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Winter wheat yields in the UK: uncertainties in climate and management impacts

Kyungsuk Cho[1,]*, Pete Falloon[2], Jemma Gornall[2], Richard Betts[2], Robin Clark[2]

[1]Korea Meteorological Administration, 61 Yeoeuidaebang-ro 16-gil, Dongjak-gu, Seoul 156-720, Korea
[2]Met Office Hadley Centre, Fitzroy Road, Exeter EX1 3PB, UK

ABSTRACT: Winter wheat is an important UK cereal, suited to the current climate. However, recent climate projections show changes in temperature and precipitation are likely, potentially affecting UK crop yields. Assessments of future yields contain several sources of uncertainty including those associated with climate and potential adaptation. Here we address these uncertainties using the CERES-Wheat model fed with an ensemble of regional model projections and different sowing dates and fertiliser regimes. In all of the 13 administrative regions in the UK Climate Projections (UKCP09), increases in temperature accelerated the development rate of wheat, a result that was robust across the ensemble. This generally leads to positive impacts on yield and a northward shift in cultivation, with some decreases in the south. Uncertainties in yield became greater towards 2100, a result of corresponding increases in the uncertainty of climate changes. Sensitivity analysis suggests that CO_2 fertilisation could compensate for yield losses due to changes in temperature and precipitation in most regions. Earlier sowings appear to be more beneficial in the future over the UK, whilst later sowings increase the risk of yield losses. In a warmer climate, increasing the amount of fertiliser did not improve yields and in fact increased the risk to productivity. Critically, adjustments to sowing date and fertiliser addition did not mitigate the loss of yield experienced in southern regions, suggesting limited adaptation potential in this case. We propose that regional yield changes may not be critical for wheat production in the UK as a whole, as losses in some regions are more than compensated for by gains in others.

KEY WORDS: UKCP09 · SRES A1B · Uncertainty · CERES-Wheat · UK winter wheat · Yield

1. INTRODUCTION

Winter wheat is currently the most extensively grown arable crop in the UK. The UK's temperate climate allows winter wheat to be grown throughout the winter, achieving larger yields than varieties that are planted in spring. The UK climate has been suitable for wheat for thousands of years. However, observations and future projections suggest that the UK climate is changing and temperatures are increasing (and will continue to rise) beyond those observed previously (Jenkins et al. 2009). Central England temperature has already increased by approximately 1.0°C since the 1970s. Mean daily maximum temperatures in the UK are projected to further increase by between 1.0 and 9.5°C in the summer and by between 0.7 and 2.7°C in the winter by the 2080s (Jenkins et al. 2009).

Changes in climate and atmospheric CO_2 concentration are likely to have positive and negative effects on the agricultural sector at both regional and global scales. Increases in productivity may arise from longer growing seasons and the expansion of climatically suitable areas. However, altered precipitation patterns, increased frequency of extreme weather events and increased likelihood of pests and diseases may result in higher yield variability and a reduction in suitable areas for crops. Future food

*Email: cks0716@korea.kr

security is consequently likely to be affected (Gornall et al. 2010).

Future winter wheat yield increases appear possible in most European regions except for small areas such as southern Portugal, southern Spain and the Ukraine. The largest yield increases are found in southern Europe (northern Spain, southern France, Italy and Greece; Harrison & Butterfield 2000, Moriondo et al. 2011). From other studies, yield increases have also been indicated for cooler regions, e.g. Austria and Russia (Alexandrov 1997, Sirotenko et al. 1997). Findings from the 2002 UK Climate Impacts Programme (UKCIP02), based on the regional climate model (RCM) HadRM3 simulations with a high emissions scenario for the 21st century, suggest that by the 2080s, yields of UK winter wheat (Mercia and Consort) could increase by up to 33% (Hulme et al. 2002).

Research also indicates that larger yields, although uncertain in magnitude, could result solely from increases in atmospheric CO_2 concentration (Parry et al. 2005, Torriani et al. 2007, Liu et al. 2010). Results from the Free-Air CO_2 Enrichment (FACE) programme experiments generally suggest positive effects of elevated CO_2 on several food crops; at 550 ppm enrichment, mean yields increase by about 17 to 20% (Kimball et al. 2002, Long et al. 2006). According to a recent field experiment on wheat, greater CO_2 concentrations positively activate photochemistry and resource allocation to light harvesting, and also mitigates photochemistry inhibition as a result of increased temperatures (Gutiérrez et al. 2009).

