Land use, climate change & water availability (Phase 2a)

TASK B: DEVELOPMENT OF A RANGE OF PLAUSIBLE FUTURE LAND USE, LAND MANAGEMENT AND GROWING SEASON CHANGES

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Disclaimer

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Contents

SUMMARY

Based on a review of the literature, plausible characteristics of future land use and management changes (induced by climate or social change by the 2050s) that are likely to influence water availability include:

- Changes in land cover:
    - A decline in the area of agricultural land used for food production;
    - Increased use of agricultural land for bioenergy crop production;
    - Continued increase in urban areas;
    - An increase in forested area, generally at the expense of land that is no longer required for agriculture;
    - Reversion of coastal agricultural areas, due to changing defence policy and sea level rise.
- Changes in cropping calendars, growing season and plant physiology:
    - The growing season is likely to start earlier and end later in the year;
    - The date of the end of the field capacity period in spring is likely to be little changed, restricting improvements in access to land at the start of the growing season;
    - Soil moisture deficits increase, with longer periods when soil moisture is at levels that restrict crop growth and leading to a later start of the autumn/winter recharge period;
    - Flowering timings of spring and summer plant species will get progressively earlier as the climate warms;
    - Climate change causes faster rates of development in many crops, leading to earlier harvest;
    - Increased atmospheric CO_2 concentration can affect evapotranspiration directly due to the decreased stomatal conductance on transpiration (reducing ET), and indirectly due to increased biomass growth (increasing ET);
    - Small potential increases in evapotranspiration from higher-yielding cereal varieties.
- Changes in land management practices:
    - Earlier sowing or planting of many crops, including wheat, potatoes, sugar beet.
    - Later harvesting of sugar beet to compensate for drought-related losses on light soils.
    - Supplementary irrigation will allow approximately 85% of the total arable land in central and eastern England to remain suitable for potato production.
- Changes in the type of crops grown:
    - The distribution and choice of future cropping is very sensitive to the socio-economic scenarios;
    - There are likely to be changes in the relative proportions of autumn and spring-sown crops, in response to soil conditions and profitability;
    - Some scope for introduction of new food and bioenergy crops, although it is uncertain whether they will have an economic advantage over existing crops (e.g. sunflower vs oilseed rape).

The potential importance of these changes for water availability are assessed within the Task C reports of Holman and Hess (2014) and Hughes and Mansour (2014)

1. INTRODUCTION

Landuse or land management change can potentially impact the availability of water, through changing the amount of precipitation that is returned to the atmosphere by evapo-transpiration or by changing the soil hydrology and the partitioning of water between fast (runoff) and slow (groundwater) pathways. The systematic review described in the Task A report (Houghton-Carr et al., 2013) identified the important role of trees, bare soil and improved soil-water management in affecting water availability.

The aim of Task B reported herein was to use the available literature to identify a range of plausible future land use, land management and growing season changes against which to test potential hydrological impacts, including recharge. Given the diverse range of possible futures (climate models, emissions scenarios, socio-economic scenarios, etc.) it is important to understand that this report is not intended to predict or develop scenarios of future land use.

Based on a review of literature, previous studies and the insights from Houghton-Carr et al. (2013), characteristics of projected land use changes (that may be induced by climate or social change by the 2050s) that are likely to influence catchment hydrology have been reviewed, focussing on:

- Identifying those existing land cover classes which may change significantly in extent (either increasing or decreasing)
- Changes in cropping calendars (e.g. planting and harvesting dates) or growing season length and plant physiology (e.g. rooting depth, transpiration efficiency) as a result of changed climate, elevated CO_2 and crop improvement.
- Changes in land management that may be promoted as drought resilience measures.
- Changes in the type of crops grown within a land cover class including “new” crops (such as energy crops, industrial crops and crops not previously widely grown in the UK) which may have different water consumption.

The review was carried out using the Web of Knowledge bibliographic system, using the search terms of “Climate change” and “UK” combined with “crop*”, “growing season”, planting “harvest date”, “crop phenology*”, sowing, senescence, “crop suitability”, “root* depth”, LAI, “Leaf Area”, grass, forage, fodder, silage, hay and “vegetation grow*”. Additional studies were identified through cited references.

2. IDENTIFICATION OF LAND USE CLASSES WHICH MAY CHANGE SIGNIFICANTLY IN EXTENT

Future land use distribution in the UK depends on the complex interplay of supply, demand, prices and profitability at multiple scales from farm to global. A number of studies (Table 2.1) have developed future land use change scenarios at the global, European and UK scales based on the assessment and modelling of multiple drivers of change, including climate change (e.g. Verburg et al., 2006a; Busch, 2006).

Table 2.1 Principal studies of future land use change assessment at various scales of application (adapted from Rounsevell and Reay 2009)

Scale or geographic extent	Study or model name	References
UK regional scale	*RegIS* (Regional Impact Simulator) applied to East Anglia and north west England	Holman et al. (2005a,b), Audsley et al., 2006, 2008
UK national scale	*CLUAM* (Climate-Land Use Allocation Model) *UK National Ecosystem Assessment*	Hossell et al. (1996) UK NEA (2011)
European scale	*ATEAM* (Advanced Terrestrial Ecosystem Analysis and Modelling) *ACCELERATES* (Assessing Climate Change Effects on Land use and Ecosystems: from Regional Analysis to The European Scale) *ALARM* (Assessing LArge-scale environmental Risks for biodiversity with tested Methods) and Ecochange projects *EURuralis*	Ewert et al. (2005), Reginster and Rounsevell (2006), Rounsevell et al. (2006), Schröter et al. (2005), Zaehle et al.(2007) Schröter et al. (2005), Audsley et al. (2006), Fekete-Farkas et al. (2006), Berry et al. (2006), Rounsevell et al. (2006) Settele et al. (2005) van Meijl et al. (2006), Verburg et al. (2006b)

