projected changes in agricultural water demand were produced. Projections of approximately 15% (range of -20% to 52% for p10 to p90) for the medium 2020s scenario, rising to 35% by the 2050s (range of -9% to 75% for Low p10 to High p90) and 50% by the 2080s (range of -4% to 110% for Low p10 to High p90) across England and Wales regions, may be expected. These findings are consistent albeit with much lower values than research by Weatherhead *et al.* (2008) who considered future agricultural demands under a range of socio-economic scenarios of between +22% to +180%. Socio-economic changes would thus add further pressure on underlying increasing in water abstraction, potentially more than doubling the increase in agricultural demand over and above that due to climate change.

Reductions in summer river flows, as characterised by the Q95 Low Flow metric, could lead to restrictions on agricultural abstractions. For the 2050s there may be an 8% reduction (i.e. -8%, with a range of -4% to -9%) in abstraction allowed in the Anglian river basin region, which has the greatest demands and a 17% reduction (i.e. -17% with a range of -7% to -17%) in the South West England river basin region (Water Sector Report). This is an important measure as licences from unsustainable sources will be limited in future with consequences for farmers who may not use licences under the current climate but could need them in the future in order to grow horticultural crops. Conflicts with other water users could also be likely in areas that experience increasing water scarcity due to climate change (Evidence Report, 2012). Reduction in flows also has an impact on water quality and the WFD targets.

Livestock production

The metric analysis for livestock was based on modelling the production system, including the effects of thermal humidity and heat stress on dairy milk production. It is important to note that the losses defined in this study related to the average change in climate and do not include extreme weather events that may result in higher numbers of heat stress losses (e.g., heat wave, drought). Overall, the current UK climate does not result in losses from dairy system production or pose a major risk to dairy production and this is likely to continue in the near term (2020s).

The projections going forward suggest that heat stress related losses only begin to become relevant by the 2050s. For example, for the 2050s (p50 Medium emissions) central estimate the percentage loss of national milk production, due to heat stress is projected to be 3 million kg/annum, less than 0.03% of UK current milk production but there would be costs related to declines in herd fertility. In the longer term (2050s, 2080s) consequences are projected to become more significant under some scenarios with more humid and hotter conditions to the extent that they would impact on farmers operating on low margins and regional economies that rely on export of dairy products.

The livestock production model indicates small and largely insignificant projected increases in the number of days of heat stress for typical dairy herds. For example, in the worst case scenario (p90 High emissions scenario in the 2080s) the model indicates a maximum of 3 days per annum where livestock would be classified as stressed. Consequently the expected number of deaths from heat stress is considered negligible and the overall risk for the production system is related to the metric on decline in milk production and fertility.

Changes to crops

Climate change provides the opportunity to introduce new crops that may be more suited to the changing climate. These could include, for example, new food crops (e.g. blueberries, maize, table grapes), new energy crops (for biogas, biomass or bioethanol production), new pharmaceutical crops (drugs or cosmetics), and new industrial crops (e.g. for biopolymers, biolubricants, oil, fibre, paper and pulp).

Grassland productivity

An assessment of increases in grassland productivity has been made for four UK sites (West Wales, Central Devon, Gloucestershire and Cumbria). These results provide an indication of the sensitivity of different systems to warmer conditions and suggest a 15 percent increase in yield per degree of warming for conditions with adequate water and nitrogen.

This relationship can be used, within reason, to scale and estimate possible outcomes for UKCP09 projections. On this basis grass yields are projected to increase in the UK with suggested increases in yield of between approximately 35% (with a range of 15 to 54%) in the 2050s, although in some parts of the UK this increase may be limited by drier conditions associated with higher temperatures. Increases of yield in Scotland and Northern Ireland may exceed those of England as water stress is likely to be less limiting in these countries.

Soil erosion

Soil erosivity has been used to indicate how soil erosion might change. Erosivity is related to kinetic energy of rainfall which in turn is related to the duration and intensity of rainfall. The results show increases in soil erosivity throughout the UK. However this parameter must be considered alongside other factors such as soil type and vulnerability before an assessment of soil erosion can be made.

Changes to lowland and upland farming

Changes in climatic conditions may lead to changes in farming conditions in both lowland and upland areas. As yields increase the viability of farming marginal land could increase, leading to increases in the area of land used for agriculture and changes to the type of farming in some areas.

For example, grassland productivity in upland areas could increase and some upland areas may become more suited to arable crops. This increase in the intensity of farming in upland areas could lead to adverse consequences including an increase in soil erosion and damage to biodiversity.

Other factors such as concerns regarding methane emissions could also affect upland based production systems which could affect the amount of upland grazing. Any increase in machinery use could lead to increased soil erosion, returning stored carbon to the atmosphere and thus impacting on GHG emissions. The projected reductions in soil moisture content for Scotland could further exacerbate this problem. In peatlands, drier soils may lead to a reduction in Sphagnum mosses; peat-forming vegetation. This could be a particular problem for the south-east of Scotland, where drier conditions combined with land more suited to agriculture (for livestock or cropping) could combine and return greater amounts of stored carbon to the atmosphere.

The areas most vulnerable as a result of climate change are those where the peat has been degraded through loss of vegetation and structure. Of the 6.9 billion tonnes of soil organic carbon in Scotland, 4.5 billion tonnes are held in peatlands, blanket bog, lowland raised bogs and fen (Smith *et al.*, 2007a.b). In reviewing current evidence and model predictions, Smith *et al.*, (2007a) suggest that land use change and management have been the more significant historical drivers of change in soil organic matter while climate change will likely become more significant over time. It has been projected that up to 50% of the suitable climate space for peat-forming vegetation could become vulnerable by the 2050s (Biodiversity and Ecosystem Sector Report), although western Scotland is the least vulnerable. If this corresponds to an actual loss in peat-forming vegetation, then peatlands which are vital for regulating services such as water flow, quality and carbon storage, will be severely degraded or lost. This loss may result in the release of GHG such as carbon dioxide and methane. However, the processes that surround the flow of carbon between soils and the atmosphere are complex and not fully understood.

9.2 Other impacts

UK agriculture – global context, future 'non-climate' risks and outlook
The UK is a small player in the international agricultural sector, essentially a 'price taker' at least under a market driven model. The prospects facing UK farmers will depend largely on global conditions, and particularly EU agriculture, where most UK agricultural trade is now based. The biggest threat to future UK agriculture is likely to be centred around energy prices, particularly for 'high input-high output' energy intensive production systems. In addition, there will be major challenges in meeting soil, water, conservation and animal, worker and consumer welfare standards. The UK will thus become a high cost provider, needing high prices to keep farming, if CAP reform affects income support. Lowland farms will polarise even more, serious farmers and hobbyists, and then other land uses –unless there are regional /local policies to counteract this, such as in the uplands. Climate change is thus likely to exacerbate production fluctuations and lead to the return of buffer stocks and intervention buying – there are signs that this phenomenon, which was last seen in the 1930s, is re-occurring.

Given the multifunctional nature of UK agriculture, many of the challenges facing the sector can be linked to socio economic, environmental and technological challenges – with climate change being an additive impact, rather than necessarily the driving force of change (Table 9.2). The majority of risks occur 'off-farm' and impact on farmers via various national and European agro-economic policy interventions; the increasing obligation of environmental regulations; limitations in the availability of finance; fluctuating exchange rates; and the relative power of supermarkets as these affect the operation of markets, including requirements for auditing and traceability (Knox *et al*., 2010c).

Table 9.2 Summary of 'non-climate' risks to UK agricultural crop production, grouped according to whether they are economic, technological and environmental, and off or on-farm (from Knox *et al*., 2010c)

	Economic risks	Environmental risks	Technological risks
Off Farm	Impacts of European agro-economic policy and CAP reform on business viability Impacts of instability in commodity markets at global and European levels on UK crop prices Foreign exchange rates, especially £:Euro and £:US$ ratios Supermarket pressures on the food supply chain Cheap overseas food imports High costs of borrowing limiting investment in new technologies and mechanisation Reduced availability of loans and finance reduce investment and promote risk-avoidance in decision making Higher UK taxes deter on-farm investment Rising environmental costs associated with charges for water and pollution	Low river flows limiting availability and reliability of water for irrigation abstraction Environmental regulation (e.g. Birds, Habitats Directives) constraining agricultural production Imported, or mutated indigenous, plant diseases Monoculture reduces biodiversity (increases epidemic risks) Fear of GMOs and novel technology Actual damage caused by GMOs and novel technology Unidentified, tipping points that lead to catastrophic failure of ecosystems e.g. rapid soil loss, disease epidemics	Inadequate research and development of new technologies appropriate to UK farming conditions Adoption and uptake of technological advances lags behind European competitors Improved storage and transport technologies remove barriers to imports Cross-contamination of genetically modified plant material Lack of investment in new research and technology (resulting in reduced competitiveness) Reduced number of people employed in the agricultural sector with a risk of dislocation to urban areas
On-farm	Energy costs for crop production Rising labour costs and labour supply problems Rising environmental costs relating to meeting supermarket grower protocols Rising costs of fertiliser (linked to energy costs) and seed Reduced expenditure on flood defence and land drainage infrastructure	Soil degradation: compaction (heavy machinery, inappropriate management) /salinity build up (excessive use of fertilisers) Excessive use of pesticides and herbicides (risks of soil, air and water pollution affecting human and animals health and disrupting the pray-predator equilibrium) New diseases	Reduced standards of land drainage (including flood defence) Inadequate knowledge transfer and understanding of new technologies which limit technology uptake Rising cost of energy on which technology is dependent (affect irrigation abstraction and machinery used in agriculture/food processing)

The most significant economic impacts 'on-farm' relate to CAP reform, as it could affect farm income support, compliance requirements and incentives for environmental sensitive farming. Rising production costs for water, energy, labour and fertiliser, coupled with increasing risks associated with infrastructure damage due to flooding are other sources of economic risk. Much depends whether these increased costs are offset by higher commodity prices arising from strong global demand - the latest OECD-FAO (2010) forecast is that average crop prices over the next ten years will be 15-40% higher in real terms relative to 1997-2006. The main environmental impacts off-farm relate to changes in water availability due to low surface water flows and groundwater levels, increasing demands for water from other sectors, increasing environmental regulation and abstraction control, and the risks associated with GMO cultivation (Knox *et al*., 2010c).

The on-farm risks relate mainly to the control of the use of pesticides and fertilisers and their consequent impacts on local environments via diffuse water pollution, the risks of new disease and poor soil management. The main technological risks off-farm are insufficient R&D investment in agriculture (Royal Society, 2009), coupled with a lag in technological uptake compared to European neighbours. A decline in the capacity of skills in UK agriculture, as well as the number of people willing to work on the land are also constraints (Spedding, 2009) common to other parts of Europe and North America (IAASTD, 2009). On-farm technological risks relate to the observed widespread deterioration in maintenance of land drains, inadequate staff training and the rising costs of energy on which new technologies are dependant.

In addition, there are a raft of international drivers that will affect UK agriculture including the consequences for world trade, affecting both demand for, and supply and prices of agricultural commodities in global and regional markets and an increased volatility of market conditions. There are also the actions being taken by governments to address climate change effects – with consequences for agricultural markets, including protectionism. There is also likely to be greater instability in international food and energy prices, affecting fuel costs and fertiliser use, and greater global water scarcity with consequent impacts on food production especially in relation to food exports to the UK from Southern Europe (Yang *et al*., 2007). Other international risks also include:

- Agri-support funds for competitors. For example, European funds for the modernisation of southern European irrigation schemes could provide competitive advantage over UK growers.
- The conversion of agricultural land from food production to production of biofuel and raw materials. The use of agricultural food commodities (such as wheat or sugarcane) for bio fuels rather than for human consumption could impact on UK food imports and prices.
- Internationally agreed GHG mitigation policies may inadvertently affect agriculture, through for example, policies to reduce energy use which will impact on fertiliser production.
- Migration - climate change could increase the inward flux of migrants from drought affected areas in North Africa and southern Europe northwards towards climatically 'safe havens' such as the UK, with possible impacts on local demand for land for housing, food and natural resources.

There are also likely to be societal factors, such as public and political resistance to the use of GMOs that could help to adapt to environmental change; changing dietary preferences towards healthy eating via for example, the Food Standards Agency 'Eatwell Plate' campaign; increasing demand for year-round fresh supplies favouring food imports; and competition for land and water for development and non-agricultural use, such as nature conservation and recreation.

Small businesses and family farms with limited capacity to adapt will be most vulnerable. Conversely, large horticultural agribusinesses, with high investment capital at stake, may select risk-averse options that minimise the 'regret' under a range of possible future outcomes (e.g. high flow storage reservoirs). Whilst such investments may be marginally beneficial now, they become more attractive if the value of longer term resilience and security is taken into account. Some crop sectors, such salad and soft fruit production, may be more vulnerable since they are highly seasonal, and dependant on consumer demands and the weather. Other crops such as potatoes and field vegetables may be less vulnerable as their consumption patterns are less sensitive to the ambient weather. Given the uncertainty and long time scales, most responses to climate change will require combinations of adaptive management and technology. Developing this adaptive capacity will involve a commitment of resources now, both by the private and public sectors, in order to enhance future ability to cope with the uncertain impacts of future climate change. But for all these coping strategies there are both barriers and enablers to adaptation.