Evaluation of different adaptive management options is important for efficiently dealing with future climate change impacts. For example, it may be necessary to adapt future crop production to climate change by implementing alternative management regimes and developing new cultivars. However, it is not possible to predict what new technologies for future climatic conditions will be suitable for producing maximum yields. In previous studies, Crop Estimation through Resource and Environment Synthesis-Wheat (CERES-Wheat) model and climate projection data have been used to identify optimal or maximum configurations of plant traits and management practices that improve winter wheat yield under climate changes. For example, at 3 winter wheat-growing areas in Nebraska, USA, with differing altitude and rainfall (Lincoln, Dickens and Alliance), the identified optimal winter wheat cultivar under elevated CO_2 conditions had a larger number of tillers, larger kernel size, and fewer days to flower, grew faster and had more kernels m^{-2} than the control cultivar under normal CO_2 conditions (Dhungana et al. 2006). In addition, optimal sowing dates were later, and optimal plant densities were smaller, than under normal conditions (Luo et al. 2009).

Future changes in climate may be beneficial for wheat yield in some regions but could reduce productivity in zones where optimal temperatures already exist (Ortiz et al. 2008). Warmer temperatures over winter and spring are likely to affect the length of the potential growing season by reducing the thermal duration for development of wheat (Alexandrov 1997); although the length of the potential growing season may increase, the vegetative and reproductive growing season lengths may decrease due to greater accumulated temperatures. As such, planting dates may need to be altered to maximise the growing period. With temperature limitations to growth, it is also possible that crops may or may not benefit from additional fertiliser. Therefore, some studies suggest that new management regimes may be necessary to maximise food production under a future climate (Hulme et al. 2002, Yao et al. 2007).

Climate change assessments have applied single or multi-model ensembles based on global climate models or RCMs to explore uncertainty in simulations (e.g. Murphy et al. 2004). In particular, recent studies have adopted multi-model ensembles to assess the uncertainties in the impacts of climate change on agricultural systems (Challinor & Wheeler 2008, Semenov & Stratonovitch 2010). Challinor et al. (2005) suggest that uncertainty in climate prediction is a key component of uncertainty in yield variability under elevated CO_2 concentrations. In some applications, ensemble hindcasts created by perturbing climate model parameters have been used to capture the impacts of climate variability and the uncertainties on crop yield over regional scales (Tao et al. 2009). However, to our knowledge there have been no climate impact assessments on UK crop production that have utilised the climate model ensemble based on the latest UK Climate Projections (UKCP09) scenarios (Jenkins et al. 2009). The UKCIP02 dataset (previous UK climate scenarios; Hulme et al. 2002) was derived using an ensemble of 3 climate models, generated by running the model with 3 different initial conditions and averaging the output so that the user was presented with only one projection. However, the full UKCP09 dataset includes a perturbed physics ensemble (PPE) consisting of 280 model variants of the Hadley Centre climate model, which is very novel (see Section 2.3).

In the present study we use outputs from the UKCP09 perturbed physics regional model ensemble to assess impacts of climate-related uncertainty under increased CO_2 concentrations on future potential UK winter wheat yields. As noted by Ghaffari et al. (2002), the most likely response to higher annual temperatures may be earlier cultivation in order to maximise vegetative growth during the cooler early season and to avoid high temperatures in the grain-filling period, or planting earlier-maturing varieties that avoid terminal season drought and heat stress. On the other hand, altered fertilisation regimes may be necessary to take full advantage of the CO_2 fertilisation effect, and to compensate for any yield losses caused by climate change (Ghaffari et al. 2002, Hulme et al. 2002, Yao et al. 2007). We therefore also investigate the effects of altered sowing date and fertiliser load in combination with changing climate to see if these climate adaptation options are beneficial to productivity. We do not include effects caused by negative soil conditions such as salinity, acidity and compaction, extreme weather events or pests and diseases, all of which are likely to be directly or indirectly affected by climate change and resulting changes in management practices.