Although there is great uncertainty in these studies, even with regard to the direction of future land use change, with the area of agricultural land use being especially contentious (Busch, 2006), Rounsevell and Reay (2009) used these studies to draw some general conclusions about plausible future land use change in the UK:

- a decline in the area of agricultural land used for food production, with this decrease being partly offset by the increased use of agricultural land for bioenergy crop production;
  - According to Rounsevell and Reay (2009), the predominant view in the literature is that the combined effects of climate and technological drivers will be a net increase in the UK's agricultural productivity, which most studies of future agricultural land use suggest is unlikely to be compensated for by the increase in the demand for UK agricultural goods, leading to a decline in the area of agricultural land in both Europe and the UK
  - Simulated yield mapping for *Miscanthus* showed that areas with the highest biomass yields co-locate with food producing areas on high grade land, but that when high grade agricultural land and unsuitable areas are excluded, a policy-related scenario for increased planting on 350,000 ha utilised only 4-28% (depending on the region) of lower grade land and would not necessarily greatly impact on UK food security (Lovett et al., 2009)
- continued increase in urban areas, in response to population increases and residential location choices;
- an increase in the area of forested land, generally at the expense of land that is no longer required for agriculture
  - Much of this increase arises from declines in the area of agriculture, but is also due to the reforestation strategies embedded in rural development policy;

- o The commercially suitable range for Sitka spruce (a leading commercial conifer) is predicted to contract in England, but with increased productivity in much of Wales and Scotland.
- a retreat in coastal land areas, primarily as a consequence of changing defence policy, but also due to sea level rise.

The National Ecosystem Assessment (UK NEA, 2011) completed a study that produced six scenarios aimed at determining how ecosystem services may change to the 2060s. For each scenario, two Low and high climate impacts scenarios were used within a Bayesian modelling approach that used 1 km^2 LCM 2000 data to produce a maps showing the distribution of eight broad habitat classes - Open water, Wetlands and Floodplains; Urban; Mountains, Moorlands and Heaths; Semi-natural Grasslands; Marine; Coastal Margins; Woodlands and Enclosed Farmland. Figure 2.1 shows the changes in categories for England and Wales as separate diagrams. These scenarios show significant changes (increases and decreases) in the proportion of land within Semi-natural grasslands and Woodland and significant decreases in the proportion with Enclosed Farmland (which includes both Arable and Horticulture and Improved Grassland).

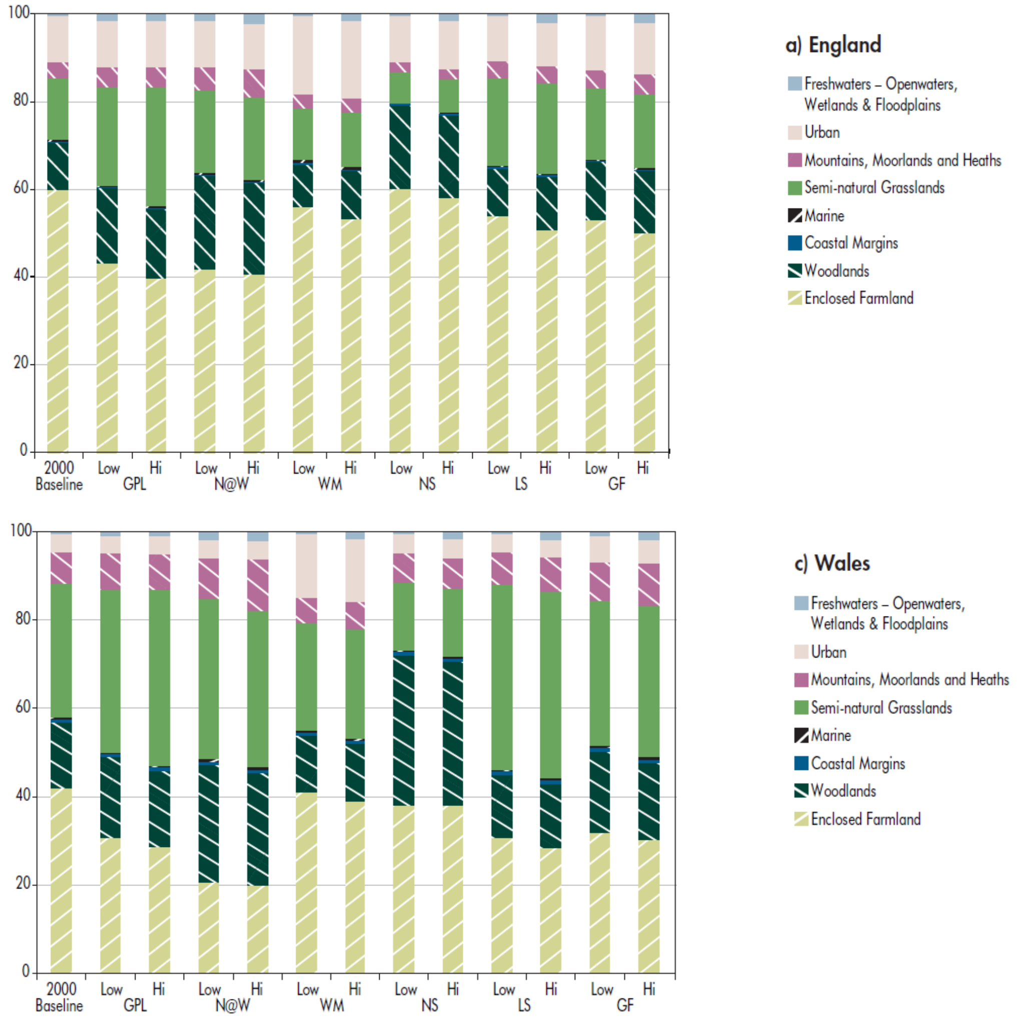

Figure 2.1 Projected changes in the stock of the UK NEA habitats for the six scenarios for (top) England and (bottom) Wales. The Scenarios are: GPL = Green and Pleasant Land; N@W = Nature@Work; WM = World Markets; NS = National Security; LS = Local Stewardship; GF = Go with the Flow. Low and Hi refer to Low and High climate change impacts (from UK NEA, 2011)

