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Impacts of climate change on irrigated potato production in a humid climate

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ABSTRACT

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 A1FI and B1) for the 2050s, including CO_2 fertilisation effects. The simulated baseline yields were validated against independent experimental and field data using four reference sites. Probabilistic distribution functions and histograms 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.

1. 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., 2010). 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 (Fig. 1). 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).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)

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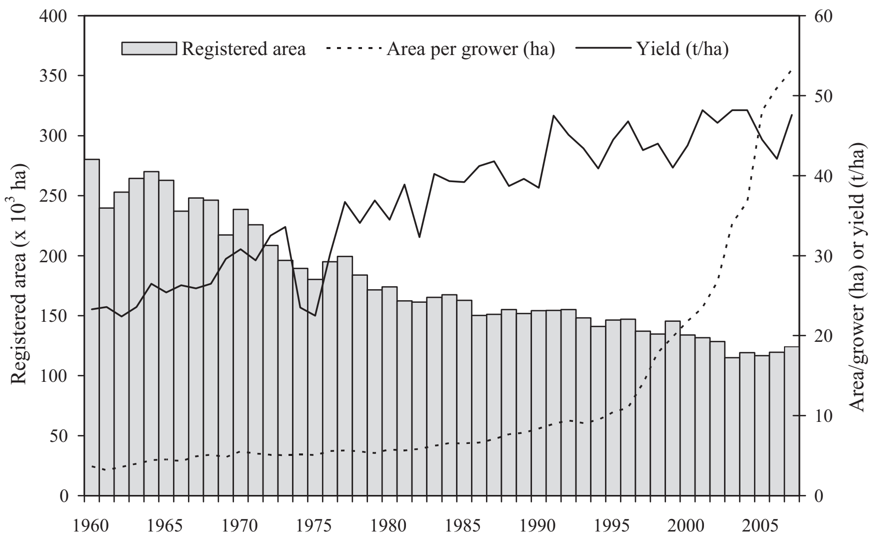

Fig. 1. Reported total potato cropped area (ha), average cropped area per grower (ha) and average yield (t ha^{-1}) in the UK, 1960–2007.
Source: Potato Council, 2010.

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 CO_2 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 and 12%, excluding CO_2 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.

2. Materials and methods

In summary, the climate change projections based on an ensemble of model runs from multiple general circulation models (GCMs) have been combined with a potato crop model to simulate the net annual irrigation water requirements (IR_{net}) and crop productivity (t ha^{-1}) for a historical baseline and selected future emissions scenarios, including CO_2 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 probabilistic assessment of GCM modelling uncertainty on future irrigation needs was then completed using a water balance model, and a weather generator used to assess the impacts of different climate downscaling techniques on yield and irrigation need. A description of the study sites, emissions scenarios and crop modelling is provided below.

2.1. 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 1970–91, the mean rainfall was 50 mm $month^{-1}$, mean daily summer temperatures were 16 °C (ranging from 11 to 21 °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.

2.2. 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 main analysis using SUBSTOR-Potato, the 10,000 derived 'change factors' for each climate variable and emission scenario were analysed to identify those that were statistically 'most likely' to occur (50% probability). This assumed all the 10,000 samples had an equal probability of occurrence (1 in 10,000).

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To investigate climate uncertainty, a sensitivity of yield and irrigation needs using all 10,000 probabilistic samples was also completed using a separate water balance model and perturbing two contrasting climate years (using 1991 defined agroclimatically as a 'wet' year and 1982 as a 'dry' year in rainfall terms). To illustrate the effects of climate uncertainty but limit computational modelling time, the approach was applied to only one reference site (CUF); the findings and implications, however, have relevance to all 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 (A1FI) and low (B1) scenarios for the 2050s were used. The assumed atmospheric CO_2 concentration for the baseline (1961–90) was 330 ppmv based on data presented by the IPPC SRES (Nakicenovic et al., 2000).

The UKCP09 climatology provides future monthly gridded data at 25 km resolution, expressed as either relative or absolute change with respect to the baseline (1961–90) for each variable. For simulating future climate, long-term daily historical (1970–91) datasets for each site were used. Prior to their use, these data were checked for consistency with the UKCP09 baseline climatology for rainfall and ETo, the main climate variables that influence irrigation demand. An example of baseline validation for the CUF site is given in Fig. 2, and similar results were observed for the other sites. Although the time-series were slightly different (1961–90 and 1970–91), the simulated UKCP09 values were in the range of the inter-annual variation of the observed values, confirming that the historical (site) datasets (1970–91) were comparable to the UKCP09 baseline (1960–91) and thus suitable for simulation. The use of the monthly 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 grid box of UKCP09 for each site and each emissions scenario. The CF's were applied to the historical daily baseline (1970–91) for each site – adding the changes in temperature to the observed temperature, and multiplying ratio changes for precipitation and total cloud cover (Table 2).