Adaptation barriers:

- Very high degree of short to medium term uncertainty in agricultural policy and markets, including speculative agricultural commodity trading.
- Negative impacts of adaptation in other sectors – for example, the implementation of adaptation measures to address the increased risks to urban areas from river flooding using agricultural floodplain land for attenuation could impact on crop productivity and land value.
- Land use restrictions e.g. due to EU regulations and/or agri-environmental support schemes could hamper crop diversification.
- Inflexibility in the abstraction licensing regime may limit the potential for water trading and allocation of water to high value cropping.
- Poor availability of finance and investment in research and technology development.
- Restrictions from Planning Regulations and development control.
- Attempts to preserve 'existing' environments.
- The negative impact of energy policies on food production.
- Risk of overseas food suppliers failing due to extreme events, e.g. food imports from southern Europe at risk – increased vulnerability of overseas suppliers.

Adaptation enablers:

- Mechanisms and initiatives to promote improved resource efficiency. The converse of above, including supporting education and knowledge transfer, investments, incentives, property rights, building capacity in the agriculture sector and governance systems.
- Collaborative funding of science and technology to enhance adaptability to climate change.
- Addressing market, institutional and regulatory failure, for example by payments for environmental services and conservation of natural resources.
- Water user associations providing opportunities for collective action.
- Tax breaks, for example capital allowance schemes, to invest in adaptation measures.

- Legislative enablers, such as the Flood and Water Bill which help promote adaptation by providing more flexible regulation for abstraction licensing.

Animal welfare

A detailed systematic review of the impacts of climate change on animals reared in the UK, and the relevant wider impacts, such as transport has recently been completed by Haskell *et al* (2011). A summary of the key findings from that study are provided below. The systematic review undertaken by Haskell *et al.* (2011) screened the scientific literature to explore the evidence that dealt directly with the effects of climate change including thermal stress, and the potential impacts of adaptation and mitigation strategies on animal welfare.

The impacts of climate change on animal health and welfare can be both direct and indirect. The evidence presented considered animals within specific agricultural sector classifications, as the environment and management systems used dictates to a large extent the exposure to the climate change effect.

The impacts of climate change are variable across agricultural sectors, with the greatest risks to animal welfare from climate change are during transport of animals due to extremes of temperature which, if not mitigated, can result in mortality and thermal stress. These losses also pose a significant level of inefficiency for food production. Other significant direct impacts are with animals experiencing on-farm environments outside their thermal comfort zones during, with the risk to young animals being the most significant. The conditions of animals reared outside can be adapted through improvements in provision of shelter and those reared inside with mechanical ventilation systems practices must have systems robust enough to withstand unpredictable extreme weather conditions to ensure animal welfare is maintained. The farming industry may adapt by shifts in geographical location to reduce the likelihood of animals experiencing these extremes in weather conditions on-farm.

Indirect challenges to animal welfare of climate change include more favourable conditions for the survival of certain vectors and hosts resulting in an increase in contagious disease. Similarly, conditions for certain parasites may become more favourable. However, indirect effects do not lie solely in disease risk; availability and price of grain may be impacted by arable and land use strategies which could alter nutritional availability or compromise availability of appropriate feed. Similarly, land use change could affect pasture and forage crop production.

Mitigation strategies to reduce the likelihood of climate change occurring are numerous, but the development of ‘sustainable intensification’ as a mitigation strategy has the potential to have both benefits and costs to animal welfare. Further research is needed to ascertain the costs and benefits to animal welfare of sustainable intensification.

Climate change will also affect contagious disease by making conditions more favourable for the survival of certain vectors and hosts. Ruminants are dynamic and adaptable, and are able to maintain life and productive performance in a relatively broad range of environments. There are a number of challenges that a changing climate will bring to livestock systems, particularly related to thermal challenges. These range from cold stress, which will be more prevalent due to projected wetter and windier winter months, to heat stress exacerbated by warmer summer months. They will affect livestock systems, impacting on livestock production, health and welfare and may lead to increased mortality rates due to thermal challenges year round. Some of the impacts of climate change on animal production and functionality may be exacerbated by adaptations farmers make in other areas of their farming systems, such as out wintering cattle or extended grazing, taking advantage of a longer growing season and keeping animals outdoors for longer periods, thus increasing livestock exposure to prevailing weather conditions.

The welfare of dairy cows will be most affected by an increase in temperature. Heat stress during summer months at which time the majority of the UK dairy cattle graze on pasture may be a concern as early as the 2050s in areas such as the south west of England, and of considerable concern in many dairy producing regions by the 2080s. Increasing levels of heat stress over time is projected to have an unfavourable effect on livestock survival, across all age groups. Climate related losses in production will thus be a major concern for the dairy industry. Reproductive problems are one of the main reasons for involuntary culling in the dairy herd and therefore, in regions where the impact of heat stress is large, the rate of involuntary culling may increase, having an overall negative impact on welfare. Animals grazed outdoors are also expected to suffer from high ambient temperatures, high direct and indirect solar radiation, and high humidity, particularly during heat-waves; all stressors which will negatively impact on animal welfare.

Beef cattle will be spared the major effects of heat stress, as the geographical areas in which the majority are reared (west and north UK) will not experience major temperature increases until the 2080s (High emissions scenario). Higher altitudes are less likely to experience excessive temperatures. Extreme heat-waves may have some effects, and cattle in the south and south-east may experience some heat stress. However, cold stress, from exposure to higher winter rainfall or extreme weather events, may be a major welfare issue in out-wintering systems. Producers need to prepare for such events to minimise impacts on animal welfare.

Domestication has resulted in sheep being managed in many ways that suit their human keepers. There is great diversity in the management, habitats and feedstuff. An extensive environment is often considered as synonymous with good welfare. However, merely being outside does not necessarily ensure that the environment will meet all the requirements of sheep. In the UK the most common environmental stressor is likely to be cold temperatures, often intensified by heavy precipitation and wind. The wetter winter conditions projected under climate change will increase exposure. But the literature regarding the effects on sheep is limited.

As most pigs produced for meat are reared in intensive, indoor systems the direct effects of climate change are inextricably linked to the capacity and efficiency of environmental control systems. Both increased average temperatures and an increased frequency of extreme events (both hot and cold) will potentially place increased demands upon environmental control. Where systems are of low specification the capabilities of the control systems may be exceeded and heat stress or cold stress may be imposed upon the pigs. When inadequate environmental control allows temperatures to fall in winter then the risk of cold stress will be greatest in young pig or piglets. Heat stress in summer during heat waves or extreme events will have the greatest effects upon slaughter pigs at their highest body weights. Indoor environments or housing should reduce the effects of wind, rain and solar radiation although in old or poorly constructed houses (inadequate ventilation) the latter may exacerbate the risks of heat stress in summer for older and larger pigs. Breeder pigs at low stocking densities and generally better and more modern housing conditions will be least affected directly by climate change scenarios. Geographically, the demands upon environmental control will be greatest in the north of the UK during winter and in the south and east during summer. For indoor pig production, technology is available to combat external extremes of heat and cold through appropriate heating and ventilation systems and insulation. Cooling systems in summer, misting, and direct convective cooling all provide useful adaptations, but at a cost, and if coupled with reduced stocking densities and growth rates may be economically unviable. Full air conditioning of specialist housing is a possible strategy but is expensive. Genetic selection of more heat or cold tolerant lines or strains is another possible approach, but losses in production efficiency may prove too costly. Nutritional manipulations to reduce heat production/growth rate may suffer from the same problems. Reductions in stocking densities in intensive systems involving high quality housing will be the most likely adaptations. The relocation of production to more northerly regions to reduce the risk of summer heat stress, for all systems also provides a viable strategy to minimise the risks of summer heat stress but will necessitate improved environmental control and heating during the winter periods.

Almost all meat poultry are produced in intensive systems therefore many of the risks to poultry are similar for pigs. Thus, in indoor systems the direct effects of climate change are inextricably linked to the capacity and efficiency of environmental control systems. Both increased average temperatures and an increased frequency of extreme events (both hot and cold) will potentially place increased demands upon environmental control. Where systems are of low specification the capabilities of the control systems may be exceeded and heat stress or cold stress may be imposed upon the birds. When inadequate environmental control allows temperatures to fall in winter then the risk of cold stress will be greatest in young chicks or poults. Heat stress in summer during heat waves or extreme events will have the greatest effects upon slaughter meat birds (broiler and turkeys) at their highest body weights. Indoor environments or housing should reduce the effects of wind, rain and solar radiation although in old or poorly constructed houses (inadequate ventilation) the latter may exacerbate the risks of heat stress in summer for broilers and turkeys and the former appear to be the most susceptible to heat stress mortalities, pathologies and meat quality and welfare problems. Broiler and turkey breeder hens at low stocking densities and generally better and more modern housing conditions will be least affected directly by climate change scenarios. Laying hens are reported to be more resistant to heat stress and cold stress than their meat counterparts but the same principles will apply although threshold temperatures may differ. Spent laying or end-of-lay hens are very susceptible to cold stress but this may primarily be a problem associated with transportation. Geographically, the demands upon environmental control for poultry housing will be greatest in the north of the UK during winter and in the south and east during summer. The welfare problems associated with deterioration of poultry litter in broiler houses in response to poor ventilation and/or changing external environments have been described in detail. It may be stressed that litter quality in large scale boiler facilities may become an important issue in various climate change scenarios as water economy of the houses and water usage and excretion of the birds is altered under heat stress conditions.

Animal transportation is perhaps the component of livestock production most vulnerable to the immediate effects of climate change. It is likely that both increased average temperatures and increased frequency of extreme events, particularly heat waves will have measurable impacts in the UK in a very short timescale (pre 2020s) and may be more apparent in southern and eastern regions in the short term. The full range of impacts of climate change scenarios upon the various components of the animal transport process and the consequent welfare and production issues have been considered in detail for all the livestock species of central significance. Clearly, the problems are associated with the internal thermal micro-environment of vehicles and transport containers become more serious during extremes of external temperatures and other weather conditions. Also, as stationary vehicles are poorly ventilated, the risk of heat stress is increased in all weather events resulting in “hold-ups”, and delays will greatly increase the risk of heat stress in transit for all species. Journey duration is also an important feature of the imposed stress. It is perhaps necessary to highlight the most vulnerable species and animal categories. Young animals tend to be more vulnerable to cold stress in transit with day-old chicks, piglets/weaner pigs and calves being of major concern. In terms of heat stress, broiler chickens and slaughter pigs may be considered to be at the greatest risks and longer journey time will exacerbate the problems. It may be concluded that the welfare of animals raised intensively in indoor systems may be at greater risk of reduced welfare in the face of the proposed climate change scenarios, but the adaptations available through environmental control may be able to provide workable solutions.

Other factors Outdoor and extensively reared animals may be exposed to a lesser risk in the UK but in some regions (southern and eastern England) the risks will become significant by 2050 and 2080 and some of the strategies discussed will have to be implemented. Young animals are generally at higher risk than their more mature counterparts and there are significant gaps in knowledge relating to thermal stress, thermoregulatory capacity, thermal comfort zones, thermal stress and welfare status in lambs, calves and weaner pigs. These issues constitute important areas for further research in order to better understand the problems created by developing climate change and to provide the basis for appropriate adaptation strategies. Animal transport has been identified as an area that is very vulnerable / susceptible to the effects of the increased thermal challenges associated with climate change and the time course of onset of these untoward effects may be shorter than for production issues. Again, the effects on the welfare of young animals may be most important and more knowledge is needed for the thermal comfort zones in transit for calves, young pigs and lambs. Potential adaptations applicable to animal transport are known and require better definition and an improved basis for application and implementation. In addition, climate change may have a profound influence upon the welfare of animals on ferries. An increased frequency of extreme and extremes of thermal conditions may cause excessive transport stress and fatigue in cattle, calves and sheep and other species carried on sea-going vessels. It is essential that a better understanding of these issues is obtained through appropriate research. Work on the interactions of motion and acceleration with thermal loads in cattle, calves and sheep is specifically required.

Water Quality

The increase in flood risk also increases runoff and leaching of nutrients from agricultural land. This can also occur due to heavy rainfall and irrigation and water use.

Runoff and leaching of nutrients is a major concern for local water quality, with heightened nutrient level responsible for algal blooms and eutrophication of water bodies. This can have an impact on biodiversity and ecosystems (Biodiversity and Ecosystem Services Sector Report) as well as downstream water abstraction. Additionally there are health impacts regarding agricultural effluent runoff with a possible link to Cryptosporidium outbreaks existing (Health Sector Report).

The Water Sector report indicates that while a number of water bodies were classified as high or good WFD status, many were also classified as having less than good status. There are a number of environmental problems which affect waters in Scotland, mainly around the agricultural areas along the east coast in Scotland, and larger urban areas including Edinburgh and Glasgow (SEPA, 2011). Pressures affecting water bodies include pollution and alterations to water flows and levels.

Transport dependence

The transport sector is continuously subjected to meteorological hazards which impact directly on the efficiency of its operations (Thornes, 1992). Despite its importance as a key economic enabler, Eddington (2006) and Jaroszweski *et al.* (2010) report that there is remarkably little research into how vulnerable the UK transport network is to climate change. This is surprising, considering studies from other countries that show how the lack of efficient and reliable transportation can severely impact on economic growth (Crafts and Leunig, 2005).