Audsely et al (2008) investigated future regional land use in East Anglia and North West England under a range of scenarios defining climate, technological and socio-economic changes, estimating the most likely cropping and its profitability at each location, and thereby classifying land use as arable, intensive or extensive grassland or abandoned. This showed modest changes of around 5-10% in many of the land cover classes (Fig 2.2). In contrast Clark et al. (2010) suggested that projected climatic changes are likely to lead to significant reductions (of between 13-84% by 2071-2100) in the upland area which is not suitable for the production of crops (classified by the EU as Severely Disadvantaged Areas) suggesting the potential for agricultural expansion into these marginal areas

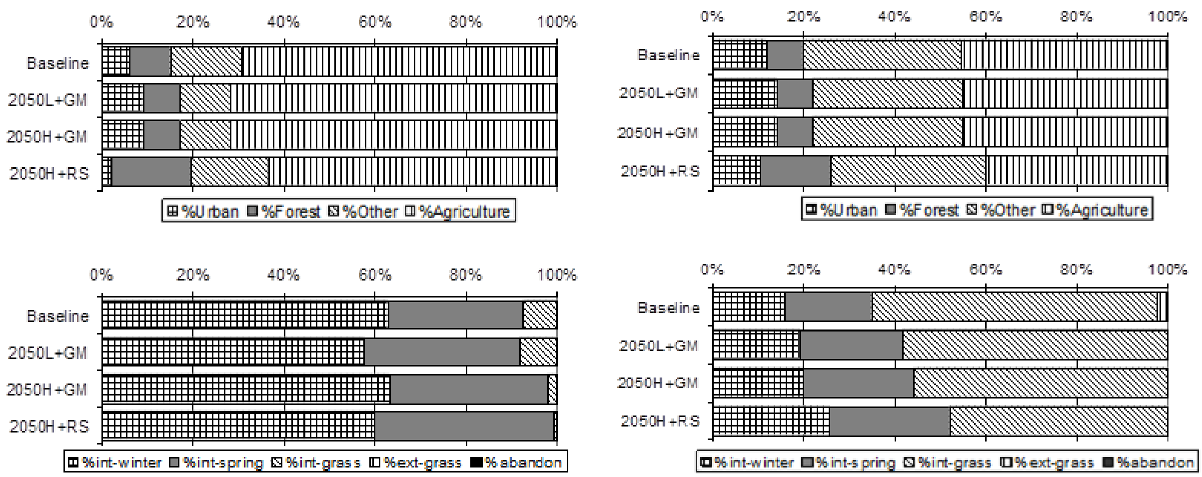

Figure 2.2 Effect of RegIS2 scenarios in (left) East Anglia and (right) North West England on (top) % regional land use and (lower) % of each intensity of agricultural land use. The scenarios are a) baseline b) 2050s Low (climate) + Global Market (economics) c) 2050s High+Global Market d) 2050s High + Regional Stewardship (from Audsley et al., 2008)

3. CHANGES IN CROPPING CALENDARS OR GROWING SEASON LENGTH AND PLANT PHYSIOLOGY.

The likelihood of climate change affecting the development of crops is indicated by Sparks et al (2005), who examined a large number of agricultural and other phenological records kept by a farmer in Sussex from 1980 to 2000. Twenty five of the 29 events occurred, on average, 5.5 days earlier in the period 1990-2000 than in 1980-1989, whilst January-March mean temperature increased by 1.4 ^{o}C. Response rates to temperature varied between 4 and 12 days earlier for each °C warmer

3.1 Agrometerology indices

Rivington et al (2013) used simulated Scottish climate data for the 2070–2100 ('future') time period produced by the Hadley Centre's HadRM3 RCM A2c configuration (medium-high GHG emissions scenario) combined with a simple soil water balance model to derived the date and lengths of a number of agrometerological metrics (Figure 3.1). Their results show that:

- the growing season may start earlier and end later in the year;
- the date of the end of field capacity in spring remains the same, restricting access to land at the start of the growing season.
- soil moisture deficits increase, with longer periods when soil moisture is at levels that restrict crop growth and a later start of the autumn/winter recharge period
- Milder winters and the last spring frosts occurring earlier are likely to have a positive impact on pests and pathogen survivorship and dispersal, increasing the risks to crops and livestock.