For modelling, the 2050s time slice was chosen to demonstrate potential crop responses to a strong changing climate signal and yet within a timescale suitable for planning on-farm adaptation measures. Two new daily climate datasets (21 year time series) were thus generated for each site, for the low (2050L) and high (2050H) emissions scenarios, respectively. 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 van Oijen, 2002). This approach has the virtue of simplicity and maintains the historical 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 (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

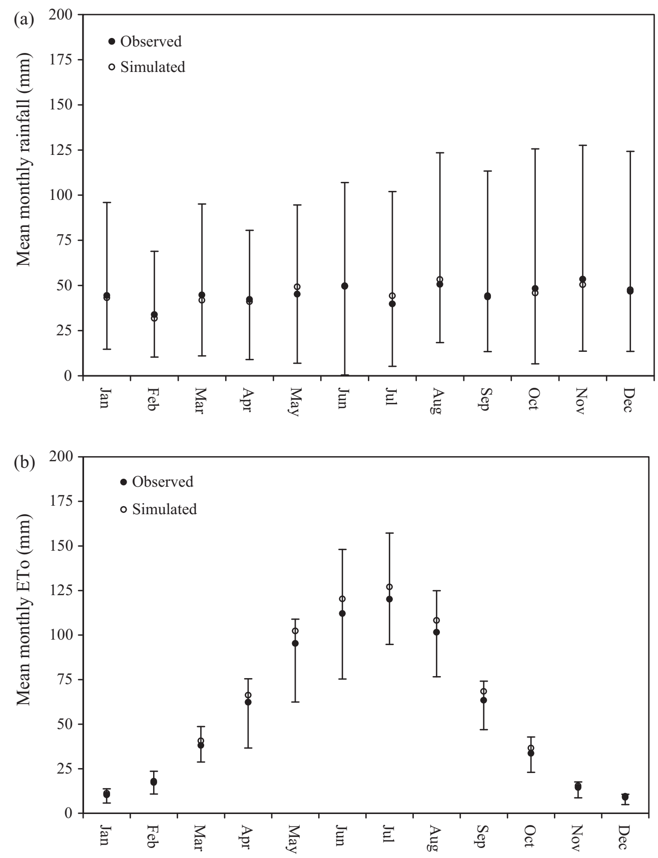

Fig. 2. Comparison of (a) observed mean monthly rainfall (mm/month) and (b) reference evapotranspiration (ETo) (mm/month) at the experimental site (CUF, Cambridge) for 1970–91 against UKCP09 grid data for the baseline climatology (1961–90). Vertical bars show the observed inter-annual variation.

datasets for each site were then used in the crop modelling. This approach has inherent limitations, in that the temporal sequencing of wet and dry days remains unchanged, a time slice approach rather transient changes in climate are considered, and any natural climate variability is not explicitly incorporated. However, by using the probabilistic data in UKCP09 (comprising 10,000 outputs from 11 GCM model runs for each climate variable) the full range in climate uncertainty could be investigated, as discussed in Section 3.3. This helps to offset one of the major limitations in the 'CF approach' regularly cited by others (e.g. Zhang, 2007). However, by incorporating the probabilistic analyses into the CF approach, the modelling routines of course become significantly more computationally intensive.

2.3. 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

Table 1
Main variables used to parameterise the SUBSTOR–Potato model for the experimental station (CUF) and three farm sites.

Variable	Site			
	CUF	Buxton	Woodbridge	Spalding
Planting depth (m)	0.12	0.15	0.13	0.19
Plant population (per m^2)	3.4	3.4	2.9	3.3
Planting date	16 April	1 April	1 April	5 April
Date of harvest	30 September	16 October	15 August[a]	12 September
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

[a] Defoliation practices were applied.

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.

The soil water balance in DSSAT is based on Ritchie's model (Ritchie, 1981a,b) 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 (field capacity). The SCS method (Soil Conservations Service, 1972) modified to account for layered soil (Williams, 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). 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 CO_2 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 1970–91, and the two equivalent datasets generated for the 2050L (B1) and 2050H (A1FI) 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 1. 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^{-1} at 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.

These management data were used in SUBSTOR-Potato model to simulate the annual yield and net irrigation needs for the baseline (1970–91) 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}).

2.4. 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 (°C). The coefficient G2 ($cm^2\ m^{-2}\ d^{-1}$) 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, 17 °C, 2000 $cm^2\ m^{-2}\ d^{-1}$, 25 $g\ m^{-2}\ d^{-1}$ and 0.8 for P2, TC, G2, G3 and PD, respectively.

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Table 2
Changes in mean monthly climate between the baseline and each SRES emissions scenario, by variable and month for the selected sites (°C change or % change as shown).

2005L

Site	Variable	January	February	March	April	May	June	July	August	September	October	November	December
CUF	T_{min} (°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
	T_{max} (°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
	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
	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
Buxton	T_{min} (°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
	T_{max} (°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
	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
	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
Woodbridge	T_{min} (°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
	T_{max} (°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
	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
	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
Spalding	T_{min} (°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
	T_{max} (°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
	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
	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

2050H

Site	Variable	January	February	March	April	May	June	Julu	August	September	October	November	December
CUF	T_{min} (°C)	2.8	2.4	2.0	2.0	2.3	2.4	2.8	2.6	2.4	2.3	2.2	**2.4**
	T_{max} (°C)	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 (%)	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 (%)	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	T_{min} (°C)	2.9	2.4	2.0	2.1	2.3	2.3	2.6	2.4	2.3	2.3	2.2	**2.4**
	T_{max} (°C)	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 (%)	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 (%)	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	T_{min} (°C)	3.0	2.5	2.0	2.1	2.3	2.4	2.7	2.5	2.4	2.3	2.3	**2.4**
	T_{max} (°C)	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 (%)	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 (%)	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	T_{min} (°C)	2.2	2.2	2.4	2.4	2.6	3.0	2.9	3.2	2.7	2.5	2.4	**2.4**
	T_{max} (°C)	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 (%)	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 (%)	1.5	1.0	−2.4	−2.7	−4.8	−3.8	−7.8	−12.4	−6.6	−2.4	−0.3	**1.2**