There is a dependence on a functioning transport infrastructure for the agriculture sector. With agricultural exports vital for the economy (e.g. £400 million of food exports in Scotland) there is a need to transport fresh and live (lambs, cattle etc.) produce quickly and efficiently. Even for those businesses not exporting abroad, there is a reliance on transport to get the produce to markets on time. Increased flood events and short-term extreme weather (flooding, snowfall and ice) may act to disrupt transport links for a significant length of time (Transport Sector Report). Delays may have a negative financial knock-on to those wishing to transport animals to market, or fresh, perishable goods to the retailer. Flood disrupted transport infrastructure has the possibility to impact on agricultural businesses without directly affecting the land or farm.

9.3 Complexities, similarities and differences

Whilst numerous studies have attempted to quantify the risks and impacts of climate change on specific sub sectors of agriculture, such as crop productivity (e.g. Daccache *et al*., 2011a) and livestock (Haskell, *et al.,* 2011), in reality, these all ignore the multifunctional role of agriculture within the UK economy, the importance of positive and negative feedbacks between different components of agricultural production systems and the high degree of socio economic uncertainty that surrounds future agricultural production. It is therefore important to recognise the inherent complexities of the agricultural sector and the range of both 'climate' and 'non climate' risks that the sector faces over the next 20 years, particularly when planning adaptation options and responses (Knox *et al*., 2010c).

The complexity of the agricultural sector is largely a consequence of its multifunctional role. In addition to 'food' production (crop and animal based), it sits at the interface between the natural environment and society, and contributes to a wide range of environmental services including landscape enhancement, leisure and recreation and the provision of non-food raw materials. Quantifying the risks, impacts and consequences in one particular sector (e.g. crop production) inevitably ignores the consequent knock on impacts that this might have on its 'other' roles, including environmental enhancement, and vice versa. In this context, it is important to recognise the complex links between agricultural land and 'land use', in a more general sense. Whilst the productive capacity of land helps to underpin the UK economy through provision of food, timber and other goods, and other uses for housing, business, transport, energy, recreation and tourism, it also plays a critical role in supporting the wellbeing of society including clean air, water and healthy soils. Agricultural land is also inextricably tied into some of the most beautiful and historic landscapes in the UK, underpinning our national identity, cultural heritage and mental wellbeing (Foresight, 2010). Any assessment of climate change risks to agriculture therefore need to take a broad perspective and consider not only the specific impacts in particular sub-sectors but also to combine the knowledge to generate a more integrated assessment.

However, the multifunctional nature of agriculture, whilst adding to the value and versatility to the sector, also creates problems. Many uses of agricultural land will conflict with each other in future and with other land uses – for example, increasing food production to meet demands for a burgeoning population or the conversion of productive land from food to biofuel production will inevitably mean some land uses suffer. In the future, greater pressure on natural resources will therefore mean agricultural land needs to deliver increased multiple benefits (Foresight, 2010), but balancing the conflicting priorities will be the challenge.

Climate change is expected to impact on both crop and livestock production. Crop yields and crop/livestock quality are both implicitly linked to water availability, rainfall and temperature, as well as being influenced by land suitability and pests and diseases. Each potential impact is connected to a range of climatic factors, with their own future uncertainty, meaning there are likely to be different outcomes depending on the future pattern of climate. However, gaps in knowledge on the links between climate variability and pests and diseases and the limiting factors of water availability and nutrients on crop productivity, mean that for some risk metrics there remains a wide and of uncertainty (especially magnitude) in precisely how agriculture might be affected (although the direction of impact for many metrics is robust).

The trends in climate impact on agriculture in Scotland and Northern Ireland are likely to be broadly similar although differences in the nature and composition of agriculture within each, and the socio economic conditions under which they operate are quite different. Changes in agroclimate may provide opportunities for expansion of existing crops into regions where production was previously marginal (e.g. see Daccache *et al*., 2011b). Wales and England share impacts and magnitude of some risks although regional differences vary greatly however, importantly, data exists for England and Wales where it does not for Scotland and Northern Ireland (e.g. flood risk analysis and grassland productivity) allowing differences to be considered in more detail and with greater confidence.

The cultivation of 'new' crops might also be encouraged by changes in land suitability due to modified soil and agroclimate conditions. For example, changes in the spatial and temporal patterns of rainfall and temperature are likely to lead to the introduction of new crops in some regions, generally the mid and northern UK. New plant breeding coupled with investment in farming technologies (e.g. irrigation) might also lead to the introduction of new crops in the south. Since agriculture is no longer viewed as being solely a provider of food crops – its multifunctional role will inevitably lead to a much broader range of crops being grown.

However it is highly likely that any changes in rainfall and temperature will also impact on available water supplies for agriculture in precisely those regions where new crops might emerge. Increased risks of water shortages and greater aridity might constrain the uptake of new crops unless farmers secure more reliable water supplies via winter storage and/or collaborative water resource investments.

9.4 Major risks and consequences to UK agriculture

A qualitative assessment of the major risks and consequences to UK agriculture, grouped by metric together with anticipated adaptation to reduce negative consequences is given in Table 9.1. Although the majority of risks identified are projected to have negative impacts, including for example increased flooding risk, or increased pressure on water resources for irrigation, it is important to remember that there are also likely to be opportunities for agriculture arising from climate change (e.g. introduction of new crops, increased production potential, etc).

It should be noted that potential increases in soil erosion, projected changes to grassland yields and the introduction of new crops was commissioned as additional work after Release 1 of this report.

Finally, it is also important to remember that UK agriculture also faces a range of 'non-climate' risks which could be argued present a more immediate threat to sustainable food production than climate change. The majority of these occur 'off-farm' and impact on growers via various national and European agro-economic policy interventions; the increasing burden of environmental regulations; limitations in the availability of finance; fluctuating exchange rates; and the relative power of supermarkets as these affect the operation of markets, including requirements for auditing and traceability.

The most significant economic impacts 'on-farm' relate to CAP reform, as it could affect farm income support, compliance requirements and incentives for environmental sensitive farming. The identified climate change risks and adaptation responses for agriculture must therefore be considered in this wider context. It is concluded that there are likely to be a range of both positive (e.g. yield gains) and negative (e.g. increased water stress) impacts on UK agriculture. Either way this would require new investments in adaptive management and technology, including new collaborations between the public and private sectors, to enable UK agriculture to respond to the potential effects of climate change.

9.5 Methodological limitations

The methodology adopted in this report, drawing on public domain datasets and deriving national risk metrics, has a number of inherent limitations which need to be recognised. The main limitations are summarised briefly below:

The risk metrics assumed a direct relationship between a variable and climate, but in reality the impact of climate on an underlying change is likely to be much more complex. For example, regarding the yield metric, in reality the relationship between climate, crop growth and yield are complicated by a large number of climate, soil and crop management factors, all of which were implicitly included in the response function.

A lack of a clear agro-economic policy for the baseline and future scenarios– for example, the future changes in agricultural productivity (yield) and water use (abstraction) excluded any consideration of the underlying economic conditions under which crop production might be practiced.

There are a raft of international drivers that could affect future UK agriculture including the consequences for world trade, affecting both demand for, and supply and prices of agricultural commodities in global and regional markets and an increased volatility of market conditions. There are also the actions being taken by governments to address climate change effects – with consequences for agricultural markets, including protectionism. There is also likely to be greater instability in international food and energy prices, affecting fuel costs and fertiliser use, and greater global water scarcity with consequent impacts on food production especially in relation to food exports to the UK from Southern Europe (Yang *et al.*, 2007). Other international risks include:

- Agri-support funds for competitors. For example, European funds for the modernisation of southern European irrigation schemes could provide competitive advantage over UK growers.
- The conversion of agricultural land from food production to production of bio fuel and raw materials. The use of agricultural food commodities (such as wheat or sugarcane) for bio fuels rather than for human consumption could impact on UK food imports and prices.
- Internationally agreed GHG mitigation policies may inadvertently affect agriculture, through for example, policies to reduce energy use which would impact on fertiliser production.
- Migration - climate change could increase the inward flux of migrants from drought affected areas in North Africa and southern Europe northwards towards climatically 'safe havens' such as the UK, with possible impacts on local demand for land for housing, food and natural resources.

There are also likely to be societal factors, such as public and political resistance to the use of GMOs that could help to adapt to environmental change; changing dietary preferences towards healthy eating via for example, the Food Standards Agency 'Eatwell Plate' campaign; increasing demand for year-round fresh supplies favouring food imports; and competition for land and water for development and non-agricultural use, such as nature conservation and recreation. All of these socio-economic factors were excluded from the risk metric approach, but clearly impose significant impacts on the future direction and intensity of UK agriculture.

The most significant economic impacts on-farm relate to CAP reform, as it could affect farm income support, compliance requirements and incentives for environmental sensitive farming. Rising production costs for water, energy, labour and fertiliser, coupled with increasing risks associated with infrastructure damage due to flooding are other sources of economic risk. Much depends whether these increased costs are offset by higher commodity prices arising from strong global demand - the latest OECD-FAO (2010) forecast is that average crop prices over the next ten years will be 15-40% higher in real terms relative to 1997-2006. The main environmental impacts off-farm relate to changes in water availability due to low surface water flows and groundwater levels, increasing demands for water from other sectors, increasing environmental regulation and abstraction control, and the risks associated with GMO cultivation (Knox *et al.*, 2010c). These factors were all excluded from the assessment, but need to be integrated into subsequent risk assessments.

The study deliberately focussed on the agronomic aspects of climate change by using the reference crops and developing yield/productivity metrics. However, it is important to stress that climate change is also likely to impact on the economics of farm management and particularly to agribusiness approaches to risk management. For example, yields will be affected by the so-called 'yield gap', where farmers do not seek to achieve the best possible yields because it is not profitable to do so or it might be environmentally undesirable.

There is thus a need to consider the business risks to agriculture, for example, how structural shifts in agro-economic policy driven by changes in global commodity markets etc might impact on agribusiness. Some of these on-farm and off-farm economic risks were identified by Knox *et al.* (2010c)and would warrant further investigation, particularly in the context of the economics of farm level adaptation.

Care is also needed in the interpretation of the results and, in particular, extrapolation to agriculture as a whole. Whilst some results for example, wheat yields, provide an indication of how yields may change for similar crops, the extrapolation of other results could provide could lead to erroneous conclusions. For example, potato was selected as a reference field-vegetable crop but other field vegetables and horticultural crops are quite different in terms of their physiological responses to a changing climate. The results presented are therefore crop specific but intended to provide 'indicative' estimates of the direction and magnitude of impact.

Finally, the assessment ignored the range of potential adaptation options (autonomous and planned) and responses available, and the institutional and regulatory barriers to their uptake by farmers. There are likely to be both positive (e.g. yield gains) and negative (e.g. increased water stress) impacts. This will inevitably require new investments in adaptive management and technology, including new collaborations between the public and private sectors, to enable UK agriculture to respond to the potential effects of climate change. But it is important that policies that lead to mal-adaptation are avoided, for example, responses by the food and farming industry to changes in temperature/water quality and water supply/soil suitability might lead to significant over-abstraction and exacerbate water stressed areas, with negative impacts on the natural as well as social/economic (rural employment) environment.

Adaptation is to be covered in the proposed Economics of Climate Resilience (ECR) which will follow the CCRA.

9.6 Gaps in evidence

There are inevitably a number of gaps in evidence which impact on the methodologies used in this sector, and these must be taken into account when looking at the outputs from the analyses. Firstly, not all of the metrics developed for agriculture cover the whole of the UK, with several (including AG2, AG5, AG6, and AG10) covering only England and Wales. This is partly due to the level of information available at the time of the analysis, but for others, such as (irrigation water demand AG5) there was simply no data for Scotland. Conversely, some metrics were relevant for the whole of the UK with a consistent level of detail (e.g. AG4). There are also some areas where there is a noticeable of climate impacts research (e.g. AG9 new crops) and hence the current levels of understanding on climate risks are limited.

Knowledge gaps within the sector are related to the potential combined impacts of a range of different climate factors on agricultural performance (productivity), the importance of local geography on the sustainability of specific agricultural systems, uncertainty in future socio and agro economic policies, and changes in market demands for agricultural services and products driven by changing population demographics and societal preferences. Given the multifunctional nature of agriculture, there is also uncertainty about the risks to many of the other 'non food' services of this sector including landscape and amenity, environmental enhancement and ecosystems services. In addition, the forthcoming Government report on biofuels may provide an opportunity for the agricultural sector to diversify, altering the magnitude and extent of the risks and impacts.

One of the problems with identifying the potential impacts of climate change on crops, however, is that the approach used in CCRA assumed that all other factors remained constant; in reality, of course, climate change will result in a combined set of changes in climate with some variables increasing, others decreasing and some remaining unchanged. Although the latest UKCP09 climatology provides probabilistic assessments of future climate for individual variables (rainfall, temperature etc), it is conceptually difficult to decide on which combination/s of probabilities should be used. The agriculture metrics also assumed a single climate impact with no direct links to other climate parameters or feedbacks to other aspects of the agricultural system, which itself is unrealistic. Consideration of impacts and feedbacks within an integrated framework, similar to those developed in RegIS (Holman *et al*., 2007), might allow for more objective assessment of the risks and consequences, taking into account not only the climate impact but also the underlying socio economic drivers of change (and their sensitivity to climate change).

