Final Report

Climate Change Impacts on the UK Potato Industry

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1. SUMMARY

Internationally, agriculture is widely regarded as one of the sectors at most risk from a changing climate, due to the impact of increased temperatures, reduced rainfall and increased frequency of extreme events, not only in the tropics, but also in temperate environments such as the UK. Climate change will influence the way crops develop, grow, and yield. Outdoor field crops such as potatoes will be particularly sensitive, both directly from changes in rainfall and temperature but also indirectly, since any changes will also impact on the agricultural potential of soils by modifying soil water balances, with consequences for land management, including trafficability and workability. Climate change will also impact on land suitability, the viability of rainfed potato production, and demand for supplemental irrigation. The aim of this project was to assess the impacts of climate change on UK potato production, focussing on (i) crop growth and production, notably yield and water use, (ii) land suitability and soil management, and (iii) irrigation water demand. The key findings and suggested adaptation responses for growers and the industry are summarised below.

1.1. Impacts on potato yield and water use

The impacts of climate change on the yield (t ha-1) and irrigation needs (mm) of a pre-pack variety cv. Maris Piper were assessed by combining the outputs from the latest UK scenarios of climate change (UKCP09) with a potato crop growth model (SUBSTOR–Potato) for a historical baseline and then for selected emissions scenario for the 2050s. The crop model was validated using experimental and field data from four reference sites (Cambridge University Farm, and three farms in Norfolk, Lincolnshire and Suffolk). Assuming crop husbandry factors are unchanged, farm yields would show 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, were projected to increase by 13-16%, mainly due to increased temperatures, radiation and CO_2 fertilisation effects. Future average irrigation needs, assuming unconstrained water availability, were predicted to increase by 14-30%, depending on the emissions scenario. A probabilistic distribution function was used to assess uncertainty in the projected irrigation needs. Current irrigation schemes and infrastructure are typically designed to satisfy needs in the 5th driest year in 20 (i.e. with an 80% probability of non-exceedance). However, the analyses showed that future peak irrigation needs might exceed current design criteria in nearly 50% of future years. Growers should consider these potential consequences carefully when planning investments in irrigation technology (application equipment) and water resources (e.g. winter storage) to ensure future potato yields and quality are not compromised.

As with all climate change impact assessments, the results need to be interpreted with caution. The crop modelling assumed unchanged farm practices in the future, but in reality there would be some degree of autonomous adaptation even if not planned. For potatoes, this could include earlier planting and harvest dates, changing to better adapted varieties, less dependence on soils with low water holding capacities, crop movement to regions with suitable agroclimate and water availability, and the uptake of GM technology.

1.2. Impacts on land suitability and crop husbandry

The commercial viability of potato production is influenced by the spatial and temporal variability in soils and agroclimate, and availability of water resources where supplemental irrigation is required. Knowledge of potential changes in land suitability is a key determinant influencing the sustainability of potato enterprises, as any future changes will influence cultivar choice, agronomic husbandry practices and the economics of production, for both rainfed and irrigated cropping. The current land suitability for maincrop potato production was initially modelled and mapped using a set of pedo-climate transfer functions and a geographical information system (GIS). This provided a reference or 'baseline' from which land suitability classes could be checked against observed data (PCL 2009) on the distribution of potato cropping (rain-fed and irrigated production). The projected future changes in land suitability were then modelled using the UKCP09 climatology for selected emissions scenarios (2050s and 2080s). A comparison with the baseline showed how land suitability classes (well, moderate, marginal, unsuited) might shift in the future due to the changing patterns of rainfall, temperature and other agroclimatic variables, and hence on current centres of potato production. Finally, the relationships between land suitability and water resource availability were assessed to identify where future irrigated production might be at risk and whether it might need to relocate to catchments where water resources are less constrained, or adapt to changing water reliability. From this, the implications on the potato industry were assessed, including where rain-fed production could become limiting, the varieties most/least suited to the projected changes in land suitability, and the adaptation options for growers (e.g. shifting production, new soil management techniques, new irrigation and drainage infrastructure).

The analyses showed that the locations of rainfed production in 2009 were very closely related to the theoretical assessment of land suitability for rainfed potatoes. The majority of rain-fed potatoes are located on well (24%) and moderately suited (41%) lands as these guarantee commercially acceptable levels of production. Irrigated potatoes are concentrated on moderate (57%) and marginally (37%) suited lands as irrigation overcomes the risks associated with droughtiness. However, with climate change, the analyses suggest that by the 2050s, for the most likely probability (50%), the area of land that is currently well to moderately suited for rain-fed production is expected to decline significantly (74-95%) owing to increased droughtiness. As with the impact modelling on potato yield, there is large uncertainty around these median value projections, but the direction and potential magnitude of impact is clear.

Regarding water resources, for the baseline, the analysis showed that approximately a third (34%) of growers involved in irrigated production are on moderate land and two thirds (59%) are on marginal land, and that 41% of these are located within catchments defined as being under water stress (over abstracted and/or over-licensed). By the 2050s, if the spatial distribution of growers remained unchanged, then the majority of irrigated production (87%) would be on marginal land, with 43% located in catchments defined as being either over-licensed and/or over-abstracted. Clearly, this situation would be unsustainable, particularly since the analysis assumed no change in future water resource availability, which itself is projected to worsen significantly.

The results show that growing rainfed potatoes in England and Wales may become increasingly risky as the climate changes, and limited to a few favourable areas. In contrast, with irrigation, the land suitability hardly changes, and most of the current rainfed crop could remain at its present location if irrigated. Although only around 1% of water abstraction in England and Wales is used for irrigated agriculture, there is limited prospect of the industry obtaining significant additional licensed quantities for the summer months in the face of competing demands. Many existing licences are unused or underused so some farm of water transfers or abstraction license trading may be an option, though there are environmental arguments against re-activating 'sleeper' licences in water short catchments. Previous research has suggested that irrigated potato production might move north and west as an adaptation to climate change. Given that most of the current locations remain suited to irrigated production, and that future summer water resources may not be reliable even where licenses are available at present, this may be a slow process. Many growers have sizeable investment in fixed assets for potato production, and may prefer to remain near their present locations, renting land from nearby farmers with unused or partially used licences as a preferred adaptation response.

Where irrigation is restricted during crucial times (e.g. scab control), tuber quality can suffer to the extent that certain varieties would be rejected. This would force a shift to those that are less susceptible or towards processing varieties. Any reduction in irrigation availability or reduction in rainfall would severely affect the profitability of crops such as Maris Piper and Maris Peer, where skin finish is crucial for packing. Determinate crops, i.e. those that only produce a limited leaf area and have short periods of active root growth are very sensitive to water restriction during the mid-late canopy expansion phase. Current widely-grown examples include Estima, Lady Rosetta and Saturna. Absence of rain or irrigation during these periods can an cause premature senescence with a large yield loss. For this reason, the cropped area of these cultivars is likely to reduce due to concerns regarding crop failure particularly where they are grown under rain-fed conditions or where there is an increased risk of irrigation restrictions. However, the yield response to irrigation of many of these varieties is large, so they will continue to be grown where irrigation is less limited. There will be a shift in un-irrigated areas to varieties that are able to either a) survive early drought periods so that they can use rainfall later in the season (e.g. King Edward, Markies, Russet Burbank or Rooster) or b) partition dry matter towards tuber production during periods of drought rather than canopy production so that they become more efficient at producing yield per unit of water use (e.g. Hermes or Desiree).

Finally, climate change is likely to lead to the dates of the last spring frosts becoming earlier and autumn frosts becoming rarer and/or later, thereby extending the growing season. Planting could therefore take place earlier as the thermal environment experienced by crop canopies would be more favourable. However, soils would still be at field capacity, leading to the same problems in workability that growers currently experience during March and April in many regions of the country. Reduced rainfall and higher temperatures will result in a depletion of organic matter, increasing the risk of structural damage to sensitive soils. Harvesting windows could become longer, thereby reducing the risk of adverse soil conditions causing harvesting problems or crop damage.

1.3. Impacts on irrigation water demand

In 2005, potatoes accounted for nearly half (43%) the total national irrigated area and 56% of the total volume of irrigation water applied in agriculture. For many agribusinesses, irrigated potato production is driving force behind farm investment, but competition between water sectors, coupled with increasing environmental regulation and the longer-term threat of climate change are limiting water supplies for irrigation. In 2008, demand forecasts for the Environment Agency's water resource strategy suggested increases in total irrigation demand of between 25% and 180%. This wide range reflected the contrasting effects of assumptions regarding sustainability, consumption, globalisation and regionalisation embedded within the socio-economic scenarios. In this study, the methodology developed by Weatherhead et al (2008) for the EA was updated to include the latest climate projections (UKCIP09). Demand forecasts were produced for two periods; (i) the short-term (up to 2020s) for a 'business as usual' scenario under current economic and water policy conditions, and (ii) the medium to long-term (2050s) for four socio-economic scenarios. All potato demand forecasts were for 'unconstrained demand in a dry year', i.e. the volume abstractors would take in a dry year assuming water was available under conditions similar to the baseline (2005). In reality, actual water use would be constrained by future water availability and allocation policy, which may also lead to a relocation of potato water demand, depending on where water resources are under pressure relative to the location of potato cropping. The demand forecasts were modelled at catchment level for England and Wales, then regionalised to EA Demand Forecast Areas (DFAs), which correspond to the EU Water Framework Directive (WFD) river basins.

For the short term projections, a baseline extrapolation based on underlying trends in cropped and irrigated areas was developed, using national cropping and irrigation statistics for 1982-2005. This involved analysing the underlying growth rates in the areas irrigated, volumes and depths applied as linear functions over time after allowing for the annual weather variation, using multiple regression techniques. The analyses showed an underlying linear growth rates of 3.0% and 3.5% per annum for the irrigated area and volume of water applied for maincrop potatoes, respectively. The equivalent figures for early potatoes were 0.3% and 2.1%. The Irrigrowth model was then used to extrapolate these underlying rates forward to the 2020s. The projected mean increases in potato irrigation demand from the baseline (2005) to the 2020s were +35% (without climate change) and +50% (with climate change).

The projected increases in volumetric demand for potatoes for the 2050s suggested increases of between 25% and 80% depending on socio-economic scenario, with projections largely influenced by the assumptions regarding population growth, food demand and patterns of food consumption. Higher demands reflected the need to increase production to cope with increased food demand from a growing population, whilst the lower projected demands reflected scenarios where the population begins to accept lower quality and more locally sourced produce. Detailed descriptions of each of the four scenarios and their impacts on potato consumption were derived. There is of course a high degree of uncertainty associated with projecting potato water demands into the 2050s, so the values presented here should be interpreted with caution – it is suggested they are used to demonstrate the effects of the assumptions embedded within the scenarios, rather than necessarily to infer trends in future water demand per se. They do, however, demonstrate the sensitivity of policies to promote either consumerism or sustainability, and their consequent effects on potato production, consumption and water demand. The projections for the 2050s also ignore any impacts of potato new cultivars, genetic improvements, and the effects of elevated CO_2 on water demand, many of which could significantly offset future increases in potato water demand.

Of course, in reality it is likely that these future projections will also be influenced by actual water availability. Licences are still available for winter (high flow) abstraction in most catchments, and recent years have seen a significant increase in the construction of on-farm reservoirs for summer irrigation. Though expensive, these provide growers with greater security of supply, and it seems likely that this will become the preferred water resource adaptation for potato irrigation. Most reservoir investments have probably been more a response to legislative or other pressures (e.g. supermarkets), rather than purposeful (deliberate) adaptations to any perceived future climate change. Nevertheless they may still prove to be a useful climate change adaptation strategy. Once irrigation water is assured but expensive, it will become increasingly sensible to invest more heavily in water efficiency measures, including better application methods (e.g. drip) and precision irrigation, and scientific scheduling methods will become more widely adopted. Earlier planting and harvesting would reduce water use per unit area, but with some varieties growers might prefer to use the longer grower season to increase yield. There has been a steady increase in average potato yields over the last few decades; with national consumption roughly constant this has led to a gradually reducing area planted; whether this trend can be intensified and how far it could counteract the increasing underlying demand for water is not clear.

Greater uncertainty in seasonal weather patterns will mean growers need to adapt and consider short-term coping strategies as well as longer-term strategic developments to reduce their vulnerability to changing water availability. How they respond will depend to a large extent on their perception of risk and the opportunities that climate change presents to their business. Farmers generally have two adaptation options - to reduce their water needs or try to secure additional water supplies. Options to reduce water needs include investing in improved irrigation technology (scheduling) and equipment to increase application uniformity and efficiency, using weather forecasting to increase the effective use of rainfall, encouraging deeper rooting of crops, introducing lower water use or drought tolerant crop varieties, decreasing the overall irrigated area, or modifying soil structure to improve soil moisture retention. Adaption options to obtain more water include purchasing land with water, obtaining additional licensed capacity and building on-farm storage reservoirs (individually or shared with neighbours), installing rainwater harvesting equipment, re-using waste water from farm buildings, or switching water supplies to public mains where feasible. Many of these potential adaptations (e.g. reservoirs) are already ‘no regret’ options, in that they already make sense by solving existing water resource issues, which then contribute to a farms future adaptability. The feasibility of other adaptations (e.g. water harvesting) will be farm specific and will depend on their technical and economic viability for that particular enterprise.

1.4. Non climate risks to UK potato production – putting climate change in context

Finally, it is important to recognise that the UK potato industry faces a wide range of ‘non-climate’ risks (environmental, economic, technological and societal), which it is often argued present a greater and more immediate threat than climate change. Growers have a challenging period ahead, trying to maintain productivity whilst controlling spiraling farm costs, particularly in relation to energy, whilst also demonstrating compliance with regulations associated with environmental protection, food safety and bio-security. 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. The key to tackling these will be in adaptation – securing access to the relevant skills, resources and knowledge to increase production efficiency, improve management and embrace new technology. This will require new collaborations between individual growers, the PCL, and other public and private sectors, to enable the UK potato sector to respond positively to the potential effects of climate change.

2. INTRODUCTION

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). It is strategically important in the provision of food - including both cropping (arable, horticulture) and livestock (beef, dairying, pigs, poultry) - and provides over half of all food consumed in the UK (Defra, 2010a). 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.

Recent concerns regarding future global food shortages have 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.

2.1. Climate risks to potato production

Internationally, agriculture is widely regarded as one of the sectors likely to be most impacted by climate change (Falloon and Betts, 2010), and UK agriculture is no exception. 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 such as potatoes are thus particularly sensitive to future changes in climate, both directly from 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 affects the availability of water to plants and impacts on other land management practices (e.g. trafficability for seed bed preparation, spraying, harvesting). The projected increases in atmospheric CO2 concentration (Jenkins et al., 2009) will also have direct impacts on potato crop growth by increasing the resource efficiencies for radiation, water and nitrogen (Kang et al., 2009; Daccache et al., 2010). As a consequence, for most crops grown in northern Europe, the impacts of climate change with warmer temperatures and elevated CO2 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.

2.2. Non-climate risks to potato production

In the UK potato growers also face a range of 'non-climate' risks which it is often argued present a potentially greater and more immediate threat to sustainable food production than climate change (Knox et al., 2010b). These can be categorised into economic, environmental and technological risks, with the majority occurring 'off-farm' and impacting 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. 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.

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 dependent.

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). There are also 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.

In this context, the UK Potato Council funded a 2 year study to investigate the impacts of climate change on the UK potato industry, to assist the agri-food industry in identifying suitable adaptation responses. The research was undertaken by a joint team from Cranfield University and Cambridge University Farm (CUF). The project commenced in April 2008 and was completed in December 2010. This report summarises the research approaches and methodologies, the key findings and the implications of the research for the UK potato industry.

2.3. Project aim, approaches and experimental methods

The specific project objectives and approaches used are summarised below:

Objective 1: To assess potential impacts on crop growth and production (yield and water use)

The impacts of climate change on the yield and water requirements of potatoes was assessed by combining the downscaled outputs from an ensemble of general circulation models (GCM) with a potato crop growth model. The SUBSTOR–Potato model (embedded within the DSSAT program) was used to simulate the baseline and future irrigation needs (mm) and yield (t ha-1) for selected emissions scenario, including CO_2 fertilisation effects. The simulated baseline yields were validated against independent experimental and field data using four reference sites (CUF and 3 grower sites). Probabilistic distribution functions were derived to assess the effect of GCM modelling uncertainty on future irrigation needs. For crop modelling and analysis, the variety (cv. Maris Piper) was chosen as being representative, assuming irrigated management practices designed to optimise yield and quality for the pre-pack market. The research for Objective 1 is summarised in Chapter 3.

Objective 2: To assess potential impacts on land suitability and soil management

For this objective, a combination methodology was developed using existing pedo-climate functions developed for the Agricultural Land Classification (ALC) (Jones et al., 1997) and a geographical information system (GIS) to model and map current and potential future changes in land suitability for potato production in England and Wales. The current land suitability for maincrop potato production was first modelled and mapped – this provided a ‘baseline’ scenario from which the derived land suitability classes can be compared against observed data on the spatial distribution of potato cropping (for rainfed and irrigated production). Secondly, future changes in potato land suitability were then modelled using the latest scenarios of climate change produced by the UK Climate Impacts Programme - UKCIP - (Jenkins et al., 2009). This identifies how land classes might shift both spatially and temporally due to the impacts of changing patterns of rainfall, temperature and other agroclimatic variables. This helps to quantify the potential impacts on current centres of production which tend to be regionally concentrated. Finally, the relationships between land suitability and water resource availability were assessed to identify catchments where future irrigated production might be at risk and conversely where production might need to relocate to catchments where water resources are unconstrained. From this, the implications of climate change was assessed including where rain-fed production might become limiting, what varieties are likely to be most/least suited to changes in land suitability, and the range of adaptation options (e.g. shifting production, new soil management techniques, drainage, new irrigation infrastructure etc) that might be considered. The research for Objective 2 is summarised in Chapter 4.

Objective 3: To assess potential impacts on water demand and water resources stress

For this objective, the research combined literature review with extensive computer modelling, GIS mapping, and interviews with key informants. A demand forecasting methodology developed by Weatherhead and Knox (2008) for predicting future agricultural water abstractions in England and Wales was used but modified to incorporate PCL data. Future socio-economic scenarios developed by the Henley Centre Headlight Vision for the Environment Agency's Water Strategy (EA, 2008) were used to assess the effects of changes in population demographics, consumption and consumer preferences under contrasting government policies (globalisation to local markets, consumerism to sustainability). Forecasts for future water demand for irrigated potatoes were produced and mapped by EA catchment. All forecasts are were for 'unconstrained potato demand in a dry year', i.e. the volume potato abstractors would abstract in a dry year assuming water is available under conditions similar to the 2005 baseline. Actual future potato water use is very likely to be constrained by future water availability and allocation policy, which may also lead to a relocation of demand. The research for Objective 3 are summarised in Chapter 5.

Objective 4: To identify suitable adaptation options and responses (industry and grower level)

Greater uncertainty in future seasonal weather patterns mean potato growers will need to adapt and consider short-term coping strategies as well as longer-term strategic developments to reduce their vulnerability to climate variations. How growers respond will depend to a large extent on their perception of risk and the opportunities that climate change presents to their business. For this objective, a range of adaptations (autonomous and planned) were identified and assessed in the context of the adaptive capacity of growers and the UK potato industry. Two grower meetings (one in Yorkshire and another in Suffolk) were used to assess grower sentiment regarding climate change and likely responses. The results for Objective 4 are included as discussion in Chapters 3, 4 and 5.

2.4. Project outputs and deliverables

The outputs from this research include (i) a technical report summarising the research approaches, methodologies, and key findings, (ii) an information booklet for PCL growers and stakeholders outlining the issues relating to climate change impacts on potato production, (iii) a series of regional workshops for growers to raise awareness of climate change and the adaptation options, and (iv) three scientific papers submitted to internationally leading peer review journals.

Levy funded research must of course deliver high quality outputs to its grower base and be complemented by appropriate knowledge transfer. In addition, it is important that the quality of the research is recognised by the scientific community. The quality and impact of research is measured through publication in the best scientific journals, each of which themselves are ranked according to their quality and impact. The research in this project has led to the submission of 3 papers to international journals specialising in crop modelling, climate change and agricultural production. The research presented in Chapter 3 has been submitted to the Journal of Agricultural and Forest Meteorology, an international journal ranked 3rd out of 66 in its subject category (Daccache, A., Weatherhead, E.K., Stalham, M.A., and Knox, J.W. (2010). Impacts of climate change on irrigated potato production in a humid climate). The research presented in Chapter 4 has been submitted to the Journal of Agriculture, Ecosystems and Environment, an international journal ranked 1st out of 44 in its subject category (Daccache, A., Keay, C., Jones, R.J.A., Weatherhead, E.K., Stalham, M.A., and Knox, J.W. (2011). Current and future land suitability for potato production). Other aspects of the research in this report have been combined to produce a paper for Climatic Change, an international journal ranked 8th out of 63 in its subject category (Knox, J.W., Weatherhead, E.K., Daccache, A., and Hess, T.M. (2011). Agroclimate impacts on irrigated crop production.

In addition, data and information from this project have also contributed to a book chapter “Managing the water footprint of irrigated food production in England and Wales” by T. M. Hess, J. W. Knox, M. G. Kay, and E. K. Weatherhead. This was published in Issues in Environmental Science and Technology, No 31: 78-92 “Sustainable Water” edited by R.E. Hester and R.M. Harrison and published by the Royal Society of Chemistry (2011).

3. CLIMATE CHANGE PROJECTIONS

3.1. UKCIP09 climatology

Climate projections for this study were based on the latest UK Climate Impacts Programme climatology, termed UKCP09 (Jenkins et al., 2009). 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 (Meehl et al., 2007). As a result, 10,000 different sets of possible future monthly changes in climate are provided for each time slice and emission scenario. This is more informative than previous UKCIP datasets (UKCIP02) 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.

The UKCP09 emissions scenarios are based on those developed by the IPCC (Nakicenovic et al., 2000), known as SRES (Special Report on Emission 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 SRES scenarios are available, renamed for simplicity as high, medium and low emissions, respectively. In this study, climate data for the high and low emissions are presented, and for decadal time slices from the 2020s through to the 2080s. The projected changes in climate for each variable shown below are for the ‘most likely’ probability (50%) but using the probabilistic data (based on 10,000 samples), the extremes (5% and 95%) representing the ‘very unlikely’ probabilities also presented to illustrate the uncertainty in the projections. For this study, data on the projected changes in climate for four variables are presented, namely, rainfall, mean temperature, evapotranspiration (ETo) and agroclimate (potential soil moisture deficit). When downscaling, these changes in climate need to be considered relative to a ‘baseline’. For this, a baseline climatology derived from observed data for 1961 to 1990 was used, to match the World Meteorological Organisation (WMO) standard. A summary of the projected changes in climate for the UK based on UKCP09 are given below.

3.2. Projected changes in rainfall

The projected changes in summer (April to September) and winter (October to March) rainfall from the baseline to the 2050s, for the low and high UKCP09 emissions scenario are shown in Figure 1. For the baseline, the data show mean summer rainfall across eastern, central and southern England to be between 126-175 mm. There is a north and westerly gradient with rainfall gradually increasing up to 300-400 mm on high ground. By the 2050s, there are projected to be widespread reductions in summer rainfall notably in parts of East Anglia (Suffolk, Essex), and in Kent, and along the south coast (<125 mm). Conversely, in winter, mean rainfall is shown to increase. However, these national assessments mask significant regional impacts – for example, the projected changes in seasonal rainfall for the low and high emissions scenario from the 2020s to 2080s is shown in Figure 2 for a site in Suffolk.

In Spring, the projections are for relatively minor increases in rainfall (0 to +5%) with little change over time. For Summer, a decrease in rainfall is expected, ranging from -10% to -25% but increasing in magnitude and variability with time. The Autumn impacts are similar to Spring (0 to +5%), and in Winter, increases in rainfall of +5% to +20% are projected. These are for the 50% (most likely) probability. The dotted lines show the uncertainty, expressed as 10% (very unlikely to be less than) and 90% (very unlikely to be greater than) probability levels.

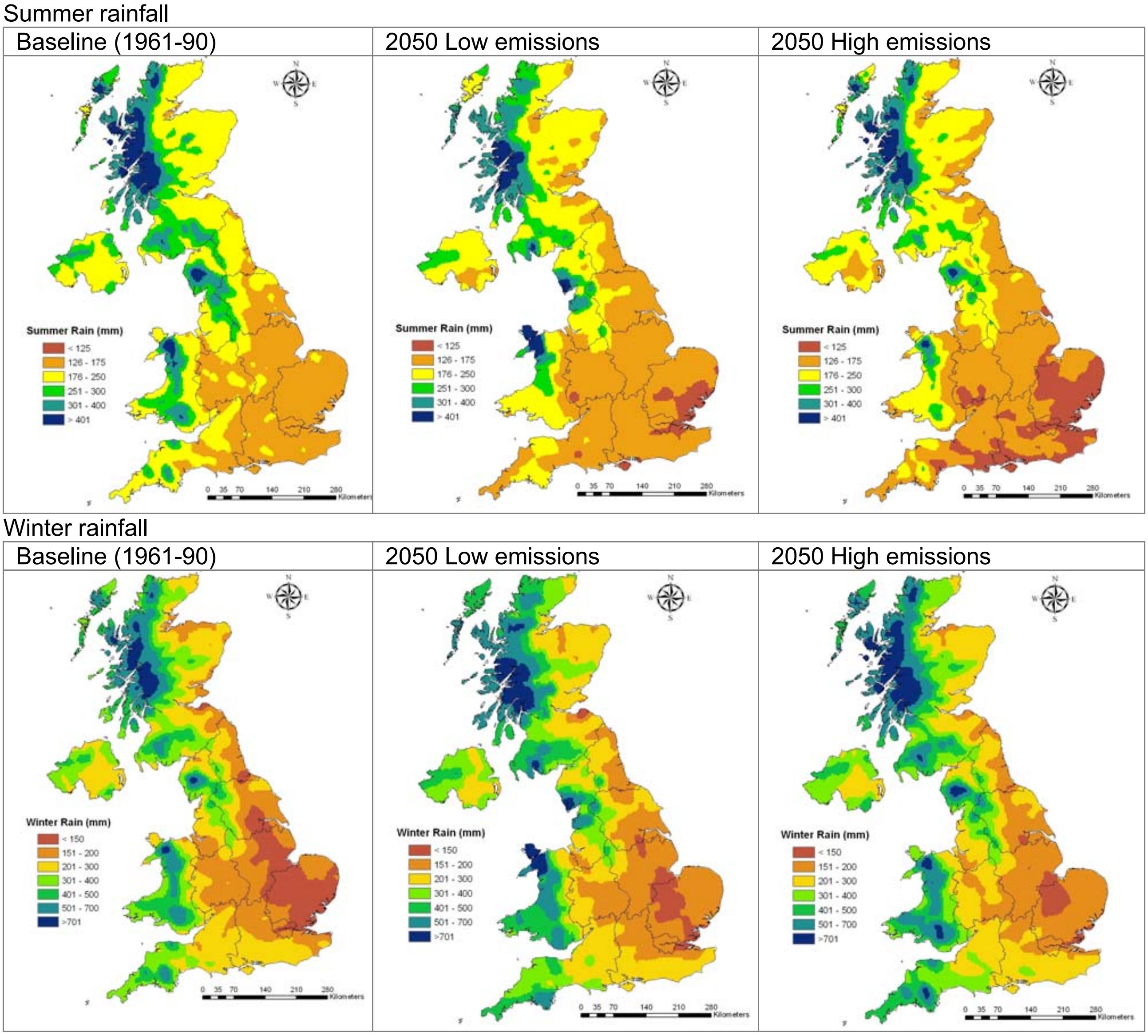


FIGURE 1 PROJECTED CHANGES IN MEAN SUMMER AND WINTER RAINFALL FROM THE BASELINE (1961-90) TO THE 2050S, FOR THE LOW AND HIGH UKCP09 EMISSIONS SCENARIO.