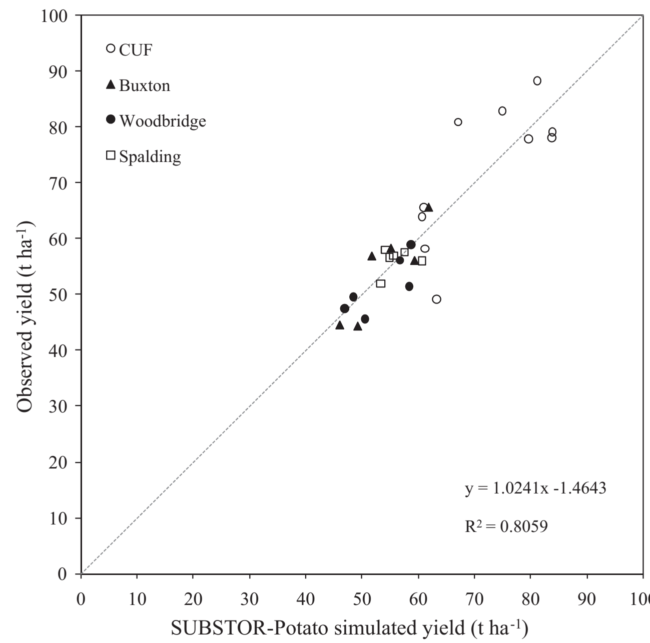

Fig. 3. Comparison between SUBSTOR-Potato simulated annual potato yield (t ha^{-1}) and observed average annual yield (t ha^{-1}) at the experimental and farm sites.

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 undertaken (Fig. 3). 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 (R^2) assesses how well the shape of the simulation matches the shape of the observed data (Huang et al., 2009). The coefficients from the regression analysis confirmed that the slope was not significantly different from 1 at the 95% confidence interval, and that there was very close agreement between the model simulated and observed yields (R^2 = 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:

$$\mathrm{RMSE} = \left(\frac{1}{N} \sum_{i=1}^{N} d_1^2 \right)^{1/2} \qquad (1)$$

where N is the number of data pairs and d_i is the difference between ith predicted and ith measured values (Kennedy and Neville, 1986).

Table 3
Summary statistics from the SUBSTOR-Potato validation for each study site.

Statistic	Experimental site			Farm site
	CUF	Buxton	Woodbridge	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 (SD_o)	12.5	8.3	5.1	2.2
Standard deviation simulated (SD_s)	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

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 (2.3–3.6 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 (expressed as a percentage) between the simulated and observed mean yields were also very small (1–3.5%).

3. 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.

3.1. 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 Fig. 4, across the range of wet to dry years, ranked by irrigation need, and based on UKCP09 data for the 'most likely' probability (50%). Under warmer climate conditions and where water is not limiting, plants will transpire more; this accounts for the 6.5–11.4% increase in crop evapotranspiration (ET_{crop}) (Table 4). The combined effects of reduced rainfall (−7 to −12%) and increased ET_{crop} results in a significant increase in average irrigation need (IR_{net}) of 14–30%, 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).

3.2. Impacts on yield and irrigation use efficiency

The predicted changes in average actual yield (t ha^{-1}) and irrigation use efficiency, IUE (kg m^3) 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), Fig. 5 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 13–16% on average depending on scenario, but with significant inter-annual variability (5–24%). 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 and −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 m^3 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.

3.3. Impacts of climate uncertainty on irrigation need

As discussed in Section 2.2, the UKCP09 climatology includes 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 level of confidence (50%). To assess the impact of GCM uncertainty on irrigation need, the daily weather pattern for a representative dry (1982) and wet (1991) year at the experimental site (Cambridge) was perturbed using all 10,000 samples for each climate variable. It would not be computationally practical to run SUBSTOR-Potato for all 10,000 samples, so the irrigation needs were simulated using a water balance model termed WaSim. This model has been specifically designed and used for estimating irrigation requirements and evaluating scheduling strategies internationally (e.g. Depeweg and Fabiola Otero, 2004). For fully irrigated crops, the crop growth is not affected by drought, and hence this model provides an acceptable approximation. The model runs on a daily time-step and estimates the daily soil water balance for the selected crop and soil type using weather data and schedules irrigation according to a set of management rules or strategies. The crop and soil characteristics and irrigation schedule used in the WaSim model were defined to match those used in the SUBSTOR-Potato model.

The WaSim model was run for all 10,000 samples in each year and histograms of the 10,000 model predictions for future potato irrigation needs (mm) generated (Fig. 6). The highest frequency predictions (or 'most likely' using IPCC terminology) for future irrigation need in a 'dry' and 'wet' year in the 2050s (low and high scenario) were approximately 400 mm and 200 mm, respectively, compared to baseline values of 291 mm for the 'dry' (1982) and 132 mm for the 'wet' (1991) year.

Similarly, the 'very unlikely' probabilities for each year could also be derived. As every sample in the 10,000 dataset is a possible