Patterns of food consumption and dietary preferences may also shift as a consequence of a changing climate. For example, with warmer summers, there may be greater demand for salads and pasta and conversely a reduction in demand for certain winter foods as the seasonal distinctions change and become more blurred (with Autumn arriving earlier and Spring later). Similarly, changes in markets and trade opportunities, as foreign production alters, may also have a large effect on cropping patterns and livestock. There are also complex interactions with natural resources, social and political systems, economics, trade and policy and potential conflicts with the drive to boost crop production without undue depletion of the natural resource base. However, in reality, it will be the more arid parts of the world from where we import most of our food that will suffer most from a changing climate – here increasing aridity and competition for food, energy and water are all likely to exert a much greater impact on the reliability and cost of future food supplies in the UK (Beddington, 2010).

Further specific research is needed into the impact of climatic drivers on crop and livestock pest and disease vectors. Current research provides conflicting evidence on the degree of control climate exerts on pests and diseases (e.g. Bluetongue virus) and a further understanding of pest and disease pathology and responses would allow for their impact to be assessed with a greater confidence.

Within the CCRA analysis, the following specific gaps in knowledge have been identified for individual metrics:

AG1 – Crop Yield

- Rainfed crop yields are susceptible to changes in land suitability. Daccache *et al* (2011b) showed how sensitive rainfed potato yields were to changes in land suitability with increased droughtiness significantly reducing the area in England and Wales well suited to rainfed production. Similar analyses would be beneficial for extrapolating into Scotland for potatoes (and other important rainfed field vegetable crops) particularly where quality assurance is an important market determinant.

AG2 – Agricultural land at risk of flooding.

- Risk metric only considers flooding in England and Wales.
- Scotland and Northern Ireland have yet to produce flood maps to allow for analysis. Northern Ireland has produced a preliminary flood risk assessment, although this only considers climate change up to the 2030s.
- Costing to include direct and indirect costs of flood events.

AG5 – Water abstraction for crops

- No water abstraction figures for agriculture exist for Scotland or Northern Ireland, therefore an assessment of the risks due to climate change on abstraction patterns cannot be made.
- The development of the Abstraction and Impound Regulation licences in Northern Ireland provide an opportunity monitor the volume of abstraction which may allow for future projections to be made.
- An investigation to whether the earlier onset of Spring may allow for greater early year production, reducing the need for irrigation during drought years could provide useful additional information to assess future abstraction risks. Conversely drought events may occur earlier causing a greater loss in farm production. These seasonal sensitivities need to be considered, in the context of water demand for agriculture, but also set against the latest projections in river flow (available water supplies).

AG6 – Water Abstraction for livestock

- Current and changes in future water demand for livestock could not be assessed at the UK-wide scale due to limitations in data availability. . However, current Defra research (WU0310) is investigating the future sustainable use of water for livestock.

AG 7 – Climate impact on livestock production

- Further analysis on a range of livestock systems and consideration of indoor and outdoor farming. Further research on husbandry systems would allow for a more robust assessment of the impacts.

AG10 – Grassland Productivity

- Grassland productivity was only assessed for England and Wales. There is a significant knowledge gap on how productivity may change for grassland productivity in Scotland and Northern Ireland.
- Improved knowledge of the effects of CO_2 fertilisation on crop growth and yield would inform future grassland yield projections.
- Changes in land-use patterns and crop rotations due to socio economic factors (e.g. a switch to biofuel and/or changes in dietary habits) might reduce the extent of grassland cultivation with impacts on rural livelihoods.

10 Conclusions

Climate change can influence the way crops grow and develop and the yield attained. It may influence livestock productivity, health and may alter farming systems. There will also be indirect impacts on the risks to agricultural potential of soils by modified soil water balances, affecting water availability and land management practices including trafficability and workability. There will be many other indirect risks including for example, changes in the range of native/non-native pests and crop diseases, increased crop damage during extreme temperatures, crop diversification and introduction of new or novel crops. Many of these risks are inextricably linked and can have either positive or negative impacts, depending on farmer perspectives to climate risk and their adaptation responses.

For outdoor livestock and animal farming, the effects of climate change will be complex and variable. Grass production is likely to be enhanced by increases in the length of the growing season especially in upland areas benefiting livestock production, although future water shortages could limit production in some years especially in lowland areas. A changing climate could impact on livestock health, forage yields, feedstuff quality availability and cost, water availability, thermal stress and related welfare issues, including disease spread and control measures. Changes in rainfall can affect agriculture through increased flooding could reduce the area of high value land and impact on farm operation through soil quality, transportation and crop growth, or conversely, through water abstraction and PSMD. Many of the issues identified for outdoor livestock are equally relevant to housed animals, although increasing energy costs pose a significant additional risk.

Although the majority of risks identified were projected to have negative consequences, including for example increased flooding risk, and increased pressure on water resources for irrigation, it is important to remember that there are also likely to be a range of new opportunities for agriculture arising from a changing climate. These include, for example, the introduction of new or novel crops allowing a diversification into energy and pharmaceutical markets, increased production potential for sugar wheat and potatoes and market opportunities for providing other goods and services.

For many sub-sectors within agriculture, there remains much uncertainty regarding the indirect impacts of climate change – uncertainty on the sustainability of rural communities, the viability of particular production sectors and on the natural resources on which agriculture is heavily dependent. However, by combining the quantitative evidence with expert opinion it has been possible to frame the possible consequences to agriculture, and identify the scope for adaptation. This shows the major climate change risks relate to increases in soil erosion, flooding of agricultural land, increases in aridity with consequences for water demand, and increased susceptibility to new pests and disease for crop production. For livestock (outdoor and housed), there are potentially negative impacts on animal welfare and morbidity (related to heat stress) and production. However, there are also opportunities – improved productivity for grassland, arable and horticulture, and scope for the cultivation of new crops.

The identified risks will of course have an economic impact on the viability and sustainability of UK agriculture. The financial consequences of climate change on each risk metric for agriculture have been estimated, relative to the baseline period for the medium emissions, central estimate (probability 50%). The output monetises the risks as far as is reasonably possible and provides a common metric across sectors and impacts, to allow cross-comparison and an initial indication as to the relative importance of different climate change risks in the UK.

As with the risk metric outputs, there exists much uncertainty around these data – they should be interpreted with caution.

Finally, it is also important to remember that UK agriculture also faces a range of 'non-climate' risks, both off-farm and on-farm, which could present a more immediate threat to sustainable food production than climate change. The climate change risks and adaptation responses for agriculture must therefore be considered in this wider context.

It is concluded that there are likely to be a range of both positive (e.g. yield gains) and negative (e.g. increased water stress) impacts on UK agriculture.

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Appendices

Appendix 1 Consultees

Agriculture workshop held at NFU Newmarket

Name	Organisation
Keith Weatherhead	Cranfield University
Cecile Smith	Scottish Natural Heritage
Melvyn Kay	UK Irrigation Association
Eileen Wall	Scottish Agricultural College
Michael Stubbs	East Midlands Development Agency
Tim Papworth	BAWAG + LF Papworth Ltd
Mike Storey	Potato Council
Gordon Davies	Environment Agency
Ed Moorehouse	G's Marketing
Paul Hammett	NFU
Peter Scott	DARD N.Ireland
Ceris Jones	NFU Climate Change Advisor
Dewi Jones	Welsh Assembly
Lindsay Hargreaves	Independent Consultant
Jerry Knox	Cranfield University
Paula Orr	CEP
Dominic Hames	HR Wallingford

Tier 2 consultation, August - September 2010

Arable	**Organisation**
Jonathon Hall	NFUS
Guy Smith	Essex farmer and AHDB HGCA Board member
Dr Anthony Biddle	PGRO, Pulses R&D
Derek Holliday	CLA, Environment and Agriculture
Mike May	BBSRC Brooms Barn, sugar beet
Dr Ceris Jones	NFU HQ, Climate Change Advisor
Horticulture	**Organisation**
Dr Rosemary Collier	HRI Warwick
Dr Ceris Jones	NFU HQ, Climate Change Advisor
Dr Mike Storey	PCL and AHDB
Dr Chris Atkinson	East Malling Research
Tim Papworth	LG Papworth and Sons, Board Member PCL
Livestock	**Organisation**
Dr Eileen Wall	Scottish Agricultural College
Dr Marie Haskell	Scottish Agricultural College (Animal welfare)
Dr Kairsty Topp	Scottish Agricultural College (Systems Modeller)
Prof Mike Appleby	World Society for the Protection of Animals
Dr Karen Wannacott	DairyCo
Dr Alistair Stott	Scottish Agricultural College (Economist)

Appendix 2 Workshop feedback and records

The first agriculture workshop was held in Newmarket in May 2010.

At the first workshop, stakeholder feedback was as follows:

- There was a reluctance by participants to prioritise consequences.
- Impacts relating to livestock were under-represented; the project literature review had referred to Sugden (unpublished) and Reynolds *et al* (2009) and not then covered all the impacts and consequences in the draft Tier 1 list.
- There was a bias towards negative impacts, and in many cases a negative consequence could be balanced by a positive one (e.g. new pests displacing current/existing pests).
- Impacts were presented as a snapshot in time but farmers rotate crops, therefore the impacts need to be considered in the context of crop rotation and overall farm management.
- Some impacts were very specific (e.g. references to peas, potatoes) and were not consistent across a range of crops.
- All the impacts were commented on in a comprehensive workshop report.

Following this workshop there were more extensive discussions with experts in arable, horticultural and livestock sub-sectors. This involved appointing experts in these sectors who then worked with colleagues to review and revise the draft Tier 1 list.

Appendix 3 Selection of consequences for Tier 2 assessment

The impacts were scored according to standard CCRA method as follows (Defra, 2010c):

$$100 * \left(\frac{\text{Social} + \text{Environmental} + \text{Economic}}{9}\right)\left(\frac{\text{Likelihood}}{3}\right)\left(\frac{\text{Urgency}}{3}\right)$$

The above was used along with a similar version that considered urgency separately and combined results using a logical rule, i.e. the highest scoring potential impacts were ‘high risk’ AND required ‘urgent’ action. The final results were almost identical to using a multiplicative rule, although the latter provided more discrimination between potential impacts that had close scoring results.

The summary scores for each impact and for each sub-sector are given in (HR Wallingford, 2010). Scores were allocated in line with the high/medium/low category descriptions provided in the CCRA method report (Defra, 2010a) for each scored element. Evidence and justification for the scoring was from a variety of published research sources and expert judgement from the sector champion and colleagues.

Table A1.1 Summary impact scores for the arable sub-sector. Magnitude score listed is the highest of the three scores for the economic, environment and social elements of magnitude. T – threat, O – opportunity.

No	Climate change impact	T / O	Magnitude			LH	URG	Score	Rank
			Econ	Env	Soc				
1	Changes in crop development (sowing dates, day length effects, growth rates, earlier springs, flowering dates, yield building, harvest dates). Wide range of consequences dependent upon crop/variety but tendency enhanced performance	O	2	2	1	3	2	37	8
2	Changes in crop rotation – influence the range of crop types in a rotation and the number of years e.g. potato rotation may get longer	O	2	2	1	2	2	25	22
3	Pest and diseases – air borne pathogens influenced by changes in air temp and humidity – soil borne pathogens by soil temp, soil moisture, and winter kill effects (range of consequences dependent upon pathogen/pest characteristics but tendency will be for enhanced	T	3	3	2	3	3	89	1
4	Weeds – changes in weed spectrums driven by winter survival, soil conditions, crop competition changes (range of consequences dependent upon species and environment but tendency will be for greater weed activity)	T	2	2	1	3	3	56	5
5	Crop yield – could increase or decrease dependent upon the crop/variety response to the projected change (e.g. yield of heat/drought/waterlogging stress sensitive spp/cvs depressed, yield of less sensitive spp/cvs enhanced)	O/T	3	2	2	3	3	78	2
6	Crop quality – could increase or decrease dependent upon crop/variety response to the projected change (as 5 above)	O/T	2	1	1	2	2	32	10
7	Storage quality of outputs – higher temp and RH could affect storability and/or need for storage (refers especially to ambient stored crops, removing field heat may be a bigger problem for many crops if average temps are higher	T	2	1	1	2	2	20	26

No	Climate change impact	T / O	Magnitude			LH	URG	Score	Rank
			Econ	Env	Soc				
8	Stress factors – changing temperatures could increase risks associated with frost damage, drought and field water logging (wide range of effects dependent upon crop but tendency will be for deleterious consequences)	T	2	2	2	3	3	67	3
9	Increase in soil biological activity due to higher temperatures leading to higher rates of organic matter breakdown	O	2	2	1	2	2	25	22
10	GHG emissions - increased due to enhanced soil biological activity from warmer soils, releasing greater quantities of carbon dioxide, methane, nitrous gases	T	2	2	2	2	2	30	11
11	Carbon sequestration – higher plant growth rates should sequester more carbon, mitigating some effects of 10 above	O	2	2	1	2	2	25	22
12	Leaching – increased risk of nutrient and pesticide loss due to more frequent high intensity rainfall events	T	2	2	2	2	2	30	11
13	Run-off / erosion risks - increased risk due to more frequent high intensity rainfall events	T	2	2	2	2	2	30	11
14	Drought effects (soil moisture availability) – increased risk due to higher ET rates combined with reduced summer rainfall	T	3	3	2	2	3	59	4
15	Water logging effects (seasonal, anaerobic conditions) due to due to more frequent high intensity rainfall events	T	2	2	1	2	3	37	8
16	Flooding – increased risk due to more frequent extreme rainfall events, both in winter and summer	T	3	2	2	2	3	52	6
17	Salinity – increased risk of inundation of low lying land on coastal regions due to sea level rise	T	2	2	2	3	2	44	7