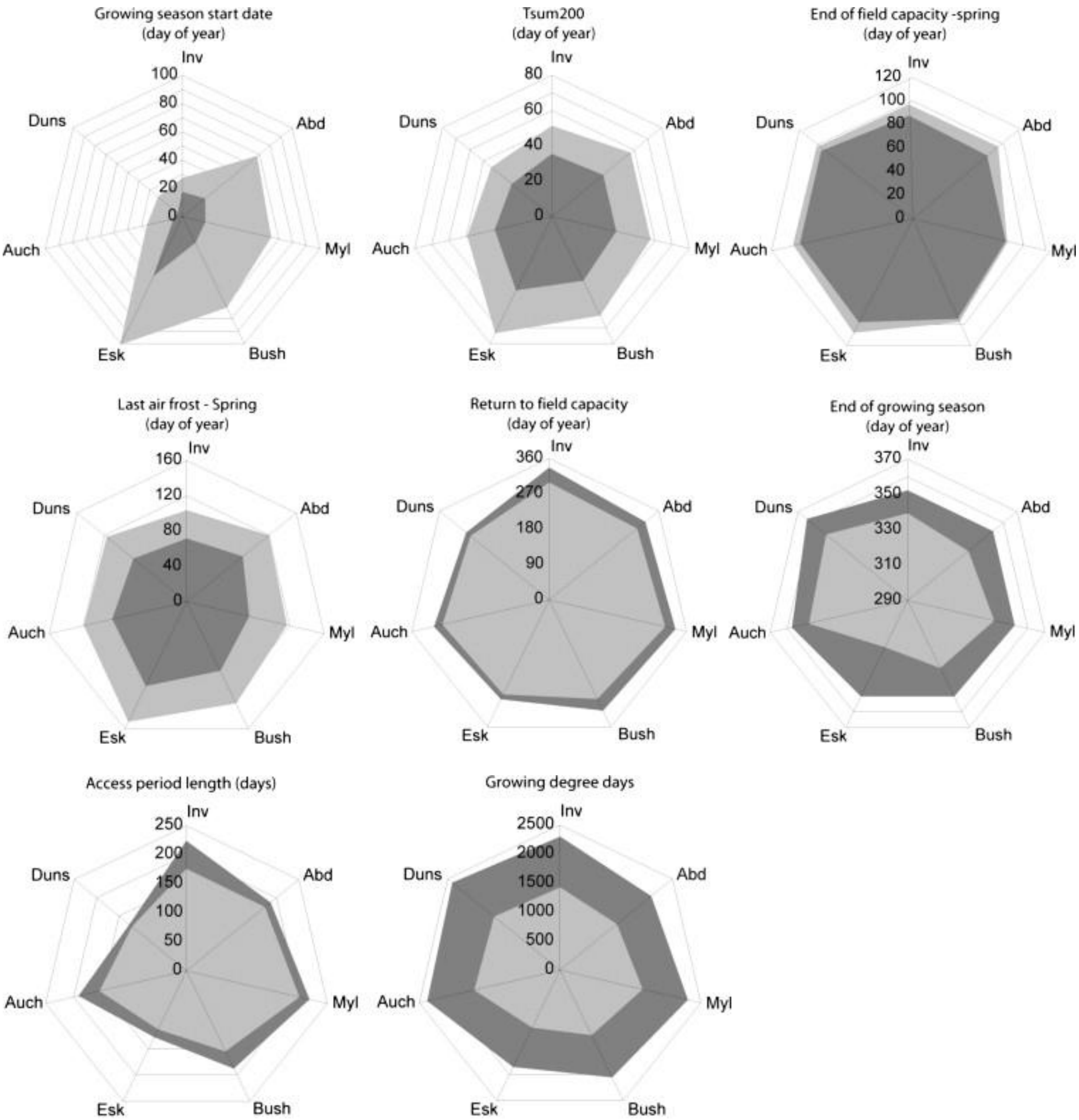

Figure 3.1. Median single agro-meteorological metrics at multiple sites polar plots for the observed (light grey) and future projection (dark grey) periods. Sites: Inv, Inverness; Abd, Aberdeen; Myl, Mylnefield; Esk, Eskdalemuir; Auch, Auchincruive; Duns, Dunstaffnage (from Rivington et al 2013)

3.2 Vegetation-specific impacts

A number of studies have looked at the modelled effect of climate change scenarios on key crop growth dates:

- **Wheat**: early crop modelling work by Harrison et al (1995) suggested that climate change caused faster rates of wheat development, which will shorten the length of the growing period. This would lead to an earlier start to crop growth in the spring and a shorter grain filling period. The magnitude of the shortening of the growing period varied according to the scenario and GCM but was between 1 and 8 weeks.
  In all of the 13 administrative regions in the UK Climate Projections (UKCP09), Cho et al. (2012) found that increases in UKCP09 temperature accelerated the development rate of wheat - a result that was robust across the ensemble. This generally leads to positive impacts on yield and a northward shift in cultivation, with some decreases in yield in the south.
  Increasing temperatures are predicted to accelerate plant development of wheat, with Richter and Semenov (2005) stating that anthesis flowering (growth stage 65) will occur two to three weeks earlier in the 2050s - at the end of May instead of mid-June as at present. Madgwick et al. (2011) also suggest that it will get progressively earlier, by about 11–15 days across the whole country by the 2050s, with this effect being slightly greater with time, emissions scenario and near the south coast of England than in the north of Scotland. However, Richter and Semenov (2005) consider that the period of grain filling is predicted to be less affected by climate change, being shortened by up to two days
- **Onions**: Climate change caused faster rates of onion development, shortening the length of the growing period 2-4 weeks under four transient GCM scenarios (Harrison et al (1995), but leading to increases in potential yield.
- **Grapevines**: The simulated date of maturity for grapevine under two climate change scenarios advanced by between 20-50 days, whilst bud burst and flowering occurred earlier by 10-25 days (Butterfield et al., 2000).
- **Cauliflower**: The phases of juvenility and curd growth in cauliflower were shortened by increased temperature, while in most cases that of curd induction was increased. The net effect was to advance maturity in most situations (Wurr et al. 2004)
- **Grasses**: Van Vliet et al. (2002) suggest that the start of the grass pollen season (linked to flowering) might start 11 days earlier in 2090s compared to 2000s, with a mean start date of 132 Julian Days

3.3 Plant physiology

3.3.1 Rooting

Whitmore and Whalley (2009) review the literature on the physical effects of soil drying on roots and crop growth. There is evidence in the literature that growing a large root system often penalized above-ground growth, although a large root system seemed to reduce the risk of crop failure as a result of nutrient or water stress. This perhaps explains why the root systems of modern wheat cultivars are small, having around two-thirds of the root mass of the landraces from which they derive, resulting from selection for larger grain yields when grown under optimal management, nutrient and water supply. They conclude that drought is not a single, simple stress and that agronomic practice that seeks to adapt to climate change must take account of the multiple facets of both the stress induced by insufficient water together with other interacting stresses such as heat, disease, soil strength, low nutrient status, and even hypoxia.

3.3.2 CO_2 effects

Increased atmospheric CO_2 concentration can affect evapotranspiration directly due to the effect of decreased stomatal conductance on transpiration, and indirectly, due to increased biomass growth.