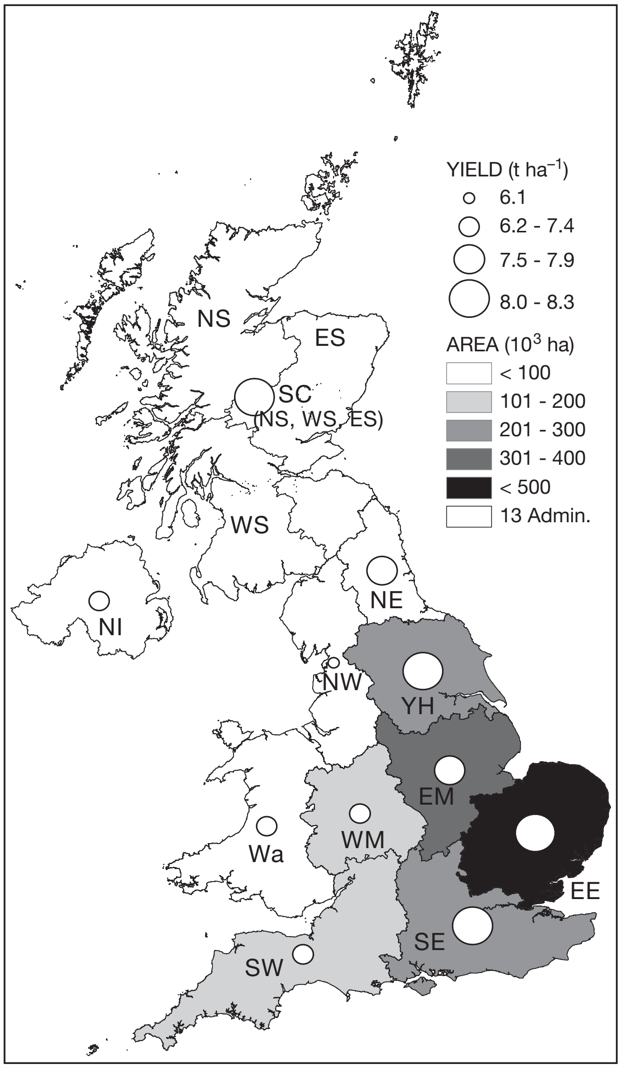

Fig. 1. UK winter wheat cultivation area and yield during 11 yr (1999–2009). SC: Scotland (consists of NS, WS and ES). See Table 1 for other region abbreviations. Source: Defra Cereal and Oilseed Production Survey (Defra 2010)

2. MATERIALS AND METHODS

2.1. Geographic location and climate

Winter wheat is one of the most important crops grown over the UK under the current climate. Though winter wheat is well suited to the production over the UK generally, it is mainly grown in the southern and eastern regions (Fig. 1); over the last decade the mean of annual production was approximately 15 million tonnes (Defra 2010).

In the present study, we focus on the main 13 administrative regions defined by UKCP09, which are classified as Northern Scotland (NS), Western Scotland (WS), Eastern Scotland (ES), Northern Ireland (NI), North East England (NE), North West England (NW), Yorkshire and Humberside (YH), Wales (Wa), West Midlands (WM), East Midlands (EM), South West England (SW), South East England (SE) and East of England (EE). Table 1 shows the geographical location and climatology (for the period 1971 to 2000) of these regions.

2.2. Crop simulation model and validation

The CERES-Wheat model in the Decision Support System for Agrotechnology Transfer (DSSAT) version 4.0 (Hoogenboom et al. 2004) is a dynamic process-based, and management-oriented crop model that can simulate the impacts of various environmental factors. This model has been extensively applied and tested since its initial development and evaluation (Ritchie et al. 1998, Southworth et al. 2002). Also, it has been validated and assessed for a wide range of environments and regions across the world (Rinaldi 2004, Singh et al. 2008, Langensiepen et al. 2008, Liu & Yuan 2010) and used for climate impact studies over the UK (Ghaffari et al. 2002).

The present study includes assessment of altered planting dates and nitrogen (N) fertilisation regimes as potential future adaptation options, and includes a

Table 1. Geographic location and climatology (1971–2000) of the 13 main administrative regions. Data for Altitude, Tmax, Tmin and precipitation are means. NS: Northern Scotland, WS: Western Scotland, ES: Eastern Scotland, NI: Northern Ireland, NW: North West England, NE: North East England, YH: Yorkshire and Humberside, Wa: Wales, WM: West Midlands, EE: East England, EM: East Midlands, SE: South East England, and SW: South West England. Source: Jenkins et al. (2009)