Changes in summer precipitation will impact on potato yields and the need for supplemental irrigation, particularly as the importance of irrigation for quality assurance becomes more important (Knox et al., 2009). Increases in winter rainfall may create new poaching (surface soil damage) and water logging problems, and may require additional drainage to cope with higher rainfall intensities. It might also create harvest problems in late summer due to excess wet ground. These issues are explored in more detail in Chapter 4.

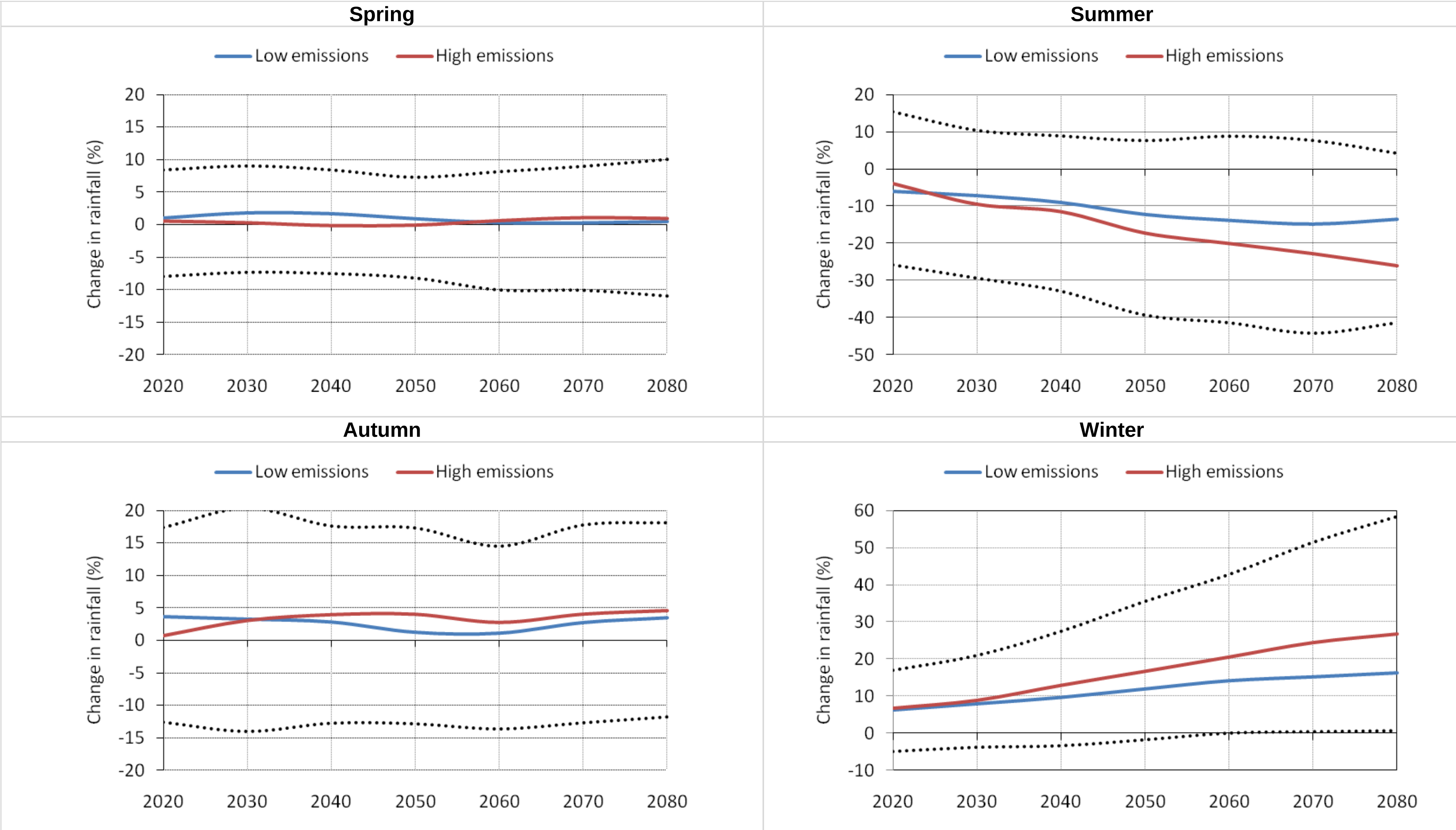


FIGURE 2 SEASONAL CHANGES IN RAINFALL FROM THE BASELINE FOR THE 2020S TO THE 2080S, FOR THE LOW AND HIGH UKCP09 EMISSIONS SCENARIO, FOR A SITE IN SUFFOLK. DOTTED LINES REPRESENT THE 10% AND 90% PROBABILITIES.

3.3. Projected changes in temperature and evapotranspiration (ET)

The projected changes in mean summer and mean winter temperature from the baseline to the 2050s, for the low and high UKCP09 emissions scenario are shown in Figure 3. As before, the equivalent changes for a site in Suffolk from the 2020s to 2080s is shown in Figure 4 to illustrate the temporal trend over time, and climate uncertainty.

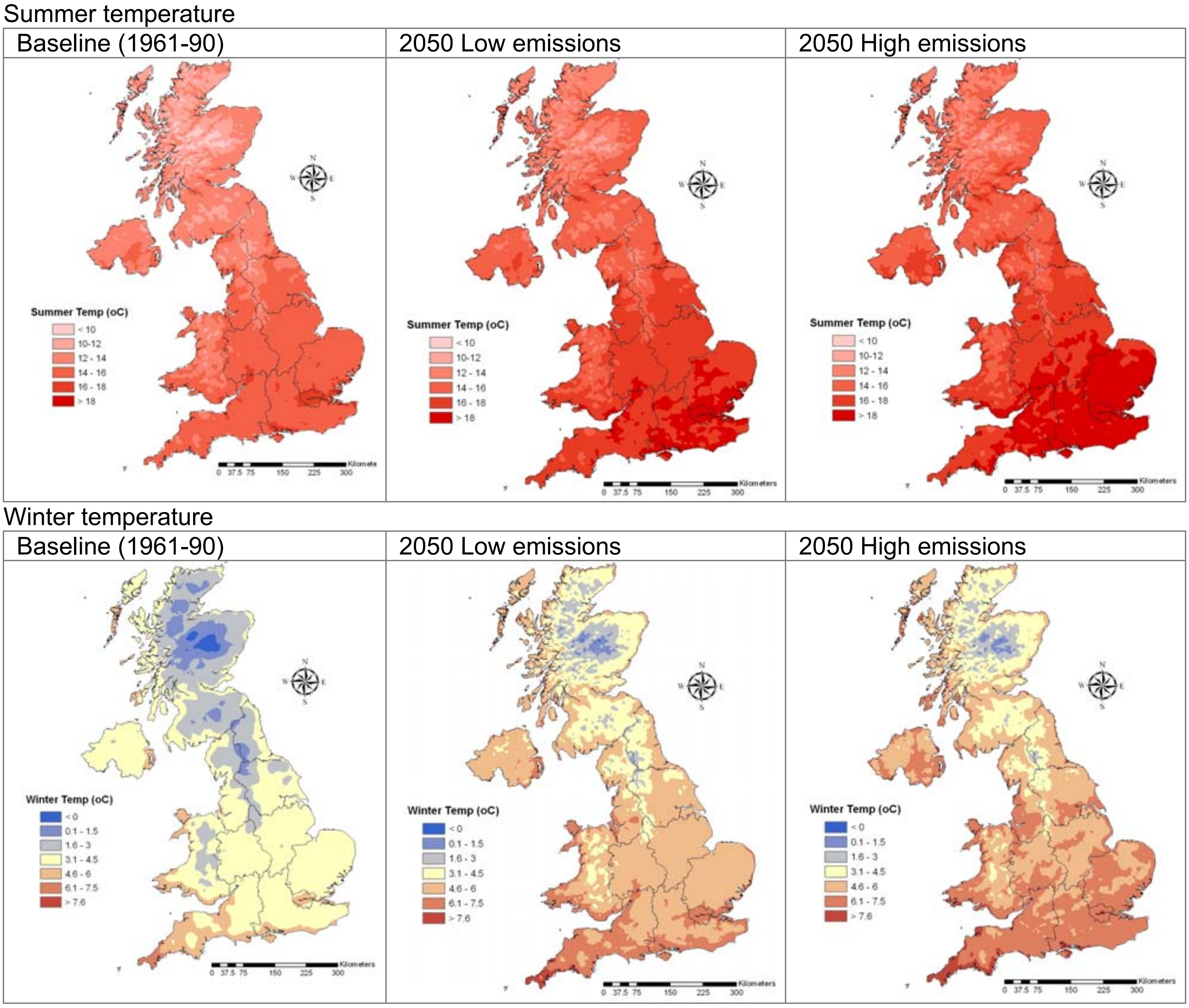


FIGURE 3 PROJECTED CHANGES IN MEAN SUMMER AND MEAN WINTER TEMPERATURE FROM THE BASELINE TO THE 2050S, FOR THE LOW AND HIGH UKCP09 EMISSIONS SCENARIO.

As with rainfall, the temperature for the baseline shows a gradient from southern England extending north and westwards – by the 2050s, mean summer temperatures in southern England are expected to increase from around 12-14 degrees up to 18+ degrees. The projected changes are slightly higher in the south east than in the north. For the Suffolk site, the projected increases are between 1.5 to 4.0 degrees, but with a wide band of uncertainty.

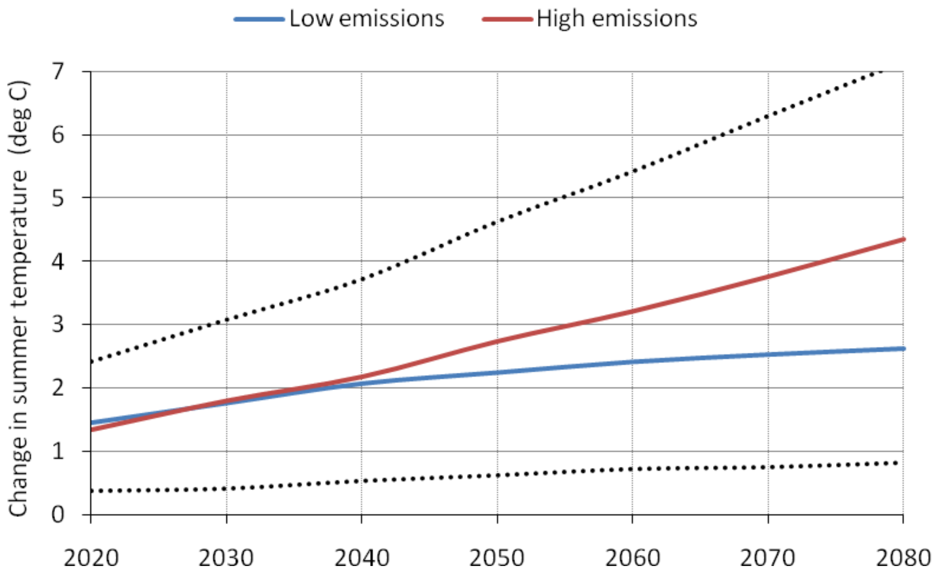


FIGURE 4 PROJECTED CHANGES IN MEAN SUMMER TEMPERATURE FROM THE BASELINE (1961-90) FOR THE 2020S TO THE 2080S, FOR THE LOW AND HIGH UKCP09 EMISSIONS SCENARIO FOR A SITE IN SUFFOLK. DOTTED LINES REPRESENT THE 10% AND 90% PROBABILITIES.

For impact assessments in crop production, it is also useful to know the projected changes in reference evapotranspiration (ETo) which combines the effects of temperature, wind speed, solar radiation and relative humidity on crop growth and development (Figure 5). This shows daily ETo values are projected to increase, with the largest increase in the summer months. When combined with the expected reductions in summer rainfall this will have significant impact on local agroclimate and soil moisture conditions, potentially increasing drought risks to rain-fed production, and increasing the need for supplemental rainfall.

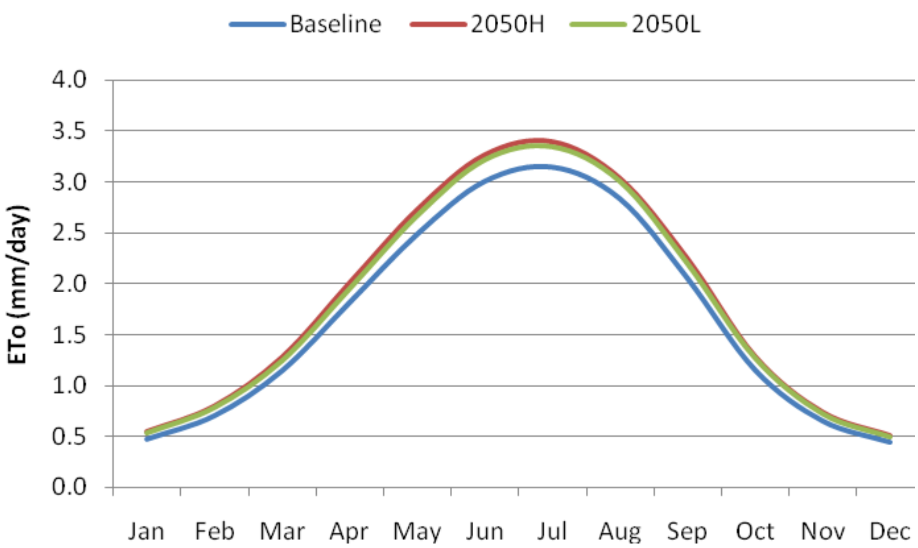


FIGURE 5 PROJECTED CHANGES IN ETO FROM THE BASELINE FOR THE 2050S LOW AND HIGH UKCP09 EMISSIONS SCENARIO, FOR A SITE IN SUFFOLK.

3.3.1. Projected changes in agroclimate

The main variables that directly influence local agroclimate and soil moisture are rainfall and reference evapotranspiration (ETo). To assess the impacts of climate change on future agroclimate a variable known as potential soil moisture deficit (PSMD) is commonly used. PSMD is calculated from:

$$PSMD_i = PSMD_{i-1} + ET_i - P_i \qquad [1]$$

Where:
PSMDi = potential soil moisture deficit in month i, mm
ETi = reference evapotranspiration in month i, mm
Pi = rainfall in month i, mm

At the start of the year, the PSMD is assumed to be zero. 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 start to build up in Spring as ET > P, peak in Summer and then decline through the Autumn and Winter. Therefore in the UK, the estimation of PSMD starts with January as month i = 1. The maximum PSMD of the 12 months of the year is $PSMD_{max}$. Using the UKCP09 climatology, a national dataset containing the $PSMD_{max}$ at 5km resolution was produced and used to map the spatial variability in agroclimate for the baseline and UKCP09 emissions scenario (Figure 7). Major regional shifts in agroclimate are predicted, with eastern regions becoming significantly drier and central England experiencing soil moisture deficits more typical of eastern England at present (Figure 7). Predicted average increases in PSMD are +85-111% for 2050s. However, it must be remembered that these agrolcimate changes assume future 'average' rainfall and 'average' ETo rates, but the data presented for Suffolk clearly demonstrate the uncertainty that exists around these means. Future changes are thus likely to be much greater than the future 'average' increases presented. This effect can be demonstrated by considering rainfall at a site in Cambridge (Figure 6).

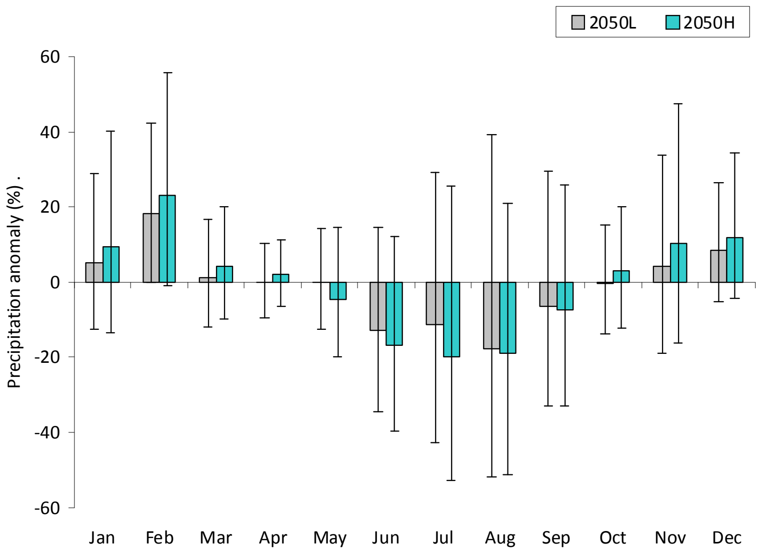


FIGURE 6. PRECIPITATION ANOMALY (%) FOR CAMBRIDGE FOR THE 2050S LOW AND HIGH EMISSIONS SCENARIO.

Figure 6 shows how the variability around the mean is greater than the projected climate change effect. For example, future mean summer rainfall in July is projected to reduce by -15 to 20%, but could range from +30% to -50%. This highlights one of the major challenges in trying to develop robust adaptation strategies to cope with climate change.

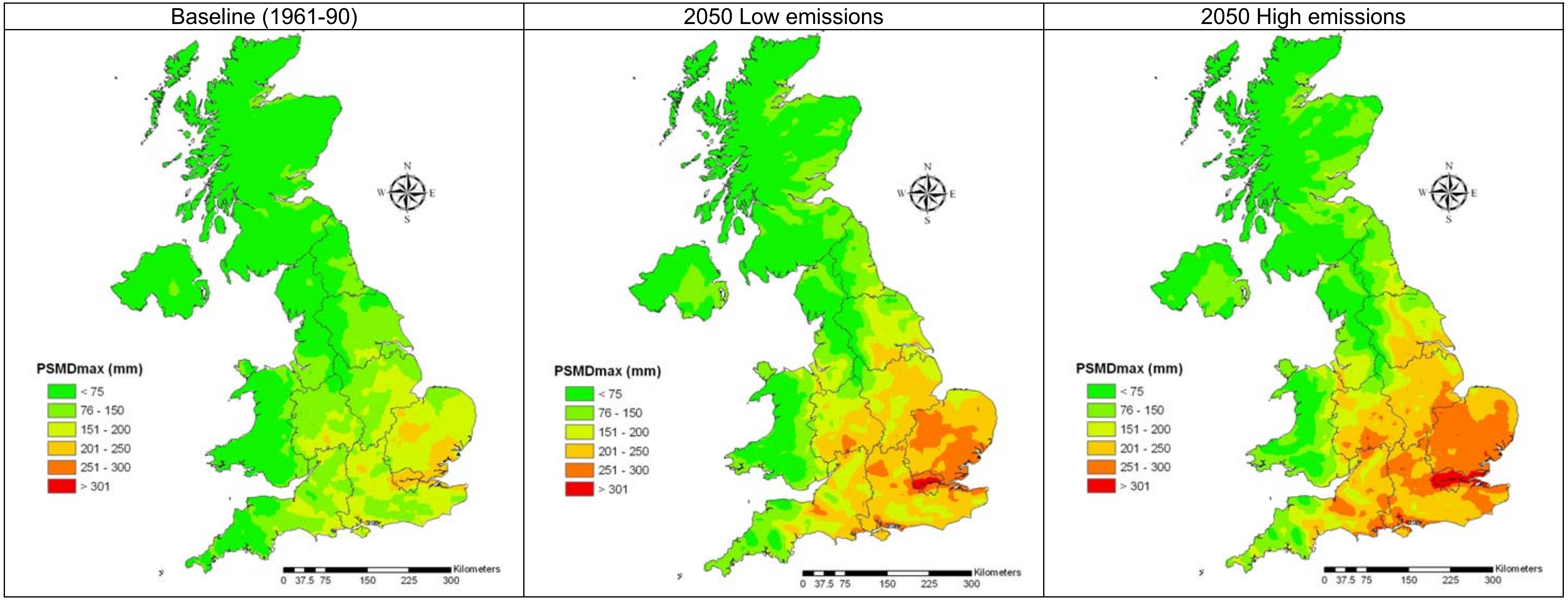


FIGURE 7 PROJECTED CHANGES IN AGROCLIMATE (USING PSMDMAX AS AN ARIDITY INDICATOR), FROM THE BASELINE TO THE 2050S, FOR THE LOW AND HIGH UKCP09 EMISSIONS SCENARIO.

4. IMPACTS ON POTATO YIELDS AND WATER USE

4.1. Summary

The impacts of climate change on the irrigation water requirements and yield of potatoes (Solanum tuberosum L.) grown in England have been assessed, by combining the downscaled outputs from an ensemble of general circulation models (GCM) with a potato crop growth model. The SUBSTOR–Potato model (embedded within the DSSAT program) was used to simulate the baseline and future irrigation needs (mm) and yield (t ha-1) for selected emissions scenario (SRES A1F1 and B1) for the 2050s, including CO2 fertilisation effects. The simulated baseline yields were validated against independent experimental and field data using four reference sites. Probabilistic distribution functions were derived to assess GCM modelling uncertainty on future irrigation needs. Assuming crop husbandry factors are unchanged, farm yields would show 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, are expected to increase by 13-16%. Future average irrigation needs, assuming unconstrained water availability, are predicted to increase by 14-30%, depending on emissions scenario. The present 'design' capacity for irrigation infrastructure would fail to meet future peak irrigation needs in nearly 50% of years. Adaptation options for growers to cope with these impacts are discussed.

4.2. Introduction

The potato industry in England has changed dramatically in recent decades, from a sector comprised of many small individual farms to one with fewer but much larger agribusinesses, driven by the need to provide high quality product to the major processors and supermarkets (Knox et al., 2010a). Over the second half of the last century, the number of UK registered growers fell by 96% and the total cultivated area of potatoes (Solanum tuberosum L.) halved whilst the average yields have nearly doubled (Figure 8). The total potato production of the country thus remained almost the same.

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. The irrigation season typically extends from May to September when reference evapotranspiration (ETo) exceeds rainfall. Nationally, potatoes are the most important irrigated crop, accounting for 43% of the total irrigated area and 56% of the total volume of irrigation water abstracted (Knox et al., 2009). Potato irrigation is supplemental to rainfall and concentrated in the drier eastern regions of England. Although the volumes abstracted are relatively small, irrigation peaks in the summer months in the driest catchments when water resources are most scarce, creating conflict with other water demands, most notably those for public water supply and environmental protection.

Potato production is strongly influenced by water availability, as the crop is very sensitive to water stress (Opena and Porter, 1999), in part due to soil compaction which can reduce the depth and density of the rooting system considerably (Stalham et al., 2007). Even brief periods of water stress can affect both yield and tuber quality

(Lynch et al., 1995). Any changes in climate, such as increased summer temperatures or changes in the seasonality of rainfall could have a dramatic impact on production and water requirements (Mearns, 2000). The latest climate change predictions for England suggest drier summers with higher temperatures and reduced rainfall (Jenkins *et al.*, 2009). In general, at higher latitudes a rise in temperature tends to increase the developmental rate of the crop and extend the length of the growing season, resulting in a positive impact on crop production. On the other hand, reduced summer rainfall is likely to increase soil moisture deficits reducing yield under rain-fed regimes and increasing the need for supplemental irrigation (Richter *et al.*, 2006).

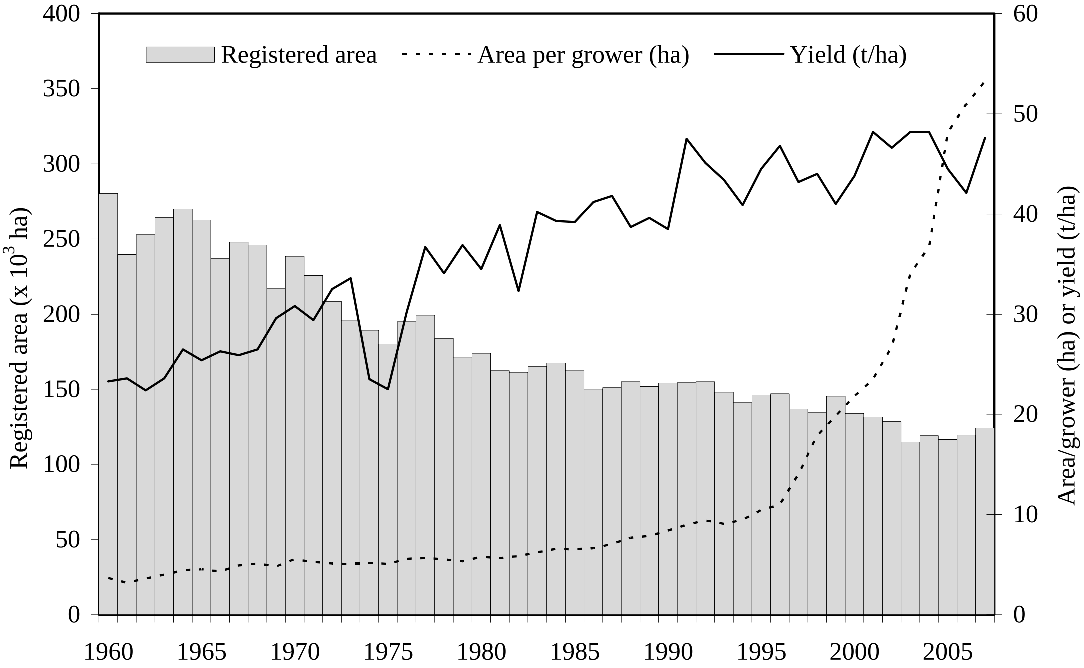


FIGURE 8 REPORTED TOTAL POTATO CROPPED AREA (HA), AVERAGE CROPPED AREA PER GROWER (HA) AND AVERAGE YIELD (T HA^{-1}) IN THE UK, 1960 TO 2007 (SOURCE: POTATO COUNCIL, 2010).

Various studies on the impacts of climate change on European potato production are reported in the literature, although comparison between the individual studies is difficult and potentially misleading due to the use of different GCMs, different crop models, and contrasting approaches to downscaling. Using a crop growth model (LPOTCO) Wolf and van Oijen (2003) reported that irrigated tuber yields (cv. Bintje) would increase by between 2000 and 4000 kg ha-1 dry matter for most regions of Europe in the 2050s, largely due to the positive response to increased levels of CO2 concentration. In Scotland, Peiris et al. (1996) used the SCRI water-constrained potato model (Jefferies and Heilbronn, 1991) and 100 year runs using a weather generator based on statistical changes in temperature and rainfall. They reported that future higher temperatures would lead to faster crop emergence and canopy expansion and thus a longer growth period, with yield increases of between 6 to 12%, excluding CO2 effects. More recently 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. Since future water availability is likely to be a major limiting factor for agricultural production, the objective of this study was to investigate the impacts of climate change on potato yield and irrigation water use to assist the UK agri-food industry in identifying suitable adaptation responses.