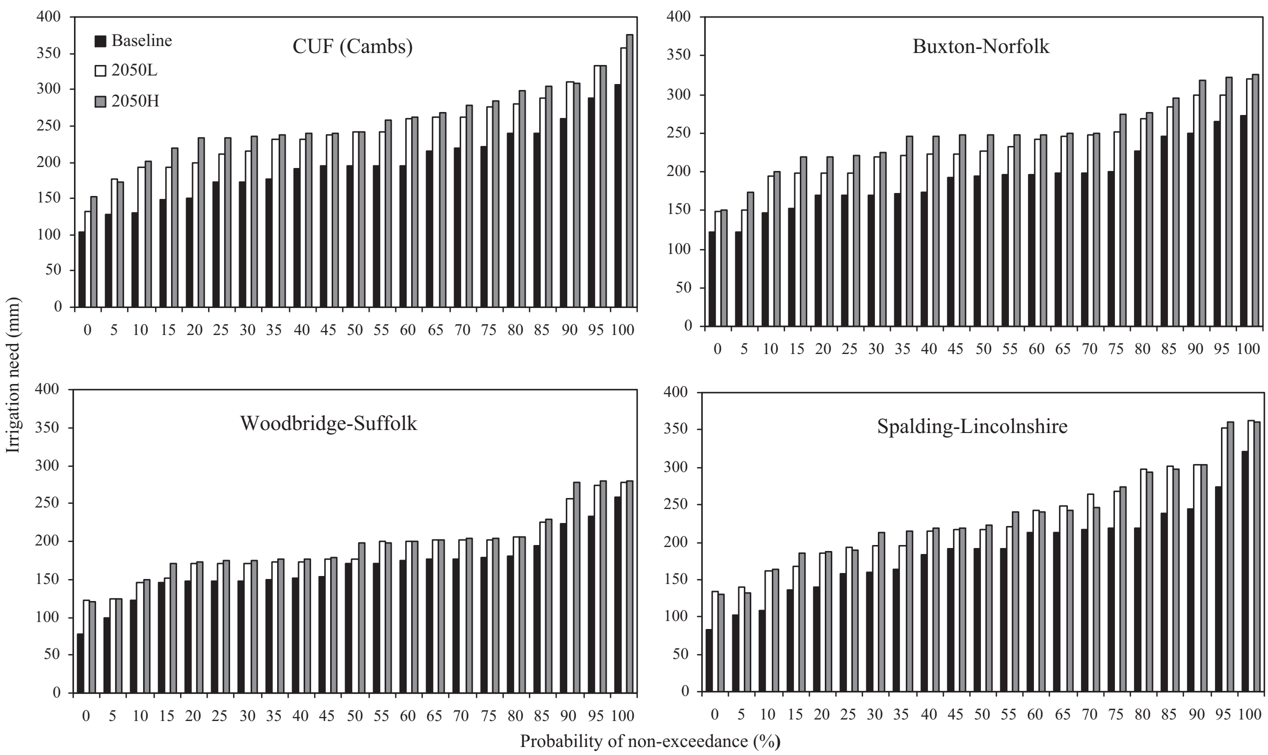

Fig. 4. SUBSTOR-Potato simulated annual irrigation needs (mm) for potatoes (*cv.* Maris Piper), ranked (probability of non-exceedance) for the experimental site (Cambs), for the long-term average baseline (1961–90) and for selected SRES emissions scenario (2050 low and high).

and plausible projection, Fig. 6 reflects the uncertainty in climate change modelling and error that could arise when assessing impacts based on a single climate projection. This probabilistic approach helps to frame the levels of confidence in likely future impacts and is useful for assessing the costs and reliability of adaptation options such as developing new water resources (e.g. irrigation storage reservoirs) or investment in new technologies to improve water efficiency (e.g. switching from overhead to micro irrigation). By considering different probability levels farmers can thus invest in adaptation responses which minimise the 'regret' rather than opting for 'no regret' measures which would prove excessively expensive.

The UKCP09 climatology also provides scenarios of daily weather data from a stochastic weather generator (LARS-WG v5) which incorporates climate predictions from 15 climate models from the multi-model ensemble used in the IPCC Fourth Assessment Report (AR4) (Semenov and Stratonovitch, 2010). In order to assess the inherent limitation of using the 'CF' approach described earlier, the yields and net irrigation needs for the experimental site were re-modelled using projection data-sets from the LARS-WG,

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.

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)

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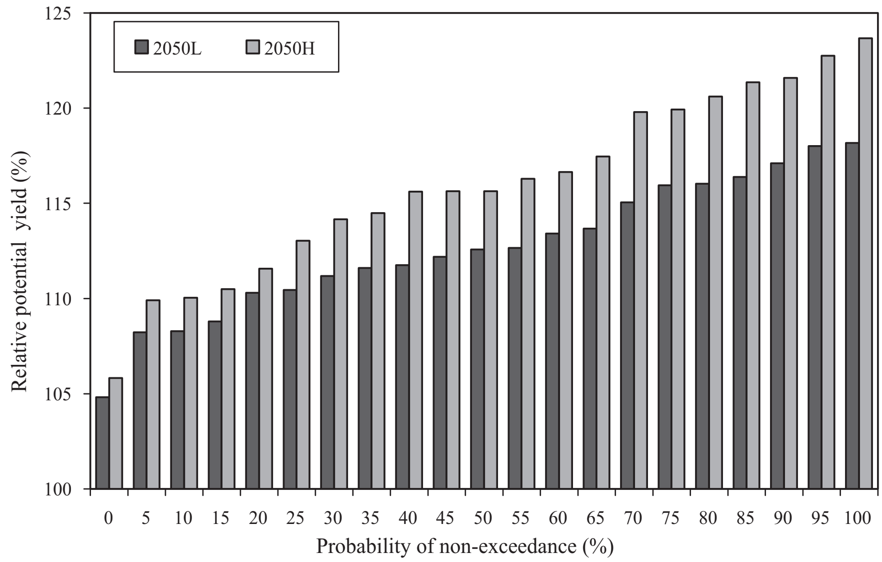

Fig. 5. Predicted changes in potential yield (t ha^{-1}) for potatoes (*cv.* Maris Piper) from the long term average baseline (1961–90) to the 2050s for the experimental site at Cambridge. Simulated yields assume the crop is unconstrained by water and fertilizer availability.