No	Climate change impact	T / O	Magnitude			LH	URG	Score	Rank
			Econ	Env	Soc				
18	Trafficability/access/field operations – increased risk due to changing soil conditions (too dry/too wet), particularly in late summer and spring	T	2	2	1	2	2	25	22
19	Subsidence/landslides – increased risk due to over abstraction	T	2	2	2	2	2	30	11
20	Agricultural land classification and crop suitability – changes in soil and agroclimatic conditions affecting soil and crop suitability	T/O	2	1	1	2	2	20	26
21	TH - Biodiversity / wildlife changes (changes in environmental conditions will influence range of spp supported be that plant, animal, birds, microbial etc)	T	2	2	2	2	2	30	11
22	TH - Migration patterns of farmland birds (e.g. already noted in Breckland that succession of mild winters has resulted in an increasing number of traditionally migratory Stone Curlew staying all year)	T	2	2	2	2	2	30	11
23	Breeding habits / reproductive behaviour of species (e.g. storms could wipe out newly hatched, vulnerable bird spp, stimulating secondary nesting by parents, warmer winters could increase survival rates of late-born young, longer summers could increase life expectancy)	T/O	2	2	2	2	2	30	11
24	Air quality – especially GHG – increasing CO_2 levels, good for crop growth but bad for global warming	T	2	2	2	2	2	30	11
25	Wind effects – changes in direction and speed could influence distribution of pathogens and vectors, higher wind speeds could increase wind erosion of vulnerable soils, lower speeds could reduce dispersal of contaminants	T	2	2	2	1	1	7	30
26	Water resources –availability for direct abstraction could change due to reduced runoff and recharge, leading to more frequent low flows and licence restrictions	T	2	2	2	2	2	30	11

No	Climate change impact	T / O	Magnitude			LH	URG	Score	Rank
			Econ	Env	Soc				
27	Water demand – pattern of irrigation abstraction could change with existing crops needing more water, new crops needing irrigation and seasonal changes in the timing of abstraction	T	2	2	2	2	2	30	11
28	Water quality – more frequent low flows could increase the micro-biological risks associated with abstraction downstream from sewage treatment works (STWs)	T	2	2	2	2	2	30	11
29	Heat stress on workers – e.g. changing work patterns, labour costs	T	1	1	1	1	1	4	31
30	Opp - Biodiversity / wildlife changes (changes in environmental conditions will influence range of spp supported be that plant, animal, birds, microbial etc)	O	1	1	2	2	2	20	26
31	OPP - Migration patterns of farmland birds (e.g. already noted in Breckland that succession of mild winters has resulted in an increasing number of traditionally migratory Stone Curlew staying all year)	O	1	1	2	2	2	20	26
46	Changes to levels of pollination affecting crop yield	N	2	1	1	3	1	15	22

Table A1.2 Summary impact scores for the horticulture sub-sector. Magnitude score listed is the highest of the three scores for the economic, environment and social elements of magnitude. T – threat, O – opportunity.

No	Climate change impact	T/O	Magnitude			LH	URG	Score	Rank
			Econ	Env	Soc				
1	Changes in crop development (sowing dates, day length effects, growth rates, earlier springs, flowering dates, yield building, harvest dates). Wide range of consequences dependent upon crop/variety but tendency enhanced performance	O	2	1	1	3	2	30	14
2	Changes in crop rotation – influence the range of crop types in a rotation and the number of years e.g. potato rotation may get longer	O	2	1	1	3	2	30	14
3	Pest and diseases – air borne pathogens influenced by changes in air temp and humidity – soil borne pathogens by soil temp, soil moisture, and winter kill effects (range of consequences dependent upon pathogen/pest characteristics but tendency will be for enhanced	T	2	2	2	3	2	44	2
4	Weeds – changes in weed spectrums driven by winter survival, soil conditions, crop competition changes (range of consequences dependent upon species and environment but tendency will be for greater weed activity)	T	2	1	1	2	2	20	21
5	Crop yield – could increase or decrease dependent upon the crop/variety response to the projected change (e.g. yield of heat/drought/waterlogging stress sensitive spp/cvs depressed, yield of less sensitive spp/cvs enhanced)	O/T	2	2	2	3	2	44	2
6	Crop quality – could increase or decrease dependent upon crop/variety response to the projected change (as 5 above)	O/T	2	1	1	2	2	20	21
7	Storage quality of outputs – higher temp and RH could affect storability and/or need for storage (refers especially to ambient stored crops, removing field heat may be a bigger problem for many crops if average temps are higher	T	2	1	1	2	2	20	21

No	Climate change impact	T/O	Magnitude			LH	URG	Score	Rank
			Econ	Env	Soc				
8	Stress factors – changing temperatures could increase risks associated with frost damage, drought and field water logging (wide range of effects dependent upon crop but tendency will be for deleterious consequences)	T	2	2	1	3	2	37	8
9	Increase in soil biological activity due to higher temperatures leading to higher rates of organic matter breakdown	O	1	1	1	2	1	7	29
10	GHG emissions - increased due to enhanced soil biological activity from warmer soils, releasing greater quantities of carbon dioxide, methane, nitrous gases	T	2	2	1	3	2	35	13
11	Carbon sequestration – higher plant growth rates should sequester more carbon, mitigating some effects of 10 above	O	2	2	1	3	2	37	8
12	Leaching – increased risk of nutrient and pesticide loss due to more frequent high intensity rainfall events	T	2	2	1	2	2	25	17
13	Run-off / erosion risks - increased risk due to more frequent high intensity rainfall events	T	2	2	1	2	2	25	17
14	Drought effects (soil moisture availability) – increased risk due to higher ET rates combined with reduced summer rainfall	T	2	2	1	2	3	37	8
15	Water logging effects (seasonal, anaerobic conditions) due to due to more frequent high intensity rainfall events	T	2	2	1	2	2	25	17
16	Flooding – increased risk due to more frequent extreme rainfall events, both in winter and summer	T	2	2	2	2	3	44	2
17	Salinity – increased risk of inundation of low lying land on coastal regions due to sea level rise	T	2	2	2	3	2	44	2

No	Climate change impact	T/O	Magnitude			LH	URG	Score	Rank
			Econ	Env	Soc				
18	Trafficability/access/field operations – increased risk due to changing soil conditions (too dry/too wet), particularly in late summer and spring	T	2	2	1	2	2	25	17
19	Subsidence/landslides – increased risk due to over abstraction	T	1	2	1	2	1	10	28
20	Agricultural land classification and crop suitability – changes in soil and agroclimatic conditions affecting soil and crop suitability	T/O	2	2	1	2	1	12	26
21	TH - Biodiversity / wildlife changes (changes in environmental conditions will influence range of spp supported be that plant, animal, birds, microbial etc)	T	2	2	1	3	2	37	8
22	TH - Migration patterns of farmland birds (e.g. already noted in Breckland that succession of mild winters has resulted in an increasing number of traditionally migratory Stone Curlew staying all year)	T	1	2	1	2	2	20	21
23	Breeding habits / reproductive behaviour of species (e.g. storms could wipe out newly hatched, vulnerable bird spp, stimulating secondary nesting by parents, warmer winters could increase survival rates of late-born young, longer summers could increase life expectancy)	T/O	2	2	2	3	2	44	2
24	Air quality – especially GHG – increasing CO_2 levels, good for crop growth but bad for global warming	T	1	2	2	3	2	37	8
25	Wind effects – changes in direction and speed could influence distribution of pathogens and vectors, higher wind speeds could increase wind erosion of vulnerable soils, lower speeds could reduce dispersal of contaminants	T	2	2	1	1	2	12	26
26	Water resources –availability for direct abstraction could change due to reduced runoff and recharge, leading to more frequent low flows and licence restrictions	T	1	1	1	2	1	7	29

No	Climate change impact	T/O	Magnitude			LH	URG	Score	Rank
			Econ	Env	Soc				
27	Water demand – pattern of irrigation abstraction could change with existing crops needing more water, new crops needing irrigation and seasonal changes in the timing of abstraction	T	1	1	1	2	1	7	29
28	Water quality – more frequent low flows could increase the micro-biological risks associated with abstraction downstream from sewage treatment works (STWs)	T	2	2	2	2	2	30	16
29	Heat stress on workers – e.g. changing work patterns, labour costs	T	2	2	1	3	3	56	1
30	Opp - Biodiversity / wildlife changes (changes in environmental conditions will influence range of spp supported be that plant, animal, birds, microbial etc)	O	2	2	2	3	2	44	2
31	OPP - Migration patterns of farmland birds (e.g. already noted in Breckland that succession of mild winters has resulted in an increasing number of traditionally migratory Stone Curlew staying all year)	O	1	1	2	2	2	20	21

Table A1.3 Summary impact scores for the livestock sub-sector. Magnitude score listed is the highest of the three scores for the economic, environment and social elements of magnitude. T, threat; O, opportunity; N, neutral.

No	Climate change impact	T/O/N	Magnitude			LH	Urg	Score	Rank
			Econ	Env	Soc				
1	Changes in crop (grass and fodder crops) development – sowing dates – day length effects – growth rates – earlier springs – flowering dates – yield building – harvest dates	O	1	1	1	3	1	11	28
2	Crop rotations in mixed farming systems	N	1	1	1	2	1	7	37
3	Plant pest and diseases – air borne pathogens influenced by air temp and humidity – soil/pasture borne pathogens by soil temp, soil moisture, winter kill effects	T	2	2	1	3	2	37	1
4	Weeds – changes in weed spectrums driven by winter survival, soil conditions, crop competition changes	T	1	2	1	2	1	10	29
5	Crop yield – could increase or decrease dependent upon crop/variety response to changes	O	2	1	1	2	1	10	29
6	Crop quality – could increase or decrease dependent upon crop/variety response to changes	T	2	1	1	2	1	10	29
7	Crop stress factors – high temp/low temp (frost)/drought/waterlogging/humidity	T	2	2	1	2	1	12	23
8	Flooding – increased risk due to more frequent extreme rainfall events, both in winter and summer. This will impact on moving animals from in and outdoors and require adequate housing in these emergencies.	T	2	2	2	2	2	30	8
9	Salinity – increased risk of inundation of low lying land on coastal regions due to sea level rise. Coastal livestock systems could be compromised due to land erosion and/or impact of increased salinity of land	T	2	2	1	3	2	37	1

No	Climate change impact	T/O/N	Magnitude			LH	Urg	Score	Rank
			Econ	Env	Soc				
10	Trafficability/access/field operations – increased risk due to changing soil conditions (too dry/too wet), particularly in late summer and spring. Impacts on the ability to graze animals consistently during these periods	T	2	2	1	2	1	12	23
11	Subsidence/landslides – increased risk due to over abstraction. Impacts on upland systems and the management of animals and the land	T	1	1	1	2	1	7	37
12	Threat to some systems that may shift from livestock production to crop. - Agricultural land classification and crop suitability – changes in soil and agroclimatic conditions affecting soil and crop suitability. Improvement of land classification from grass	T	1	2	2	2	1	12	23
13	Biodiversity / wildlife changes (changes in livestock systems will impact on the ability of farmers to maintain different ranges of habitats – threat for current, opportunity for new biodiversity indicators)	T	1	2	2	2	1	12	23
14	Migration patterns of farmland birds	T	1	2	1	2	1	10	29
15	Breeding habits / reproductive behaviour of species	T	1	2	2	2	2	25	11
16	Air quality – especially GHG. Different population dynamics and spread of differing livestock systems will impact on the ability to livestock systems to produce GHG emissions	T	1	2	1	2	2	20	20
17	Wind effects – in exposed pasture based systems (e.g., hill) there may be unfavourable impacts of higher winds on pasture on hills (erosion, quality, competitor plants, lodging)	T	1	2	1	1	2	10	29
18	Water resources – availability (changing flows, low flows, groundwater recharge) Competition for water from other activities (including agriculture) could limit availability to livestock at critical time	T	2	2	1	2	2	25	11

No	Climate change impact	T/O/N	Magnitude			LH	Urg	Score	Rank
			Econ	Env	Soc				
19	Water demand – irrigation abstraction (timing, volume). Irrigation less of an issue with many of UK livestock production systems. However for those that may rely on higher energy crops (not grass) it may become an issue	T	2	3	2	2	2	35	4
20	Water quality – low flows, micro-biological risks	T	2	2	1	2	2	25	11
21	Opportunity for improved pasture/fodder quality from currently marginal land categories – Agricultural land classification and crop suitability – changes in soil and agroclimatic conditions affecting soil and crop suitability. Improvement of land classification	O	1	2	2	2	1	12	23
22	Biodiversity / wildlife changes (changes in livestock systems will impact on the ability of farmers to maintain different ranges of habitats – threat for current, opportunity for new biodiversity indicators)	O	1	2	2	2	2	25	11
23	Migration patterns of farmland birds	O	1	2	2	2	2	25	11
24	Breeding habits / reproductive behaviour of species	O	1	2	1	2	1	10	29
25	Plant pest and diseases – air borne pathogens influenced by air temp and humidity – soil/pasture borne pathogens by soil temp, soil moisture, winter kill affects	O	1	1	1	1	1	4	43
26	Crop stress factors – high temp/low temp (frost)/drought/waterlogging/humidity	O	2	1	1	2	1	10	29
27	Loss of native breeds in favour of more breeds more resistant to new disease challenges and/or temperature changes	T	1	2	2	2	2	25	11
28	Changes in livestock breeding season – likely shift in seasonality	N	1	1	1	2	1	7	37