Region	Latitude (centre, decimal degrees)	Longitude (centre, decimal degrees)	Altitude (m)	Tmax (°C)	Tmin (°C)	Annual total precipitation (mm)
NE	55.0	–1.9	191	11.2	4.3	883
NW	54.1	–2.7	161	11.9	5.1	1174
NI	54.6	–6.5	161	12.2	5.3	1127
NS	57.6	–0.5	272	10.2	4.0	1610
WS	55.6	–3.4	200	11.2	4.6	1749
WM	52.3	–2.3	126	13.2	5.5	761
Wa	52.3	–3.9	217	12.5	5.6	1351
EE	52.3	0.5	45	13.8	5.9	603
ES	56.5	–2.8	260	10.5	3.6	1161
EM	52.9	–0.8	86	13.2	5.4	684
SE	51.3	–0.5	77	13.9	6.1	740
SW	51.0	–3.1	123	13.6	6.2	1004
YH	54.0	–1.2	130	12.2	5.1	857

comparison of CERES-Wheat simulated yields with observed yields under different N-fertiliser application rates for the Broadbalk experiment at Rothamsted, UK. CERES-Wheat has also previously been used for simulating crop yields under different sowing dates and fertilisation regimes. For example, in Southern Italy, CERES-Wheat has been used in seasonal studies to optimise N-fertilisation of durum wheat at different planting dates for crop-available water. CERES-Wheat was assessed to be an appropriate model for simulating crop management strategies in typical durum wheat (Rinaldi 2004). CERES-Wheat was validated under contrasting N management and temperate-maritime climate conditions of North Germany (Langensiepen et al. 2008). Arora et al. (2007) analysed wheat yield for optimising crop productivity under water limitations in a semi-arid subtropical irrigated field using CERES-Wheat and reported that initial soil mineral-N status influenced the amount of N-fertiliser for a given initial soil water content. CERES-Wheat also provided satisfactory estimates for the emergence, flowering and physiological maturity dates under different N (up to 150 kg ha^{-1}) and water management regimes in New Delhi (Singh et al. 2008).

Pecetti & Hollington (1997) simulated 3 sowing dates (normal, early and late) of winter wheat for optimising in 2 diverse Mediterranean regions (Northern Syria and Eastern Sicily) with historical weather data using CERES-Wheat. The results indicated that 'early' sowing had the highest simulated yield, and the lowest yield was with 'late' sowing date. Luo et al. (2009) ran experiments to quantify the potential impacts of climate change on wheat grain yield and evaluate the effectiveness of early sowing, changing the N application rate and use of different wheat cultivars driven by the APSIM-Wheat model package for studying climate impacts for Keith, South Australia. In their study, early sowing was suggested as an effective adaptation strategy when initial soil water was reset at 25 mm at sowing time, although this may not be an optimal recommendation, since drier future conditions were projected.

CERES-Wheat simulates phenological development; growth of grains, leaves, stems and roots; biomass accumulation based on thermal time accumulation; soil water balance; and soil N transformations and uptake by wheat. The growth period responds to temperature and photoperiod and this varies among cultivars; as such, genetic coefficients are used as model inputs to determine these differences. Thus, temperature plays a key role in vegetative growth and tiller development, though environmental factors such as water and nutrient stress are also linked to plant growth and development. Daily biomass production in the model is calculated using a radiation-use efficiency algorithm based on photosynthetically active intercepted radiation (Arora et al. 2007). The assimilate distribution between the plant organs is based on an empirical sink-source concept. Water and N stresses are defined as the negative impacts between the responding resource availabilities, although the development curve in CERES-Wheat mainly responds to temperature and day length (Jones et al. 2003). Grain yield is estimated from simulated grain weight, grain number, and ear number per unit area. The number of grains is determined from the estimated biomass accumulation during a thermal time phase before flowering. Grain weight is related to optimum growth and air-temperature-dependent length of the grain-filling period. Grain filling is reduced by empirically defined deficiency factors which are applied when stresses shift daily biomass production to suboptimal levels.

CERES-Wheat is also able to simulate the direct physiological effects of increased atmospheric CO_2 concentrations on plant photosynthesis and water use based on experimental data (Southworth et al. 2002). In accordance with Tubiello et al. (2007), the response ratios of the CERES model change almost linearly with CO_2 concentrations from 330 ppm to about 660 ppm, but decrease at higher levels, reaching an equilibrium of 1.5 beyond 1000 ppm. This relationship is consistent with results from FACE experiments (Kimball et al. 2002). The CERES-Wheat model only simulates positive feedbacks from the physiological effects of increased atmospheric CO_2 concentrations on crop growth and water use (Rosenzweig et al. 1994). However, the CERES-Wheat model, as with all crop models, has limitations in its ability to represent the impacts of extreme weather events, which may generally result in underestimation of yield losses (Rosenzweig & Iglesias 1998, Yao et al. 2007). In addition, CERES-Wheat does not account for the impact of possible changes in plant diseases, pest damage or weed competition (Hoogenboom et al. 1995), which may be important in a changing climate.