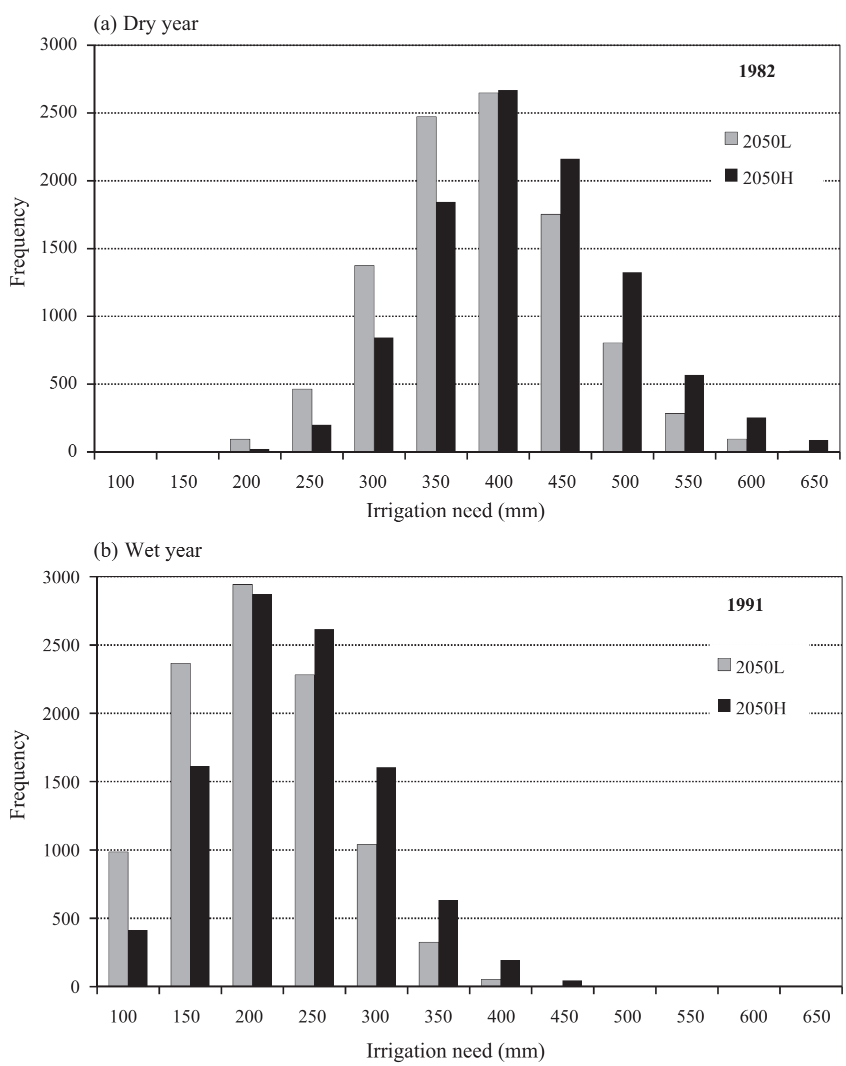

Fig. 6. Histograms showing the model predictions of future irrigation needs (mm) for potatoes (*cv.* Maris Piper) at the experimental site (Cambridge) for the 2050s low and high emissions scenarios. Data shown are for a representative dry (a) and wet (b) year weather pattern using the 10,000 samples from the UKCP09 probabilistic climate data. For each, the dashed line shows the baseline value.