No	Climate change impact	T/O/N	Magnitude			LH	Urg	Score	Rank
			Econ	Env	Soc				
29	Livestock yield and product quality – livestock performance impacted by changes in feed supply quality and/or unfavourable physiological impacts (intake, fertility, health) by less favourable prevailing weather conditions	T	2	2	1	2	2	25	11
30	Ability of "weaker" animals (newborns and/or ill animals) to survive in newer weather conditions	T	2	2	2	2	2	30	8
31	Impact on ability to transport during particular weather scenarios of animals due to regulations	T	2	1	2	2	2	25	11
32	Changes in management practices (e.g., periods indoors, shearing) – threat as animals need to be more "managed", neutral if there is simply a time shift of when current standard farm practices occur in the year	T	2	2	2	2	1	15	22
33	Livestock pest and diseases –pathogens influenced by air temp and humidity – soil/pasture borne pathogens by soil temp, soil moisture, winter kill effects (threat as conditions may be come more favourable for some pests and diseases, opportunity as the con	T	2	1	1	3	2	30	6
34	Changes in management practices (e.g., periods indoors, shearing) – threat as animals need to be more "managed", neutral if there is simply a time shift of when current standard farm practices occur in the year	N	1	1	1	2	1	7	37
35	Pest and diseases –pathogens influenced by air temp and humidity – soil/pasture borne pathogens by soil temp, soil moisture, winter kill effects (threat as conditions may be come more favourable for some pests and diseases, opportunity as the conditions may become less favourable	O	1	1	1	2	1	7	37
36	Use of more on farm energy to help keep animals in their thermo-neutral zone.	T	1	2	1	2	1	10	29
37	Increase in water use by animals in dry periods	T	2	2	1	3	2	37	1

No	Climate change impact	T/O/N	Magnitude			LH	Urg	Score	Rank
			Econ	Env	Soc				
38	Loss of particular landscapes and associated rural communities, previously managed by livestock keepers (e.g., hill systems)	T	1	2	2	2	2	25	11
39	Human food supply/security	T	2	3	2	2	2	35	4
40	Poaching of fields from livestock traffic	T	2	2	1	3	1	19	21
41	Livestock stress factors – high temp/low temp and/or humidity – heat stress related to higher temperatures and humidity, cold stress related to lower temperatures exacerbated by wet weather and wind	T	2	1	1	3	2	30	6
42	Livestock stress factors – high temp/low temp and/or humidity – heat stress related to higher temperatures and humidity, cold stress related to lower temperatures exacerbated by wet weather and wind	O	1	1	1	2	1	7	37
43	Ability to provide sufficient resources for animals during extreme events (snow, frost, drought).	T	2	2	2	2	2	30	8
44	Increased costs of energy	T	1	1	1	3	1	11	28

Appendix 4 Further notes on metric calculations

PSMD Addressing the consistency of different approaches (AG4)

The new baseline PSMDmax values were in the case of all northern regions (i.e., Northeast and Northwest England and Scotland) bigger than even the 2080s high emissions scenario projected by Daccache's work. In the other regions the new baseline value was smaller than the 2080s high emissions, but in every case was higher than the 2020s medium emissions scenario which lies at the other end of the temporal scale. According to the climatic changes projected by the UKCP09 data, there are certainly likely to be increases in PSMDmax, which were not represented by the inconsistencies between the datasets described here.

In order for the projected PSMDmax values to be consistent with the new baseline, a scaling factor was applied to the new baseline values to transform them into projections. The new baseline values were considered more accurate representations of the observed data owing to their taking into account more extremes of climatic variation.

Scaling factors were calculated as the percentage changes for each region between their averaged baseline and averaged projections from Daccache's results. This averaging, ensured that the variation across each region was taken into account rather than dealing with the regionally representative point.

Selecting a representative points for the abstraction metric (AG5)

The method of selecting a single point was to analyse the baseline point data provided by Daccache in a GIS, averaging the values for all the points falling within each Defra administration region (these were used rather than EA administration regions as a standard spatial scale for the CCRA and as it was intended to also investigate correlations of PSMD with crop yields for which data were available at the Defra administration scale). The point with the baseline value closest to the average for its region was selected to represent the region. Calculations were carried out using Met Office UKCP09 observed monthly data (1961-2004) for the five climate variables to calculate a time series of monthly PSMD from which annual maxima were drawn. The same method of calculating PSMD using the Penman Monteith equation was employed in these calculations. Data were calculated back to 1961 to enable comparison of values over the baseline period and to facilitate potential development of response functions with other impacts.

In correlating PSMDmax data with abstraction data, it was necessary to combine some regional PSMDmax values due to the differing spatial scales of the data. For example, the West Midlands and East Midlands were combined into the Midlands and North East England was combined with Yorkshire and Humberside to equate to the EA's North East region. These combinations were carried out by weighting the value from each component region by its relative size in terms of area. In the case of South East England, the sum of the Southern and Thames region abstraction data were assumed to represent an identical area to the South East England region for which PSMDmax had been calculated.

Magnitude, confidence and presentation of results

Table A4.1 defines the magnitude classes used in the assessment. These were used for scoring impacts in the Tier 2 selection process as well as for scoring risk levels for the scorecards presented for each metric in Chapter 5. For the scorecard, the risk/opportunity level relates to the most relevant of the economic/environmental/social criteria.

Table A4.1 Guidance on classification of relative magnitude: qualitative descriptions of high, medium and low classes

Class	Economic	Environmental	Social
High	• Major and recurrent damage to property and infrastructure • Major consequence on regional and national economy • Major cross-sector consequences • Major disruption or loss of national or international transport links • Major loss/gain of employment opportunities *~ £100 million for a single event or per year*	• Major loss or decline in long-term quality of valued species/habitat/landscape • Major or long-term decline in status/condition of sites of international/national significance • Widespread Failure of ecosystem function or services • Widespread decline in land/water/air quality • Major cross-sector consequences *~ 5000 ha lost/gained* *~ 10000 km river water quality affected*	• Potential for many fatalities or serious harm • Loss or major disruption to utilities (water/gas/electricity) • Major consequences on vulnerable groups • Increase in national health burden • Large reduction in community services • Major damage or loss of cultural assets/high symbolic value • Major role for emergency services • Major impacts on personal security e.g. increased crime *~million affected* *~1000's harmed* *~100 fatalities*
Medium	• Widespread damage to property and infrastructure • Influence on regional economy • Consequences on operations & service provision initiating contingency plans • Minor disruption of national transport links • Moderate cross-sector consequences • Moderate loss/gain of employment opportunities *~ £10 million per event or year*	• Important/medium-term consequences on species/habitat/landscape • Medium-term or moderate loss of quality/status of sites of national importance • Regional decline in land/water/air quality • Medium-term or Regional loss/decline in ecosystem services • Moderate cross-sector consequences *~ 500 ha lost/gained* *~ 1000 km river water quality affected*	• Significant numbers affected • Minor disruption to utilities (water/gas/electricity) • Increased inequality, e.g. through rising costs of service provision • Consequence on health burden • Moderate reduction in community services • Moderate increased role for emergency services • Minor impacts on personal security *~thousands affected, ~100s harmed, ~10 fatalities*
Low	• Minor or very local consequences • No consequence on national or regional economy • Localised disruption of transport *~ £1 million per event or year*	• Short-term/reversible effects on species/habitat/landscape or ecosystem services • Localised decline in land/water/air quality • Short-term loss/minor decline in quality/status of designated sites *~ 50 ha of valued habitats damaged/improved* *~ 100 km river quality affected*	• Small numbers affected • Small reduction in community services • Within 'coping range' *~1000's affected*

The levels of confidence used by the CCRA can be broadly summarised as follows:

Low - Expert view based on limited information, e.g. anecdotal evidence.

Medium - Estimation of potential impacts or consequences, grounded in theory, using accepted methods and with some agreement across the sector.

High - Reliable analysis and methods, with a strong theoretical basis, subject to peer review and accepted within a sector as 'fit for purpose'.

The lower, central and upper estimates provided in the scorecards relate to the range of the estimated risk or opportunity level. For risk metrics that have been quantified with UKCP09 and response functions, this range relates to the results that are given for the low emissions, 10% probability level (lower); medium emissions, 50% probability level (central); and high emissions, 90% probability level (upper). For the risk metrics that have been estimated with a more qualitative approach, these estimates cover the range of potential outcomes given the evidence provided.

The CCRA analysis uses three discrete time periods to estimate future risks up to the year 2100: the 2020s (2010 to 2039), 2050s (2040 to 2069) and the 2080s (2070 to 2099).This is consistent with the UKCP09 projections.

Appendix 5 Effects of climate change

AG1a Sugar Beet yields

Baseline data

Region	Baseline (1961-90) Yield (t/ha)	National average yield (t/ha) in 2009 (Defra, 2010)	Ha cultivated in 2009 (Defra, 2010)	Harvest assuming Defra 2009 national average yield (tonnes)	Notes
East Midlands	6.64	70.0	**25,937**	1,815,610	
East of England	7.26	70.0	**75,724**	5,300,655	
Eastern Scotland	4.32	70.0			No Defra data
London	8.08	70.0			Inc in SE England
North East England	5.11	70.0	**49**	3,407	
Northern Scotland	4.01	70.0			No Defra data
North West England	5.94	70.0	**205**	14,321	
Northern Ireland	5.77	70.0			No Defra data
South East England	7.32	70.0	**260**	18,229	Inc London
South West England	7.10	70.0	**343**	24,024	
Wales	6.09	70.0			No Defra data
West Midlands	6.65	70.0	**4,202**	294,172	
Western Scotland	4.94	70.0			No Defra data
Yorkshire and Humberside	6.03	70.0	**9,750**	682,485	

Percentage change in yield projections from baseline

	2020			2050			2080			
Region	**p10**	**p50**	**p90**	**p10**	**p50**	**p90**	**p10**	**p50**	**p90**	**Emission Scenario**
East Midlands				17	32	50	22	40	62	**Low**
East of England				15	30	46	20	37	58	
Eastern Scotland				21	44	72	26	54	89	
London				14	28	44	19	34	54	
North East England				23	42	64	28	51	80	
North West England				19	36	55	24	44	69	
Northern Ireland				17	32	49	22	40	61	
Northern Scotland				20	43	70	25	53	87	
South East England				16	31	48	21	38	60	
South West England				16	30	48	21	38	60	
Wales				18	33	53	23	42	65	
West Midlands				17	32	50	22	40	63	
Western Scotland				22	41	63	28	51	79	
Yorkshire and Humberside				18	34	53	23	42	66	
East Midlands	10	21	34	20	36	56	29	50	77	**Medium**
East of England	9	19	31	19	34	52	27	47	72	
Eastern Scotland	13	30	49	23	48	79	33	68	111	
London	9	18	29	18	32	49	25	44	67	
North East England	14	28	43	26	46	71	38	65	99	
North West England	12	24	37	22	40	61	32	56	85	
Northern Ireland	10	21	34	20	36	55	30	52	77	
Northern Scotland	12	29	48	22	47	77	32	66	108	
South East England	10	20	32	19	35	54	28	48	75	
South West England	9	20	32	19	35	54	29	49	76	
Wales	10	22	36	21	39	60	31	54	83	
West Midlands	10	21	34	20	37	57	30	52	79	
Western Scotland	13	27	43	26	46	70	37	64	97	
Yorkshire and Humberside	11	22	36	21	38	59	31	53	82	
East Midlands				22	40	62	38	63	95	**High**
East of England				21	37	57	35	59	89	
Eastern Scotland				26	54	88	42	83	134	
London				19	35	54	33	55	83	
North East England				29	52	80	48	81	123	
North West England				25	45	68	41	70	105	
Northern Ireland				22	40	61	38	64	96	
Northern Scotland				25	53	85	40	81	130	
South East England				22	39	60	36	61	92	
South West England				21	39	60	37	62	94	
Wales				24	43	66	41	68	103	
West Midlands				23	41	63	39	65	98	
Western Scotland				29	51	78	48	80	121	
Yorkshire and Humberside				24	43	65	40	67	101	

Increase %	Colour code
0% - 24%	
25% - 49%	
>50%	

AG1b Wheat Yields

Baseline data

Region	Baseline 1961-90 yield (t/ha)	National average yield (t/ha in 2009 (Defra, 2010d)	Ha cultivated in 2009 (Defra, 2010d)	2009 harvest assuming Defra 2009 national average yield (tonnes)
East Midlands	5.61	8.0	342,045	
East of England	6.51	8.0	475,345	
Eastern Scotland	2.27	8.0		No Defra Data
London	7.69	8.0		Inc. in SE England
North East England	3.41	8.0	518,038	
Northern Scotland	1.83	8.0		No Defra Data
North West England	4.61	8.0	245,747	
Northern Ireland	4.36	8.0		No Defra Data
South East England	6.59	8.0	1,830,106	Inc. London
South West England	6.28	8.0	1,341,803	
Wales	4.82	8.0		No Defra Data
West Midlands	5.64	8.0	1,241,853	
Western Scotland	3.17	8.0		No Defra Data
Yorkshire and Humberside	4.74	8.0	1,815,325	