Stomatal conductance

When atmospheric CO_2 concentration increases, the stomata of plants close partially in order to maintain a near-constant concentration of CO_2 inside the leaf, as such the stomatal conductance (for water vapour) decreases about 40% for a doubling of CO_2 (Morison, 1987). This occurs in grasses and C3 crops, trees and C4 crops (Figure 3.2). C3 plants include cereal grains (wheat, rice, barley, oats), potatoes, soybean and sugar beet, most trees, most grasses such as rye and fescue and represent about 85% of plant species; whilst C4 plants include sugar cane, maize, sorghum, millet, many tropical grasses, Bermuda grass and sedges.

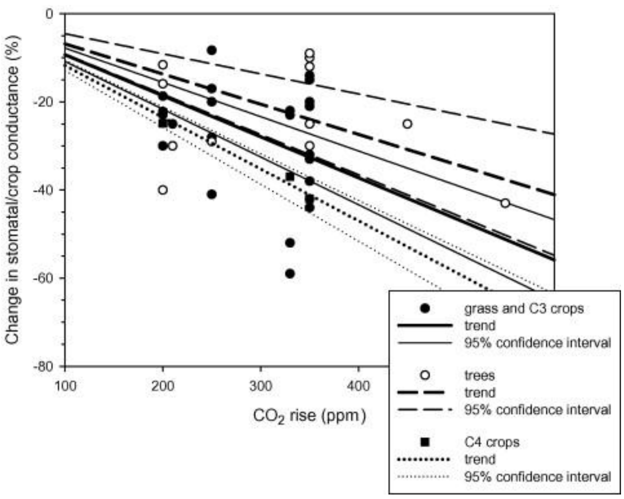

Figure 3.2 Observed effects of increased CO_2 concentrations (ppm) on change in crop conductance (Source Kruijt et al., 2008).

Transpiration

Reduced stomatal conductance has the effect of suppressing transpiration (Field et al., 1995), however, it leads to a reduction in evaporative cooling and an increase in leaf temperature, which partially offsets the effect, and thus whole-crop transpiration is maintained only slightly lower (10%) than would exist at ambient CO_2 (Allen et al., 2003). The effect of changes in stomatal conductance on transpiration depends on the aerodynamic conductance, the presence of a boundary-layer and stomatal conductance itself (with higher conductance, the sensitivity is lower, because the coupling to the atmosphere is relatively weaker) (Kruijt et al., 2008). The effect is greatest at low vapour pressure deficits, therefore more significant in arid climates (Kallarackal and Roby , 2012). Lockwood (1999) also argued that the effect will be most noticeable in dry climates where interception loss is insignificant, although in hot-arid climates (such as the Mediterranean area) the increase in air temperature inevitably leads to an evapotranspiration rise (Lovelli et al., 2010).

Photosynthesis

In the natural environment, CO_2 is normally sub-optimal, therefore photosynthesis in C3 species is stimulated by an increase of ambient CO2 (Lockwood, 1999). Elevated CO_2 increases photosynthesis substantially, leading to greater leaf area and more stomata, which may increase transpiration, partially counter-acting the effect of stomatal closure (Betts et al. 2007). In C4 species photosynthesis is already CO_2 -saturated at current CO_2 concentrations (Lockwood, 1999) and therefore photosynthesis does not increase under elevated CO_2.

Impact of elevated CO_2 on evapotranspiration

Ainsworth and Long (2005) carried out a meta-analysis of data from 120 primary, peer-reviewed articles describing physiology and production in 12 large-scale free-air CO_2 enrichment (FACE) experiments. These allow the exposure of plants to elevated CO_2 under natural and fully open-air conditions. They found that growth and above-ground production increased and stomatal conductance decreased in elevated CO_2. Trees were more responsive than herbaceous species to elevated CO_2 and biomass of C4 species showed little response. Stomatal conductance decreased on average by 20% in both C3 and C4 species.

Keenan et al. (2013) summarised results from seven forested sites in the midwestern and northeastern United States over recent years and found an increase in water use efficiency (biomass per unit transpiration) due to increasing photosynthesis and decreasing evapotranspiration.

In addition to experimental observations, a number of modelling studies have attempted to estimate the effect of increase CO_2 on evapotranspiration. Leipprand and Gerten (2006) analysed the potential effects of doubled atmospheric CO_2 on global evapotranspiration, soil moisture and runoff, under the theoretical (and unrealistic) assumption that no climate change accompanies CO_2 enrichment. When ambient CO_2 was doubled, global ET decreased by ≈6%. Kruijt et al. (2008) suggested that the combined effects of CO_2 on evapotranspiration reduction are generally modest - a few percent for short crops to about 15% for tall, rough vegetation. Leuzinger and Körner (2007) modelled a 14% reduction of tree transpiration during the growing season resulting in <10% reduction in net water consumption in a mixed forest stand (Switzerland) however, the effect varied with species. Fatichi and Leuzinger (2013) estimated that reductions in water fluxes induced by elevated CO_2 are likely to be less than 10% in a mature deciduous forest in Switzerland. Salmon-Monviola et al. (2013) modelled a catchment in Brittany (France) with land use dominated by intensive livestock farming. With increased CO_2, the main trends in water balance were a significant decrease in ET. Not considering the effects of increased atmospheric CO_2 in the agro-hydrological model led to overestimating discharge decrease and underestimating ET decrease from climate change.

Figure 3.3 illustrates the complexity of the factors affecting the evapo-transpiration response to elevated CO_2.