4.3. Materials and methods

In summary, the outputs from a general circulation model (GCM) have been combined with a potato crop model to simulate the net annual irrigation water requirements (IRnet) and crop productivity (t ha-1) for a historical baseline and selected future emissions scenarios, including CO2 fertilisation effects. Using scenarios from the latest UK Climate Impacts Programme for the 2050s, future climate datasets were derived for four reference sites. Potato yields and water use were simulated using the SUBSTOR-Potato model embedded within the DSSAT (Decision Support System for Agrotechnology Transfer) program (Jones et al., 2003). A description of the study sites, emissions scenarios and crop modelling is provided below.

4.3.1. Study sites

In this study, an experimental research unit and three farms were used to reflect contrasting agronomic and management practices under controlled and commercial production systems. From an industry perspective, growers are more likely to relate to studies based on commercial practice when considering adaptations to climate change. The experimental research unit was Cambridge University Farm (CUF) (Lat: 52°22' N; Lon: 0°10'E) where long-term potato trials have been undertaken since 1989. The three farm sites were commercial agribusinesses located at Buxton, Norfolk (Lat: 52°45' N; Lon: 1°17' E), Woodbridge, Suffolk (Lat: 52°03' N; Lon: 1°22' E) and Spalding, Lincolnshire (Lat: 52°48'N; Lon: 0°14' W). These sites are considered representative of the major irrigated potato growing areas in England. Although they are geographically widely dispersed, the characteristics of their climate in terms of rainfall, temperature and reference evapotranspiration (ETo) are broadly similar. Based on daily climate data for 1970-1991, the mean rainfall was 50 mm month-1, mean daily summer temperatures were 16o C (ranging from 11 to 21 o C in July) and peak ETo rates typically ranged from 3.5 to 4.5 mm d-1. The soil was a predominantly medium textured sandy loam soil at the CUF and Buxton sites, whilst at Woodbridge and Spalding a loamy sand and a silt soil were observed, respectively.

4.3.2. Climate change scenarios and datasets

Climate projections were based on the latest UK Climate Impacts Programme climatology, termed UKCP09 (Jenkins *et al*., 2009). 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 (Meehl et al., 2007). As a result, 10,000 different sets of possible future monthly changes in climate are provided 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. For the initial analysis, rather than considering all possible 10,000 samples, GCM data relating to the highest probability of occurrence (50%) for each climate variable, were used. However, to investigate uncertainty, a sensitivity of irrigation needs using all 10,000 probabilistic samples was also completed for one of the study sites.

The UKCP09 scenarios are based on those developed by the IPCC (Nakicenovic *et al*., 2000), known as SRES (Special Report on Emission 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) and A1B being balanced between fossil and non-fossil fuel. Conversely, the B1 scenario has the lowest atmospheric CO_2 concentration (489 ppmv), reflecting efforts to control CO_2 emissions principally through the introduction of clean and resource-efficient technologies. In this study, the high (A1F1) 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).

The UKCP09 climatology provides future monthly gridded data at 25 km resolution, expressed as either relative or absolute change with respect to the baseline (1961-1990) for each variable. For simulating future climate, long-term daily historical (1970-1991) datasets for each site were used. Prior to downscaling, these were checked for consistency with the UKCP09 baseline climatology for rainfall and ETo (Figure 9) as these are the main climate variables that influence irrigation demand. Although the time-series were different, the simulated UKCP09 values were in the range of the inter-annual variation of the observed values, confirming that the historical (site) datasets (1970-1991) were comparable to the UKCP09 baseline (1960-1991) and thus suitable for simulation. Downscaling the UKCP09 outputs for each site was based on the ‘change factor’ (CF) approach (Diaz-Nieto and Wilby, 2005) rather than statistical downscaling (SD). Future changes of each climate variable were extracted from the 25 km GCM grid box for each site and each emissions scenario. The CF’s were applied to the historical daily baseline (1970-1991) for each site – adding the changes in temperature to the observed temperature, and multiplying ratio changes for precipitation and other variables (Table 1). Two new daily datasets were thus generated for each site, representing 21 years of 2050’s weather at low (2050L) and high (2050H) emissions scenarios. Using this approach, all the daily weather values in each month are altered by the same percentage, each day and in each year of record (Wolf and Oijen, 2002). This approach has the virtue of simplicity and maintains a realistic temporal structure of weather data but assumes that the relative variability in weather from day to day and year to year and sequencing of wet and dry periods (the shape of the frequency distribution) remains constant. Whilst this is not necessarily true of future weather, it avoids introducing additional uncertainty into the analysis. The historical baseline and perturbed future climate datasets for each site were then used for the crop modelling.

Although this approach has inherent limitations, including the fact that the temporal sequencing of future wet and dry days remains unchanged, transient changes in local climate cannot be investigated (time slices need to be used), and natural climate variability is not explicitly incorporated, by using the UKCP09 probabilistic distribution data (which includes the 10,000 outputs from the individual GCM model runs for each climate variable), the full range of variability in the climate change trend could actually be investigated. This addresses one of the major limitations in the CF approach highlighted by others (e.g. Zhang, 2007) and justifies the rationale for using this approach in this study. However, by incorporating these probabilistic analyses into the CF approach, the downscaling process becomes significantly more computationally intensive.

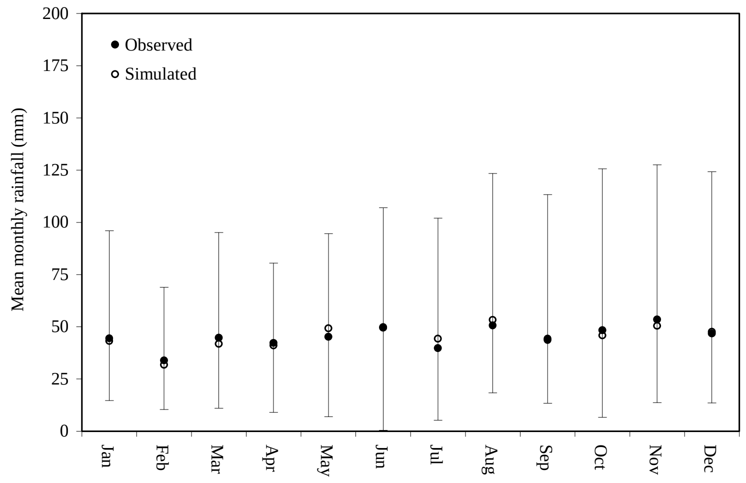
		2050_L												2050_H											
		Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
CUF	Tmin (°**C)**	2.1	1.9	1.5	1.5	1.8	1.8	2.3	2.1	1.8	2.0	1.7	1.8	2.8	2.4	2.0	2.0	2.3	2.4	2.8	2.6	2.4	2.3	2.2	2.4
	Tmax (°**C)**	1.7	1.8	1.9	1.8	2.0	2.4	2.5	2.8	2.1	2.3	1.9	1.9	2.2	2.2	2.4	2.4	2.6	3.1	3.0	3.3	2.8	2.6	2.4	2.4
	Rain (%)	5.1	18.2	1.3	-0.2	0.1	-12.9	-11.2	-17.7	-6.4	-0.5	4.2	8.4	9.5	23.1	4.3	2.1	-4.6	-16.9	-19.8	-19.0	-7.5	2.9	10.4	11.9
	Cloud (%)	0.4	0.8	-4.2	-2.9	-3.4	-3.6	-8.2	-9.9	-5.3	-2.9	-0.4	0.0	1.5	1.2	-2.3	-2.5	-5.1	-4.1	-8.5	-13.5	-7.3	-2.6	-0.3	1.7
Buxton	Tmin (°**C)**	2.1	1.9	1.5	1.5	1.8	1.8	2.2	2.0	1.8	1.9	1.7	1.8	2.9	2.4	2.0	2.1	2.3	2.3	2.6	2.4	2.3	2.3	2.2	2.4
	Tmax (°**C)**	1.7	1.8	1.9	1.8	1.9	2.2	2.2	2.4	2.0	2.3	1.9	1.8	2.2	2.2	2.4	2.4	2.5	2.8	2.7	2.9	2.5	2.5	2.4	2.4
	Rain (%)	7.2	16.6	2.8	-0.3	0.1	-12.9	-11.3	-20.2	-8.2	-0.3	-1.8	6.8	9.9	20.7	4.0	2.3	-4.1	-17.0	-20.1	-26.1	-12.1	3.0	0.6	9.5
	Cloud (%)	0.5	0.7	-4.2	-2.8	-3.3	-3.4	-4.9	-9.5	-5.0	-3.0	-0.4	0.0	1.6	1.1	-2.4	-2.4	-4.9	-3.9	-4.1	-13.0	-6.7	-2.7	-0.3	1.3
Woodbridge	Tmin (°**C)**	2.2	2.0	1.5	1.5	1.8	1.9	2.2	2.1	1.9	2.0	1.8	1.9	3.0	2.5	2.0	2.1	2.3	2.4	2.7	2.5	2.4	2.3	2.3	2.4
	Tmax (°**C)**	1.7	1.8	1.8	1.8	2.0	2.4	2.4	2.5	2.0	2.3	2.0	1.9	2.2	2.2	2.4	2.4	2.6	3.0	2.8	3.0	2.6	2.5	2.4	2.4
	Rain (%)	5.4	19.8	3.4	0.8	0.1	-13.9	-12.2	-20.9	-8.6	0.0	-1.8	8.6	9.9	24.5	1.8	1.2	-3.9	-18.0	-21.5	-27.1	-12.6	-5.9	1.0	12.0
	Cloud (%)	0.5	0.9	-4.3	-3.2	-3.6	-5.3	-8.5	-10.3	-5.6	-3.3	-1.1	0.0	1.8	1.3	-2.3	-2.7	-3.9	-7.6	-8.9	-14.3	-7.4	-3.0	-0.7	1.3
Spalding	Tmin (°**C)**	2.1	1.8	1.5	1.4	1.8	1.8	2.2	2.1	1.8	2.0	1.7	1.8	2.2	2.2	2.4	2.4	2.6	3.0	2.9	3.2	2.7	2.5	2.4	2.4
	Tmax (°**C)**	1.7	1.8	1.9	1.8	2.0	2.3	2.4	2.7	2.1	2.3	1.9	1.8	2.2	2.2	2.4	2.4	2.6	3.0	2.9	3.2	2.7	2.5	2.4	2.4
	Rain (%)	4.8	16.6	1.3	0.7	0.0	-12.9	-10.2	-16.3	-5.9	-0.6	3.8	7.5	8.7	21.1	4.5	1.0	-4.4	-16.8	-17.9	-17.8	-7.2	2.5	10.0	10.6
	Cloud (%)	0.4	0.7	-4.2	-3.0	-3.3	-3.4	-7.4	-9.0	-5.1	-2.6	-0.3	0.0	1.5	1.0	-2.4	-2.7	-4.8	-3.8	-7.8	-12.4	-6.6	-2.4	-0.3	1.2

TABLE 1 PROJECTED CHANGES IN MEAN MONTHLY CLIMATE BETWEEN THE BASELINE AND EACH SRES EMISSIONS SCENARIO, BY VARIABLE AND MONTH FOR EACH SITE (°C CHANGE OR % CHANGE).

4.3.3. Modelling potato yield and water use

For simulating the baseline and future yield and irrigation needs, the SUBSTOR-Potato model was used. This is one of 16 models embedded within the DSSAT (v4) program. A brief review of the SUBSTOR-Potato model is provided here for convenience but readers interested in a comprehensive description are referred to Griffin *et al*. (1993). The SUBSTOR-Potato model simulates on a daily basis the growth and development of the potato crop using information on climate, soil, management and cultivar. The model is divided into four main sub models simulating simultaneously the phenological development, the biomass formation and partitioning, soil water and nitrogen balances to provide a realistic description of the plant-soil-atmosphere system. The phenological development is controlled by cumulative temperature whilst the growth rate is calculated as the product of absorbed radiation, which is a function of leaf area, using a constant ratio of dry matter yield per unit radiation absorbed. Cultivar specific coefficients known as 'genetic coefficients' are used by the model to control tuber initiation, leaf area development and tuber growth rate.

(a)



(b)

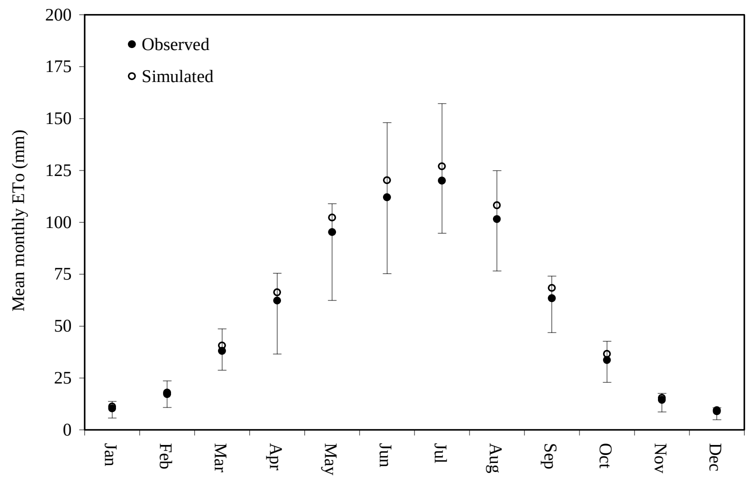


FIGURE 9. COMPARISON OF (A) OBSERVED MEAN MONTHLY RAINFALL (MM/MONTH) AND (B) REFERENCE EVAPOTRANSPIRATION (ETO) (MM/MONTH) AT THE EXPERIMENTAL SITE (CUF, CAMBS) FOR 1970-1991 AGAINST UKCP09 DATA FOR THE BASELINE CLIMATOLOGY (1961-90). VERTICAL BARS SHOW THE INTER-ANNUAL VARIATION.

The soil water balance in DSSAT is based on Ritchie's model (Ritchie 1981a; Ritchie 1981b) where the concept of drained upper limit and drained lower limit of the soil is used as the basis of the available soil water. This one dimensional and multi-layer model uses the 'tipping bucket' approach to compute the soil water drainage when a layer's water content is above a drained upper limit parameter. The SCS method (Soil Conservation Service, 1972) modified to account for layered soil (Williams *et al.*, 1984) is used to partition rainfall and/or irrigation into runoff and infiltration, based on a curve number that attempts to account for texture, slope, and tillage. The nitrogen balance in the soil is simulated using the CERES N model where processes such as mineralization, immobilization, nitrification, denitrification, nitrogen uptake by plants, distribution and remobilization within the plants are simulated (Godwin and Singh

1998). At each growth stage, deficits in soil water or nitrogen will affect the growth of the modelled crop and hence final yield.

The SUBSTOR-Potato model has been used extensively for crop studies internationally (e.g. Han *et al*., 1995; Travasso *et al*., 1996; Hodges, 1998) and more recently for climate change impact assessments (Holden *et al*., 2003; Knox *et al.,* 2010). Although other potato models have been developed for UK conditions (e.g. Jefferies and Heilbronn, 1991), the SUBSTOR-Potato model was chosen for its ability to actively simulate the canopy response to temperature and radiation change and to incorporate the direct effects of changes in atmospheric CO2 concentration on potato production. The weather, crop, and soil datasets, management practices (fertiliser and irrigation) and assumptions used to parameterise the SUBSTOR-Potato model are outlined below.

For each site, three weather datasets were used; a historical baseline dataset containing daily maximum and minimum temperature, solar radiation and rainfall for 1970-1991, and the two equivalent datasets generated for the 2050L (B1) and 2050H (A1F1) scenarios. In England, a wide range of potato cultivars are grown, depending on whether the tubers are destined for seed, processing, fresh or pre-pack markets. In this study, *cv.* Maris Piper was modelled, a high yielding cultivar with good disease resistance and post-harvest storage suitability. In 2009, *cv.* Maris Piper accounted for 18.5% of the total UK cropped area with over half (56%) grown in eastern England. The main crop husbandry practices reported at each site are summarised in Table 2. They correspond to the typical agronomic management practices reported by the farmers between 2003 and 2008, recognising that management practices differ from site to site and year to year depending on many factors including farmer skill and attitudes to risk, local meteorological conditions and other agronomic and economic constraints to farming practices.

For fertiliser management, three nitrogen application programs were reported as common and best management practice. A single application of 160 kg ha-1 of nitrogen at planting in the form of ammonium nitrate was modelled for the experimental research unit (CUF). At two of the farm sites (Buxton and Woodbridge), two nitrogen applications were used; an initial 100-120 kg ha-1 at planting, followed by a second top dressing of 80-100 kg ha-1 approximately 8 weeks after planting to coincide with tuber formation. At the Spalding farm site, drip irrigation was used, and an initial application of 150 kg ha-1at planting was followed by nine small (5 kg ha-1) applications with the irrigation (fertigation), spread throughout the season. To identify the change between historical and future irrigation needs, an irrigation schedule was defined to apply water whenever 40% of the readily available water was depleted. This was defined to reflect typical current farmer practice.

Variable		Site			
		CUF	**Buxton**	**Woodbridge**	**Spalding**
Planting depth (m)		0.12	0.15	0.13	0.19
Plant population (per m2)		3.4	3.4	2.9	3.3
Planting date		16 Apr	1 Apr	1 Apr	5 Apr
Date of harvest		30 Sept	16 Oct	15 Aug*	12 Sept
N fertilizer application	Date of application - base	Planting	Planting	Planting	Planting
	Amount applied (kg ha-1)- base	180	100	150	160
	Date of application - top dressing	-	15 May	20 May; 6 June	18,26 June; 10,17,21,28 July; 4,14,20 August
	Total amount applied (kg ha-1)- top dressing	-	80	100	45
Irrigation system		Rain gun	Rain gun	Rain gun	Drip
Soil texture		Medium sandy loam	Medium sandy loam	Loamy sand	Silt

*Defoliation practices were applied.

TABLE 2 MAIN VARIABLES USED TO PARAMETERISE THE SUBSTOR – POTATO MODEL FOR THE EXPERIMENTAL AND FARM SITES.

These management data were used in SUBSTOR-Potato model to simulate the annual yield and net irrigation needs for the baseline (reference) scenario (1970-1990) at each site. The model initiates each year on the planting date and assumes the soil is at field capacity, an assumption which is reasonable under UK conditions. The model was then re-run for each emissions scenario using the same crop and soil files but with the future ‘changed’ climate datasets. For each year, model outputs included yield (t ha-1), net irrigation need (mm), and irrigation use efficiency (IUE), defined as the actual yield per unit of irrigation water applied (kg m-3).

4.3.4. Model validation

It is important that the crop model can accurately predict observed variations in historical yield, before modelling climate impacts on future yield. The genetic coefficients used in the SUBSTOR-Potato model are available for different potato cultivars and were derived from previous calibration for a wide range of geographical regions, soil and agroclimatic conditions and management intensities (e.g. irrigation, N fertilisation) (Griffin et al., 1993; Šťastnà et al.,2010). The photoperiod sensitivity to tuber initiation is represented by the coefficient P2 (unitless) and the critical temperature above which tuber initiation is inhibited by the coefficient TC (oC). The coefficient G2 (cm2 m-2 d-1) is the leaf area expansion rate in degree days and G3 (g m-2 d-1) is the potential tuber growth rate. A further coefficient (PD) is also used to describe the level of determinacy of the cultivar. The genetic coefficients used in this study are those reported by Griffin et al. (1993) for the *cv.* Maris Piper and correspond to 0.4, 17oC, 2000 cm2 m-2 d-1, 25 g m-2 d-1 and 0.8 for P2, TC, G2, G3 and PD, respectively.

The SUBSTOR-Potato model was validated using 10 years (1989-98) and 6 years (2003-08) independent data from the experimental research unit and farm sites, respectively. This was to compare the model outputs to observed experimental results and field measurements of the real system (Huang *et al*., 2009). For each site, specific field data relating to the soil characteristics, irrigation dates and scheduled amounts, fertiliser practices, planting, emergence and harvest dates, and measured yields for selected fields were collected and used. Irrigation application losses were ignored as unknown and hence net irrigation needs rather than gross irrigation amounts were used.

A linear correlation between the SUBSTOR-Potato model simulated and observed yields was first completed (Figure 10). The observed farm yields were much lower than those at the experimental research unit, typically ranging from 40 to 65 t ha-1 compared to 50 to 90 t ha-1. This is expected given the contrasting conditions under which production is practiced; an experimental site is able to provide a high degree of in-field management control compared to a farm dealing with operating constraints relating to labour, disease control and irrigation equipment. Regarding validation, the linear regression analysis helps to evaluate model performance by providing two pieces of information: the slope indicates whether or not there is a bias and the coefficient of determination (R2) assesses how well the shape of the simulation matches the shape of the observed data (Huang et al., 2009). The linear regression showed a very close agreement between the model simulated and observed yields (R2 = 0.8059). Further statistical analyses using means, standard deviation, and the root mean squared error (RMSE) were then used to test the significance of model validation (Table 3). The following equation was used for RMSE:

$$RMSE = \left(\frac{1}{N} \sum_{i=1}^{N} d_i^2 \right)^{\frac{1}{2}} \qquad [2]$$

Where *N* is the number of data pairs and d_i is the difference between *i*th predicted and *i*th measured values (Kennedy and Neville, 1986).
The RMSE provides information on model performance by allowing comparison of the actual difference between the observed and measured yield values. The very low RMSE values for the farm (2.3 to 3.6 t/ha-1) and experimental (6.2 t ha-1) sites confirmed very good model performance. For all sites, the RMSE values were lower than the average SD of the field measurements so the model validation could be accepted. The differences between the simulated and observed mean yields were also very small (1 to 3.5%).

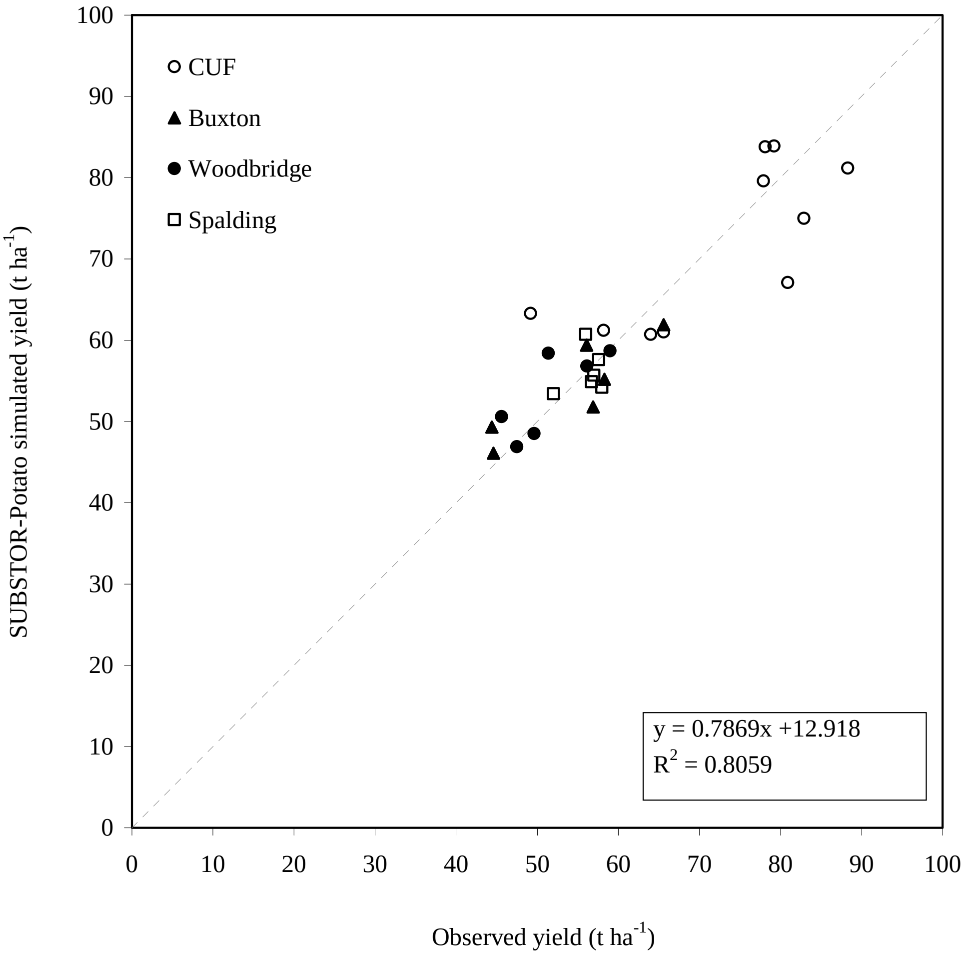


FIGURE 10 COMPARISON BETWEEN SUBSTOR-POTATO SIMULATED ANNUAL POTATO YIELD (T HA^{-1}) AND OBSERVED AVERAGE ANNUAL YIELD (T HA^{-1}) AT THE EXPERIMENTAL AND FARM SITES.

Statistic	Experimental site	Farm site		
	CUF	Buxton	Wood-bridge	Spalding
Number of samples (n)	10	6	6	6
Mean yield observed (t ha-1)	72.4	54.3	51.5	56.2
Mean yield simulated (t ha-1)	71.7	54.0	53.3	56.1
Standard Deviation observed (SDo)	12.5	8.3	5.1	2.2
Standard Deviation simulated (SDs)	10.0	6.0	5.3	2.7
RMSE (t ha-1)	6.2	3.6	3.0	2.3
Mean Difference (t ha-1)	6.6	3.6	2.5	2.2

TABLE 3 SUMMARY STATISTICS FROM THE SUBSTOR-POTATO VALIDATION FOR EACH STUDY SITE.

4.4. Results and Discussion

The outputs from the crop modelling, in terms of impacts of climate change on irrigation water requirements, yield and water efficiency are summarised and then discussed below.

4.4.1. Impacts on irrigation water requirements

The predicted changes in seasonal irrigation need (depths applied, mm) for potatoes grown from the baseline for each scenario are shown in Figure 11, across the range of wet to dry years, ranked by irrigation need. Under warmer climate conditions and where water is not limiting, plants will transpire more; this accounts for the 6.5 to 11.4% increase in crop evapotranspiration (ETcrop) (Table 4). The combined effects of reduced rainfall (–7 to –12%) and increased ETcrop results in a significant increase in average irrigation need (IRnet) of 14 to 30%, depending on the site and emissions scenario (Table 4). Clearly, these increases in water demand would have major implications for agribusinesses not only in terms of production cost that will rise with the increase in water and energy consumption, but also in terms of the water resources and the capacity of much of the irrigation infrastructure (reservoirs, pumps, mainline pipe diameters, mobile irrigators). These are typically designed to meet the irrigation need for a 'design' dry year, defined in England as one where the irrigation need do not exceed this value in more than 20% of the time (80% probability of non-exceedance). Table 4 shows that the future 'design' dry year irrigation need, and hence the required peak system capacity, would be 13-35% greater than under current (historical) conditions. A future 'average' year would thus be much drier than a current 'design' dry year. Schemes designed to current irrigation specifications would have insufficient capacity to meet future needs in approximately 50% of years. This would have significant impacts on a farmers' ability to deliver continuous supplies of premium quality produce demanded by the major supermarkets (Knox *et al*., 2000).