Projected percentage change in yield

	2020			2050			2080			
Region	p10	p50	p90	p10	p50	p90	p10	p50	p90	Emission Scenario
East Midlands				28	54	86	37	68	106	Low
East of England				25	48	75	32	59	92	
Eastern Scotland				57	121	197	71	149	245	
London				22	42	66	28	52	82	
North East England				49	90	139	61	111	173	
North West England				36	67	103	45	82	128	
Northern Ireland				32	60	93	42	75	117	
Northern Scotland				63	136	222	80	167	275	
South East England				26	49	77	33	61	96	
South West England				26	50	78	34	62	97	
Wales				32	61	96	42	76	119	
West Midlands				29	54	85	37	68	107	
Western Scotland				50	92	142	63	114	177	
Yorkshire and Humberside				32	62	97	42	77	120	
East Midlands	17	36	57	35	62	95	50	86	132	Medium
East of England	15	31	50	30	54	84	44	75	115	
Eastern Scotland	35	82	136	62	133	217	91	186	303	
London	13	28	44	27	48	74	39	66	102	
North East England	30	60	94	56	100	153	81	141	214	
North West England	22	44	69	41	74	113	60	104	158	
Northern Ireland	19	41	65	38	69	105	58	98	147	
Northern Scotland	39	93	153	70	149	244	102	209	341	
South East England	15	32	52	31	56	86	45	77	119	
South West England	15	33	53	32	57	89	47	80	124	
Wales	18	40	65	39	70	109	57	99	152	
West Midlands	16	36	58	35	63	97	51	88	135	
Western Scotland	30	61	97	57	103	157	83	145	219	
Yorkshire and Humberside	19	41	65	39	71	109	57	98	150	
East Midlands				38	68	105	64	108	163	High
East of England				33	60	92	56	94	142	
Eastern Scotland				70	148	241	115	228	368	
London				29	53	81	50	83	126	
North East England				63	113	172	104	175	265	
North West England				47	83	127	77	130	196	
Northern Ireland				42	76	117	73	122	183	
Northern Scotland				79	166	270	127	256	413	
South East England				34	62	95	58	97	147	
South West England				35	64	98	60	101	153	
Wales				43	78	120	74	124	187	
West Midlands				38	69	107	66	110	167	
Western Scotland				65	116	176	107	180	271	
Yorkshire and Humberside				44	78	120	73	123	185	

Increase %	Colour code
0% - 24%	
25% - 49%	
>50%	

AG1c Potato yields (Climate change effects without CO_2)

1960-90 potato yield baseline: 31.6 t/ha

Baseline data

Region	1961-90 rainfed %Yield	National average yield (t/ha) in 2009 (Defra, 2010)	Ha cultivated in 2009 (Defra, 2010)	Tonnes production based on 2009 yield (Defra, 2010)	Notes
East Midlands	0.95	47.0	18,257	858,066	
East of England	0.92	47.0	34,248	1,609,672	
Eastern Scotland	1.04	47.0			No Defra data
London	0.92	47.0			Inc in SE England
North East England	1.00	47.0	1,815	85,316	
Northern Scotland	1.11	47.0			No Defra data
North West England	1.08	47.0	8,309	390,525	
Northern Ireland	1.05	47.0			No Defra data
South East England	0.93	47.0	4,033	189,543	Inc London
South West England	0.99	47.0	7,586	356,538	
Wales	1.08	47.0			No Defra data
West Midlands	0.96	47.0	16,519	776,409	
Western Scotland	1.14	47.0			No Defra data
Yorkshire and Humberside	0.99	47.0	17,110	804,171	

Percentage changes from baseline in rainfed potato yields

	2020			2050			2080			
Region	**p10**	**p50**	**p90**	**p10**	**p50**	**p90**	**p10**	**p50**	**p90**	**Emission Scenario**
East Midlands				-11	-4	4	-12	-4	3	
East of England				-12	-4	4	-12	-4	4	
Eastern Scotland				-8	-3	2	-9	-4	1	
London				-13	-4	5	-14	-5	4	
North East England				-9	-4	2	-10	-4	1	
North West England				-11	-5	2	-12	-5	1	
Northern Ireland				-8	-3	2	-9	-3	2	Low
Northern Scotland				-7	-2	2	-8	-3	2	
South East England				-13	-4	5	-14	-5	4	
South West England				-13	-5	5	-14	-5	4	
Wales				-11	-4	4	-12	-4	3	
West Midlands				-11	-4	4	-12	-4	3	
Western Scotland				-8	-3	2	-9	-4	1	
Yorkshire and Humberside				-12	-5	2	-13	-5	1	
East Midlands	-7	-2	3	-12	-5	2	-15	-6	2	
East of England	-8	-2	3	-13	-5	2	-16	-7	2	
Eastern Scotland	-5	-2	2	-9	-4	0	-12	-5	0	
London	-8	-2	4	-14	-6	2	-18	-7	2	
North East England	-6	-2	2	-10	-5	0	-13	-6	0	
North West England	-7	-2	3	-12	-6	0	-16	-7	0	
Northern Ireland	-5	-2	2	-9	-4	1	-11	-5	1	Medium
Northern Scotland	-5	-1	2	-8	-3	1	-10	-4	2	
South East England	-8	-2	4	-14	-6	2	-18	-8	2	
South West England	-9	-2	4	-15	-6	2	-19	-8	2	
Wales	-7	-2	3	-13	-5	2	-16	-6	2	
West Midlands	-7	-2	3	-13	-5	2	-16	-6	2	
Western Scotland	-5	-2	2	-9	-4	0	-11	-5	0	
Yorkshire and Humberside	-7	-2	3	-12	-6	0	-16	-8	0	
East Midlands				-13	-5	2	-19	-8	2	
East of England				-14	-6	2	-20	-9	2	
Eastern Scotland				-10	-4	1	-14	-7	0	
London				-15	-6	3	-22	-10	2	
North East England				-10	-5	1	-16	-7	0	
North West England				-13	-6	1	-19	-9	0	
Northern Ireland				-9	-4	1	-14	-6	2	High
Northern Scotland				-8	-3	1	-13	-5	2	
South East England				-16	-6	2	-22	-10	2	
South West England				-16	-7	3	-23	-10	2	
Wales				-14	-5	2	-20	-9	1	
West Midlands				-14	-5	2	-20	-9	1	
Western Scotland				-9	-4	1	-14	-6	0	
Yorkshire and Humberside				-13	-6	1	-20	-9	0	

	Positive percentage change
	Negative percentage change
	No change

AG4 Agro-climate

Current PDSM (mm):

Region	2010 baseline
Wales	170
Western Scotland	166
Northern Scotland	157
Eastern Scotland	192
South West England	207
North West England	162
West Midlands	222
North East England	210
South East England	260
Yorkshire and Humberside	220
East Midlands	270
East of England	265

Daccache, A. (2010) personal communication

PSMD projections

	1961-90	2020			2050			2080			
	Baseline	p10	p50	p90	p10	p50	p90	p10	p50	p90	Emissions
Wales					132	250	382	154	279	429	
Western Scotland					145	250	376	167	287	436	
Northern Scotland					124	213	320	138	237	359	
EasternScotland					154	265	399	169	291	441	
South West England					144	262	399	165	287	438	
North West England					117	224	339	136	246	376	
West Midlands					153	278	424	169	296	451	
North East England					159	282	422	179	305	457	
South East England					168	317	485	189	340	513	
Yorkshire and Humberside					156	280	420	172	299	449	
East Midlands					183	331	499	200	352	528	
East of England					170	312	472	185	331	495	Low
Wales	129	90	197	313	171	306	461	214	366	545	
Western Scotland	106	96	189	299	169	284	424	227	375	558	
Northern Scotland	118	88	174	269	138	232	345	172	284	423	
EasternScotland	145	109	214	332	176	296	442	214	354	527	
South West England	167	105	226	359	171	298	449	205	338	505	
North West England	129	81	182	288	142	257	383	176	303	450	
West Midlands	190	112	239	380	174	303	458	200	334	498	
North East England	171	117	231	358	183	312	460	220	360	528	
South East England	230	140	280	430	201	341	497	236	377	546	
Yorkshire and Humberside	185	115	238	368	179	305	448	209	341	500	
East Midlands	231	137	287	444	207	356	525	240	392	575	
East of England	234	131	278	431	190	330	489	220	359	527	Medium
Wales					172	311	468	263	450	670	
Western Scotland					190	314	461	295	473	702	
Northern Scotland					150	249	365	212	340	506	
EasternScotland					187	309	453	261	418	622	
South West England					177	301	443	237	384	563	
North West England					149	264	395	215	362	540	
West Midlands					179	306	452	232	375	551	
North East England					191	318	468	265	418	611	
South East England					218	348	499	269	418	595	
Yorkshire and Humberside					191	311	446	244	389	559	
East Midlands					221	362	523	274	438	629	
East of England					204	336	487	246	394	566	High

Change in PSMD (%)

	Baseline (1990 - 2003)
Wales	129
Western Scotland	106
Northern Scotland	118
EasternScotland	145
South West England	167
North West England	129
West Midlands	190
North East England	171
South East England	230
Yorkshire and Humberside	185
East Midlands	231
East of England	234

	2020			2050			2080			
	p10	p50	p90	p10	p50	p90	p10	p50	p90	Emissions
Wales				2	94	196	19	117	232	
Western Scotland				37	136	254	57	171	311	
Northern Scotland				5	81	171	17	101	204	
EasternScotland				6	83	175	16	100	204	
South West England				-14	57	139	-1	72	162	
North West England				-9	74	163	6	91	191	
West Midlands				-19	47	123	-11	56	138	Low
North East England				-7	65	147	5	78	167	
South East England				-27	38	111	-18	48	123	
Yorkshire and Humberside				-15	51	127	-7	62	143	
East Midlands				-21	43	116	-14	52	128	
East of England				-27	33	102	-21	41	112	
Wales	-30	52	142	33	137	257	66	183	322	
Western Scotland	-9	79	182	60	168	300	114	254	427	
Northern Scotland	-25	47	128	17	96	193	46	141	259	
EasternScotland	-25	47	129	22	104	205	48	144	264	
South West England	-37	36	115	2	79	169	23	102	202	
North West England	-37	41	123	10	99	197	36	135	249	
West Midlands	-41	26	100	-8	60	141	5	76	162	Medium
North East England	-31	35	109	7	82	169	29	110	208	
South East England	-39	22	87	-13	48	116	3	64	137	
Yorkshire and Humberside	-38	29	99	-3	65	142	13	85	170	
East Midlands	-41	24	92	-10	54	127	4	70	149	
East of England	-44	19	84	-19	330	109	-6	53	125	
Wales				34	141	263	104	249	420	
Western Scotland				79	196	335	178	346	563	
Northern Scotland				27	111	209	80	188	329	
EasternScotland				29	113	213	80	188	329	
South West England				6	80	165	42	130	237	
North West England				16	105	206	66	181	318	
West Midlands				-6	61	138	22	97	190	High
North East England				12	86	173	55	144	257	
South East England				-5	51	117	17	82	159	
Yorkshire and Humberside				3	68	141	32	110	202	
East Midlands				-4	57	126	19	90	172	
East of England				-13	44	108	5	68	142	

	Positive percentage change
	Negative percentage change

AG5 Water abstraction for crops

2010 baseline (Ml/day)

Region	**2010 baseline**
Wales	8.7
South West England	9.1
North West England	7.0
West Midlands	26.5
North East England & Yorkshire and Humberside	27.0
South East England	34.7
East Midlands	68.4
East of England	163.7

Abstraction changes (%)

Abstraction percentage changes

	2020			2050			2080			
	p10	p50	p90	p10	p50	p90	p10	p50	p90	Emission Scenario
Wales				5.2	60.9	123.6	15.7	75.0	145.5	
South West England				-17.8	64.5	159.9	-2.9	81.8	187.2	
North West England				11.3	-28.5	-71.1	4.2	-36.6	-84.7	
West Midlands				-17.7	19.7	63.3	-13.2	24.8	71.4	
North East England & Yorkshire/Humberside				-15.2	20.2	60.5	-10.2	26.2	69.6	
South East England				-12.2	24.8	66.6	-6.9	30.6	73.7	
East Midlands				-16.8	35.0	93.7	-10.9	42.4	103.8	
East of England				-9.2	6.6	24.5	-7.5	8.8	27.2	Low
Wales	-14.5	35.9	90.6	24.0	87.3	160.5	44.0	115.6	200.2	
South West England	-44.7	39.8	131.9	1.3	89.9	195.0	24.8	117.4	233.9	
North West England	24.5	-12.9	-52.0	2.0	-40.5	-87.3	-10.5	-57.7	-112.3	
West Midlands	-30.1	8.0	50.2	-11.6	27.0	73.3	-3.8	36.2	85.4	
North East England & Yorkshire/Humberside	-27.1	7.3	44.3	-8.4	28.0	69.6	0.8	39.7	86.2	
South East England	-19.0	15.6	52.9	-4.0	30.8	69.6	4.7	39.9	81.7	
East Midlands	-32.8	19.8	74.7	-8.3	43.8	102.7	3.2	56.3	120.2	
East of England	-13.6	2.9	19.9	-7.0	8.7	26.4	-3.6	11.9	30.7	Medium
Wales				24.5	89.8	163.9	67.0	155.2	259.4	
South West England				5.1	91.7	190.7	47.2	149.5	274.6	
North West England				-0.7	-43.2	-91.6	-24.9	-79.7	-145.4	
West Midlands				-10.1	28.0	71.5	5.8	48.5	101.3	
North East England & Yorkshire/Humberside				-5.5	29.7	70.1	11.8	54.4	105.6	
South East England				0.2	32.6	70.1	12.9	50.0	93.9	
East Midlands				-3.4	46.0	102.0	15.0	72.4	139.3	
East of England				-5.5	9.3	26.2	-0.7	15.8	35.1	High