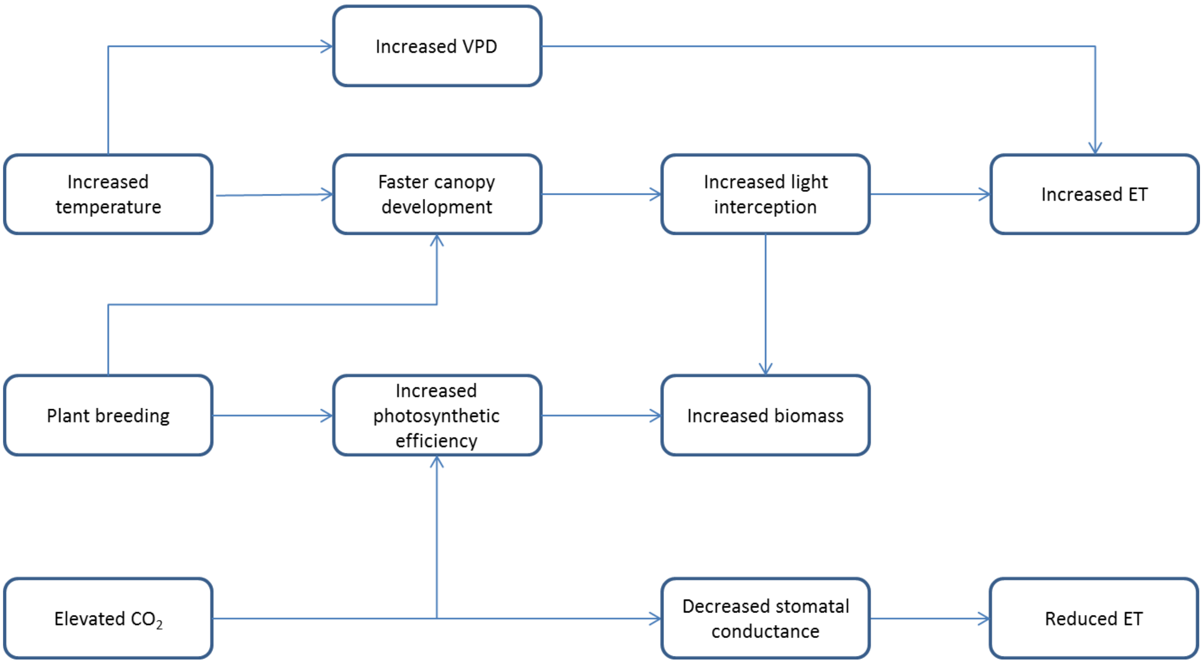

Figure 3.3 Overview of the factors affecting the evapo-transpiration response to elevated CO_2

Impact of elevated CO_2 on Runoff

Gedney et al. (2006) attributed part of the observed increases in continental runoff to suppression of plant transpiration due to CO_2 -induced stomatal closure, and Betts et al. (2007) suggest that the effect on global mean runoff is comparable in importance to that of radiatively forced climate change (as the effect of doubled CO_2 concentrations on plant transpiration was to increase simulated global mean runoff by 6% relative to pre-industrial levels). Nugent and Matthews (2012) found similar modelled results, with vegetation responses to elevated CO_2 leading to a simulated 13% increase in global runoff and a 12% increase in the northern latitude region, similar to that of the direct effect of climate warming.

Impact of elevated CO_2 on Recharge

Ficklin et al. (2010) modelled the sensitivity of groundwater recharge (under irrigated agriculture in California) to changes in climate and CO_2 concentrations. Increasing CO_2 alone decreased average daily ET_o however the magnitude of the effect depended on the modelled combination of CO_2 and temperature. The impacts on recharge mostly related to changes in irrigation need. Kersebaum and Nendel (2013) predicted higher rates of annual deep percolation for wheat cultivation in Germany and the effect was larger for areas with low precipitation and “better” soils. Kruijt et al. (2008) suggested that direct effects of CO_2 reducing evapotranspiration in the Netherlands can be expected to be moderate, up to 15% reduction in soil water deficits by 2100, with relatively stronger effects in summer and in rougher, natural vegetation such heath lands and (deciduous) forests.

3.3.3 Increasing wheat yield and water requirements

The Wheat Yield Consortium (WYC) has speculated as to how the global yield of wheat may be increased. Historic increases in yield have been due to improvements in harvest index (HI) associated with the development of dwarf varieties with reduced stature; whilst radiation use efficiency has barely changed in recent years. Future yield gains will be achieved by considering all three components in the equation below. The WYC propose a 10 – 50% increase in biomass of through modification of radiation use efficiency and light interception in the next 10 – 25 years (see box below).

The scientific basis for future increases in wheat yield is presented in three linked papers (Reynolds et al., 2011; Parry et al., 2011; Foulkes et al., 2011) that have been used as the basis for the discussion below.

Yield potential = LI x RUE x HI

Where: LI = Light interception

RUE = radiation use efficiency

HI = Harvest Index

LI. Light interception can be increased by improving the rate of early leaf area growth in order to reach maximum light interception earlier and extending the growing season. This is particularly important in high-input conditions in the UK provided that there is enough water available during the late grain-filling stage.

RUE: Increasing photosynthetic potential through traditional plant breeding and transgenic technologies. The aim is to increase output per unit of land without increased inputs of fertiliser or water.

HI: Genetic modification of structural and reproductive aspects of the plant to optimise partitioning to grain will increase biomass and harvest index (HI). In addition, it will be important for higher yielding wheat plants to have stronger stems and root systems to avoid/reduce lodging. In addition, increased biomass is likely to require increased access to water through deeper rooting systems.

(Reynolds et al., 2011; Parry et al., 2011; Foulkes et al., 2011)

If the water use efficiency (WUE; g grain/ g water) is unchanged, a 10 – 50% increase in biomass would extrapolate to a 10 – 50% increase in water consumption. However, this is unlikely to occur.