The input dataset for CERES-Wheat simulations include weather and soil conditions, plant characteristics, and crop management options. The minimum weather dataset required is daily maximum and minimum temperature, total precipitation, and solar radiation. Soil input data consist of soil albedo, soil water coefficients for evaporation, drainage and run-off and per-layer coefficients including water retention variables, root growth, bulk density, organic carbon and texture information. Crop genetic inputs include coefficients related to photoperiod sensitivity, duration of grain-filling rates and vernalisation requirements. The main management inputs include planting date and seed density (see Sections 2.3, 2.4 and 2.5).

To assess the ability of CERES-Wheat to reproduce trends in current UK winter wheat yields, an experimental run was performed and compared to observed data (1999–2009) from the continuous wheat section in the Broadbalk experiment of UK Rothamsted Research (51.82° N, 0.35° W) located in Harpenden, Hertfordshire, eastern UK (Rothamsted Research 2006). In the validation experiment, winter wheat (Cultivar: Hereward) was planted between September and November with a seed rate of 350 to 450 seeds m^{-2}. N-fertilisation was applied at 4 treatment levels (48, 96, 144 and 192 kg ha^{-1} yr^{-1}) based on the actual experimental treatments at Broadbalk. Soil texture was silty-clay loam over 1 m depth and meteorological variables were taken from experimental site data measured by an Automatic Weather Station (AWS). We used a general genotype, European winter wheat in DSSAT v4.0 to represent the cultivar, Hereward. Hereward is one of the most popular winter wheat varieties planted in the UK. Our aim was to assess the ability of CERES-Wheat to reproduce observed crop yields and development with a generic variety which would then be applied across the UK in the climate impact analysis. Southworth et al. (2002) performed a similar study for the Midwest in the USA, also applying a generic cultivar for the validation run and future simulations; in their study of future winter wheat yields for the UK, Ghaffari et al. (2002) also applied the same cultivar for baseline and future conditions, and in addition used their calibrated cultivar characteristics for Mercia to assess model performance against the observed yields of the variety Maris Funden at Rothamsted.

2.3. Climate data

Ensembles of climate model simulations are required for assessments of climate change in which climate uncertainties are quantified (Collins et al. 2011). The use of such ensembles in climate impacts assessments is a relatively new technique and here allows the investigation of climate-related uncertainties in climate impacts on winter wheat yield in the UK for the first time.

In the present study we used climate projection data from a PPE of 11 RCM simulations (HadRM3 at 25 km horizontal resolution) which formed part of the UKCP09 projections. The PPE in the climate models that were used as a basis for UKCP09 took into account different key climate model parameter values, for example to account for incomplete knowledge of the 'actual' values of these parameters. Consequently the PPE was created to allow better quantification of uncertainties arising from representation of modelled physical processes in climate model projections (Moore et al. 2001).

For this PPE, experts identified those parameters that controlled the key physical processes in the model and were therefore likely to have an effect on the model projections. Thirty-one parameters were selected for perturbation, representing layer cloud, convection, radiation, atmospheric dynamics, boundary layer, land surface and sea-ice. Since HadCM3 (GCM, the third version of the Hadley Centre climate model) is expensive to run, this ensemble was constructed from HadSM3 models (an equilibrium slab model version of HadCM3 coupled to a simple ocean). Each model used a combination of parameter values that systematically sampled part of the plausible prior parameter range (Murphy et al. 2007). Eleven RCM simulations were then performed using

Table 2. Generic soil profiles used for the simulation. SALB: albedo, SLU1: evaporation limit, SLDR: drainage rate, SLRO: run-off curve number, SLNF: soil mineralisation factor, SLPF: growth limiting factor other than nitrogen, SMHB: pH (code given), SMPX: phosphorus extraction method, SMKE: potassium extraction method (code given), SLB: depth (cm), SLLL: drained lower limit of soil ($cm^3 cm^{-3}$), SDUL: drained upper limit of soil ($cm^3 cm^{-3}$), SSAT: saturated upper limit of soil ($cm^3 cm^{-3}$), SRGF: root growth factor, SBDM: bulk density ($g cm^{-3}$), SLOC: organic carbon (%), SLCL: clay (%), SLSI: silt (%), SLCF: coarse fraction (%), SLNI: total nitrogen (%), SLHW: pH in water, IB: International Benchmark Sites Network for Agrotechnology transfer. Source: Hoogenboom et al. (2004)