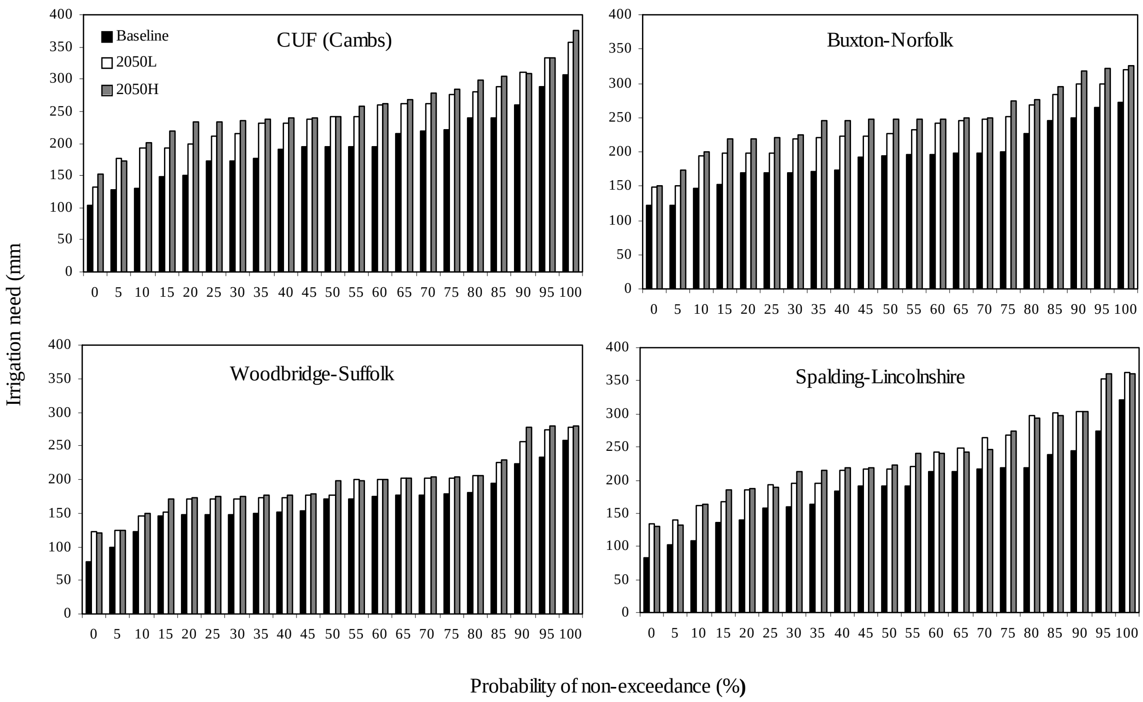


FIGURE 11 SUBSTOR-POTATO SIMULATED ANNUAL IRRIGATION NEEDS (MM) FOR POTATOES (*CV*. MARIS PIPER), RANKED (PROBABILITY OF NON-EXCEEDANCE) FOR THE EXPERIMENTAL SITE (CAMBS), FOR THE LONG-TERM AVERAGE BASELINE (1961-90) AND FOR SELECTED SRES EMISSIONS SCENARIO (2050 LOW AND HIGH).

4.4.2. Impacts on yield and irrigation use efficiency

The predicted changes in average actual yield (t ha-1) and irrigation use efficiency, IUE (kg m3) from the baseline for each scenario are summarised in Table 4. The modelling predicts minor increases in yield (+ 2.9 to +6.5%), depending on site and scenario, mainly in response to increased radiation and higher temperatures from the baseline. These results are consistent with Davies *et al*. (1997) and Wolf (2002) who also predicted only minor increases in future potato yield for the UK. The predicted yields obtained in this study reflect future expected yields under current nitrogen management practices assuming unconstrained water availability; thus they do not represent the potential yield that could be attained if nitrogen applications were unlimited. To illustrate the difference between predicted future actual yield (constrained by current fertiliser regime) and future *potential* yield (unconstrained), Figure 12 shows the predicted increases in relative potential yield (%) for potatoes under a future unconstrained (optimal) irrigation and fertilisation regime. The data relates to the experimental site at Cambridge, but a similar pattern was observed for the farm sites. This shows that the average potential yield is predicted to increase by 13 to 16% on average depending on scenario, but with significant inter-annual variability (5 to 24%). These findings compare against previous estimates reporting a 30% increase in potential yield under UK conditions (Peiris *et al*., 1996). However, these results are unlikely to be achieved as optimal water and fertiliser management practices are always influenced by economic, technical and practical constraints. The predicted increase in irrigation needs (+14 to +30%) combined with the minor increase in actual yield (+ 2.9 to +6.5%) leads to a noticeable reduction in IUE of between –10 to –22% depending on the site and scenario. This indicates that the future yield obtained when one unit of irrigation water is applied will decrease. For example, 1 m3 of irrigation water applied currently produces 31-40 kg tubers, but by the 2050s the same amount of water may only yield 26-35 kg tubers.

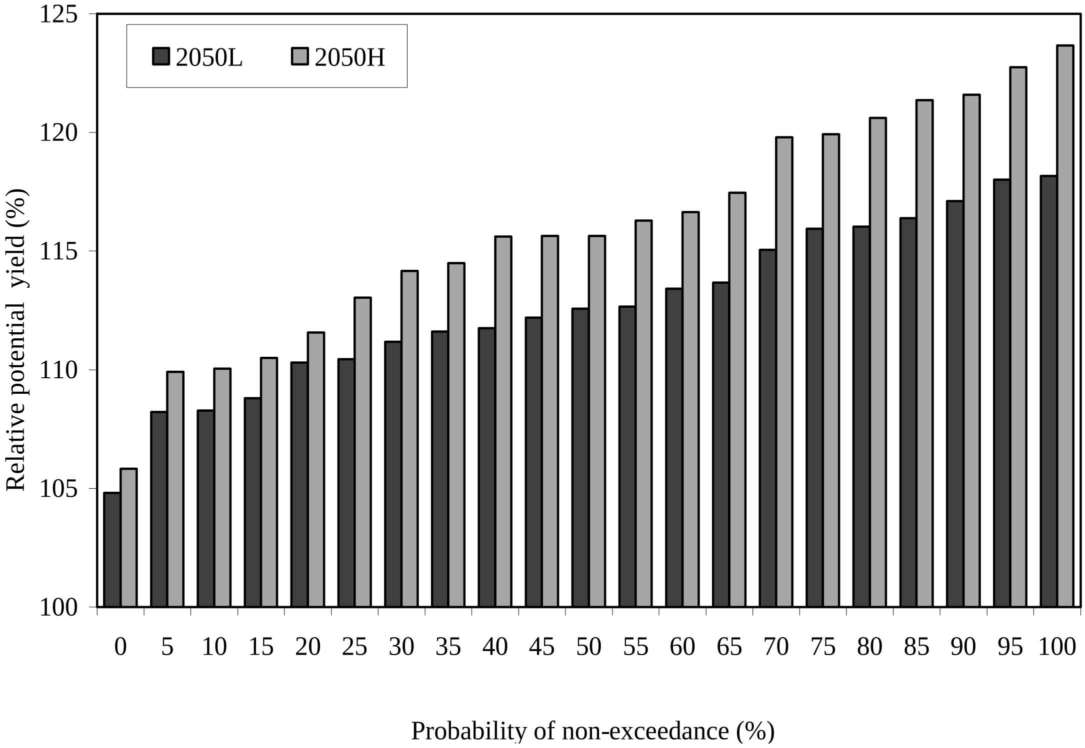


FIGURE 12 PREDICTED CHANGES IN POTENTIAL YIELD (T HA^{-1}) FOR POTATOES (*CV*. MARIS PIPER) FROM THE LONG TERM AVERAGE BASELINE (1961-90) TO THE 2050S FOR THE EXPERIMENTAL SITE AT CAMBRIDGE. SIMULATED YIELDS ASSUME THE CROP IS UNCONSTRAINED BY WATER AND FERTILIZER AVAILABILITY.

Scenario	Site	Average seasonal rainfall (mm)	Average seasonal ETo (mm)	Average seasonal ETcrop (mm)	Average IRnet (mm)	Design irrigation need (mm)	Average potato yield (t.ha^{-1})	IUE (kg.m^{3})
Baseline	CUF	248	449	396	197	239	74	40
	Buxton	266	491	393	192	227	58	31
	Woodbridge	169	367	321	166	181	61	40
	Spalding	238	505	397	189	219	56	33
2050L	CUF	226	487	433	244	281	76	33
	(% change)	(-8.9)	(8.5)	(9.3)	(23.8)	(17.6)	(2.9)	(-18.4)
	Buxton	244	525	427	232	268	60	27
	(% change)	(-9.0)	(6.4)	(7.9)	(17.2)	(15.3)	(4.6)	(-15.9)
	Woodbridge	157	394	342	190	206	65	35
	(% change)	(-7.1)	(7.3)	(6.5)	(14.4)	(13.8)	(6.5)	(-10.7)
	Spalding	219	543	435	232	297	58	26
	(% change)	(-7.9)	(7.5)	(9.5)	(22.7)	(35.6)	(3.5)	(-19.3)
2050H	CUF	218	496	441	256	299	76.8	31
	(% change)	(-12.1)	(10.5)	(11.4)	(29.9)	(25.1)	(3.5)	(-22.2)
	Buxton	233	533	434	247	277	61	25
	(% change)	(-12.4)	(8.5)	(10.4)	(28.6)	(22.0)	(6.2)	(-18.2)
	Woodbridge	150	401	344	195	205	64	35
	(% change)	(-11.2)	(9.2)	(7.1)	(17.4)	(13.2)	(4.9)	(-13)
	Spalding	211	554	435	235	293	58	26
	(% change)	(-11.3)	(9.7)	(9.5)	(24.3)	(33.7)	(3.5)	(-19.6)

TABLE 4 MODELLED YIELD (T HA-1), AVERAGE AND 'DESIGN DRY YEAR' IRRIGATION NEEDS (MM YEAR-1) AND IRRIGATION USE EFFICIENCY (KG M–3) FOR THE LONG TERM AVERAGE BASELINE AND EACH EMISSIONS SCENARIO, FOR EACH STUDY SITE.

4.4.3. Impacts of climate uncertainty on irrigation need

The UKCP09 climatology includes the outputs from 10,000 different sets of possible future changes in monthly climate, for a range of climate variables, intended to reflect modelling uncertainty from the multi-GCM model runs. The projections used in the analyses above were based on the GCM outputs corresponding to those with the highest levels of confidence (50%). To assess the impact of GCM uncertainty on irrigation need, the weather pattern of a single year (1995) at the experimental site (Cambridge) was perturbed using all 10,000 UKCP09 samples for each climate variable, and a probability distribution function for future irrigation needs (mm) generated (Figure 13). Using IPCC terminology, for the 2050L scenario, the 'very likely' probability estimate (50%) for future irrigation need is 300 mm and the 'very unlikely' probabilities (10% and 90% exceedance) are 390 mm and 210mm, respectively, compared to the 200 mm for the baseline (1995). A slight increase was observed for the 2050H scenario with 313 mm, 404 mm and 252 mm corresponding to the 50%, 10% and 90% probabilities, respectively. As every sample is a possible and plausible projection, Figure 6 reflects the uncertainty that could be observed in climate change modelling and the error that could be obtained when modelling based on a single climate projection. This probabilistic approach helps to frame the levels of confidence in the future impacts and is very useful for assessing the likely costs and reliability of adaptation options such as developing new water resources (e.g. irrigation storage reservoirs) or investment in new technologies to improve application efficiency (e.g. switching from overhead to drip or trickle irrigation).

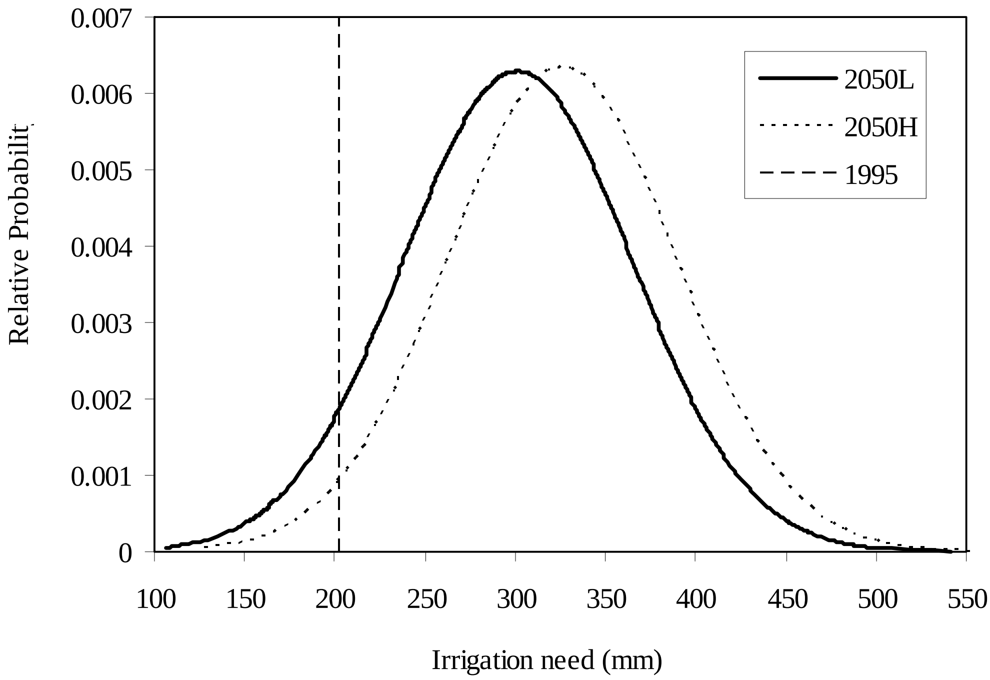


FIGURE 13 PROBABILITY DISTRIBUTION FUNCTION OF FUTURE IRRIGATION NEEDS (MM) FOR POTATOES (*CV.* MARIS PIPER) AT THE EXPERIMENTAL SITE (CAMBRIDGE), BASED ON 1995 WEATHER PATTERN AND THE 10,000 SAMPLES OF CLIMATE CHANGE FOR THE UKCP09 2050S LOW AND HIGH EMISSIONS SCENARIOS.

4.4.4. Model sensitivity

The sensitivity of the SUBSTOR-Potato model to systematic changes in climate was also analysed. The climate at the experimental site was assumed to be representative of all sites. The daily weather data for the baseline (1970-1990) was adjusted independently, in a step-wise manner, to assess the sensitivity of the model to changing values of each variable. Specifically, the impacts of varying temperature, solar radiation and atmospheric CO2 concentration on yield were simulated under an unconstrained irrigation and fertiliser management regime.

Temperature: The maximum yield for irrigated potato was observed when the mean daily temperature was increased by 4oC (Figure 14). Higher temperatures will affect not only the vine and root growth but also might cause a delay in tuber initiation and consequently reduction in the final yield. Higher temperatures will also accelerate both emergence and harvesting date as the number of days required to accumulate temperature (growing degree days) for the phenological development are reached sooner. The inter-annual yield variability (vertical bars) depends greatly on the weather pattern and is specific to the weather conditions observed in that year. However, for an extremely warm year an increase in temperature will have a higher negative impact on potential yield compared to an average year or one with relatively cold weather.

Solar radiation: A higher sensitivity and greater inter-annual variability was observed when solar radiation was below levels observed for the baseline – for example, a 20% reduction in radiation resulted in an average 40% yield reduction (Figure 14) coupled with higher inter-annual variability. In SUBSTOR-Potato, the photosynthetic carbon assimilation rate of the plant under no water or nitrogen stress conditions depends primarily on solar radiation and this explains the large yield reductions when solar radiation levels are reduced. Conversely, if the photosynthetic carbon assimilation is greater than daily growth demand, the excess of carbon assimilated enters a soluble carbohydrate pool (Ng and Loomis, 1984). If the daily reserve pool increases above 10% of the plant's current leaf and stem dry mass, then the excess carbohydrate is released from the reserve pool. This has the net effect of reducing the positive effect of higher levels of solar radiation on final tuber production (Figure 7).

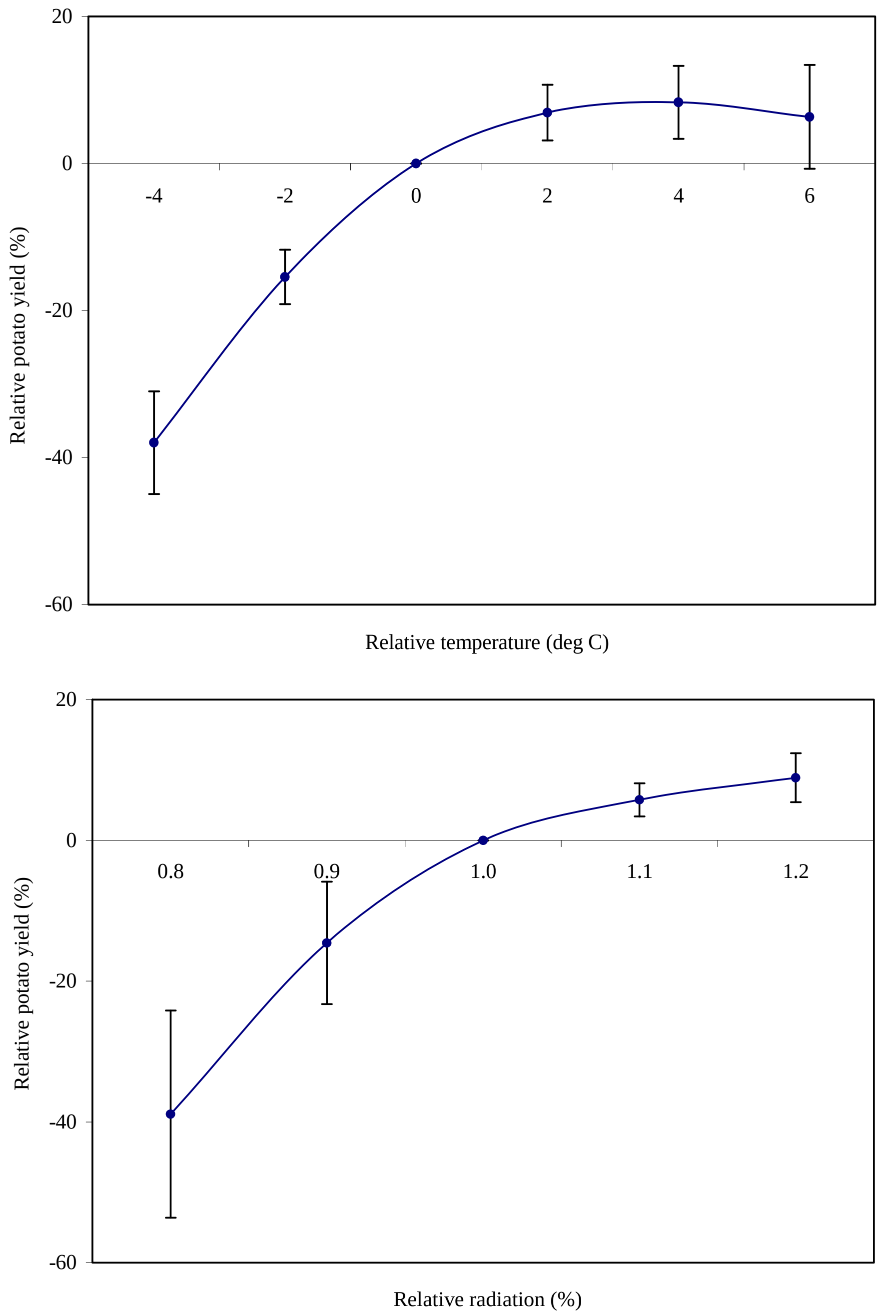


FIGURE 14 SENSITIVITY OF SIMULATED YIELD (SUBSTOR-POTATO) TO CHANGES IN (A) TEMPERATURE AND (B) SOLAR RADIATION FOR IRRIGATED POTATO PRODUCTION AT THE EXPERIMENTAL SITE (CAMBRIDGE), BASED ON DATA FROM 1970-1990. VERTICAL BARS REPRESENT THE INTER-ANNUAL VARIATION.

Atmospheric CO_2: The photosynthesis routine in SUBSTOR-Potato uses an asymptotic exponential response equation, where quantum efficiency and light-saturated photosynthesis rate variables are dependent on atmospheric CO_2 and temperature (Boote and Pickering, 1994). Consequently, the amount of new dry matter available for growth each day is not only limited by temperature, water or nitrogen stress but also is sensitive to atmospheric CO_2 concentration. For the experimental study site, the yield for irrigated potato showed a positive response to carbon assimilation enhancement due to increased levels of atmospheric CO_2 (Figure 15).

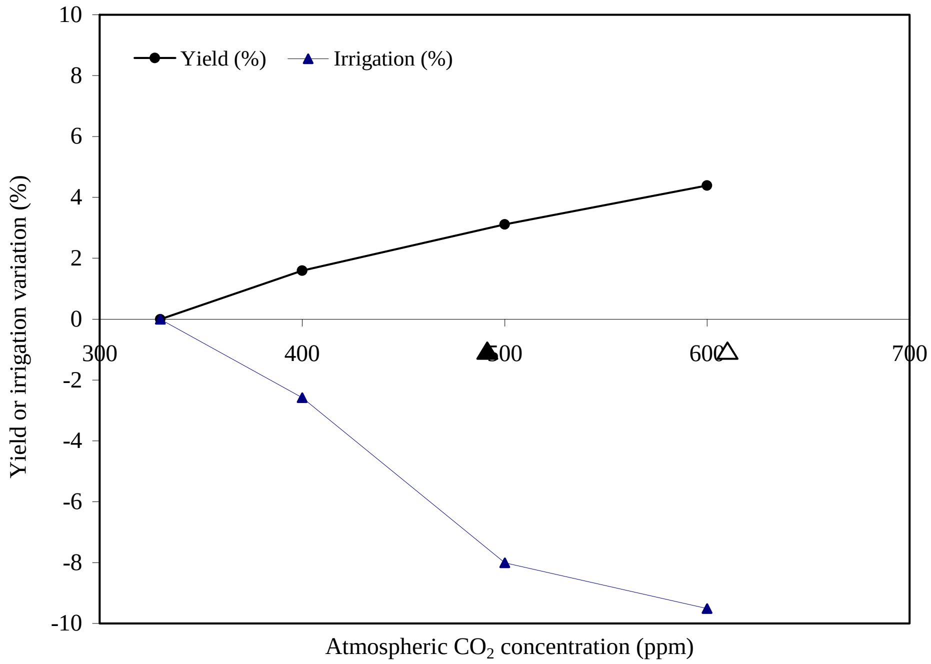


FIGURE 15 SENSITIVITY OF SUBSTOR-POTATO SIMULATED YIELD (%) AND IRRIGATION WATER REQUIREMENTS (%) TO CHANGES IN ATMOSPHERIC CO_2 CONCENTRATION (PPM), BASED ON DATA FROM 1970-1990. CONCENTRATIONS FOR THE 2050L (B1) (▲) AND 2050H (A1F1) (△) EMISSIONS SCENARIO ARE SHOWN.

As the vegetative development including root growth is enhanced by CO_2 fertilisation, plants are able to draw on available soil moisture from a greater depth thus extending irrigation intervals and reducing irrigation needs. However, the main reduction in irrigation needs is due to stomatal closure and the enhanced CO_2 concentration making the photosynthesis process more efficient in C3 plants.

4.5. Discussion

4.5.1. Methodological limitations

The methodology has a number of limitations regarding the crop and climate modelling, as in reality the relationships between climate, crop growth and yield are complicated by a large number of climate, soil and crop management factors, many of which need to be simplified for the purposes of crop simulation. In the SUBSTOR-Potato model, the physical structure of the farm soils was assumed to be optimal, with no limitations associated with compaction or poor drainage. There was no consideration of the impact of extreme events such as hailstorms, heavy rains or strong winds on crop canopy development and soil structure. Hence crop establishment, crop development and rooting were all assumed to proceed under optimal conditions. The planting and harvest dates were also fixed each year for the baseline and future simulations regardless of whether ambient weather conditions were suitable for cultivation and harvesting. However, under climate change, drier Springs and wetter Autumns will impact on land suitability at both planting and harvest. Further crop modelling would benefit from assessing the effects of varying planting and harvest dates for different potato cultivars and simulating a broader range of soil types (textures and depths). In this study only one cultivar (cv. Maris Piper) suitable for pre-pack production was considered; further modelling should assess the impacts of different irrigation scheduling strategies for a wider range of cultivars grown for both the processing and pre-pack (supermarket). Modelling should also investigate the impacts of future changes in the reliability of water supply (abstraction). This study assumed unconstrained demand, but reducing the availability of water for irrigation at differing times during the season, due for example, to low river flows or droughts, would impact on crop development, potato yield and quality and hence crop price.

Downscaling the GCM outputs to each site is a potential source of error, although the UKCP09 climatology deals with this by providing outputs appropriate for impact assessments without any further resolving being necessary (Jenkins *et al.*, 2009). Using the 'change factor' method the future temporal distributions of each climate variable were assumed to be identical to that of the historical baseline, with the future changes applied using perturbation techniques. This approach ignores any effects of increases in the probability of extreme events such as short periods of drought or excess rainfall which impact on plant growth and yield. Although the UKCP09 climatology provides probabilistic distributions for each climate variable, it does not provide guidance on which combinations of probabilities for a particular range of climate variables (e.g. temperature, relative humidity, solar radiation) might be most or least likely. The crop and climate modelling were based on two emissions scenarios and one time-slice. Further work would need to consider additional time slices (e.g. 2030s, 2080s) or transient climate changes using SD, and an ensemble of emission scenarios, to consider the impacts of alternative demographic, socio-economic and technological changes on crop yield and irrigation demand.

The study identified a major risk to future production relating to the capacity of existing irrigation infrastructure being insufficient to meet future 'dry' year needs. However, the projected changes (Figure 11) relate to seasonal need (mm), whereas the design of pumps, pipes and associated infrastructure is also governed by 'peak' daily rates. Further work would need to assess how these might be impacted. Finally, further research needs to consider the spatial distribution of potato cropping and relate this to current and future water resource availability (by catchment) and land suitability, in order to identify appropriate adaptations. This will help identify areas where both rainfed and irrigated production might be at most risk and where new cultivation might be most suitable.

4.5.2. Adaptation

UK farmers are used to dealing with the vagaries of summer weather and particularly unreliable rainfall, which makes irrigation management much harder than in arid environments. But greater uncertainty in seasonal weather patterns means growers need to adapt and consider short-term coping strategies as well as longer-term strategic developments to reduce their vulnerability to changing water availability. How they respond will depend to a large extent on their perception of risk and the opportunities that climate change presents to their business. Farmers generally have two options; either to reduce their water needs or try to secure additional water supplies. Options to reduce on-farm water needs include investing in improved irrigation technology (scheduling) and equipment to increase application uniformity and efficiency, using weather forecasting to increase the effective use of rainfall, encouraging deeper rooting of crops, introducing lower water use or drought tolerant crop varieties, decreasing the overall irrigated area, or modifying soil structure to improve soil moisture retention. Options to obtain more water include purchasing land with water, obtaining additional licensed capacity and building on-farm storage reservoirs (either individually or shared with neighbouring farms), installing rainwater harvesting equipment, re-using waste water from farm buildings, or switching water supplies to public mains where feasible. Many of these potential adaptations are already 'no regret' options, in that they already make sense by solving existing water resource issues, which then contribute to a farms future adaptability.