1. Firstly, it is unlikely that WUE of improved high-yielding wheat would remain constant.
    a. Improvements in photosynthetic efficiency are likely to be accompanied by improvements in transpiration efficiency (g biomass / g water), for example, by including characteristics of C_4 plants, in which case the increase in transpiration would be less than the increase in biomass.
    b. Some of the increase in transpiration from earlier canopy development and longer growing seasons is offset by reductions in soil evaporation.
    c. Shorter crops (developed to increase HI and reduce lodging risk from heavier grains) are less well coupled to the atmosphere, have lower aerodynamic resistance and, as a result, have lower ET under constant weather conditions.
2. Secondly, there is an upper limit to evaporation from a cropped surface imposed by available energy. On a catchment scale, the upper limit to evaporation is the net radiation, so plant water use cannot increase linearly, indefinitely. Allen et al. (1998) estimate that this represents 1.05 to 1.30 times the grass reference evapotranspiration (ETo) depending on humidity and wind speed. For typical weather conditions in the UK, the upper limit is closer to 1.20. Given that evapotranspiration (ET) from wheat at full cover is approximately 1.10 times ETo this represents a maximum increase of <10%.

Deeper-rooted wheat would result in increased actual ET in locations and years when otherwise it would have been depressed due to water stress and extended growing seasons are likely to increase net ET. Earlier establishment means more ground cover early in the season and higher relative ET at that time of year. However, higher ET in the spring may result in more total water use, or it may just mean that the crop runs out of water sooner.

The above would suggest a potential increase in evapotranspiration from high-yielding wheat of between 0 - 10% - the latter only occurring in windy, low-humidity conditions; where water, light and nutrients are not limiting; and crop husbandry is optimised.

3.4 Other vegetation impacts

Sparks et al (2000) determined that the flowering timings of spring and summer species will get progressively earlier as the climate warms, based on their analysis of the relationship between flowering dates for 24 plant and tree species and the Central England Temperature. The average first flowering date of 385 British plant species has advanced by 4.5 days during the past decade compared with the previous four decades, whilst 16% of species flowered significantly earlier in the 1990s than previously (with an average advancement of 15 days in a decade) and ten species (3%) flowered significantly later in the 1990s than previously (Fitter and Fitter, 2002).

Amano et al. (2010) derived a 250-year index of first flowering dates for 405 plant species in the UK which suggested that flowering occurs 5.0 days earlier for every 1 ^{o}C increase in February-April mean Central England Temperature.

4. CHANGES IN LAND MANAGEMENT PRACTICES.

A range of changes in land management practices are described in the literature which may represent climate change adaptation:

- **Earlier sowing or planting**: Wolf (2000, 2002) pointed to the need for advancing the planting date of potatoes with climate change. Earlier wheat sowings appear to be more beneficial in the future over the UK, whilst later sowings increase the risk of yield losses (Cho et al. 2012). Harrison et al (1995) found that modelling an earlier sowing date (by 30 days) for wheat considerably reduced the shortening of the growing period, and led to slightly increased yields. In contrast, sowing 30 days later than at present caused larger reduction in the length of the growing period and to decreases in yield. Richter et al (2006) advocates earlier sowing for sugar beet to compensate for drought-related losses on light soils, although van Oort et al. (2012) report that there is no correlation between spring temperature and observed sugar beet sowing dates in the Netherlands;
- **Later harvesting**: Richter et al (2006) also suggests later harvesting for sugar beet to compensate for drought-related losses on sandy soils
- **Crop breeding**: Although winter waterlogging is expected to become an increasingly serious problem due to climate change (due to increased winter precipitation), Dickin et al (2009) found that all wheat cultivars showed considerable ability to compensate for winter waterlogging damage by vigorous spring growth. They suggest that the overall good level of tolerance and ability to compensate has been selected for, either inadvertently, or as a

result of selecting the best cultivars in UK conditions, where tolerance to waterlogging is a part of the general winter hardiness required.

- **Supplementary irrigation**: the area of land that is currently well or moderately suited for rainfed potato production would decline by 88 and 74%, respectively, by the 2050s under the 'most likely' UKCP09 climate projections for the low emissions scenario and by 95 and 86%, respectively, for the high emissions scenario, owing to increased likelihood of dry conditions. However, with supplementary irrigation, approximately 85% of the total arable land in central and eastern England would remain suitable for potato 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. (Daccache et al, 2012).

5. CHANGES IN THE TYPE OF CROPS GROWN WITHIN A LAND USE CLASS

Whilst it has earlier been shown that many of the studies do not envisage large climate-induced changes in land use in the UK, there may be opportunities for significant changes in the crop composition as changes in the climate alter the relative profitability of existing and new crop types (such as energy crops, industrial crops and crops not previously widely grown in the UK).

The farm model of Holman et al. (2005a,b) indicates that the future distribution of cropping in the East Anglian and North West regions show little change in type of cropping due to climate change alone. The distribution of cropping is very sensitive to the socio-economic scenarios, consistent with the results of Abler et al. (2002), with both socio-economic scenarios modelled producing substantial changes. In the East Anglian region, the proportion of the area in winter crops reduces under all scenarios, due to corresponding increases in spring crops, sugar beet and potatoes. In the North West region, both socio-economic scenarios generate a large increase in arable cropping (and expansion of sugar beet), due to the reduced competitiveness of dairy farming. The results of Audsley et al (2008) are broadly similar for the two regions, although there is less of a switch from winter to spring crops.