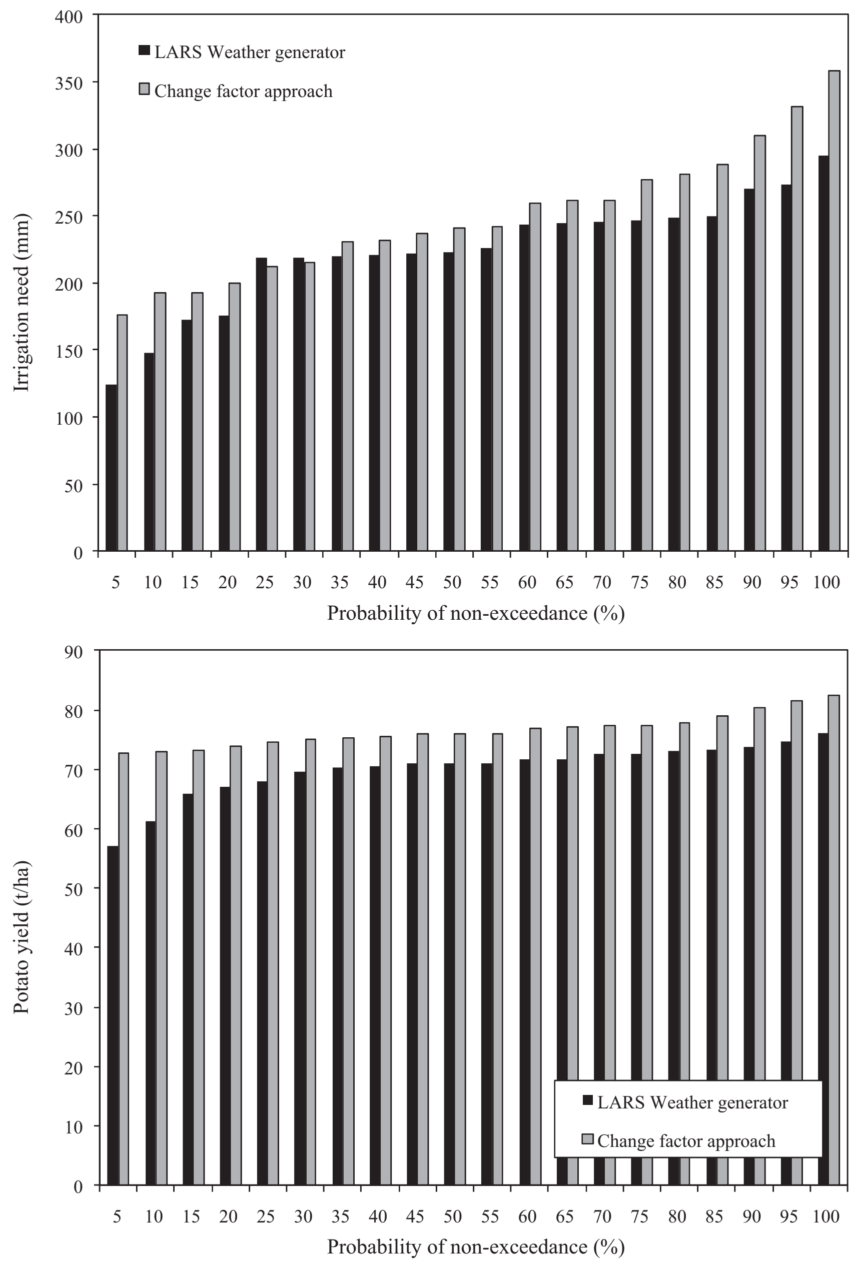

Fig. 7. Comparison of SUBSTOR-Potato simulated annual (a) irrigation needs (mm) (*cv*. Maris Piper) and (b) yield (t ha^{-1}) using the LARS-WG stochastic weather generator and 'change factor' approach. Data relate to the experimental site (Cambs) for the 2050 low emissions scenario.

and then compared to the equivalent 'CF' results. The LARS-WG was used to generate a future synthetic weather dataset from the historical baseline (1970–91) using future temperature (minimum and maximum), precipitation and solar radiation derived from the 10,000 samples of UKCP09 for the 'most likely' probability (50%). For irrigation need, the LARS-WG resulted in consistently lower values and less variability, although the means were similar (Fig. 7a). Similarly, for yield, the CF approach consistently simulated higher yield but with less variation; in contrast the LARS-WG approach led to greater variation and much reduced yields at low probability levels (Fig. 7b). These differences would be important in the context of designing infrastructure and particularly in planning systems to cope with future changes in peak capacity. These comparisons highlight the importance of exploring the uncertainty associated with using different approaches for downscaling or generating future climate data.

3.4. Model sensitivity

The sensitivity of the SUBSTOR-Potato model to systematic changes in climate was also analysed. The sensitivity of the climate at the experimental site was assumed to be representative of all sites. The daily weather data for the baseline (1970–90) was adjusted independently, step-wise, to assess the sensitivity of the model to changing values of each variable. Specifically, the impacts of varying temperature, solar radiation and atmospheric CO_2 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 4 °C (Fig. 8). For comparison, using the historical climate data for the site, the temperature anomaly (defined as the difference between the mean daily temperature and the overall mean) over

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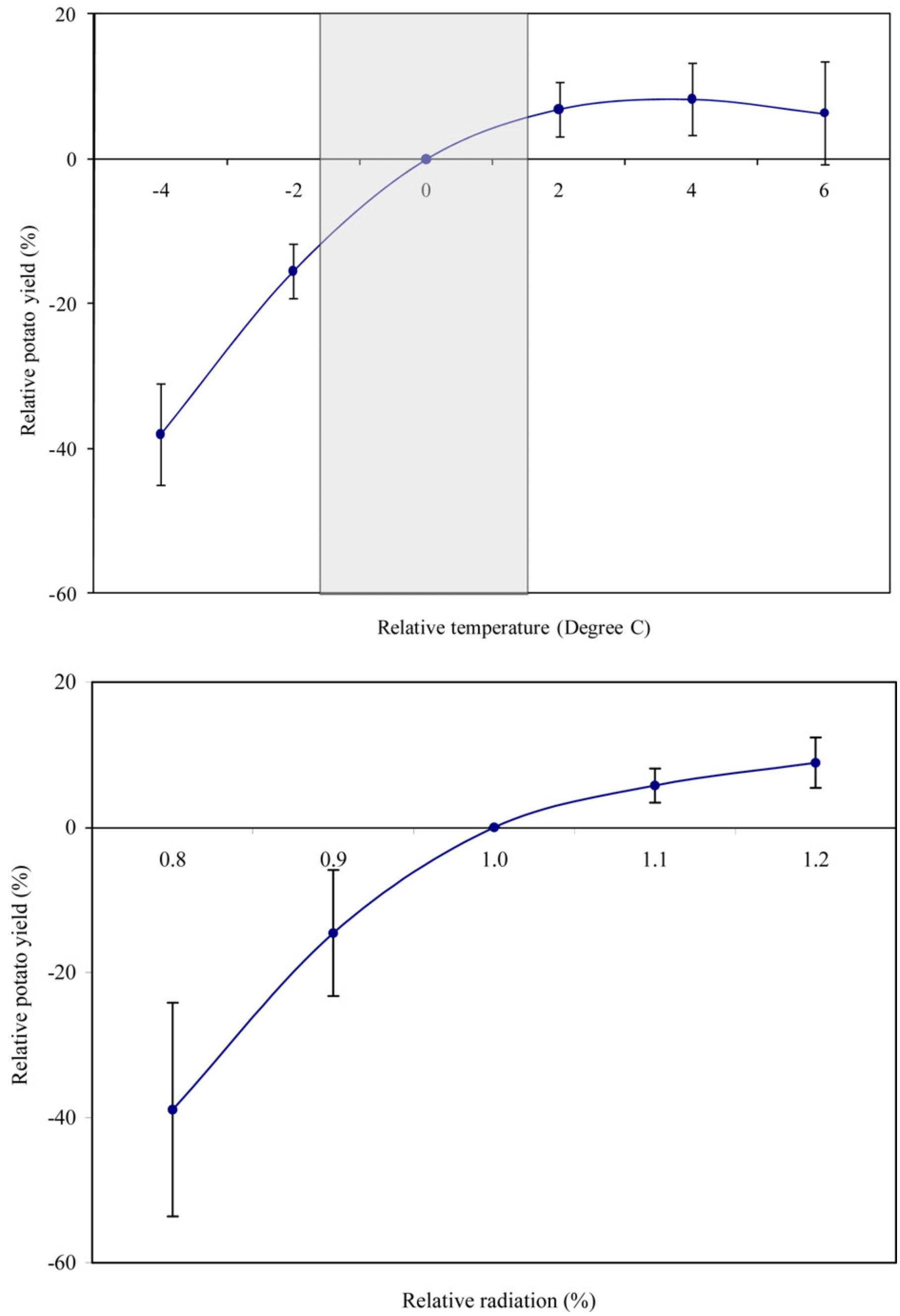