Silty loam (deep)											
SALB	SLU1	SLDR	SLRO	SLNF	SLPF	SMHB	SMPX	SMKE			
0.12	6.0	0.40	77.0	1.00	1.00	IB001	IB001	IB001			
SLB	SLLL	SDUL	SSAT	SRGF	SBDM	SLOC	SLCL	SLSI	SLCF	SLNI	SLHW
5	0.110	0.227	0.450	1.000	1.37	1.16	10.0	60.0	0.0	0.120	6.5
15	0.110	0.227	0.450	1.000	1.37	1.16	10.0	60.0	0.0	0.120	6.5
30	0.103	0.201	0.451	0.638	1.37	1.10	10.0	60.0	0.0	0.110	6.5
45	0.099	0.193	0.452	0.472	1.37	0.97	10.0	60.0	0.0	0.100	6.5
60	0.099	0.193	0.452	0.350	1.37	0.97	10.0	60.0	0.0	0.100	6.5
90	0.088	0.173	0.450	0.223	1.38	0.72	10.0	60.0	0.0	0.070	6.5
120	0.079	0.165	0.452	0.122	1.38	0.43	10.0	60.0	0.0	0.040	6.5
150	0.086	0.178	0.450	0.067	1.39	0.20	10.0	60.0	0.0	0.020	6.5

parameter settings consistent with those in the relevant driving HadCM3 simulation. The boundary conditions that drive the RCM ensemble are a PPE version of the fully coupled global ocean-atmosphere climate model HadCM3 forced with a medium emissions scenario (SRES A1B; Collins et al. 2011).

In the present study, area-averaged climate variables (daily maximum and minimum temperature, daily mean solar radiation and total precipitation) over 13 UK administrative regions are calculated from each of the 11 RCM ensemble members for 30 yr time slices (2020s: 2010 to 2039; 2050s: 2040 to 2069; and 2080s: 2070 to 2099) and for the baseline period (1971 to 2000).

2.4. Soil and cultivar data

Soil input data in CERES-Wheat v4.0 consist of soil profile properties and are used in the soil water, N, phosphorus (P) and root growth calculations of the CERES-Wheat crop simulation model (Hoogenboom et al. 2004). Each soil profile includes physical and chemical information such as soil albedo, drainage and run-off coefficients, mineralisation and photosynthesis factors and texture, etc. Daily soil water balance is simulated in relation to rainfall and irrigation, run-off, infiltration, transpiration, soil evaporation and drainage from the soil profile.

In the present study focusing on potential winter wheat yield in the UK, soil texture (silty loam) is applied as in Ghaffari et al. (2002), where it showed the highest and most sustained yields compared with clay or sandy soils. Soil depth is assumed to be 150 cm for wheat fields in the UK (Table 2) (Rothamsted Research 2006).

CERES-Wheat requires cultivar information (genetic coefficients) including the genetic nature of development and growth to simulate characterisation among varieties of a particular crop. These parameters include thermal days for vernalisation, photoperiod sensitivity and grain-filling duration (Table 3). The number of growing leaves is a function of leaf appearance rate and duration of grain filling (P5). Organ extension depends on potential organ growth, and is limited by suboptimal temperature and water and N stresses. Partitioning coefficients of dry biomass in plant parts are influenced by phasic development. Grain yield is simulated as the product of grain number (G1), plant population, and grain mass at physiological maturity (G2) (Hunt et al. 1993).

Table 3. Genetic coefficients of European winter wheat simulated using CERES-Wheat v4.0. P1V: days at optimum vernalising temperature required to complete vernalisation; P1D: percentage reduction in development rate in a photoperiod 10 h shorter than the threshold relative to that at the threshold; P5: grain filling (excluding lag) phase duration; °D: degree days; G1: kernel number per canopy weight at anthesis; G2: standard kernel size under optimum conditions; G3: standard non-stressed dry weight (total, including grain) of a single tiller at maturity; PHINT: interval between successive leaf tip appearances