There is little detailed crop information within the NEA scenario narratives (UK NEA, 2011):

- Green and Pleasant Land – no specific information other than reduction in specialised (grain fed) livestock farms and increase in the number of mixed farms;
- Nature@Work - meat production decreases, but the nation’s protein requirements are met by an increase in pulse production (and other protein crops such as quinoa, hempseed and buckwheat); some increase in mixed farming in eastern counties.
- World Markets - Specialisation is normal in farming and there are very few mixed farms. Woody biomass cropping and other cropped biofuels increase to meet energy demand. Modern arable farms are industrialised, with large fields of cereal or protein crops. Apart from a huge increase in willow for short-rotation coppice (SRC), most surviving woods have been replanted with exotic species to maintain timber production. Large conifer and Eucalyptus woodlands have begun to appear in many hilly areas of the UK
- National Security - Biotechnology crops are also heavily utilised; Plant-based protein is a more efficient use of agricultural land and meat production is heavily taxed which results in some surplus grassland becoming available for arable, short rotation coppice bio-ethanol

production, as well as new forest plantations for timber. Protein-based crops as well as more traditional grain and starch crops increase to offset a reduction in meat production. Overseas conifer species are widely used in upland areas (Monterey and Corsican pines)

- Local Stewardship - wheat exports reduce, to be replaced by more protein and vegetable crops; many arable farms have become mixed; Lower grade agricultural land is converted to woody biofuel in peri-urban areas and in lowland rural counties
- Go with the Flow – cropping changes to reflect the impacts of climate change occur; these include new crop species [unspecified], more perennial crops and biofuels; National production of cereals and protein crops increases overall

The growth attributes and perenniality of Miscanthus and SRC willow present important differences to most current rural land-uses, as unlike arable crops, biomass crops remain in situ for 7–25 years, harvest is carried out in winter/early spring and the crops are very tall (3–5 m) and dense. Commercially grown Miscanthus undergoes C4 photosynthesis, and is more cold-tolerant than maize, producing commercially sufficient biomass yield in the temperate climate of the mid-southern UK. Rhizomes are planted in early spring and shoots emerge once mean daytime temperatures exceed c. 9 ^{o}C. Miscanthus reaches heights of about 3 m in the UK, before senescing over the winter months. It is harvested annually in late winter/early spring for up to 20 years. Willows are C3 shrubs and trees. Stem cuttings planted in spring achieve single stem heights of up to 2.5 m by September, before being cut back in December-March. Multiple 'coppice' shoots are subsequently harvested after 3 years, by which time they may be about 5 m in height, on a 3-year cycle for up to 25 years.

Haughton et al. (2009) suggested that 3·1 million ha of land in England is currently suitable for planting of Miscanthus and short rotation willow, based on mapping of environmental and physical constraints. Bellarby et al. (2010) predicted the potential distribution of 26 bioenergy crops in the UK under present and future climate, based crop growth limitations due to elevation, temperature, high and low rainfall. Most of the crops currently grown are predicted to remain prevalent in the UK. A number of crops are suitable for introduction to the UK under a changing climate, whereas others retreat to northern parts of the UK (Table 5.1). The greatest changes are expected in England.

Harrison et al (1995) showed an expansion of sunflower suitability into much of the UK, from a baseline suitability confined to south east England. However, future yields are likely to be marginal, as climate change led to decreases in simulated water-limited yields in northern Europe under all scenarios. This is supported by Ausdley et al (2008) who found that sunflowers were only selected in one scenario in East Anglia, even though they are feasible in climate terms for all of them. This arose because the Farm model's production-target approach meant that sunflowers were competing to produce oil with oilseed rape which has a higher yield. Gibbons and Ramsden (2008) also found no modelled no major shift from native cropping to exotic crops (oilseed rape [*Brassica napus L.*] to sunflowers [*Helianthus annuus L.*]) in either the 2020s or 2050s.

Table 5.1 Overview of potential changes in bioenergy crop distribution in the UK (from Bellarby et al., 2010)

Change in suitability		Crops	Comments
No change	Cannot be grown anywhere in the UK	Safflower, castor, groundnut, sugarcane, prickly pear	
	Can be grown in large areas of the UK	Oilseed rape, linseed, barley, wheat, sugar beet, Jerusalem artichoke, maize, eucalyptus	
Increase	Could not be grown in the UK previously and can now be introduced	Cardoon, sorghum	In England only
		Sunflower, olives	England and Wales; only sunflower in Scotland and Northern Ireland
	Could be grown in England and Wales	Kenaf	In all parts of the UK
	Could be grown all over the UK	*Miscanthus*	Decrease in England under high emissions
Decrease		Reed canary grass, oats, rye, potato, SRC	In England and small parts of Wales
		Hemp	Decrease only in England whereas increase in other parts of the UK

The water resource impacts associated with four potential energy tree species -*Eucalyptus nitens*, *Eucalyptus gunnii*, *Nothofagus sp*. (southern beeches), and *Fraxinus excelsior* (European or Common Ash) were assessed by Calder et al (2009) at eight UK locations under present and future climate. They report published findings that evaporation from a tree crop of *Fraxinus excelsior* is less than that from grass. Their model predictions indicate that all tree species, excepting *Fraxinus excelsior*, have greater mean annual evaporation, (8 to 84%) and reduced water yields (-6 to -97%) at all sites compared with grass under the present climate, due to both increased rainfall interception and higher transpiration due to deeper rooting depths. Under future climate scenarios,

(1) "potential annual yield'' (difference between actual rainfall and potential evaporation) will decrease, becoming negative at all studied sites in England and Wales by 2080;
(2) at drier sites and for species with highest evaporation rates, *E. nitens* and *Nothofagus*, evaporation rates will decrease;
(3) at wetter sites and for all species, evaporation rates will increase;
(4) at all sites and for all species, water yields will decrease;
(5) differences between species remain the same, with evaporation rates increasing and water yield decreasing in the order *Fraxinus excelsior*, grass, *E. gunnii*, *Nothofagus*, and *E. Nitens*; and
(6) there is an overall trend through time toward convergence in water yields from trees and grass.

Assuming future climate changes match those predicted, soil moisture deficits will occur for longer periods during the year and will become increasingly limiting for evaporation.

6. CONCLUDING REMARKS

This review has shown that there is the potential for climate change to lead to many changes in the extent and types of crops and vegetation with the catchments of England and Wales. However, it is also apparent that there is great uncertainty in the direction and magnitude of many of these changes due to the important role of socio-economic change in the agricultural decision making process. Nevertheless it is plausible that future changes will lead to changes in the agricultural and forested areas, increases in the length of the growing season, changes in cropping calendars and changes in crop selection. The effects of these on water availability are investigated within Task C (Holman and Hess, 2014).

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