In this study, the crop modelling assumed unchanged practices, but in reality there would be some degree of autonomous adaptation even if not planned adaptation. For potatoes, this would include earlier planting and harvest dates, changing to better adapted varieties, less dependence on soils with low water holding capacities, crop movement to regions with suitable agroclimate and water availability and the uptake of GM technology.

4.6. Conclusions

Assuming current fertiliser management practices remain unchanged, crop modelling using field data from four sites in England suggest the impacts of climate change (for the 2050s) on potato yield will be relatively minor (+3 to +6 %) , particularly when compared against the long-term underlying trend in yield increase. However, under conditions of optimal irrigation and fertiliser management, potential yields could increase by 13-16% on average. With climate change, future seasonal irrigation needs for potatoes would increase by 14-30%. Given these increases, the capacity of existing irrigation schemes would fail to meet future peak daily irrigation demand in nearly 50% of years. These findings have significant implications for the UK potato industry.

5. IMPACTS ON SOIL AND LAND MANAGEMENT

5.1. Summary

The viability of commercial potato production is influenced by spatial and temporal variabilities in soils and agroclimate, and the availability of water resources where supplemental irrigation is required. A wide range of cultivars (rainfed and irrigated) are grown depending on the target market, whether destined for pre-pack (supermarkets) or for processing. Knowledge of land suitability for production, and likely changes due to climate change, are key determinants influencing the sustainability and profitability of agribusinesses. Changes in soils and agroclimatic conditions will influence cultivar choice, agronomic husbandry practices, and the economics of production. Using the latest (UKCP09) scenarios of climate change for the UK, this paper describes a methodology using pedo-climatic functions and a GIS to model and map current and future changes in land suitability for potato production in England and Wales.

The outputs identify regions where rain-fed production will become limiting and where future irrigated production will be constrained due to water stress, for selected emissions scenarios (low and high) and time slices (2050s and 2080s). The results suggest that by the 2050s, the available land that is currently well to moderately suited for rain-fed production is expected to decline by 74-95% owing to increased droughtiness. However, with supplemental irrigation, around 85% of the total arable land in central and eastern England will be suitable for production, although most of this land is within catchments where water resources are already over-licensed and/or over abstracted. Although irrigation will provide an opportunity for growers to maintain production, the expansion of irrigated cropping in many regions will be constrained by existing constraints on water supplies and increasing competition for limited resources. The implications of climate change on the UK potato industry, the range of adaptation options and responses available, and the uncertainty associated with the land suitability projections, are discussed.

5.2. Introduction

In England and Wales, the potato industry (*Solanum tuberosum L*.) has changed dramatically in recent decades, from a sector comprised of many small individual farms to one with far fewer but much larger agribusinesses, driven by the need to provide high quality product to the major processors and supermarkets (Knox *et al.,* 2010a). In 2009, more than 94,000 ha of potatoes were cropped in England and Wales and have registered an average productivity of 48 t ha-1. Over half (56%) of that area was irrigated, mainly by hose reels fitted with rain guns or booms. The irrigation season typically extends from May to September and is supplemental to rainfall. Nationally, potatoes are the most important irrigated crop, accounting for 43% of the total irrigated area and 56% of the total volume of irrigation water abstracted (Knox *et al*., 2009). Although the volumes abstracted are relatively small, irrigation is concentrated in the drier eastern regions of England (Figure 16) and peaks in the summer months, in the driest catchments when water resources are most scarce, creating conflict with other water demands, most notably those for public water supply and environmental protection.

The shallow and sparse rooting system of potato plants (Opena and Porter, 1999), often resulting from soil compaction (Stalham *et al.*, 2007) makes it very sensitive to soil moisture stress (Lynch *et al.*, 1995; Porter *et al.*, 1999; Onder *et al.*, 2005). This provides little scope for error in terms of irrigation management and losses in yield and quality can result even from brief periods of water shortage following tuber set (Stalham *et al.*, 2010, Eldredge *et al.*, 1992; Shock *et al.*, 1992; Wright and Stark, 1990). Thus most rain-fed production in UK is concentrated on the heavier soils in regions where summer rainfall is higher, such as Yorkshire, Lancashire and the West Midlands. However, potatoes grown on coarse-textured and well drained soils are more susceptible to water stress, and growing potatoes on these soils requires supplemental irrigation to maintain yield and quality.

FIGURE **16** PROPORTION OF TOTAL IRRIGATED POTATO FIELDS BY REGION IN THE UK. PCL DATA REFER TO 2009.

The viability of rain-fed potato production in the UK depends not only on the pedo-climatic conditions but also on the cultivar being grown, its resistance to drought stress and the tuber quality required by the target market. More than 170 potato varieties are commercially grown in the UK and are classified based on their planting and lifting dates into 'earlies' and 'maincrop'. Earlies are usually planted in mid March (southern UK) or early April (in the north) and lifted after 10 to 13 weeks, while maincrop potatoes are usually planted in the first half of April in southern England and in late April further north and lifted normally after 15 to 20 weeks. These dates may vary from one year to another depending on the weather conditions. Having a shorter growing season, earlies normally yield less than maincrop. Therefore, even though they occupy 25% of the total potato cropped area, earlies contribute only 5% to total UK potato production.

Maris Piper is by far the most popular maincrop variety in the UK. In 2009, 19% of the UK potato area was cropped with Maris Piper, followed by Estima (9%), Lady Rosetta (6%) and Markies (6%). Estima, Maris Peer, Harmony and Marfona are mainly pre-pack varieties for supermarkets whilst Lady Rosetta, Hermes, Saturna and Pentland Dell are favoured for processing. A summary of the cropped area, proportion irrigated and yield of the top 10 varieties in the UK is given in Table 5.

Variety	Cropped area (ha)	Propn irrigated (%)	Average yield (t/ha)	Total production (t)	Maturity
Maris Piper	23,670	54.3	50.9	1,188,895	Maincrop
Estima	10,470	61.0	50.2	502,306	Maincrop
Lady Rosetta	6,989	58.4	50.3	335,296	Maincrop
Markies	6,303	52.8	48.0	316,380	Maincrop
Marfona	4,763	44.4	48.4	238,551	Earlies
Harmony	3,980	59.5	56.0	222,946	Maincrop
Maris Peer	6,063	79.7	33.5	201,266	Earlies
Hermes	4,054	16.8	47.3	191,516	Maincrop
Saturna	3,569	22.8	44.8	159,994	Maincrop
Pentland Dell	3,255	58.9	42.7	138,473	Maincrop

TABLE 5 SUMMARY OF CROPPED AREA (HA), PROPORTION IRRIGATED (%), AVERAGE YIELD (T/HA) AND TOTAL PRODUCTION (T) OF THE TOP 10 VARIETIES GROWN IN THE UK (DERIVED FROM PCL DATA FOR 2009).

Future changes in climate, could affect potato production directly by impacting the plant growth but also indirectly by perturbing the land management practices (e.g. trafficability for seed bed preparation, spraying, harvesting) (Knox *et al.*, 2010b). Warmer temperatures and elevated CO2 levels are expected to result in more favourable growing conditions for most crops grown in northern Europe including potatoes (Olesen and Bindi, 2002), although of course there will also be negative consequences, which will vary spatially and temporally.

The impacts of climate change on the irrigation needs and yield of potatoes grown in England have been assessed by Daccache et al. (2010). That study combined the downscaled outputs from an ensemble of general circulation models (GCM) with a potato crop growth model (SUBSTOR–Potato) to simulate future irrigation needs and yield for selected emissions scenario for the 2050s. Assuming crop husbandry factors remained unchanged, farm yields were shown to increase marginally (3-6%) whilst the average irrigation needs was predicted to increase by 14-30%. However, these simulations are for specific locations and consequently neglect any spatial variation in the land suitability on the crop production and exclude any impacts on the viability of rain-fed production.

Internationally, many studies have considered the impacts of climate change on future agricultural land use through scenario modelling and their consequent policy impacts (e.g. Ewert *et al.*, 2005) but there is remarkably limited literature on the impacts of potential changes in land suitability, a key factor influencing a country's or region's ability to adapt agricultural practices to a changing climate. But such analyses can play a critical role in formulating future land policies given the multi-functionality of agricultural land and its importance for ecosystem services (Winter, 2009). For example, Hood *et al.* (2005) determined the potential for growing cool season grapes, high yield pasture and blue gum in Victoria (Australia) by combining land suitability analysis with climate change scenarios within a GIS framework. In Scotland, Brown *et al.* (2008) 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.

As part of a broader study investigating the impacts of climate change on the UK potato industry, the objective of this paper was thus to develop a methodology using pedo-climate functions and a geographical information system (GIS) to model and map the current and future changes in land suitability for potato production in England and Wales. The outputs will help the industry and the 3,000 growers it represents to identify regions where future rain-fed potato production might become limiting, and where future irrigated production might be constrained due to water resource limitations.

5.3. Methodology

In summary, a three staged methodology was developed. Firstly, the current land suitability for maincrop potato production was modelled and mapped using a GIS. This provided a reference or 'baseline' scenario from which the derived land suitability classes could be compared against observed data on the spatial distribution of potato cropping (for rainfed and irrigated production). Secondly, future changes in potato land suitability were then modelled using the latest scenarios of climate change produced by the UK Climate Impacts Programme - UKCIP - (Jenkins et al., 2009). This identifies how land classes might shift both spatially and temporally due to the impacts of changing patterns of rainfall, temperature and other agroclimatic variables. This helps to quantify the potential impacts on current centres of production which tend to be regionally concentrated. Finally, the relationships between land suitability and water resource availability were assessed to identify catchments where future irrigated production might be at risk and conversely where production might need to relocate to catchments where water resources are unconstrained. From this, the implications of climate change can be assessed including where rain-fed production might become limiting, what varieties are likely to be most/least suited to changes in land suitability, and the range of adaptation options (e.g. shifting production, new soil management techniques, drainage, new irrigation infrastructure etc) that might be considered. A brief description of each stage is given below.

5.3.1. Assessing current potato land suitability

Characterising the edaphic and climate regions suitable for the production of a specific crop type generally requires a long time frame, coupled with extensive experimentation and experience, and significant resources (Siddons et al., 1994). However, provided that land types and local climates can be adequately specified and sufficient knowledge is available regarding crop responses to soil and weather factors, then land suitability models offer an alternative and rapid means of producing maps and data sets showing suitable areas for a particular crop. In this context, the Soil Survey of England and Wales (now incorporated in the National Soil Resources Institute) developed a suite of land suitability models, for a range of arable crops (Jones and Thomasson, 1987; Hallett *et al*., 1996) and in thus study, the land suitability model for potatoes was used. It defines a number of parameters, most of which are climatic or soil related, but some are site specific. A summary of each parameter, described in detail by Jones and Thomasson (1987), is given below.

5.3.2. Definitions of land suitability and criteria for their assessment

In the potato land suitability model, various criteria are used to define unsuitable and suitable land. However, it is important to first define the four classes of agronomic suitability used by soil scientists and growers, termed well, moderate, marginal and unsuited. *Well suited land* has a high and sustainable production potential and from year to year. There is adequate opportunity to establish the crop in average years at or near the optimum sowing time and harvesting is rarely restricted by poor ground conditions. Even in wet years, working conditions are acceptable and do not prevent crop establishment. There are sufficient soil water reserves to meet the average atmospheric demands on the crop. *Moderately suited land* is where potential production may be moderate or high, but is variable from year to year due to either shortage of soil water to sustain full growth, or to poor conditions at crop establishment affecting either sowing time or soil structure. Harvesting potato crops can be difficult with consequent penalties for the following crop. *Marginally suited land* has a potential production that is variable from year to year with considerable risks, high costs, or difficulties in maintaining continuity of output. These are due to climate interacting with soil properties, disease or pest problems. In some years there may be failure to establish the potato crop. For some crops, such as potatoes, marginal suitability may imply not so much a high risk in producing the crop as problems of fitting it into a continuous system. The criteria for *unsuited land* vary from crop to crop but are mainly related to climate, gradient and, for potatoes, stoniness. Clearly, near the climatic limits there will be favourable years which allow efficient production and others which are too wet or too cool (Jones and Thomasson, 1987).

5.3.3. Criteria for 'unsuitable' land assessment

Given these land suitability definitions, three variables are used to distinguish between unsuited and suitable (well, moderate, marginal) land; namely, potential soil moisture deficit (PSMD), accumulated temperature (AT) and slope. In the model, these identify areas where either climatic conditions (extreme cold and/or wet areas) and/or soil characteristics (high levels of stoniness and sloping relief) would limit potato production. A brief description of each is given below.

Maximum potential soil moisture deficit ($PSMD_{max}$) has been widely used as an agroclimatic indicator internationally to assess the level of drought or to quantify the spatial and temporal changes in crop water requirements (Knox et al., 2010c; De Silva et al., 2007; Rodríguez Díaz et al., 2007). It represents the monthly maximum accumulated excess of reference evapotranspiration (ETo) over rainfall (P) during the summer months, and is calculated using a monthly water balance model:

$$PSMD_i = PSMD_{i-1} + ET_i - P_i \quad [1]$$

Where:

PSMDi : potential soil moisture deficit in month i, mm

Pi : rainfall in month i, mm

ETi : Reference evapotranspiration of short grass in month i, mm, calculated using Penman-Monteith method.

Under UK climatic conditions, PSMD calculation starts in January as month i = 1. The moisture deficit starts to build up in early spring as ET > P, peaks in mid summer (July-August) and then declines in autumn and winter as P > ET. The maximum PSMD of the 12 months (PSMDmax) for the baseline is the PSMD for that grid pixel. In this study, the long term average PSMDmax was used to identify areas of excess wetness or aridity across England and Wales; a value of PSMDmax less than 75 mm is considered too wet to establish potato crop as wetness encourages disease development and limits mechanisation operations (trafficability) in field. Conversely, high values for PSMDmax (>200 mm) are associated with areas with a high crop water demand, and reliance on supplemental irrigation.

The second variable, accumulated temperature (AT) is defined as the integrated excess of temperature above a fixed base value or threshold over an extended period (month or year). It is a reasonable guide to the energy input since it correlates with crop potential and vegetation growth. AT is thus a measure of the degree of the warmth necessary for plant growth. In this study, an AT value from January to June above 0oC was generated using a methodology developed by Hallett and Jones (1993). A value of AT < 1125 day-degrees above 0oC is considered too cold for potatoes, in which case production would be constrained by low temperature.

The final variable for assessing unsuited land relates to slope. For sloping potato fields, an angle of 7° (15%) is considered too steep and hence exceeds the reliable limit for using heavy harvesting equipment.

5.3.4. Criteria for 'suitable' land assessment

The two main criteria for suitable land are determined by trafficability and droughtiness, the former being measured as machinery work days (MWD) described in detail by Thomasson and Jones (1989), and the latter from available water (AW) and soil moisture deficit (SMD) data (see Jones and Thomasson 1985). As Innes and Thomasson (1983) showed, both droughtiness and MWD are important parameters which strongly influence crop yield. The MWD variable is a more complex indicator than PSMDmax as it combines information on soil structure, permeability and water regime to predict the number of days when heavy machines can have reasonable access to fields for crop husbandry practices (Rounsevell and Jones, 1993). For example, a delayed planting date caused by spring rains will shift the growing season and increase the cold damage risk during late development stages. The harvesting date may also coincide with heavy rainfall causing a further delay in the harvesting period with consequences on market price, potato yield and quality. The duration of zero soil moisture deficit conditions, used as a measure of land accessibility depends not only on the amount and rainfall pattern but also on the properties of the soil. Field capacity or the field inaccessible period could occur much faster and last longer with fine textured and slow impermeable soils than with well drained coarse textured soils under similar climatic conditions.

For potatoes, damage caused by soil clods and stones during harvesting can damage tuber quality, and hence crop price. Stoniness is alleviated to a certain extent by modern harvesting machinery, but soils with proportions of > 15% stones larger than 6 cm diameter in the top 25 cm soil were considered unsuitable for potato cultivation. Land topography is another important aspect to be considered in assessing land suitability for mechanised potato production. To achieve potential yields, appropriate soil moisture conditions need to be maintained during the growing season. This can be achieved by appropriate irrigation scheduling but under rain-fed practices, yield will be dependent on the level of droughtiness in that area. This depends on the pattern of rainfall, rates of evapotranspiration (ET) and on local soil characteristics. The method used to assess the droughtiness is based on Thomasson (1979) and takes into account the crop rooting and foliar characteristics to obtain an estimate of the average soil moisture balance (SMB) at a given time and location:

$$SMB = AWC_{pot} - SMD_{pot} \qquad [2]$$

Where:
AWC_{pot} is the available soil water holding capacity adjusted to potato crop, mm,
SMD_{pot} is the moisture deficit adjusted to potato crop, mm,
AWC_{pot} is a measure of the quantity of water held in the soil profile that can be taken up by the potato crop. It is highly dependent on soil texture, structure, organic matter, and stone content but also on potato rooting depth. A detailed description of the method used to calculate AWC_{pot} for potato is given in MAFF (1988).

PSMD is relevant to grass but for potato the moisture deficit calculation needs to be modified to allow for the limited ground cover during the early stages of growth. Under UK conditions, maincrop potato has an almost negligible leaf cover until mid-May and full leaf cover is achieved only after the end of June (Stalham ref). Jones and Thomasson (1985) described the following equation for deriving SMD_{pot} for potatoes from the monthly accumulated values of *PSMD* grass:

$$SMD_{pot} = PSMD_{Aug} - 1/3 PSMD_{June} - 1/3\ PSMD_{mid\text{-}May} \qquad [3]$$

After excluding unsuitable land (based on slope, stoniness and temperature), the land suitability for potato cultivation was classified by combining data on the MWD with droughtiness (Table 6). Well suited lands are those defined as having sufficient MWD from January until the end of April and a level of droughtiness low enough to not restrict potato crop development. On the other hand, very dry areas will be restricted for potato production unless supplemental irrigation is used. The potential potato production in well suited lands is high in an average year and sustainable from one year to another. In normal and wet years, working conditions remain acceptable and do not prevent crop establishment while in a normal dry year, soil water reserves are good enough to meet the crop water requirement and to ensure an acceptable yield under rain-fed practices.

MWD	**Droughtiness**			
(1 Jan- 30 Apr)	> 50	0 - 50	0 - -50	< -50
> 30	Well	Moderate	Marginal	Marginal
20 - 30	Well	Moderate	Marginal	Unsuited
10 - 20	Moderate	Marginal	Marginal	Unsuited
< 10	Marginal	Marginal	Marginal	Unsuited

TABLE 6 LAND SUITABILITY CLASSES BASED ON MACHINERY WORK DAYS (MWD) AND DROUGHTINESS, FOR RAIN FED MAINCROP POTATOES.

Moderately suited lands have a high to moderate production potential with a variation from one year to another caused by either water shortage to satisfy the plant needs or by poor soil working conditions affecting its structure or delaying the planting dates with negative impacts on production. When the inter-yearly variation in production is large enough, these lands will be classified as marginal for rain-fed potatoes. The productivity in these lands depends greatly on the rainfall pattern. Potatoes have a high risk of establishment failure in the dry parts of the country and a high risk of limited trafficability in the wet areas of the country. On lands where drought is intense and trafficability restricted in an average year, these lands will be classified as unsuited for rain-fed production due to the high risk of failure from extreme drought or extreme wetness.

5.3.5. GIS modelling and mapping potato land suitability

The individual components in the potato land suitability model are summarised in Figure 17. This shows how the parameters described above were integrated to assess land suitability. However, in order to assess spatial changes in land suitability, the model relies on two national data sets; the soil data set contains detailed spatial soil properties relating to texture, structure, permeability, drainage status, accessibility and workability, with data aggregated to a 5 km x 5km grid resolution in LandIS (Proctor *et al*., 1998; Keay *et al.*, 2009), in which the properties of the dominant soil types from the National Soil Map of England and Wales (Soil Survey Staff, 1983; Mackney *et al*., 1983) have been averaged. The climate data set uses the UK Meteorological Office database, containing long term mean monthly climate data for 1961-90 for a wide range of variables, also resolved to a 5km x 5km grid resolution.

Using a GIS, the spatial data sets on soil and agroclimate, and variables described in Figure 17, the criteria for land suitability assessment (PSMD, slope, AT, MWD, droughtiness) were integrated to model and map potato land suitability in each 5km x5km grid square across England and Wales. However, this data set included all non-arable areas, for example, urban areas, water bodies, and forests. An arable land use mask was therefore needed to exclude all 'non-arable' land. For this, the Corine land cover data set was used (CLC2000). This is based on IMAGE2000, a satellite imaging programme undertaken jointly by the Joint Research Centre of the European Commission and European Environment Agency (EEA) (Bossard *et al*., 2000). Corine provides land cover data for five different land use categories (artificial surfaces, agricultural areas, forest and semi natural areas, wetlands and water bodies), which are then further disaggregated into 44 land cover classes. Based on this CLC2000 data set, 6.2 million hectares or 42% of the total area of England and Wales is classified as 'arable' land. Using the GIS, the national potato land suitability data set was overlaid onto this CLC 2000 arable land data set to map current potato land suitability for rain-fed and irrigated production in England and Wales.

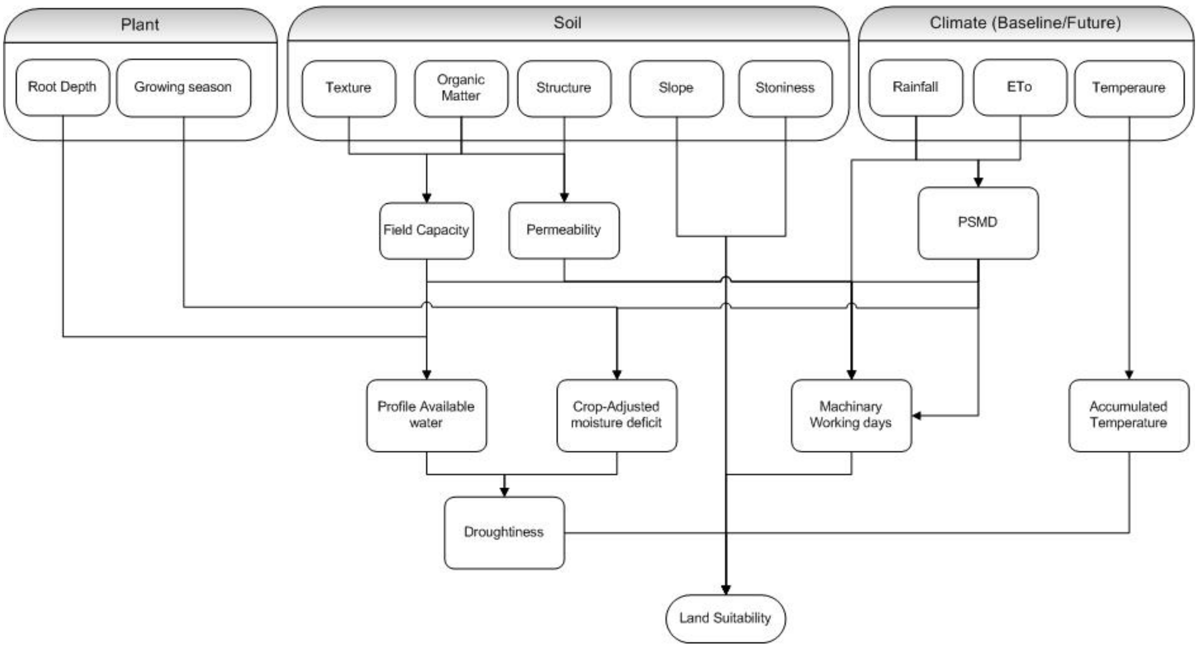


FIGURE 17 SCHEMATIC FRAMEWORK FOR ASSESSING POTATO LAND SUITABILITY.

5.3.6. Assessing future potato land suitability

Uncertainties in the outputs from general circulation models (GCM's) are divided between emission uncertainty and modelling uncertainty (Cox and Stephenson, 2007). As greenhouse gases emissions are determined by different driving forces such as demographic development, socio-economic development and technological changes, the Intergovernmental Panel on Climate Change (IPCC) has produced four different narrative storylines to describe the relationships between the driving forces and their evolution (IPCC, 2007). For each, different emissions scenarios were used to add a quantitative interpretation representation for that given storyline. Modelling uncertainty results from our incomplete understanding of the climate system or our inappropriate representation of the complex climate system within a single model. For this reason, many studies use the outputs of multiple future climate projections to increase the confidence in the climate projections (Takahashi et al., 1998; Fisher et al., 2005; Lobell et al., 2008). The latest projections from the UK Climate Impacts Programme (UKCIP) known as UKCP09 has dealt with the major source of modelling uncertainty by using the outputs of a large ensemble of variants from HadCM3 GCM and from 12 other international GCMs (Jenkins *et al*., 2009). As a consequence, 10,000 samples of possible and plausible changes for each climatic variable are available and presented in terms of likelihood probability. For the emissions scenarios, UKCP09 uses IPCC defined scenarios (A1FI, A1B and B1) (Nakicenovic *et al*., 2000) but these are renamed for simplicity as high, medium and low, respectively.

In this study, the highest likelihood probability (50%) for each climate variable is provided for each emission scenario as a monthly gridded data set at 25 km2 resolution, expressed as a percentage change relative to the baseline (1961-1990). These values were used to perturb the UK Meteorological Office 5km2 resolution baseline climate data set (1961-1990). The baseline and future reference evapotranspiration (ETo) data were calculated using the FAO Penman-Monteith equation (Allen *et al*., 1994). Using the UKCP09 climatology and the GIS the individual criteria for land suitability (Figure 17) were integrated and used to produce a series of maps showing the changes in land suitability for rainfed and irrigated potato production, for the 2050s and 2080s, for the low and high emissions scenario, respectively. As before, the CLC2000 data set was used to constrain the spatial analysis to arable land only.

5.3.7. Modelling and mapping potato land suitability in relation to water stress

In 2009, the total potato cropped area in England and Wales was reported to be 106,678 ha, of which 36% was rain-fed production (PCL, 2010). However, as crop quality becomes an increasingly important driver in commercial production, so too does the reliance on supplemental irrigation to reduce the effects of climate variability on crop yield and quality. But water resources for irrigation abstraction are under intense pressure, due to rising demands, competition between sectors and the longer term threat of climate change (Knox et al., 2010). In dry summers, agricultural irrigation can be the largest abstractor in some catchments and concerns have been raised over the potential impacts of irrigation on the environment, particularly in catchments where irrigation abstractions are concentrated. In many catchments, summer water resources are already over-committed and additional summer licences for surface and groundwater irrigation abstraction are unobtainable.

Information on the spatial distribution of potato holdings across England and Wales are collected annually by the agricultural levy board (Agriculture and Horticulture Development Board, AHDB) as part of their statutory duty. The information and level of detail in the public domain depends on its commercial sensitivity, but the baseline data can be used to map the spatial distribution of potato growers. In England and Wales, the water regulatory authority, the Environment Agency (EA), has assessed the availability of water resources for abstraction at a catchment level. Each catchment has been defined according to its resource status and allocated to one of four categories, ‘water available’, ‘no water available’, ‘over-licensed’ and ‘over-abstracted’, in order of increasing stress (EA, 2008). Using the GIS, these two data sets were combined to identify ‘hotspots’ where despite suitable land being available for irrigated cropping, production could be constrained by water resource stress.