Fig. 8. Sensitivity of simulated yield (SUBSTOR-Potato) to changes in (a) temperature and (b) solar radiation for irrigated potato production at the experimental site (Cambridge), based on data from 1970 to 1990. Vertical bars represent the inter-annual variation. Shaded band represents the range of the historical temperature anomaly.

the period 1970–91 ranged from +1.5 °C to −1.5 °C. The modelled yield response at the extremes (−4 and +6 °C) reflect the potential impact of temperature on plant growth and are site specific. Higher temperatures will affect not only the vine and root growth but also might cause a delay in tuber initiation and consequently a reduction in 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 cool 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 (Fig. 8) 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

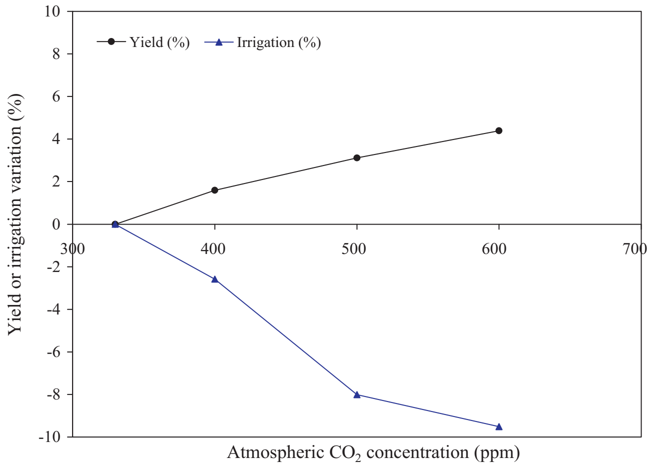

Fig. 9. Sensitivity of SUBSTOR-Potato simulated yield (%) and irrigation water requirements (%) to changes in atmospheric CO_2 concentration (ppm), based on data from 1970 to 1990. Concentrations for the 2050L (B1) (▲) and 2050H (A1F1) (△) emissions scenario are shown.

effect of higher levels of solar radiation on final tuber production (Fig. 8).

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 (Fig. 9). 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. 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. Water stress is expected to increase markedly in the UK, particularly in the south-east, with repercussions for land use (Weatherhead and Howden, 2009).

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. Ideally therefore, all of the 10,000 sets of data should be run, and the probabilities calculated for each output variable. Due to computational (batch processing) constraints, SUBSTOR-Potato model was run using the values statistically 'most likely' to occur (50% probability). 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 (Fig. 4) 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.

5. 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.

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.