P1V (d)	P1D (%)	P5 (°D)	G1 (n)	G2 (mg)	G3 (g)	PHINT (°D)
60	75	500	30	40	1.5	95

Table 4. Configuration of experiments. N: nitrogen, RCM: regional climate model

Experiment	Climate data	Sowing date	N application (kg ha^{-1} yr^{-1})
Sensitivity analysis	Unperturbed (2080s); temperature only; precipitation only; CO_2 only	Intermediate (10 Oct)	Medium (200)
Impact of climate change	Perturbed (11 RCMs)	Intermediate (10 Oct)	Medium (200)
Impact of management practices	Unperturbed	Early (10 Sep) Intermediate (10 Oct) Late (10 Nov)	Medium (200)
	Unperturbed	Intermediate (10 Oct)	Low (150) Medium (200) High (250)

Genetic coefficients are thus estimated specifically for each cultivar using the Genotype Coefficient Calculator (GENCALC, Hunt et al. 1993), which is one of the sub-modules in DSSAT (in earlier versions than 4.0). Some studies suggest that genetic coefficients are not only site-specific (Gabrielle et al. 2002), but also year-specific (Overman et al. 1992). The present study did not focus on specific sites but rather on the spatial and temporal variations in UK wheat yields under future projected climate across broad regions. As such we used the generic parameters for both soil coefficients (generic soil profile, Table 2) and cultivar genotype (winter European wheat, Table 3) from DSSAT version 4.0.

2.5. Experiments

The input variables described in Sections 2.2, 2.3 and 2.4 are used together with CERES-Wheat to calculate an ensemble of winter wheat yield projections over the UK during the 21st century. Two main sets of experiments were run to separately assess the effects of climate change and management effects, with the aim of providing useful information for future adaptation needs.

2.5.1. Effects of climate change

The first set of experiments utilised climate data from all 11 RCM ensemble members in order to assess the impact of uncertainties in projected climate on UK crop yields. Management parameters such as planting dates and fertiliser application rates and timings were held constant.

We also performed a sensitivity analysis of climate change on winter wheat yield. The sensitivity analysis only used data from the unperturbed RCM (rather than the 11 member ensembles). We altered individual climate variables (temperature, precipitation and CO_2) singly, in order to assess their importance for future yield changes.

2.5.2. Effects of management parameters

The second set of simulated experiments applied varying management parameters in order to assess the potential impact of management factors on wheat yields under a future climate. As discussed in Section 2.1, an adaptation response to higher annual temperatures may be earlier cultivation in order to maximise vegetative growth during the cooler early season and avoid high temperatures in the grain-filling period, while altered fertiliser applications may be necessary to take full advantage of the CO_2 fertilisation effect, and to compensate for potential yield losses caused by climate change (e.g. Ghaffari et al. 2002, Hulme et al. 2002, Yao et al. 2007). These simulations used climate data from a single RCM ensemble member (the 'unperturbed' simulation). Configurations of the main experiments are shown in Table 4. Sowing dates follow Ghaffari et al. (2002) and Torriani et al. (2007). N applications (kg ha^{-1} yr^{-1}) follow the Broadbalk experiment (Rothamstead Research 2006) and survey of fertiliser levels in use on UK farms (Thomas 2009). During development and growth, irrigation was not considered because an annually wetter future UK climate was projected (Jenkins et al. 2009; see also Section 3.2 in the present study).

In all simulated experiments, P and potassium (K) (35 and 90 kg ha^{-1} yr^{-1}, respectively) were both applied at planting time. Magnesium (12 kg ha^{-1} yr^{-1} at all treatment levels) was also applied in March the following year.

The same seed numbers were applied for all planting dates (350 m^{-2}) and an absence of all pests, weeds and insects was assumed. All simulations also included the physiological effects of increasing atmospheric CO_2 concentrations on the crop. CO_2

concentrations followed the IPCC SRES A1B pathway as follows: 347 ppm in the period 1971 to 2000 as baseline, 418 ppm from 2010 to 2039, 523 ppm from 2040 to 2069 and 634 ppm from 2070 to 2099.

3. RESULTS AND DISCUSSION

3.1. Validation

Physiological maturity days were reasonably simulated ($R^2 = 0.68$) during the simulation period (1999 to 2009; Fig. 2); however, grain yields were generally overestimated ($R^2 = 0.56$). These overestimated yields may have been because our simulation represents maximum potential yield at physiological maturity without any losses due to diseases, insect pests or weeds. Differences between observed and simulated yields may also be a consequence of CERES-Wheat's response to non-optimal N-fertilisation levels, since the modelled response to N-fertilisation differed between years. In addition, we used a generic cultivar in CERES-Wheat, rather than a calibrated site-specific variety (i.e. Hereward) since the aim was to assess model skill for a generic cultivar for broader application in the UK impact assessment rather than perform a detailed, calibrated validation study.