5.4. Results

5.4.1. Current potato land suitability

Figure 18 shows the spatial distribution in current land suitability for rain-fed and irrigated potato production across England and Wales. Land classified as being well suited for rain-fed production is restricted to small pockets located in Cambridgeshire (notably along the Washland Fens), in parts of north Lincolnshire and south Yorkshire. This land occupies < 4% of the total arable land in England and Wales. In a typical wet year, the land would be dry enough to support appropriate working machinery and in a dry year, the available soil moisture levels would be sufficient to meet crop water needs. Moderately suited land for rain-fed production extends across approximately a third (35%) of England and Wales, covering north Norfolk, south Yorkshire, Lincolnshire, and parts of the East Midlands. There are also small areas located in Kent, Shropshire and Hampshire. The production potential of this land ranges from high to moderate and depends largely on the inter-annual variation in climate conditions. Nearly two thirds (59%) of arable land nationally is considered to be marginal for rain-fed potato production under current climate conditions, with production unreliable and highly dependent on weather conditions. These soils extend across much of eastern, central and southern England. In dry years, potato establishment on this land might fail due to excessive drought conditions and low soil moisture levels and conversely, in wet years production would fail due to poor trafficability and saturated soils. The areas of unsuited land are found not surprisingly across large tracts of Wales, south west and north west England where low temperatures combined high rainfall and steep slopes limit successful potato cultivation (Figure 18a). Assuming water resources for irrigation abstraction are unconstrained, then suitable and moderately suitable land for irrigated potato production represents 60% and 26% of the total arable land nationally, respectively (Figure 18b). This extends across much of eastern and south east England and parts of Lincolnshire. Only a small fraction (10%) is considered marginal for production due to restricted machinery working days and <4% is marginal due to temperature restrictions (AT < 1125 oC) and/or wet conditions ($PSMD_{max}$ < 75mm). The areas of unsuited land for irrigated production correspond closely with those for rain-fed production.

Figure 18 provides a useful ‘theoretical’ assessment of land suitability for current potato production. However, its accuracy can be checked by comparing the map against the known distribution of farms practising rainfed and irrigated production. These data are collected annually by the UK Potato Council and were made available for research purposes. By combining this data with the information presented in Figure 18, the proportion of rainfed and irrigated cropping within each land suitability class was derived (Table 7). The findings are consistent with the land suitability classes where the majority of rainfed potatoes are located on well (24%) and moderately suitable lands (41%) as these can guarantee commercial levels of production (Stalham to define). Irrigated fields are mainly concentrated on moderate (57%) and marginal (37%) land since supplemental irrigation here will help overcome the risks associated with droughtiness. Potato production is absent in areas where temperatures are too cold (AT< 1125oC) for crop establishment whilst only a small proportion of rainfed (7%) and irrigated (1%) fields were observed on land with $PSMD_{max}$ < 75 mm.

Suitability class	Rain fed		Irrigated	
	Area (%)	Fields #	Area (%)	Fields #
Well	24	1169	7	453
Moderate	41	1994	57	3867
Marginal	28	1535	35	2502
Unsuited (PSMD)	7	497	1	126
Unsuited (Temp)	0	2	0	0
Total	**100**	**5197**	**100**	**6948**

TABLE 7 TOTAL AREA (%) AND NUMBER OF FIELDS CURRENTLY USED FOR RAIN-FED AND IRRIGATED POTATO PRODUCTION IN 2009, BY LAND SUITABILITY CLASS.

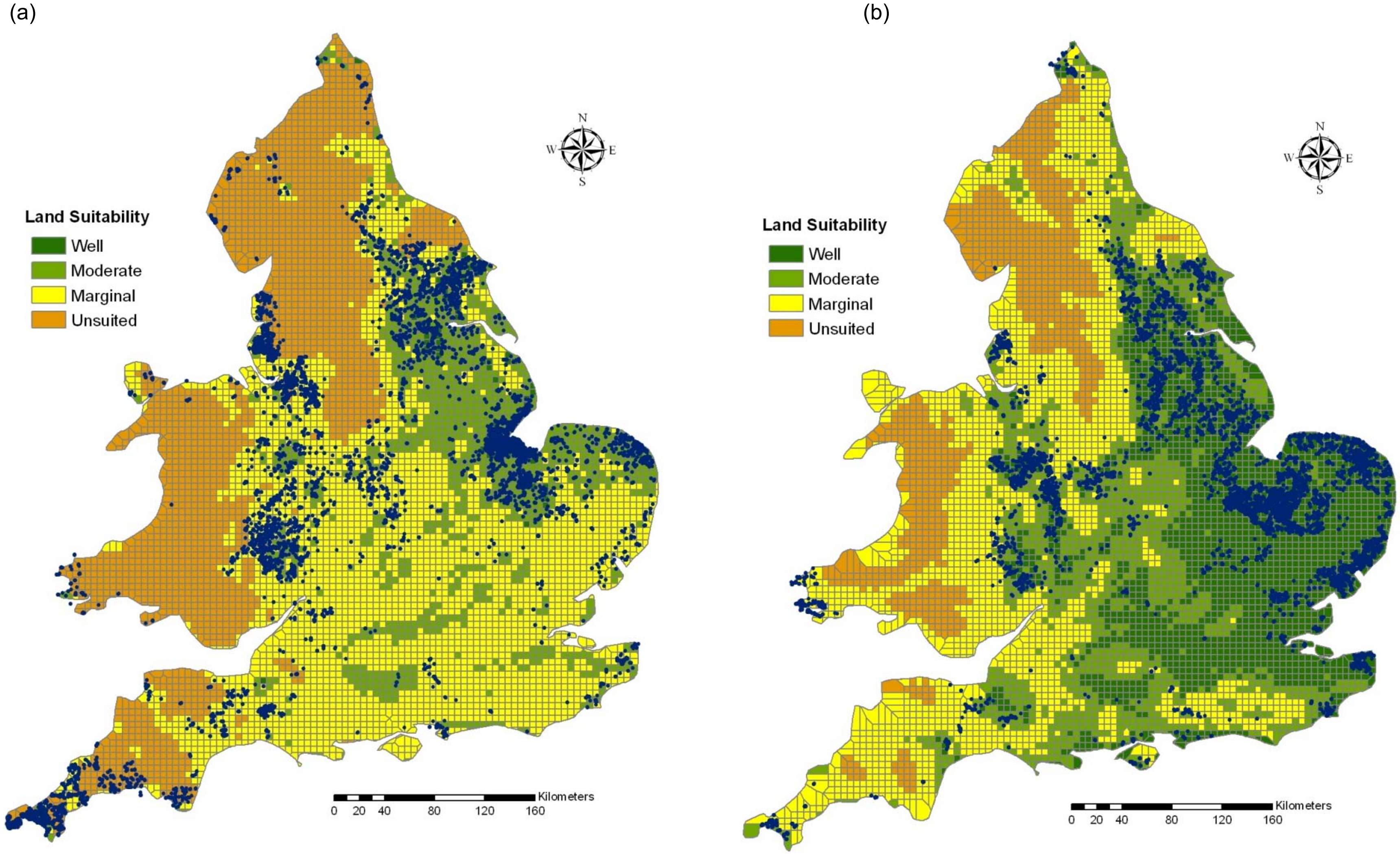


FIGURE 18 LAND SUITABILITY FOR (A) RAIN-FED AND (B) IRRIGATED MAINCROP POTATO PRODUCTION UNDER REFERENCE BASELINE CLIMATE CONDITIONS (1961-1990). THE BLUE DOTS CORRESPOND TO THE GEOGRAPHICAL LOCATION OF A) RAIN-FED AND B) IRRIGATED POTATO FIELDS FOR 2009 SEASON.

5.4.2. Future potato land suitability

Figure 19 shows the modelled changes in land suitability for rain-fed and irrigated potato production, based on the UKCP projections for the 2050s time slice, for the low and high emissions scenario.

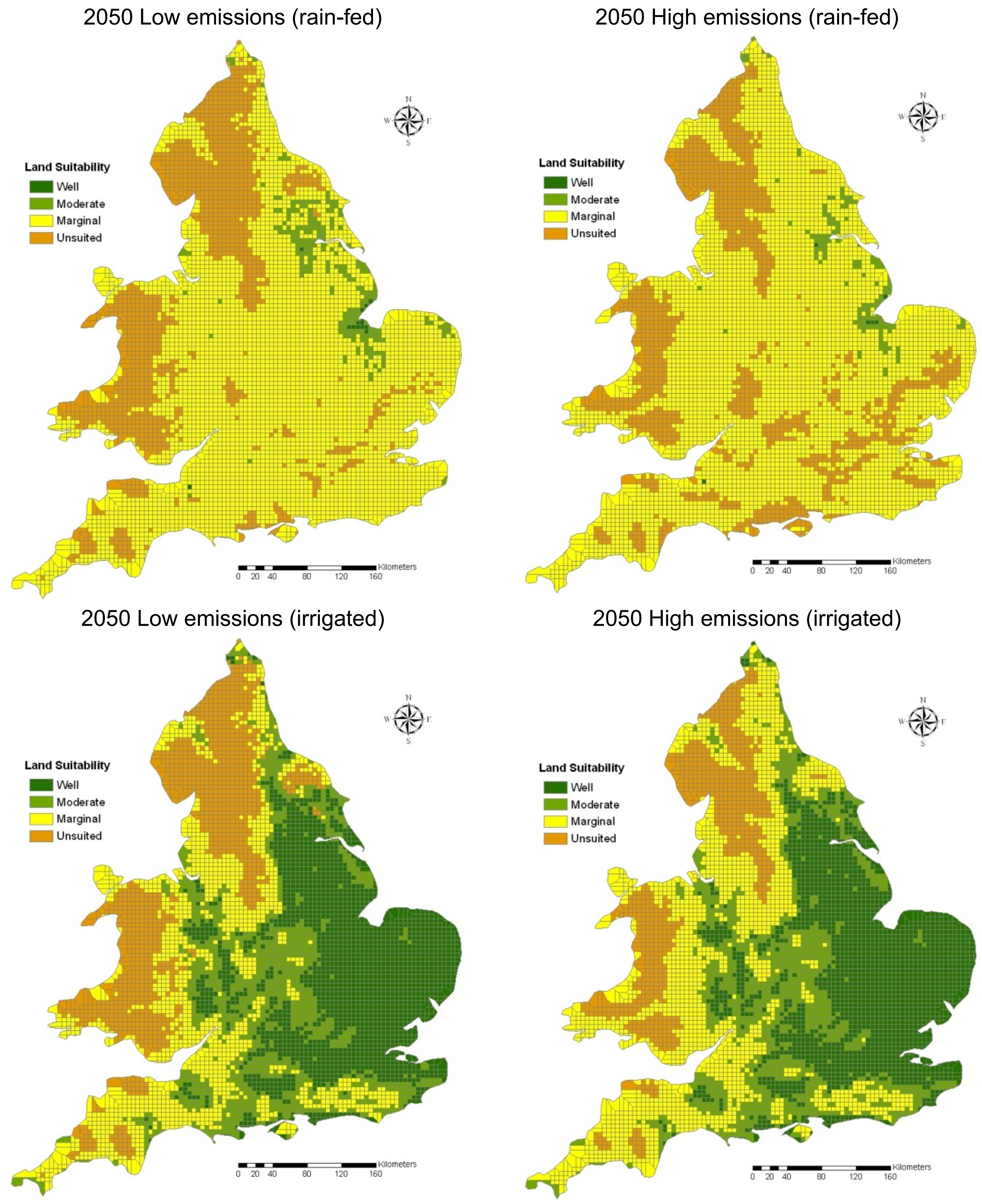


FIGURE **19** FUTURE LAND SUITABILITY FOR RAIN-FED AND IRRIGATED MAINCROP POTATOES FOR THE UKCP09 2050'S LOW AND HIGH EMISSIONS SCENARIOS.

Based on these climate projections, increases in the magnitude and extent of droughtiness could significantly reduce the land suitable and moderately suitable for rain-fed potato production, particularly around north Norfolk, the Fens and Lincolnshire (Figure 19). Most of the moderately suitable land tends to become marginally suitable in a future warmer climate with the associated changes in summer rainfall. However, some areas in south western England that were previously unsuitable, are expected to become marginal for production due to warmer temperatures and an increase in the number of machinery working days. For irrigated potato production, the projected changes in climate are expected to increase the area of land suitable for production. This positive impact is observed in areas previously considered under the baseline (1961-90) to have been either too wet or too cold for production.

A summary of the projected impacts on future rain-fed and irrigated production, by land suitability class, for the 2050s and 2080s, is summarised in Table 8 . By the 2050s, the available land that is currently well to moderately suitable for rain-fed production is expected to decline by 74-95%. Conversely, the land that is currently marginal for rain-fed production is expected to increase by 39-46%. This reflects mainly the increasing spatial and temporal impacts of droughtiness on the viability of rainfed production. For irrigated production, only minor changes in the suitability of land currently classified as being well to moderate are expected. However, the area of unsuitable land for irrigated production is projected to shrink by between 64-99% (Table 8). The main areas affected are in Wales and the north west England where unsuitable land might become marginal or moderately suitable. These changes could offset some of the negative impacts of climate change in drier parts of England, notably in eastern and southern England where despite increases in land suitability for irrigated production, access to reliable irrigation water supplies could become the limiting factor to production.

Scenario		Well	%	Moderate	%	Marginal	%	Unsuitable	%
Baseline	RF	3.4		33.7		59.4		3.5	
	IRRIG	60.5		25.7		10.3		3.5	
2050L	RF	0.4	-88	8.6	-74	86.9	+46	4.1	+17
	IRRIG	62.3	+3	24.7	-4	11.8	+14	1.3	-64
2050H	RF	0.2	-95	4.7	-86	82.7	+39	12.5	+261
	IRRIG	62.1	+2	25.0	-3	13.0	+26	0.0	-99
2080L	RF	0.3	(-93)	6.1	(-82)	85.9	(+45)	7.7	(+122)
	IRRIG	60.6	0	25.7	0	13.6	(+32)	0.0	(-99)
2080H	RF	0.0	(-99)	1.1	(+97)	60.0	(+1)	38.9	(+1023)
	IRRIG	62.6	(+4)	24.3	(-5)	13.0	(+26)	0.0	(-100)

Table 8 Estimated proportions (%) of land suitable for rain-fed (RF) and irrigated (IRRIG) potato production in England and Wales for the baseline (1961-1990), 2050s and 2080s with low and high UKCP09 emissions scenario. Values in parenthesis are % changes relative to the baseline.

5.4.3. Potato land suitability and water resource stress

Figure 20 shows the spatial distribution of potato growers relative to water resource availability. Figure 20a shows how these growers are concentrated, with major regional areas of production located in eastern England (Norfolk, Cambridgeshire, and Suffolk), the east and west midlands (Hereford, Shropshire and Staffordshire), and the north east (South Yorkshire). There are also smaller pockets in Kent and the south west, with rain-fed production generally concentrated in areas with higher rainfall. The areas of severe water resource stress are predominantly located in catchments in eastern and south east England where existing abstractions are known to be causing unacceptable damage to the environment at low flows (over-abstracted). There are also large areas of central and north eastern England defined as either 'over-licensed' (where unacceptable environmental damage would result if all existing licences were fully used) or having 'no water available' (where no additional summer abstraction is available). Only a small proportion of potato growers are located in catchments with 'water available' (where additional summer low-flow water could be made available). By combining these spatial data sets with information on current and future land suitability (Figure 18 and Figure 19) the projected impacts on land suitability relative to water resource availability were estimated (Table 9).

Land suitability		Water resource assessment					Total (%)
		No water available	Over abstracted	Over licensed	Water available	Not assessed	
Baseline	Well	0.6	0.3	0.8	0.2	1.5	**3.4**
	Moderate	10.1	5.8	7.7	4.7	5.4	**33.7**
	Marginal	21.6	15.5	12.1	7.5	2.7	**59.4**
	Unsuited	0.8	0.1	0.2	1.4	0.9	**3.5**
	Total	**33.1**	**21.7**	**20.8**	**13.8**	**10.6**	**100**
2050L	Well	0.0	0.0	0.0	0.0	0.4	**0.4**
	Moderate	2.1	0.7	2.0	1.1	2.8	**8.6**
	Marginal	29.7	19.8	18.3	12.0	7.1	**86.9**
	Unsuited	1.3	1.2	0.6	0.7	0.3	**4.1**
	Total	**33.1**	**21.7**	**20.8**	**13.8**	**10.6**	**100**
2050H	Well	0.0	0.0	0.0	0.0	0.1	**0.2**
	Moderate	0.9	0.3	1.0	0.5	2.0	**4.7**
	Marginal	27.4	17.7	17.4	12.3	7.9	**82.7**
	Unsuited	4.9	3.7	2.4	1.0	0.6	**12.5**
	Total	**33.1**	**21.7**	**20.8**	**13.8**	**10.6**	**100**

TABLE 9 ESTIMATED CHANGE (%) IN LAND SUITABILITY FROM THE BASELINE TO THE 2050S FOR IRRIGATED POTATO PRODUCTION IN RELATION TO WATER RESOURCES AVAILABILITY. THE PROJECTED CHANGES FOR EACH EMISSION SCENARIO (LOW AND HIGH) ARE SHOWN TO INDICATE THE RANGE.

The analysis shows that for the baseline, approximately a third (34%) of potato growers involved in irrigated production will be on moderate land and two thirds (59%) will be on marginal land, but that nearly half (49%) of all these growers will be located within catchments that are currently defined as having severe water stress (no water available, over abstracted, over-licensed). By the 2050s, assuming the spatial distribution of growers remains unchanged, then the majority of irrigated production (87%) will be on marginal land, with a third (30%) and a fifth (22%)

located in catchments defined as having no water available and over-abstracted, respectively. Clearly, this situation would be unsustainable from a national potato production perspective, particularly since the analysis assumes no change in future water resource availability, which itself is projected to worsen significantly (Arnell, 2010).

The potential implications for the UK potato industry, the adaptation options and uncertainties associated with the analyses are summarised below.

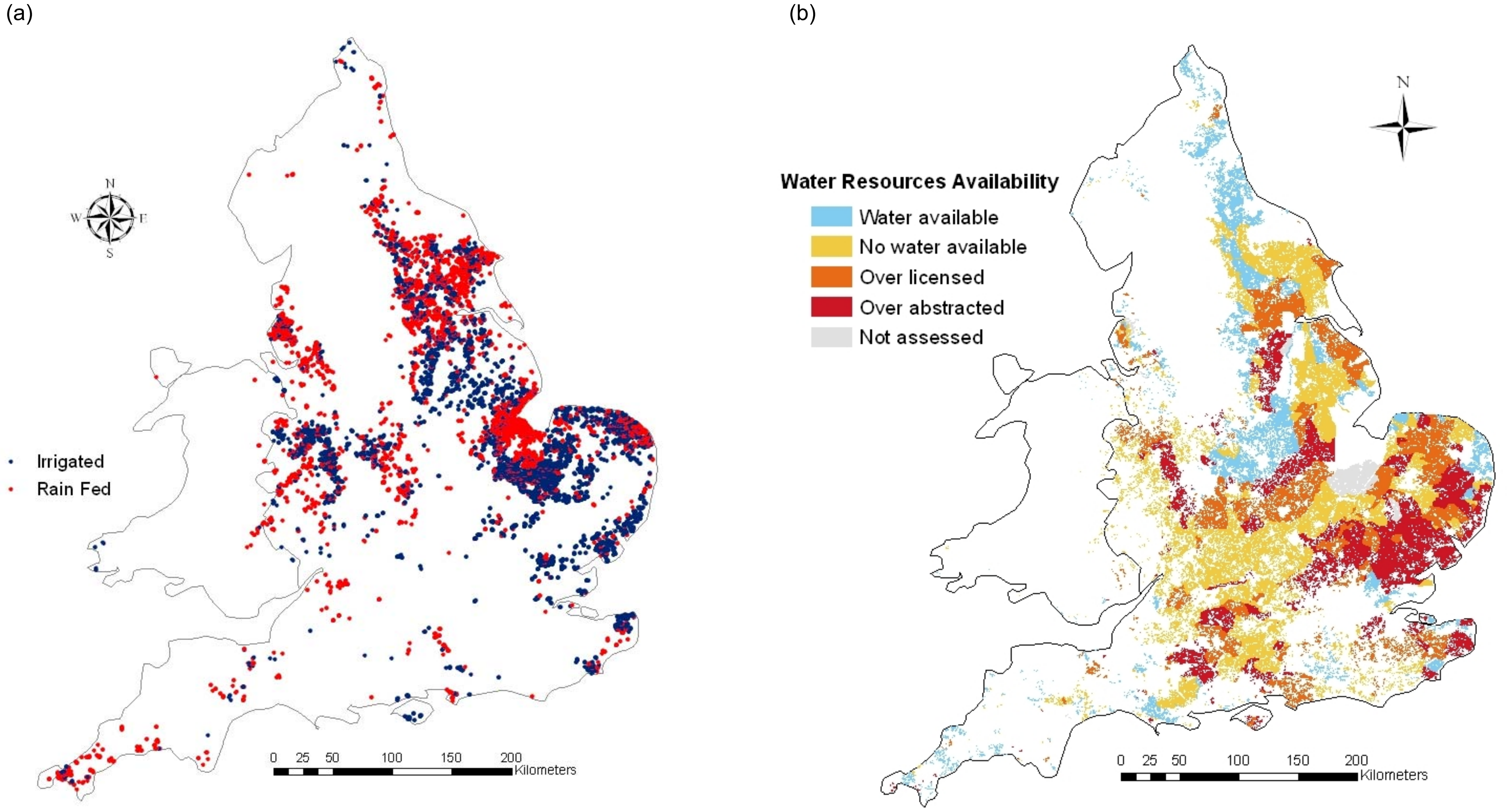


FIGURE 20 GEOGRAPHICAL DISTRIBUTION OF PCL REPORTED IRRIGATED AND RAIN-FED POTATO FIELDS IN 2009 (A) AND ARABLE LAND CLASSIFIED ACCORDING TO WATER RESOURCES AVAILABILITY (B).

5.5. Discussion

5.5.1. Implications for potato production

Based on the Potato Council's Benchmarking costs from 2009, the cost of production would not be covered by the crop value when maincrop potato yields fall below 30t ha-1. This would set a limit for rain-fed production on the dry regions and those having coarse and easily drained soils.

A restricted water supply during crucial times can cause damage to tuber quality (e.g. common scab) to the extent that certain varieties would be rejected by the market. This would force growers to shift to varieties less susceptible to scab or towards processing varieties. Any reduction in irrigation availability or reduction in rainfall would severely affect the profitability of crops such as Maris Piper and Maris Peer, where skin finish is crucial for packing. Determinate crops, i.e. those that only produce a limited leaf area and have short periods of active root growth are very sensitive to water restriction during the mid-late canopy expansion phase. Current widely-grown examples would include Estima, Lady Rosetta and Saturna. Absence of rain or irrigation during these periods can cause premature senescence with a large yield loss. For this reason, rain-fed or limited irrigation scenarios with these varieties are likely to be reduced for risk of crop failure. However, the yield response to irrigation of many of these varieties is large so they will continue to be grown where irrigation is less limited. Rain-fed areas are likely to shift in the future to varieties that are able to either a) survive early drought periods so that they can use rainfall later in the season (e.g. King Edward, Markies, Russet Burbank or Rooster) or b) partition dry matter towards tuber production during periods of drought rather than canopy production which makes them more efficient in producing yield per unit of water use (e.g. Hermes or Desiree).

Climate change is likely to lead to the dates of the last spring frosts becoming earlier and autumn frosts becoming rarer and/or later, thereby extending the growing season. Planting could therefore take place earlier as the thermal environment experienced by crop canopies would be more favourable than currently. However, soils would still be at field capacity at this time, leading to the same problems in workability that growers currently experience during March and April in many regions of the country. Reduced rainfall and higher temperatures will result in a depletion of organic matter, increasing the risk of structural damage to sensitive soils. The harvesting period (window) would become longer, thereby reducing the risk of adverse soil conditions causing harvesting problems or crop damage.

5.5.2. Adaptation options related to water stress

The results clearly show that growing rain-fed potatoes in England and Wales will become increasingly risky as a result of climate change , and limited to a few favourable areas in the UK. In contrast with irrigation, the land suitability hardly changes and most of the current rain-fed potatoes would remain in their present location if irrigated. Although only around 1% of water abstraction in England and Wales is used for irrigated agriculture, there is limited prospect of the industry obtaining significant additional licensed quantities for the summer months in the face of competing demands (Weatherhead and Howden, 2009). Many of the existing licences are unused or underused (EA, 2010), so water transfers or abstraction

licence trading between farms may be an option, though there are environmental arguments against re-activating “sleeper” licences in water short catchments.
Licences are still available for winter (off-season) abstraction in almost all catchments, and recent years have seen a significant increase in winter-filled on-farm reservoirs for irrigation use in the summer. Though expensive, this gives the grower greater security of supply. It seems likely that this will become the preferred water source for irrigation of potatoes and other high value vegetables in the south and east of England. Tompkins et al (2010) noted that there are still relatively few examples of adaptation to climate change in the UK agricultural sector, and that many apparent adaptive actions have actually been in response to legislative or other pressures, rather than purposeful (deliberate) adaptations to perceived climate change per se; nevertheless they may still be useful climate change adaptations. On-farm reservoirs would appear to fall into this category.

Once irrigation water is assured but expensive, it will become sensible to invest more heavily in water efficiency measures; better application methods, including drip and precision irrigation, and scientific scheduling methods will become standard. Earlier planting and harvesting would reduce water use per unit area, but with some varieties growers might prefer to use the longer growing season to increase yield. There has been a steady increase in average potato yields over the last 40 years; with national consumption roughly constant this has led to a gradually reducing area planted; whether this trend can be intensified and how far it could counteract the increasing water demand is not yet clear.

Previous authors have suggested that irrigated production might move north and west as an adaptation to climate change. Given that most of the current locations remain suited to irrigated production, and that future summer water resources may not be reliable, even where licenses are available at present, this may be a slow process. Many growers have sizeable investment in fixed assets for potato production, and may prefer to remain near the present locations; renting land from nearby farmers with unused or partially used licences may be a preferred way forward.

Outputs are a useful starting point for opening dialogue between the UK potato levy board, the agri-industry it serves and policy makers on adaptation options. Shifts in land-use potential have implications for both strategic resource planning and for developing anticipatory climate change adaptation actions. The land capability assessment highlights not only potential changes in agriculture and other productive land uses, but also repercussions for biodiversity and terrestrial carbon stocks (Brown et al., 2008).

5.6. Methodological limitations

The concept of land suitability for a particular crop is complex. The scheme adopted here assumes good management using appropriate varieties, fertiliser applications, rotations, crop protection, irrigation if needed and drainage measures. Suitability is assessed for sustained production in a rational cropping system (FAO, 1976). From the land manager's perspective, there can be movement between suitability classes if some of these aspects are absent, or applied in either a particularly beneficial or detrimental way, but the current system has no capacity to take this into account (Jones and Thomasson, 1987). Other social and economic factors have been excluded, as have differences in farm size and layout that can also affect cropping preferences and override intrinsic land suitability (Jones and Thomasson, 1987). Furthermore, competition between competing land uses has not been taken into account.