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References

Boote, K.J., Pickering, N.B., 1994. Modeling photosynthesis of row crop canopies. HortScience 29, 1423–1434.
Davies, A., Jenkins, T., Pike, A., Sha, J., Carson, I., Pollock, C.J., 1997. Modelling the predicted geographic and economic response of UK cropping systems to climate change scenarios: the case of potatoes. Annals of Applied Biology 130, 167–178.
Diaz-Nieto, J., Wilby, R., 2005. A comparison of statistical downscaling and climate change factor methods: impacts on low flows in the River Thames, United Kingdom. Climatic Change 69, 245–268.
Depeweg, H., Fabiola Otero, M., 2004. Optimization of water management in the RUT Irrigation District, Colombia. Irrigation and Drainage 53, 55–67.
Griffin, T.S., Johnson, B.S., Ritchie, J.T., 1993. A simulation model for potato growth and development: SUBSTOR-Potato. IBSNAT Research report series 02-05/93 (500).
Godwin, D.C., Singh, U., 1998. Nitrogen balance and crop response to nitrogen in upland and lowland cropping systems. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options of Agricultural Production. Kluwer Academic Publishers and International Consortium for Agricultural Systems Applications, Dordrecht, The Netherlands, pp. 55–77.
Han, S., Evans, R.G., Hodges, T., Rawlins, S.L., 1995. Linking a geographic information system with a potato simulation model for site-specific crop management. Journal of Environmental Quality 24, 772–777.
Hodges, T., 1998. Water and nitrogen applications for potato: commercial and experimental rates compared to a simulation model. Journal of Sustainable Agriculture 13, 79–90.
Holden, N.M., Brereton, A.J., Fealy, R., Sweeney, J., 2003. Possible change in Irish climate and its impact on barley and potato yields. Agricultural and Forest Meteorology 116, 181–196.
Huang, Y., Yu, Y., Zhang, W., Sun, W., Liu, S., Jiang, J., Wu, J., Yu, W., Wang, Y., Yang, Z., 2009. Agro-C: a biogeophysical model for simulating the carbon budget of agroecosystems. Agricultural and Forest Meteorology 149, 106–129.
IPCC-TGCIA, 1999. Guidelines on the Use of Scenario Data for Climate Impact and Adaptation assessment. Version 1. In: Carter T.R., Hulme M., Lal, M. (Eds.), Intergovernmental Panel on Climate Change. Task Group on Scenarios for Climate Impact Assessment, Switzerland.
Jefferies, R.A., Heilbronn, T.D., 1991. Water stress as a constraint on growth in the potato crop. 1. Model development. Agricultural and Forest Meteorology 53, 186–196.
Jenkins, G.J., Murphy, J.M., Sexton, D.S., Lowe, J.A., Jones, P., Kilsby, C.G., 2009. UK Climate Projections: Briefing Report. Met Office Hadley Centre, Exeter, UK.
Johns, T.C., Carnell, R.E., Crossley, J.F., Gregory, J.M., Mitchell, J.F.B., Senior, C.A., Tett, S.F.B., Wood, R.A., 1997. The second Hadley Centre coupled ocean–atmosphere GCM: model description, spin up and validation. Climate Dynamics 13, 103–134.
Jones, J.W., Hoogenboom, G., Portera, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. European Journal of Agronomy 18, 235–265.
Kennedy, J.B., Neville, A.M., 1986. Basic Statistical Methods for Engineers and Scientists, 3rd ed. Harper and Row, New York.
Knox, J.W., Weatherhead, E.K., Rodriguez-Diaz, J.A., Kay, M.G., 2009. Developing a strategy to improve irrigation efficiency in a temperate climate: a case study in England. Outlook on Agriculture 38 (4), 303–309.
Knox, J.W., Rodriguez-Diaz, J.A., Weatherhead, E.K., Kay, M.G., 2010. Development of a water strategy for horticulture in England and Wales. Journal of Horticultural Science and Biotechnology 85 (2), 89–93.
Knox, J.W., Morris, J., Weatherhead, E.K., Turner, A.P., 2000. Mapping the financial benefits of spray irrigation and potential financial impact of restrictions on abstraction: a case study in Anglian Region. Journal of Environmental Management 58, 45–59.
Lynch, D.R., Foroud, N., Kozub, G.C., Farries, B.C., 1995. The effect of moisture stress at three growth stages on the yield components of yield and processing quality of eight potato cultivars. American Potato Journal 72, 375–386.
Mearns, L.O., 2000. Climatic change and variability. In: Reddy, K.R., Hodges, H.F. (Eds.), Climate Change and Global Crop Productivity. CABI Publishing, Wallingford, pp. 7–35.
Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J., Zhao, Z.C., 2007. Global climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Avery, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, USA.
Ng, E., Loomis, R.S., 1984. Simulation of growth and yield of the potato crop. In: Simulation Monographs. Pudoc, Wageningen.
Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grübler, A., Jung, T.Y., Kram, T., La Rovere, E.L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Raihi, K., Roehrl, A., Rogner, H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N., Dadi, Z., 2000. IPCC Special Report on Emissions Scenarios. Cambridge University Press, Netherlands.
Opena, G.B., Porter, G.A., 1999. Soil management and supplemental irrigation effects on potato. II. Root growth. Agronomy Journal 91, 426–431.
Peiris, D.R., Crawford, J.W., Grashoff, C., Jefferies, R.A., Porter, J.R., Marshall, B., 1996. A simulation study of crop growth and development under climate change. Agricultural and Forest Meteorology 79, 271–287.
Richter, G.M, Qi, A., Semenov, M.V., Jaggard, K.W., 2006. Modelling the variability of UK sugar beet yields under climate change and husbandry adaptations. Soil Use and Management 22, 39–47.
Ritchie, J.T., 1981a. Water dynamics in the soil–plant–atmosphere. Plants and Soil 58, 81–96.
Ritchie, J.T, 1981b. Soil water availability. Plants and Soil 58, 327–338.
Semenov, M.A., Stratonovitch, P., 2010. Use of multi-model ensembles from global climate models for assessment of climate change impacts. Climate Research 41, 1–14.
Soil Conservations Service (SCS), 1972. National Engineering Handbook, Hydrology. Section 4 (Chapters 4–10).
Stalham, M.A., Allen, E.J., Rosenfeld, A.B., Herry, F.X., 2007. Effects of soil compaction in potato (*Solanum tuberosum*) crops. Journal of Agricultural Science, Cambridge 145, 295–312.
Šťastnà, M., Toman, F., Dufkova, J., 2010. Usage of SUBSTOR model in potato yield prediction. Agricultural Water Management 97, 286–290.
Travasso, M.I., Caldiz, D.O., Saluzzo, J.A., 1996. Yield prediction using the SUBSTOR-Potato model under Argentinean conditions. Potato Research 39, 305–312.
Weatherhead, E.K., Howden, N.J.K., 2009. The relationship between land use and surface water resources in the UK. Land Use Policy 26, S243–S250.
Williams, J.R., Jones, C.A., Dyke, P.T., 1984. A modeling approach to determining the relationships between erosion and soil productivity. Transactions on ASAE 27, 129–144.
Wolf, J., 2002. Comparison of two potato simulation models under climate change. II. Application of climate change scenarios. Climate Research 21, 187–198.
Wolf, J., van Oijen, M., 2002. Modelling the dependence of European potato yields on changes in climate and CO_2. Agricultural and Forest Meteorology 112, 217–231.

Wolf, J., van Oijen, M., 2003. Model simulation of effects of changes in climate and atmospheric CO_2 and O_3 on tuber yield potential of potato (*cv.* Bintje) in the European Union. Agriculture, Ecosystems and Environment 94, 141–157.

Zhang, X.C., 2007. A comparison of explicit and implicit spatial downscaling of GCM output for soil erosion and crop production assessments. Climatic Change 84, 337–363.