(blue)	Positive percentage change
(purple)	Negative percentage change

AG7 Climate impact on livestock production

Total milk loss by region (kg/annum)

	2020			2050			2080			
	p10	p50	p90	p10	p50	p90	p10	p50	p90	
East Midlands				0	**407,907**	**7,234,919**	0	**647,292**	**12,827,121**	
East of England				0	0	0	0	0	**3,210**	
Scotland				0	**714,020**	**9,474,752**	0	**1,007,797**	**16,224,809**	
North East England				0	0	**613**	0	0	**26,000**	
North West England				0	0	**460,998**	0	0	**1,965,699**	
Northern Ireland				0	0	0	0	0	**236,868**	
South East England				0	**226,098**	**4,579,591**	0	**345,817**	**8,117,435**	
South West England				0	**147,530**	**25,638,568**	0	**533,391**	**49,999,309**	
Wales				0	0	**1,432,908**	0	0	**4,596,292**	
West Midlands				0	**57,085**	**8,543,931**	0	**202,414**	**16,452,956**	
Yorkshire And The Humber				0	0	**868,132**	0	0	**2,323,922**	Low Emissions
East Midlands	0	0	0	0	**54,933**	**4,785,403**	0	**564,549**	**16,721,943**	
East of England	0	0	0	0	**116,752**	**2,277,870**	0	**435,383**	**6,876,427**	
Scotland	0	0	**393,950**	0	**50,576**	**4,412,244**	0	**491,130**	**16,598,197**	
North East England	0	0	0	0	**185,791**	**2,794,279**	0	**552,853**	**7,741,554**	
North West England	0	0	0	0	0	0	0	0	0	
Northern Ireland	0	0	0	0	0	**784,009**	0	0	**10,859,165**	
South East England	0	0	0	0	**14,881**	**229,153**	0	**44,354**	**1,173,426**	
South West England	0	0	0	0	**2,575,677**	**59,659,373**	0	**9,784,803**	**181,763,726**	
Wales	0	0	0	0	**189,962**	**18,559,852**	0	**1,971,287**	**64,244,302**	
West Midlands	0	0	0	0	0	**2,124,835**	0	0	**13,400,916**	
Yorkshire & The Humber	0	0	0	0	0	0	0	0	**154,255**	Medium Emissions
East Midlands				0	0	**1,025,520**	0	**9,707**	**6,236,329**	
East of England				0	**41,020**	**1,988,913**	0	**468,640**	**10,023,194**	
Scotland				0	**1,705,457**	**28,073,492**	0	**7,576,329**	**120,007,676**	
North East England				0	0	**2,630**	0	0	**807,405**	
North West England				0	0	**572,371**	0	0	**22,921,430**	
Northern Ireland				0	0	0	0	0	**212,549**	
South East England				0	**22,520**	**628,072**	0	**95,386**	**6,429,598**	
South West England				0	0	**472,196**	0	0	**27,848,338**	
Wales				0	**2,269,046**	**46,473,382**	0	**11,644,101**	**191,627,734**	
West Midlands				0	**374,556**	**20,778,749**	0	**5,104,165**	**112,284,619**	
Yorkshire & The Humber				0	**208,588**	**9,615,293**	0	**2,474,671**	**50,334,693**	High Emissions

Costs of days open assuming a standard of £2.50 per day (£/annum)

	2020			2050			2080			
	p10	p50	p90	p10	p50	p90	p10	p50	p90	
East Midlands	0	0	0	0	**41,755**	**726,690**	0	**79,927**	**1,116,277**	
East of England	0	0	0	0	**46,036**	**290,514**	0	**61,040**	**433,667**	
Scotland	0	0	0	0	0	0	0	0	**10,443**	
North East England	0	0	0	0	0	**628**	0	0	**17,022**	
North West England	0	0	0	0	0	**299,111**	0	0	**765,360**	
Northern Ireland	0	0	0	0	0	0	0	0	**198,800**	
South East England	0	0	0	0	**225,710**	**1,383,895**	0	**292,687**	**1,881,338**	
South West England	0	0	0	0	**137,770**	**4,243,658**	0	**386,292**	**7,043,426**	
Wales	0	0	0	0	0	**554,560**	0	0	**1,150,020**	
West Midlands	0	0	0	0	**51,763**	**1,480,873**	0	**144,472**	**2,392,606**	
Yorkshire & The Humber	0	0	0	0	0	**298,272**	0	0	**545,044**	Low Emissions
East Midlands	0	0	**181,001**	0	**47,257**	**811,183**	0	**213,908**	**1,910,246**	
East of England	0	**6,116**	**99,390**	0	**48,524**	**327,896**	0	**112,510**	**589,214**	
Scotland	0	0	0	0	0	0	0	0	**246,175**	
North East England	0	0	0	0	0	**4,452**	0	0	**76,497**	
North West England	0	0	0	0	0	**420,724**	0	0	**2,253,761**	
Northern Ireland	0	0	0	0	0	**46,119**	0	0	**1,214,292**	
South East England	0	**55,429**	**491,448**	0	**235,696**	**1,517,242**	0	**528,472**	**1,799,847**	
South West England	0	0	**1,157,790**	0	**294,694**	**5,408,992**	0	**1,356,587**	**10,633,477**	
Wales	0	0	0	0	0	**834,215**	0	0	**2,689,340**	
West Midlands	0	0	**399,537**	0	**107,776**	**1,848,740**	0	**484,863**	**4,167,977**	
Yorkshire & The Humber	0	0	0	0	-3,942	**361,460**	0	**13,597**	**1,138,095**	Medium Emissions
East Midlands	0	0	0	0	**96,278**	**1,122,904**	0	**454,932**	**1,940,126**	
East of England	0	0	0	0	**67,088**	**431,630**	0	**203,412**	**525,060**	
Scotland	0	0	0	0	0	**11,422**	0	0	**985,794**	
North East England	0	0	0	0	0	**18,687**	0	0	**207,684**	
North West England	0	0	0	0	0	**811,654**	0	**42,729**	**5,075,713**	
Northern Ireland	0	0	0	0	0	**222,401**	0	0	**2,988,250**	
South East England	0	0	0	0	**321,434**	**1,844,718**	0	**910,975**	**3,332,251**	
South West England	0	0	0	0	**553,565**	**7,120,610**	0	**2,911,897**	**8,874,292**	
Wales	0	0	0	0	0	**1,221,527**	0	**260,846**	**4,718,898**	
West Midlands	0	0	0	0	**211,641**	**2,425,058**	0	**1,018,974**	**3,915,808**	
Yorkshire & The Humber	0	0	0	0	0	**554,570**	0	**140,623**	**2,029,773**	High Emissions

AG8 Climate impact on livestock health

Duration of heat stress

Annual duration of Heat stress (days)										
	2020			2050			2080			
Region	p10	p50	p90	p10	p50	p90	p10	p50	p90	Emissions Scenario
East Midlands				0	0	1	0	0	1	Low
East of England				0	0	1	0	1	2	
East Scotland				0	0	0	0	0	0	
London				0	1	2	0	1	2	
North East England				0	0	0	0	0	0	
North Scotland				0	0	0	0	0	0	
North West England				0	0	0	0	0	1	
Northern Ireland				0	0	0	0	0	0	
South East England				0	1	1	0	1	2	
South West England				0	0	1	0	0	1	
Wales				0	0	1	0	0	1	
West Midlands				0	0	1	0	0	1	
West Scotland				0	0	0	0	0	0	
Yorkshire & The Humber				0	0	1	0	0	1	
East Midlands	0	0	0	0	0	1	0	1	2	Medium
East of England	0	0	1	0	0	1	0	1	2	
East Scotland	0	0	0	0	0	0	0	0	1	
London	0	0	1	0	1	2	0	1	2	
North East England	0	0	0	0	0	0	0	0	1	
North Scotland	0	0	0	0	0	0	0	0	0	
North West England	0	0	0	0	0	0	0	0	1	
Northern Ireland	0	0	0	0	0	0	0	0	1	
South East England	0	0	1	0	1	1	0	1	2	
South West England	0	0	1	0	0	1	0	1	2	
Wales	0	0	0	0	0	1	0	0	1	
West Midlands	0	0	0	0	0	1	0	1	2	
West Scotland	0	0	0	0	0	0	0	0	0	
Yorkshire & The Humber	0	0	0	0	0	1	0	0	1	
East Midlands				0	0	1	0	1	2	High
East of England				0	1	2	0	1	2	
East Scotland				0	0	0	0	0	1	
London				0	1	2	0	1	3	
North East England				0	0	0	0	0	1	
North Scotland				0	0	0	0	0	0	
North West England				0	0	1	0	0	2	
Northern Ireland				0	0	0	0	0	1	
South East England				0	1	2	0	1	3	
South West England				0	0	1	0	1	2	
Wales				0	0	1	0	0	2	
West Midlands				0	0	1	0	1	2	
West Scotland				0	0	0	0	0	1	
Yorkshire & The Humber				0	0	1	0	0	2	

Livestock deaths (AG8b)

The number is negligible

AG10 Grassland productivity

Regional percentage change in dry matter yield.

	2020			2050			2080			Emission Scenario
Admin Region	p10	p50	p90	p10	p50	p90	p10	p50	p90	
Channel Islands				19	32	47	25	41	54	Low Emission
East Midlands				19	33	48	25	42	54	
East of England				20	33	49	26	43	54	
Scotland East				16	29	44	22	37	54	
Isle of Man				17	28	42	22	36	53	
London				20	35	51	27	44	54	
North East England				19	32	47	24	40	54	
North West England				19	31	47	24	40	54	
Northern Ireland				17	28	41	22	36	52	
Scotland North				15	27	40	20	34	51	
South East England				20	35	51	27	44	54	
South West England				20	33	50	26	43	54	
Wales				19	32	47	24	41	54	
West Midlands				19	33	49	26	42	54	
Scotland West				18	30	45	23	38	54	
Yorkshire and Humber				19	32	47	25	41	54	
Channel Islands	11	21	32	23	36	54	32	51	54	Medium Emission
East Midlands	11	21	32	23	37	54	33	52	54	
East of England	12	22	32	24	38	54	34	53	54	
Scotland East	10	19	29	18	32	48	26	44	54	
Isle of Man	10	18	28	19	31	46	27	44	54	
London	12	22	33	24	39	54	35	54	54	
North East England	11	21	31	22	35	52	30	49	54	
North West England	11	21	31	21	35	51	30	49	54	
Northern Ireland	10	19	28	20	32	46	29	45	54	
Scotland North	9	18	27	17	29	44	24	40	54	
South East England	12	22	33	24	39	54	35	54	54	
South West England	12	22	33	24	38	54	33	54	54	
Wales	11	20	31	22	36	54	32	51	54	
West Midlands	11	21	33	23	38	54	33	53	54	
Scotland West	11	20	30	21	34	50	29	47	54	
Yorkshire and Humber	11	20	31	22	36	52	32	50	54	
Channel Islands				25	41	54	41	54	54	High Emission
East Midlands				26	42	54	42	54	54	
East of England				27	42	54	43	54	54	
Scotland East				21	35	52	33	53	54	
Isle of Man				22	35	51	35	54	54	
London				28	44	54	45	54	54	
North East England				25	39	54	39	54	54	
North West England				24	39	54	39	54	54	
Northern Ireland				23	35	51	38	54	54	
Scotland North				20	32	48	31	49	54	
South East England				28	44	54	45	54	54	
South West England				26	43	54	43	54	54	
Wales				25	40	54	41	54	54	
West Midlands				26	42	54	43	54	54	
Scotland West				24	38	54	38	54	54	
Yorkshire and Humber				26	40	54	41	54	54	

Appendix 6 Data sources

Metric number	Metric Name	Data source
AG1a	Crop yield using sugar beet as a reference ‘arable’ crop	Brooms Barn experimental farm for 1980-2009
AG1b	Crop yield using wheat as a reference ‘arable’ crop	HGCA for 1960-2007
AG1c	Crop yield using potato as a reference ‘field vegetable’ crop	UK Potato Council (PCL) for 1980-2008
AG2	Agricultural areas at risk from tidal flooding	Met Office (Mean annual climate data for rainfall, temperature and radiation)
AG3a	Crop disease using ‘virus yellows’ as a marker for sugar beet	Brooms Barn Experimental Farm data for 1980 to 2009
AG3b	Crop disease using ‘rust’ as a marker for wheat	HGCA for 1960-2007
AG3c	Crop disease using ‘blight’ as a marker for potatoes	UK Potato Council (PCL) for 1980-2008
AG4	Agroclimate	PSMD derived from mean monthly rainfall and ETo data for 5km grid resolution for UK, 1961-1990
AG5	Water abstraction for crops	Environment Agency National Abstraction Licensing Database (NALD) data provided for total regional licensed and actual spray irrigation volumes (Ml/day), for 1990 -2003
AG6	Livestock water abstraction	Catchment Abstraction Management Strategies (CAMS) colours system)used with UKCP09 flows
AG7	Climate impact on livestock production	St-Pierre *et al.* (2003)
AG8	Duration of heat stress in dairy cows	St-Pierre *et al.* (2003) Hudson *et al.,* (2010)
AG9	New Crops	Data on potential for new crops derived from internet searches/dedicated websites
AG10	Grassland Productivity	Defra project CC0359
AG11	Soil Erosion	Morgan (1979), Hudson (1965), work on rainfall erosivity.