Suitability is based on the average climate for the period 1961-90, average soil property data within soil classes, and the location of PCL potato fields for 2009, which was a relatively dry year. Therefore the results must be interpreted with these limitations in mind, but quartiles and standard deviations for climatic data would allow examination of the effects of extreme conditions on suitability class. However, this is not so readily achievable without significantly enlarging existing soil property databases (in LandIS) and this would be prohibitively expensive.

The main problem for all projections of future land productivity, including the land suitability assessments reported here, is spatial resolution. Crop cover and topographical can usually be spatially resolved to 10 m; but soil data are rarely resolved to closer than 100 m and, for most parts of the UK, data at 1000 m resolution are the norm. Climatic data, although often spatially resolved to 1 km, is based on relatively few fully instrumented recording stations such that the best obtainable resolution is really nearer to 5 km or even 10 km (Thomasson and Jones, 1991).

The land suitability assessment system was designed for application across wide areas and over long periods (seasons) and is not valid for assessment in the short-term (Rounsevell and Jones, 1993). However as currently configured the system provides objective assessments of land suitability based on standard data sets, thus facilitating regional comparisons, and the opportunity for forward strategic planning.

6. CLIMATE IMPACTS ON POTATO WATER DEMAND

6.1. Background

Most potato irrigation is abstracted from rivers and streams, and used direct with relatively little on-farm storage. Weatherhead (2006) reported that half (54%) of all irrigation abstraction in 2005 was from surface sources (rivers, streams). Groundwater (boreholes) accounted for 41%. However, with an increasing dependence on irrigation to attain yield and quality, irrigation of potatoes and other field-scale vegetables is the largest abstractor in some catchments in dry summers and concerns have been raised over the potential impacts on the environment, particularly in catchments where irrigation abstractions are concentrated and where water resources are under pressure (Hess *et al*., 2011). The Environment Agency (EA) has previously assessed the availability of water resources for abstraction, with each catchment defined according to its resource status and allocated to one of four categories, 'water available', 'no water available', 'over-licensed' and 'over-abstracted', in order of increasing water stress (EA, 2005). The spatial distribution of PCL registered potato fields in 2009 has been mapped and compared against resource availability, by catchment using a GIS (Figure 22). The aggregated data by water resource category for irrigated and rainfed potatoes are summarised below in Figure 21.

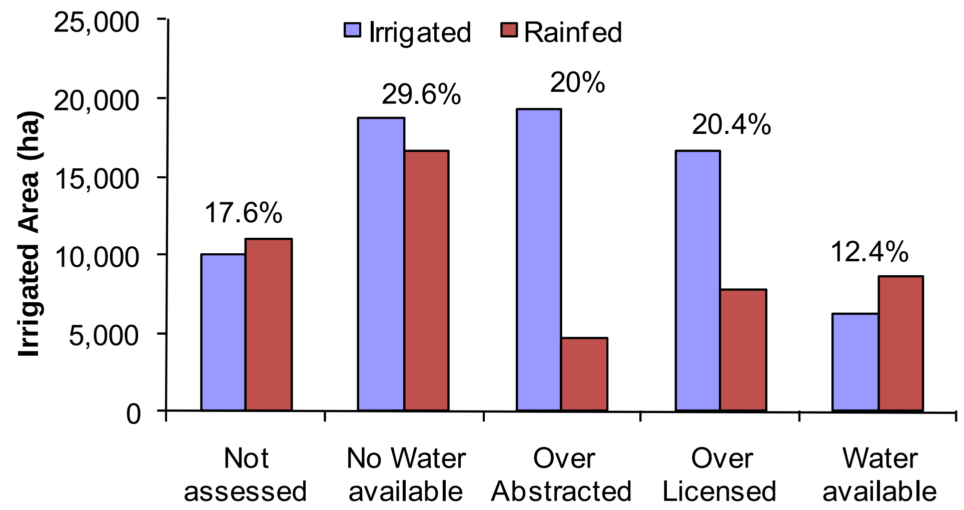


FIGURE **21** AREA (HA) AND PERCENTAGE (%) OF PCL REGISTERED IRRIGATED AND RAINFED POTATO FIELDS IN CATCHMENTS CLASSIFIED BY EA WATER RESOURCES AVAILABILITY (DATA RELATE TO ENGLAND AND WALES FOR 2009).

The analysis shows that 40% of all PCL growers are located in catchments that are currently designated as being either over-licensed and/or over-abstracted. Nearly a third (30%) are in catchments where no (more) water is available at low flows. Only 12% of growers are within catchments where additional water abstraction would be available during summer low-flow periods ("water available"). These figures highlight a serious issue regarding the availability and reliability of future water resources for potato production. The situation is exacerbated by recent projections for future water availability by Arnell and Charlton (2010) which suggests that mean summer flows in the 2030s may be reduced by between 20-30% for many rivers in eastern and southern England. In this context, it is important to know the likely future changes in potato water demand taking into account both climatic changes and a range of alternate socio economic scenarios.

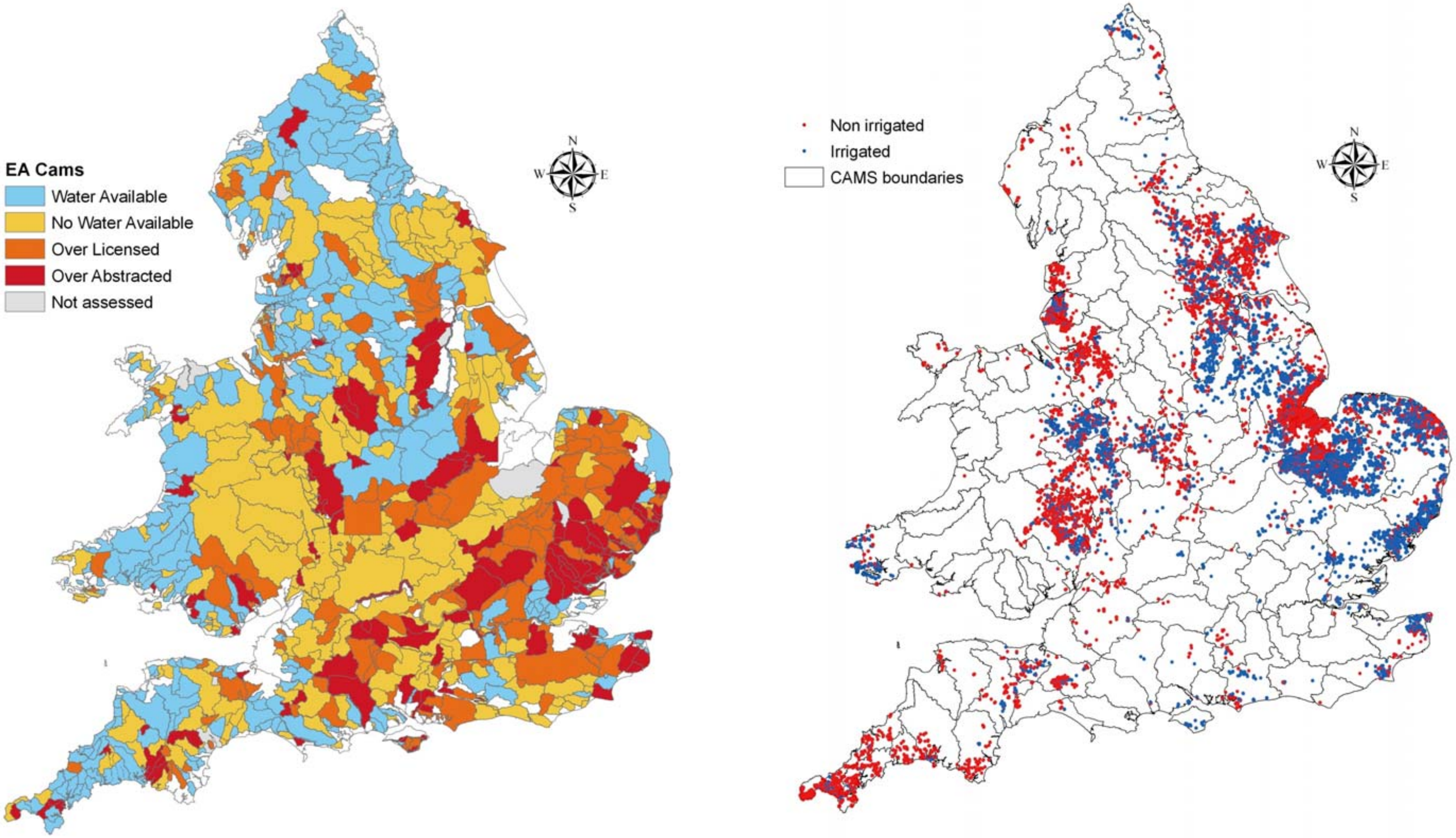


FIGURE 22 SPATIAL DISTRIBUTION OF PCL REGISTERED POTATO FIELDS (PCL, 2009) RELATIVE TO ENVIRONMENT AGENCY DEFINED CATCHMENT LEVEL WATER RESOURCE STRESS.

6.2. Methodology

In 2008 a new set of water demand forecasts were produced for the public water supply, industry and agricultural sectors in England and Wales as part of the Environment Agency's water resources strategy (EA, 2008). For agriculture, that study considered all irrigated crops of which potatoes were one of the eight crop sectors. The climate change impacts were based on the earlier set of projections from the UK Climate Impacts Programme (termed UKCIP02). For agriculture, the future demand forecasts ranged from +25% up to +180% assuming a baseline 'dry year' in 2005. The wide range in future water consumption by agriculture reflected the contrasting assumptions regarding sustainability/consumption and globalisation/regionalisation embedded within the four socio-economic scenarios.
In this project, the methodology developed for the agriculture sector by Weatherhead et al. (2008) for the EA water resource strategy (EA, 2008) was updated to include the latest climate projections (UKCIP09). But the analysis was only applied to potatoes (maincrop and early), rather than all crops, and future demand forecasts then developed for two specific time periods;

1. Short-term (2008 to 2020s) for a 'business as usual' scenario under current economic and water policy conditions, and;
2. Medium to long-term (2050s) for the four previously defined Environment Agency socio-economic scenarios (EA, 2008).

All potato water demand forecasts were for "unconstrained demand in a dry year", i.e. the volume abstractors would take in a dry year assuming water was available under conditions similar to the baseline (defined here as 2005). In reality, actual future water use is likely to be constrained by future water availability and allocation policy, which may also lead to a relocation of potato water demand, depending on where water resources are under pressure relative to the location of potato cropping. The demand forecasts were for England and Wales, then regionalised to EA Demand Forecast Areas (DFAs), which differ slightly from the more commonly used EA Regions (Figure 23). These DFAs correspond to the Water Framework Directive (WFD) river basins. The approach combined literature review with extensive computer modelling, GIS mapping, and a workshop with key informants to discuss the socio-economic scenarios (conducted as part of the previous EA demand forecast study). A brief overview of each stage is given below.

6.2.1. Defining a baseline

Future changes in irrigation water demand need to be made relative to a reference or 'baseline' year. This was defined as the unconstrained volumetric irrigation water demand if a 'design' dry year (80th centile) had occurred in 2005 (not the actual water use in 2005). The year 2005 was chosen as it was a dry year in irrigation terms and coincided with the most recent Defra Irrigation Survey. Information on the individual micro-components of irrigation demand were analysed in a GIS to estimate the 2005 baseline irrigation water use for each DFA, for both early and main crop potatoes. Spatial datasets on potato cropping were obtained from EDINA, the JISC national academic data centre based at the University of Edinburgh, based on the Defra Agricultural Cropping Census and PCL cropping data. Data on potato irrigated areas and water use were obtained from the 2005 Irrigation Survey (Weatherhead, 2006). The actual reported values were converted to equivalent 'dry year' values using relationships derived from the 7 previous irrigation surveys (1982 and 2005).

The 2005 crop areas were based Defra/Edina data, reanalysed by GIS at DFA level. The split between early and main crop potatoes was based on the ratio for irrigated crops. The 2005 dry year irrigated areas were based on the 2005 Irrigation Survey, reanalysed by GIS at DFA level, and corrected to dry year values using national level ratios. The 2005 dry year water applied values were based on the 2005 Irrigation Survey, reanalysed by GIS at DFA level, and corrected to dry year values using national level relationships based on multiple regression over the 7 Irrigation Surveys between 1982 and 2005. The percentage of the crop irrigated and the depths applied, both for a dry year, were calculated from the data above. The weighted dry year optimum demands were calculated from a GIS analysis of present dry year PSMD values at DFA level, weighted to crop location as given to the EDINA data, and converted to crop needs using previously established relationships. The ratios of economic to agronomic demand in a dry year were taken from relationships previously established at national level. The ratios of average applied to weighted economic demand were calculated from the above data. The assumed dry year efficiencies were taken from previous estimates.

FIGURE 23 ENVIRONMENT AGENCY DEFINED WATER DEMAND FORECAST AREAS (DFA).

Early potatoes	ha	ha	'000 m3	%	mm	mm	%	mm
DFA	Cropped area	Irrigated area	Water applied	Propn irrigated	Ave depth applied	Weighted OWU	Weighted ratio	Ave applied/weighted
Northumbria	79	14	16	18%	114	92	95	130
North West	2034	200	64	10%	32	91	95	37
Humber (north)	705	334	131	47%	39	98	95	42
Humber (south)	905	563	778	62%	138	102	95	142
Anglian	6545	5125	6181	78%	121	115	95	110
Severn (England)	2567	863	1065	34%	123	105	95	123
Thames	786	495	691	63%	140	113	95	130
South East	412	286	166	69%	58	112	95	54
South West	1799	172	111	10%	65	99	95	69
Total	15832	8052	9203	51%	114			

Maincrop potatoes	ha	ha	'000 m3	%	mm	mm	%	mm
DFA	Cropped area	Irrigated area	Water applied	Propn irrigated	Ave depth applied	Weighted OWU	Weighted ratio	Ave applied/weighted
Northumbria	1867	289	274	15%	95	152	100	63
North West	6753	568	297	8%	52	153	100	34
Humber (north)	13035	5273	4778	40%	91	172	100	53
Humber (south)	8928	4752	7775	53%	164	187	100	87
Anglian	43726	29265	41225	67%	141	221	100	64
Severn (England)	12734	3660	3704	29%	101	195	100	52
Thames	909	489	420	54%	86	216	100	40
South East	2807	1665	2354	59%	141	212	100	67
South West	4037	330	105	8%	32	174	100	18
Total	94796	46291	60932	49%	132			

TABLE 10 DATA USED FOR EARLY AND MAINCROP POTATOES FOR THE 2005 BASELINE.

6.2.2. Modelling short term future demand (2020s)

For the short term projections, a baseline extrapolation based on recent underlying trends was developed. Trends in cropped areas were obtained from the Defra Agricultural Survey statistics for 1983 to 2005. Trends in irrigated areas and volumes applied were obtained from the Defra Irrigation Surveys from 1982 to 2005. Changes in the optimum irrigation needs due to climate change were obtained by analysing the UKCP09 impacts on potential soil moisture deficit (PSMD), aggregated to DFA level, then weighted to the location of the potato crop in 2005 according to the EDINA data.

The base year datasets and derived trends were then used to parameterise an adapted version of Irrigrowth, an irrigation water demand forecasting model developed by Weatherhead *et al* (2000) which has been used for previous EA and Defra water demand forecasting studies. Irrigrowth allows for the spatial variability in cropping, soils, agro-climate and irrigation practices between regions (DFAs in this case), to predict volumetric water demand for a range of alternative scenarios, either with or without climate change impacts. The model can combine the baseline data with factors such as the rates of changes in the total areas of each crop type being grown, the likelihood of it being irrigated, the relationships between optimum (agronomic) demand and economic demand, projected irrigation efficiencies, and the likely proportions of the gross economic demand that the average irrigator will want and be able to apply, i.e. the actual demand. The model then calculates the 'dry year' water demand for potatoes for each year based on these assumptions.

Variable	Earlies	Maincrop
Crop area changes (as % pa) Constants used a linear growth factors on 2001 values, for all climates		
Baseline	- 1.2%	- 1.2%
Irrigated changes (as % pa) Constants used to calculate asymptotic rate of change towards 100% or 0% irrigated, for all climates		
Baseline (82-05 trend)	+ 1.50	+ 4.28
Depth applied changes (as % pa) Constants used to calculate asymptotic rate of change towards economic optimum (+) or zero application (-). Note if growth in +ve the depth already exceeds economic optimum, depth is held constant		
Baseline (82-05 trend)	+ 2.05	+ 1.61
Optimum demands Varies by Region and with climate change – see separate sheet		
2025 weighted ratio economic/optimum demand factors (%) A linear change between 2001 and 2025 baseline value is assumed until another scenario starts, followed by a linear change from there to the selected scenarios 2025 value, then constant to 2050		
cf 2005 value	95	100
Baseline 2025 value	95	100
2025 target efficiencies A linear change between 2001 and 2025 baseline value is assumed until another scenario starts, followed by a linear change from there to the selected scenarios 2025 value, then constant to 2050		
cf 2005 value	72	82
Baseline 2025 value	80	85

TABLE 11 TRENDS USED FOR THE BASELINE 2005 TO 2020 PROJECTION.

It must be noted that the baseline results obtained depend on which trends are modelled. For the baseline results presented here, the irrigated area was taken as the product of the area grown and the proportion irrigated, and based on those two trends. If the proportion irrigated approaches 100% (or 0%), then that trend must slow, and further changes depend solely on the total area of the crop. The alternative approach is to consider the irrigated crop as a separate crop, and simply project the trend in the total area of irrigated crop. This growth could then continue irrespective of changes in the un-irrigated crop area.

6.2.3. Modelling long term future demand (2050s)

The Environment Agency previously defined 4 socio economic scenarios, termed 'Alchemy', 'Jeopardy', 'Survivor' and 'Restoration' (Burdett *et al*., 2006). These provide a qualitative description of how key water users might respond to policy drivers, subject to meeting national food requirements. The main points extracted from published documents, at scenario development workshops, from discussions with Agency staff and, and our understanding of their implications for the UK irrigated agriculture (including potatoes highlighted in grey) sector by 2050, are summarised below.

6.2.3.1. Alchemy scenario

'Alchemy' is a scenario with a highly technology and knowledge-led UK, with the public continuing to consume in a relatively resource intensive manner. A significant population growth (+37% by 2050) requires significantly more food, while higher affluence has led to a demand for high quality foods. However, consumers are happy to accept intensive production methods, high fertilizer use, GM and other new technologies. Supply-side measures are the key focus in meeting demand. Nuclear and renewable power provides relatively cheap fertilizer. Scientific advances have led to very significant yield increases under highly controlled intensive production systems. Agriculture has polarised between hobby and specialist farms and large very technologically advanced agri-businesses. On-farm reservoir storage from high flow abstraction, better aquifer modelling and monitoring, and advances in environmental sciences allow higher overall agricultural abstraction within the constraints of environmental protection.

There is a significant reduction in the area of potatoes cropped despite population growth, due to a slight reduction in consumption per capita, and a very substantial increase in yield. Most is now grown under intensive conditions by large agri-business; a very high proportion is irrigated and scheduled for high yield under a drier climate. Overall the water demand for potato irrigation therefore increases slowly.

Demand for horticultural crops increases significantly due to higher per capita consumption and population growth, but is again offset by substantial yield increases. Again, most of this area is grown under intensive conditions by large agri-business; a much higher proportion is irrigated than now and scheduled for high yield under a drier climate. Overall the water demand for horticulture increases substantially. Despite a significant decrease in the area of arable crops, due to substantially higher cereal yields and the end of support for sugar beet production, a much higher proportion is irrigated than at present, particularly where grown in rotations with other irrigated crops. There is little overall change in the areas of grass and other food crops, but again significantly more is irrigated due to climate change. However, under this technology-led scenario there is a very significant growth in new non-food crops, for oils, pharmaceuticals, cosmetics etc. These are often very high value and fully irrigated. From the negligible present demand, these become one of the significant water demands. In contrast, biofuels are grown in the wetter parts of the UK, as biomass for burning, but are low value and not irrigated.

6.2.3.2. Jeopardy scenario

'Jeopardy' is a consumption based scenario, but with an uneven spread across society, with a relatively small and very affluent wealthy class and a significant deprived sector. This division is reflected in diets and attitudes to quality and variety of foodstuffs. There is no significant change in overall food demand other than to supply the very substantial population increase (+46%). However, food is imported where it's cheaper than growing in the UK. The rich are concerned about food miles (perhaps because it's fashionable) and many demand organic produce. The poor often eat lower quality food (e.g. higher yielding but lower taste varieties of potatoes and vegetables, poor skin finish) and food in-season. Home grown vegetables are common – the rich as a hobby and for variety but the poor for economy. Meanwhile intensive agriculture grows to meet the bulk demand.

The overall potato area increases slightly due to the high population growth despite some yield increases and imports, with high yield, low quality, partly irrigated crops grown for the poor but some intensively irrigated specialty potatoes for the rich. With climate change, more water has to be applied and water demand increases substantially.

There is little change in overall horticultural consumption per capita, but the population pressure leads to larger areas cropped, and, with climate change, a higher proportion irrigated and greater depths applied, leading to a substantial increases in water demand. There are similar substantial increases in water demand for new food crops and non-food crops, driven by the up-market sector for the wealthy. Some biofuels are grown as biomass for burning, but are lower priority than food production and not irrigated.

6.2.3.3. Restoration scenario

'Restoration' features a society more concerned with the environment than increased consumption. Consumers want naturally grown, sustainable food. Organic food and free range becomes more normal. Farming becomes more extensive, non-organic fertilizers are expensive and yields drop. There is high concern for water application efficiency and low wastage, but efficiency falls in terms of productivity per unit of water – 'crop per drop' - due to the lower yields.

Although population growth is only moderate (+23% by 2050), this leads to significantly larger land areas under potatoes, horticulture and arable crops. The proportions irrigated decline slowly, and climate change is partly moderated by relocating crops. Nevertheless, the increased areas and the impacts of climate change result in significant increases in water use on potatoes and horticulture. There are some new food crops and non-food crops, including some that need irrigating, due to climate change, but this remains a relatively small sector. Biofuels are widely grown as biomass for burning, but are not irrigated due to environmental sustainability concerns.

6.2.3.4. Survivor scenario

The 'Survivor' scenario features low resource consumption and local food production using green or traditional technologies, with lower yields and less emphasis on quality. Diets tend to more vegetables and less meat. Population growth is modest (+19% by 2050) but the decline in imports and low yields results in significantly more land being cultivated where suitable; livestock becomes restricted to lower value soils in the wetter parts of the country. There is very little emphasis on GM products (even if accepted) and new technologies due to the lack of past investment.

There are larger areas under potato irrigation than now, but often in small units on family farms. Without the driver for quality, much is only irrigated to protect yield or not irrigated at all. The slight increase in water demand mainly reflects climate change impacts.

The horticultural area increases, but with an emphasis on growing vegetables that do not need intensive irrigation and an attempt to adapt cropping to climate change, leading to only a modest increase in water demand. Water demand in the arable sector declines as the irrigation of sugar beet and cereals becomes less economic. Similarly, there is a little demand to irrigate grass intensively, and there is relatively little development of new crops, either for food or non-food purposes, and mostly they are not irrigated, leaving only a slight rise due to climate change. Biofuels are widely grown as biomass for burning, but are low value and not irrigated.

6.2.3.5. Modelling future demand for each scenario

To suit the data available from these socio economic scenarios, an approach was developed based on estimating for each the change in national irrigated areas needed (based on changes in population, consumption per head, the proportion home-grown, the proportion irrigated and the yield) and the changes in the depth of water that would be applied in a dry year (Table 12).

Factor	Alchemy	Jeopardy	Restoration	Survivor	Comment
Population change	1.37	1.46	1.23	1.19	Project forecasts
Consumption per head	0.90	1.00	1.10	1.20	Declining slowly (down 25% in 20 years?)
Proportion grown in UK	0.90	0.90	1.05	1.05	High but declining slowly (90% in 1996-98, 85% in 2005, 79% in 2007)
1/yield	0.50	0.80	1.10	0.90	Yields have historically been growing slowly
Derived change in crop area	0.55	1.05	1.56	1.35	
Proportion of crop irrigated	1.40	1.20	0.90	0.80	Growing @c50-60% (more if calculated by yield or value)
Derived change in irrigated area	0.78	1.26	1.41	1.08	
Optimum water use	1.30	1.40	1.20	1.40	+50-70% due to ET&P, but reduced by higher CO_2 and crop movement
Proportion of optimum applied	1.30	1.10	1.00	0.90	Depends on target market, farm size and technology
Overall change in water use	1.31	1.94	1.69	1.36	

TABLE 12 DERIVED 'CHANGE FACTORS' FOR POTATOES COMPARED TO PRESENT (BASELINE) VALUES

For simplicity, constant annual change factors (compound) were assumed over the period modelled. These national change factors were multiplied by the regional climate change factors for early and maincrop potatoes and applied to the 2005 crop production data for each region. Using a GIS, these rates of change were applied to PCL cropping data, and datasets relating to agroclimate, and optimum water use. The results are summarised below.

6.3. Results

A summary of the current underlying trends, and demand forecast projections for the short term (2020s) and long term (2050s) are summarised below.

6.3.1. Current underlying trends

The trends in total cropped areas, for all potatoes (early and maincrop) were calculated from the Defra Agricultural Census data at national level. Figure 24 shows the potato crop trend over the period 1983 to 2010, at national level. A distinct break occurs around 1996, and trends have changed again recently following the recent increases in crop prices and energy costs. However, the underlying trend over the full time period was used in this study to match the irrigation survey data.

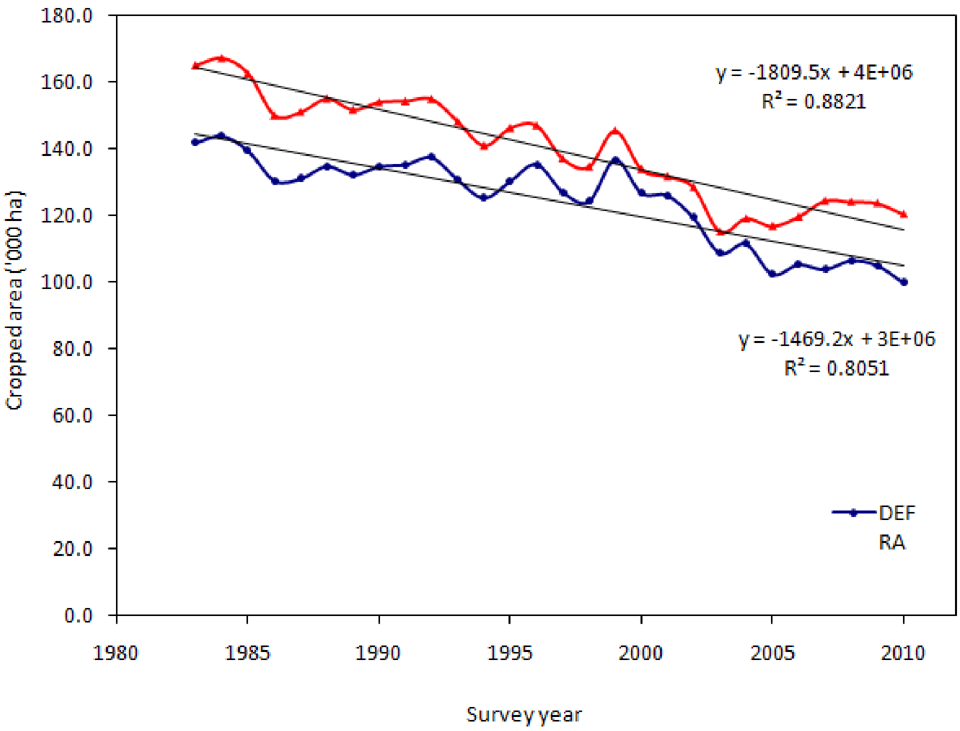


FIGURE 24 POTATO CROPPED AREA (000 HA) TRENDS FROM 1983 TO 2010 FOR THE UK (RED) AND ENGLAND AND WALES (BLUE). BASED ON PCL DATA AND DEFRA CROPPING CENSUS DATA.

The trends in dry year irrigated area, volumes applied and average depths for early and maincrop potatoes (Table 13) were obtained from the MAFF/Defra Irrigation Surveys from 1982 to 2005, based on regression analysis of the recorded values against a climatic indicator and year, for each crop at national (England) level (Weatherhead, 2006). The trend in the percentage of each crop irrigated was calculated by combining these trends. Where appropriate, the Irrigrowth model assumed these trends are exponential towards a natural limit, e.g. 0% irrigated or 100% irrigated.

Crop type	Linear growth trend (1982-2005)		
	Irrigated area	Volume water applied	Average depth applied
Early potatoes	0.3%	2.1%	2.1%
Maincrop potatoes	3.0%	3.5%	1.6%
Total (overall)	0.9%	2.1%	1.7%

Table 13 Underlying linear growth rates (% per annum) in the area irrigated, volume of water applied and average depth applied, for early and maincrop potatoes (and overall) based on 1982-2005, after allowing for annual weather variation (derived from Weatherhead, 2006).

The changes in optimum demand due to climate change were obtained by analysing the crop needs under future PSMDs obtained from the UKCP09 climatology for the 2020s and 2050s. It was assumed for the baseline modelling that the change in CO2 concentration levels would have negligible net impact, the values used in the baseline modelling are summarised in Table 11.

6.3.2. Short term demand forecast (up to the 2020s)

The outputs from the Irrigrowth model for the short term demand forecasts (up to 2020s) are summarised in Table 14.

Year	No climate change	2020 Low emissions	2020 High emissions
2005	70134 (00%)	70134 (00%)	70134 (00%)
2010	82496 (18%)	85280 (22%)	85758 (22%)
2015	90238 (29%)	96347 (37%)	97398 (39%)
2020	94628 (35%)	104256 (49%)	105916 (51%)

Table 14 Short-term demand forecasts (Mm3) from the baseline (2005) for total potatoes (early and maincrop) assuming no climate change, and a 2020s low and 2020s high emissions scenario. Percentage change from the baseline shown in parentheses.

These demand forecasts were set against a range of possible water policy scenarios intended to manage this future demand from agriculture sustainably:

Promoting increased water efficiency Increasing the “efficiency” of all irrigation, say by reducing water use by 10% without impacting yield or crop quality, if feasible, would reduce all demand proportionately, easing some of the constraints on farmers and/or allowing the EA to limit abstraction. The route to higher efficiency is most likely to include a further switch to modern application technology, (e.g. trickle irrigation, automated solid-set sprinklers, intelligent mobile booms or guns) in appropriate (but not all) situations, and improved scheduling systems and management. The geographical disparity in demand growth and between different crop types emphasises that increased efficiency is more important in some areas than others, and that any policy to promote water efficiency should be appropriately targeted for greatest benefit.

Promote abstraction licence trading Trading will only occur where supplies are constrained, therefore an increase in trading will not in itself alter the unconstrained demand. However, it could help to reduce actual shortages by allowing a higher proportion of the licensed water to be abstracted (subject to environmental constraints), and help society obtain a higher benefit from the water through transfer to higher value users. Since trading is likely to be restricted within hydrological units, it would not alter the location of demand, but might allow irrigators to grow particular crops in more favourable locations (climate, soils, markets) rather than moving to where water is available without trading.

Promote high flow storage Increased on-farm storage would allow more of the water to be abstracted at times of high flow (winter), reducing the impacts of irrigation abstraction at times of major resource constraint. Due to reservoir losses through leakage and evaporation, this policy may actually cause a small increase in total abstraction, but this will be abstraction at times of high flow. Furthermore, storage will help spread out the peaked abstraction in dry years – in most years reservoirs carry water over into the next year. Most reservoirs are likely to be built in areas where water resources are already constrained and where the benefits of irrigation are highest, typically for irrigating high value crops in the south and east England. If summer licences have to be surrendered, the water constraints will remain while the abstraction impacts will be reduced. If the winter licences are additional to existing summer licences, the reservoir size and cost will be reduced but there will be less reduction of summer abstraction; however the existence of storage will reduce the costs of imposing summer restrictions, and would allow the EA to manage supplies more effectively.

Influence food quality expectations Much of the current demand for irrigation water is reportedly due to the demand for high quality skin finish on potatoes, and potatoes remain the dominant water user into the future, suggesting that a policy of influencing consumers might be pursued. Beyond about 2020, vegetables become an increasingly important growth sector.

6.3.3. Long term demand forecast (up to the 2050s)

A summary of the projected increases in volumetric water demand for potatoes in England and Wales from the modelled baseline to the 2050s under each EA defined socio-economic scenario is summarised below in Table 15.

Time period	Socio economic scenario			
	Alchemy	Jeopardy	Restoration	Survivor
Baseline (Mm3)	70134	70134	70134	70134
2050 low (%)	+ 25.5	+ 72.5	+ 74.9	+ 20.8
2050 high (%)	+ 33.3	+ 83.2	+ 85.8	+ 28.4
Average (%)	+ 29.4	+ 77.9	+ 80.3	+ 24.6

TABLE 15 PROJECTED INCREASES VOLUMETRIC IRRIGATION DEMAND (%) FOR POTATOES (EARLY AND MAINCROP) FROM THE BASELINE (2005) TO THE 2050S UKCP09 LOW AND HIGH EMISSIONS SCENARIO, FOR EACH EA DEFINED SOCIO-ECONOMIC SCENARIO.

The modelling suggests water demand increases of between 25% and 80% depending on socio-economic scenario. ‘Alchemy’ results in a c30% increase, but with abstraction constrained by environmental limits; ‘Jeopardy’ results in a c78% increase, largely in response to the increased population food requirements; ‘Restoration’ similarly results in a c80% increase but with larger depths applied to significantly larger potato cropped areas, despite the scenario emphasis on ‘efficiency’. The ‘Survivor’ scenario shows the lowest increase (c25%) as the population begins to accept lower quality and locally sourced produce. There is of course a high degree of uncertainty associated with projecting potato water demands into the 2050s, so the values presented above should be interpreted with caution – instead it is suggested they are used to demonstrate the effects of the assumptions embedded within the scenarios, rather than necessarily to infer trends in future water demand per se. They do, however, demonstrate the sensitivity of policies to promote either consumerism or sustainability, their consequent effects on potato production and consumption and hence water demand. These projections presented here are broadly similar to those reported by Weatherhead and Knox (2008), with the main differences attributed to the use of UKCP09 rather than the earlier UKCIP02 climatology. These projections also of course ignore any impacts of potato new cultivars, genetic improvements, and the effects of elevated CO2 on water demand, many of which could significantly reduce future potato water demand. The modelling described above was also applied spatially using a GIS, to show the projected future changes in potato water demand, by EA catchment from the baseline (Figure 25) for each socio-economic scenario (Figure 26).

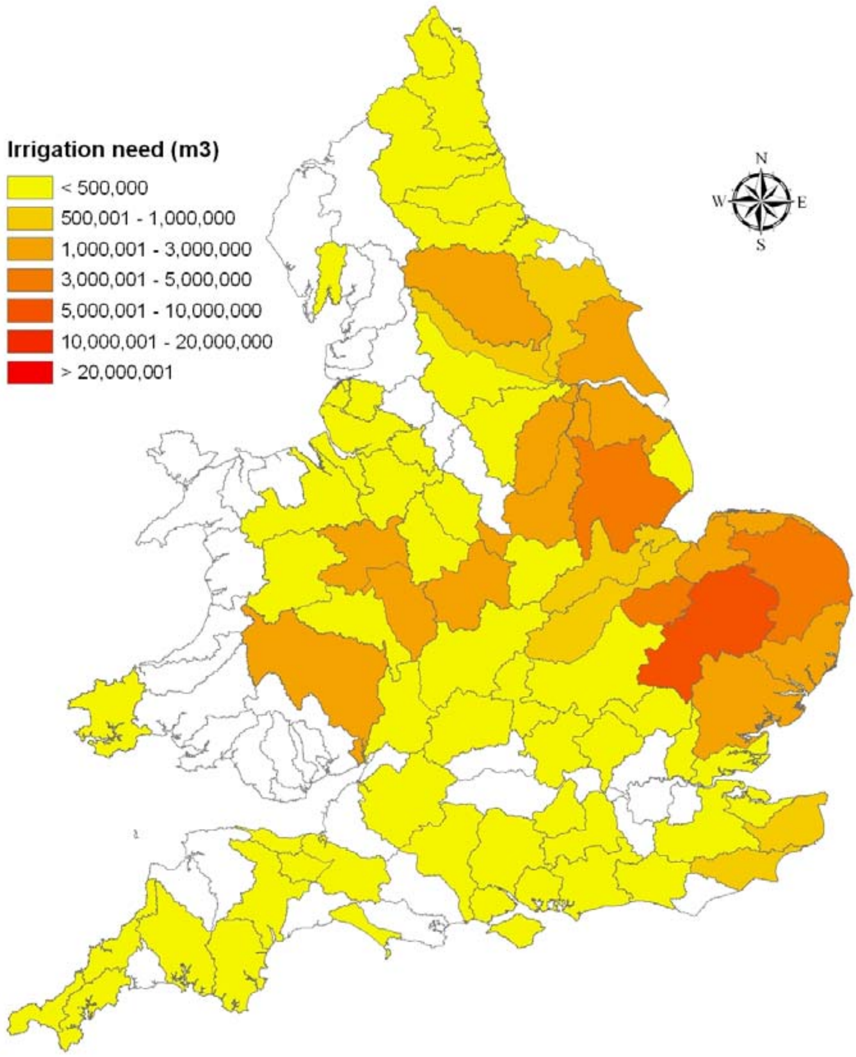


FIGURE 25 BASELINE VOLUMETRIC DEMAND FOR POTATO IRRIGATION BY EA CAMS.

For the baseline, as expected, the areas of highest water demand (modelled) for potato production are located in EA Anglian region, including the Cam and Ely Ouse, Broadland Rivers, Witham, Louth, East Suffolk, and Combined Essex CAMS catchments. In the Midlands region, the Severn, Wye, Worcestershire Middle Severn, Weaver and Dane, and Tame, Anker and Mease CAMS catchments also have significant potato water demand and the North East, the Hull and East Ridings and Swale, Ure, Nidd and Upper Ouse catchments are important for potato production.
For the 2050's, the spatial distribution of water demand remains similar, although the projected demands rise significantly.

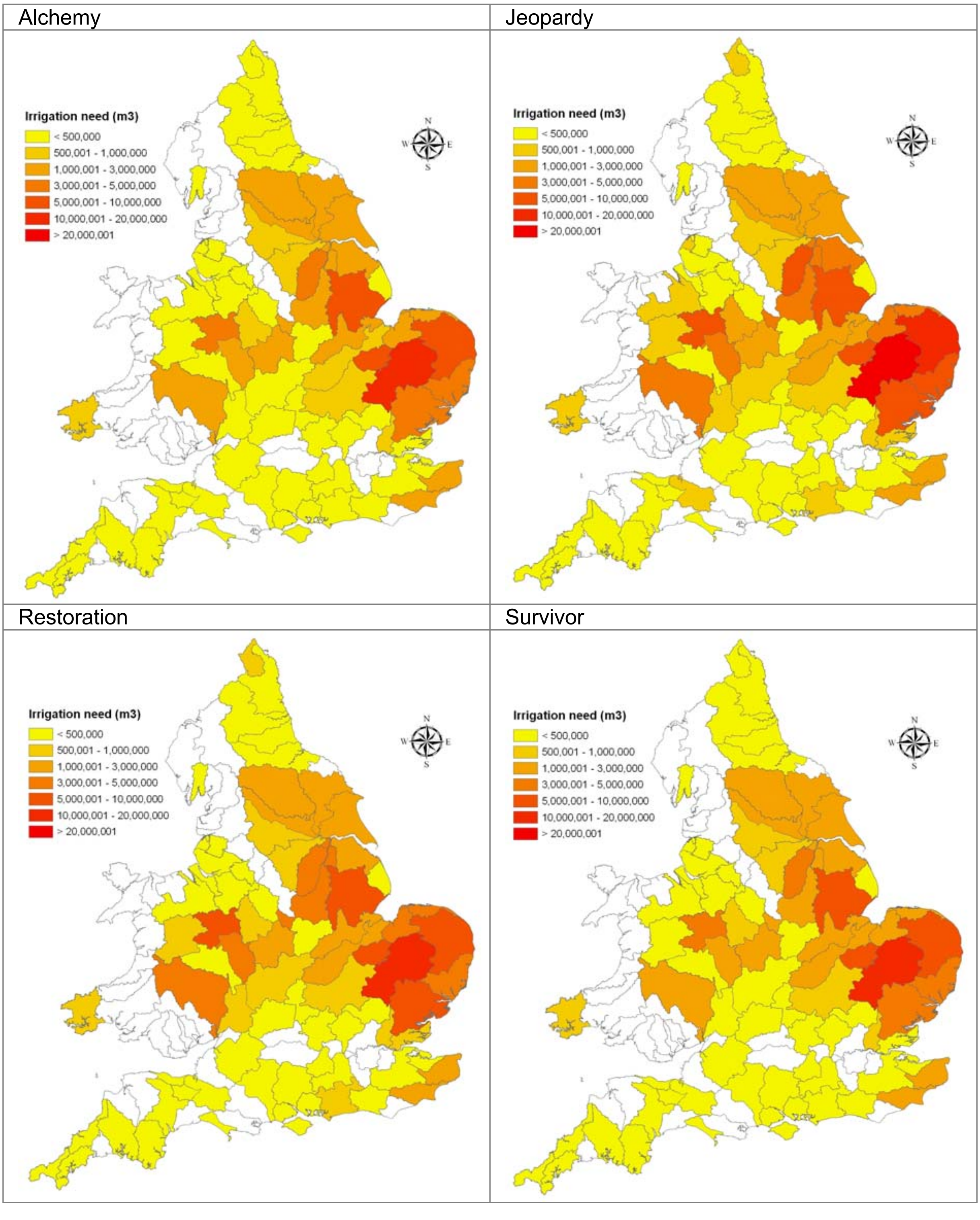


FIGURE 26 PROJECTED FUTURE VOLUMETRIC DEMAND FOR POTATO IRRIGATION FOR THE 2050S LOW UKCP09 EMISSIONS SCENARIOS., FOR EACH EA DEFINED SOCIO ECONOMIC SCENARIO.

7. SYNTHESIS AND CONCLUSIONS

The key findings arising from the research, and the implications for potato growers regarding climate change adaptation are summarised below.

7.1. Potato yield and water use

The impacts of climate change on the yield (t ha-1) and irrigation needs (mm) of a pre-pack variety cv. Maris Piper were assessed by combining the outputs from the latest UK scenarios of climate change (UKCP09) with a potato crop growth model (SUBSTOR–Potato) for a historical baseline and then for selected emissions scenario for the 2050s. The crop model was validated using experimental and field data from four reference sites (CUF and three farms in Norfolk, Lincolnshire and Suffolk). Assuming crop husbandry factors are unchanged, farm yields would show 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, were projected to increase by 13-16%, mainly due to increased temperatures, radiation and CO_2 fertilisation effects. Future average irrigation needs, assuming unconstrained water availability, were predicted to increase by 14-30%, depending on the emissions scenario. A probabilistic distribution function was derived to assess the uncertainty in the projected irrigation needs. Current irrigation schemes and infrastructure are typically designed to satisfy irrigation needs in the 5th driest year in 20 (i.e. with an 80% probability of non-exceedance). However, the analyses have shown that future peak irrigation needs might exceed this current design criteria in nearly 50% of future years. Growers should consider these potential consequences carefully when planning investments in irrigation technology (application equipment) and water resources (e.g. winter storage) to ensure future potato yields and quality are not compromised.

As with all climate change impact assessments, the results need to be interpreted with caution. The crop modelling assumed unchanged farm practices in the future, but in reality there would be some degree of autonomous adaptation even if not planned adaptation. For potatoes, this could include earlier planting and harvest dates, changing to better adapted varieties, less dependence on soils with low water holding capacities, crop movement to regions with suitable agroclimate and water availability, and the uptake of GM technology.

7.2. Land suitability and crop husbandry

The commercial viability of potato production is influenced by the spatial and temporal variability in soils and agroclimate, and availability of water resources where supplemental irrigation is required. Knowledge of potential changes in land suitability is a key determinant influencing the sustainability of potato farming enterprises, as any future changes will influence cultivar choice, agronomic husbandry practices and the economics of production, for both rainfed and irrigated cropping. The current land suitability for maincrop potato production was initially modelled and mapped using a set of pedo-climate transfer functions and a geographical information system (GIS). This provided a reference or 'baseline' from which the derived land suitability classes could be checked against observed data (PCL 2009) on the distribution of potato cropping (rain-fed and irrigated production). The projected future changes in land suitability were then modelled using the UKCP09 climatology for selected emissions scenarios (2050s and 2080s). A comparison with the baseline showed how the land suitability classes (well, moderate, marginal, unsuited) shift in the future due to the changing patterns of rainfall, temperature and other agroclimatic variables, and hence on current centres of potato production. Finally, the relationships between land suitability and water resource availability were assessed to identify where future irrigated production might be at risk and whether production might need to relocate to catchments where water resources are less constrained, or adapt to changing water reliability. From this, the implications on the potato industry were assessed, including where rain-fed production could become limiting, what varieties are likely to be most/least suited to the changes in land suitability, and the adaptation options for growers (e.g. shifting production, new soil management techniques, drainage, new irrigation infrastructure, etc).

The analyses show that the locations of rainfed production (based on PCL data for 2009) are very closely related to the ‘theoretical’ assessment of land suitability for rainfed potatoes. The majority of rain-fed potatoes are located on well (24%) and moderately suited (41%) lands as these guarantee commercially acceptable levels of production. Irrigated potatoes are concentrated on moderate (57%) and marginally (37%) suited lands as supplemental irrigation overcomes the risks associated with droughtiness. However, with climate change, the analyses suggest that by the 2050s, for the most likely probability (50%), the area of land that is currently well to moderately suited for rain-fed production is expected to decline significantly (74-95%) owing to increased droughtiness. But as with the impact modelling on potato yield, there is an inherent level of uncertainty around these median value climate projections, but the direction and magnitude of change is clear.

Regarding land suitability and water resources, for the baseline, the analysis shows approximately a third (34%) of growers involved in irrigated production are on moderate land and two thirds (59%) are on marginal land, and that 41% of these are located within catchments defined as being under water stress (over abstracted and/or over-licensed). By the 2050s, if the spatial distribution of growers remained unchanged, then the majority of irrigated production (87%) would be on marginal land, with 43% located in catchments defined as being either over-licensed and/or over-abstracted. Clearly, this situation would be unsustainable, particularly since the analysis assumed no change in future water resource availability, which itself is projected to worsen significantly.

The results show that growing rainfed potatoes in England and Wales will become increasingly risky as the climate changes, and limited to a few favourable areas. In contrast, with irrigation, the land suitability hardly changes, and most of the current rainfed crop could remain at its present location if irrigated. Although only around 1% of water abstraction in England and Wales is used for irrigated agriculture, there is limited prospect of the industry obtaining significant additional licensed quantities for the summer months in the face of competing demands. Many existing licences are unused or underused so some farm of water transfers or abstraction license trading may be an option, though there are environmental arguments against re-activating ‘sleeper’ licences in water short catchments. Previous research has suggested that irrigated potato production might move north and west as an adaptation to climate change. Given that most of the current locations remain suited to irrigated production, and that future summer water resources may not be reliable even where licenses are available at present, this may be a slow process. Many growers have sizeable investment in fixed assets for potato production, and may prefer to remain near their present locations, renting land from nearby farmers with unused or partially used licences as a preferred adaptation response.

Where irrigation is restricted during crucial times (e.g. during scab control), tuber quality can suffer to the extent that certain varieties would be rejected. This would force a shift to those that are less susceptible or towards processing varieties. Any reduction in irrigation availability or reduction in rainfall would severely affect the profitability of crops such as Maris Piper and Maris Peer, where skin finish is crucial for packing. Determinate crops, i.e. those that only produce a limited leaf area and have short periods of active root growth are very sensitive to water restriction during the mid-late canopy expansion phase. Current widely-grown examples include Estima, Lady Rosetta and Saturna. Absence of rain or irrigation during these periods can cause premature senescence with a large yield loss. For this reason, rain-fed or limited irrigation scenarios with these varieties are likely to be reduced for risk of crop failure. However, the yield response to irrigation of many of these varieties is large, so they will continue to be grown where irrigation is less limited. There will be a shift in un-irrigated areas to varieties that are able to either a) survive early drought periods so that they can use rainfall later in the season (e.g. King Edward, Markies, Russet Burbank or Rooster) or b) partition dry matter towards tuber production during periods of drought rather than canopy production so that they become more efficient at producing yield per unit of water use (e.g. Hermes or Desiree).

Finally, climate change is likely to lead to the dates of the last spring frosts becoming earlier and autumn frosts becoming rarer and/or later, thereby extending the growing season. Planting could therefore take place earlier as the thermal environment experienced by crop canopies would be more favourable. However, soils would still be at field capacity, leading to the same problems in workability that growers currently experience during March and April in many regions of the country. Reduced rainfall and higher temperatures will result in a depletion of organic matter, increasing the risk of structural damage to sensitive soils. Harvesting windows would become longer, thereby reducing the risk of adverse soil conditions causing harvesting problems or crop damage.

7.3. Water resources and irrigation water demand

In 2005, irrigated potatoes accounted for nearly half (43%) the total national irrigated area and 56% of the total volume of irrigation water applied in agriculture. For many agribusinesses, irrigated potato production is driving force behind farm investment, but competition between water sectors, coupled with increasing environmental regulation and the longer-term threat of climate change are limiting water supplies for irrigation. In 2008, demand forecasts for the Environment Agency’s water resource strategy suggested increases in total irrigation demand of between 25% and 180%. This wide range reflected the contrasting effects of differing assumptions regarding sustainability, consumption, globalisation and regionalisation embedded within the socio-economic scenarios. In this study, the methodology developed by Weatherhead *et al* (2008) for the EA was updated to include the latest climate projections (UKCIP09). Demand forecasts were produced for two periods; (i) the short-term (up to 2020s) for a ‘business as usual’ scenario under current economic and water policy conditions, and (ii) the medium to long-term (2050s) for four socio-economic scenarios. All potato demand forecasts were for ‘unconstrained demand in a dry year’, i.e. the volume abstractors would take in a dry year assuming water was available under conditions similar to the baseline (2005). In reality, actual future water use would be constrained by future water availability and allocation policy, which may also lead to a relocation of potato water demand, depending on where water resources are under pressure relative to the location of potato cropping. The demand forecasts were modelled at catchment level for England and Wales, then regionalised to EA Demand

Forecast Areas (DFAs), which correspond to the EU Water Framework Directive (WFD) river basins.

For the short term projections, a baseline extrapolation based on underlying trends in cropped and irrigated areas was developed, using national cropping and irrigation statistics for 1982-2005. This involved analysing the underlying growth rates in the areas irrigated, volumes and depths applied as linear functions over time after allowing for the annual weather variation, using multiple regression techniques. The analyses showed an underlying linear growth rates of 3.0% and 3.5% per annum for the irrigated area and volume of water applied for maincrop potatoes, respectively. The equivalent figures for early potatoes were 0.3% and 2.1%. The Irrigrowth model was then used to extrapolate these underlying rates forward to the 2020s. The projected mean increases in potato irrigation demand from the baseline (2005) through to the 2020s were +35% (without climate change) and +50% (with climate change).

The projected increases in volumetric water demand for potatoes in England and Wales for the 2050s suggested increases of between 25% and 80% depending on socio-economic scenario, with projections largely influenced by the assumptions regarding population growth, food demand and patterns of consumption. Higher demands reflected the need to increase production to cope with increased food demand from a growing population, whilst the lower projected demands reflected a scenario where the population begins to accept lower quality and more locally sourced produce. Detailed descriptions of each of the four scenarios and their projected impacts on potato consumption and production are provided. However, there is of course a high degree of uncertainty associated with projecting potato water demands into the 2050s, so the values presented should be interpreted with caution – it is suggested they are used to demonstrate the effects of the assumptions embedded within the scenarios, rather than necessarily to infer trends in future water demand *per se*. They do, however, demonstrate the sensitivity of policies to promote either consumerism or sustainability, their consequent effects on potato production and consumption and hence water demand. The projections for the 2050s also ignore any impacts of potato new cultivars, genetic improvements, and the effects of elevated CO2 on water demand, many of which could significantly offset future increases in potato water demand.

Of course, in reality it is likely that these future projections will also be influenced by actual water availability. Licences are still available for winter (high flow) abstraction in most catchments, and recent years have seen a significant increase in the construction of on-farm reservoirs for summer irrigation. Though expensive, these provide growers with greater security of supply, and it seems likely that this will become the preferred water source adaptation for potato irrigation. Most reservoir investments have probably actually been in response to legislative or other pressures (e.g. supermarket demands for security of supply), rather than purposeful (deliberate) adaptations to any perceived future climate change per se. Nevertheless they may still prove to be a useful climate change adaptation strategy. Once irrigation water is assured but expensive, it will become increasingly sensible to invest more heavily in water efficiency measures, including better application methods (e.g. drip) and precision irrigation, and scientific scheduling methods will become more widely adopted. Earlier planting and harvesting would reduce water use per unit area, but with some varieties growers might prefer to use the longer grower season to increase yield. There has been a steady increase in average potato yields over the last few decades; with national consumption roughly constant this has led to a gradually reducing area planted; whether this trend can be intensified and how far it could counteract the increasing underlying demand for water is not clear.

Greater uncertainty in seasonal weather patterns means growers need to adapt and consider short-term coping strategies as well as longer-term strategic developments to reduce their vulnerability to changing water availability. How they respond will depend to a large extent on their perception of risk and the opportunities that climate change presents to their business. Farmers generally have two options; either to reduce their water needs or try to secure additional water supplies. Options to reduce on-farm water needs include investing in improved irrigation technology (scheduling) and equipment to increase application uniformity and efficiency, using weather forecasting to increase the effective use of rainfall, encouraging deeper rooting of crops, introducing lower water use or drought tolerant crop varieties, decreasing the overall irrigated area, or modifying soil structure to improve soil moisture retention. Options to obtain more water include purchasing land with water, obtaining additional licensed capacity and building on-farm storage reservoirs (either individually or shared with neighbouring farms), installing rainwater harvesting equipment, re-using waste water from farm buildings, or switching water supplies to public mains where feasible. Many of these potential adaptations are already ‘no regret’ options, in that they already make sense by solving existing water resource issues, which then contribute to a farms future adaptability.

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