Simulated maturity days were generally similar to, or slightly faster than, the observed rate of development (Fig. 2). In particular, the same days after planting (DAP) was estimated within each year since the development curve applied in CERES-Wheat mainly responds to temperature and day length; water and nutrient stresses have little effect (Jones et al. 2003). Fig. 3 shows how simulated and observed anomalies of yield vary from year to year. Whilst Fig. 3 shows that CERES-Wheat is not perfect, it has reproduced anomalies of the same sign as those observed in 7 of the 11 years. In contrast to simulated yield, the observed yield in 2002 strongly declined due to disease damage during spring 2002 (M. J. Glendining pers. comm.).

This validation exercise did not generally show very high agreement between CERES-Wheat and the observed data. As mentioned above in this section, this may be partly because the specific cultivar for Hereward in the Broadbalk experiment was not used; instead we applied a generic cultivar without specific tuning. Our study focused on winter wheat variability under future climate changes based on temperature and precipitation across the UK. A similar approach was applied by Ghaffari et al. (2002), who used their generically applied calibrated cultivar characteristics for Mercia to assess model performance against the observed yields of the variety Maris Funden at Rothamsted. Therefore, we consider that these validation results are acceptable for the purposes of this study.

3.2. Climate variability and uncertainties

Fig. 4 indicates the differences from baseline in 30 yr mean maximum and minimum temperatures during the 3 periods in the future. Across the UK, 30 yr mean daily maximum temperature is projected to increase by between 0.8°C (NS region) and 1.7°C

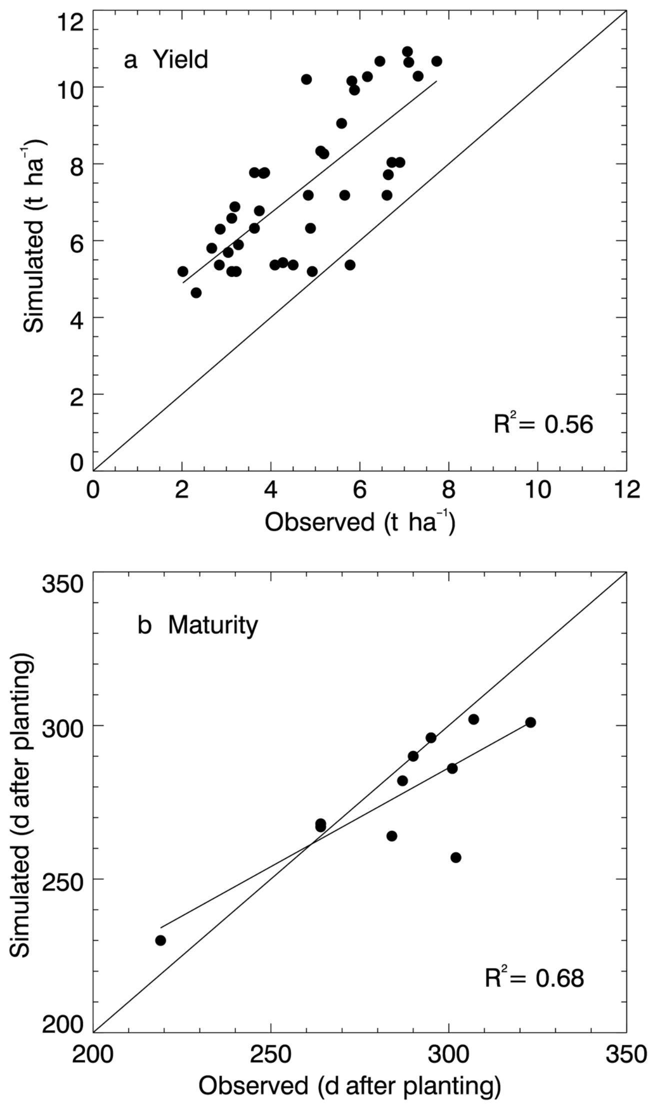

Fig. 2. Comparison between simulated and observed (a) yield of winter wheat (Cultivar: Hereward) and (b) physiological maturity. Observed data are from nitrogen fertiliser application treatments in Broadbalk field, Rothamsted during 1999–2009

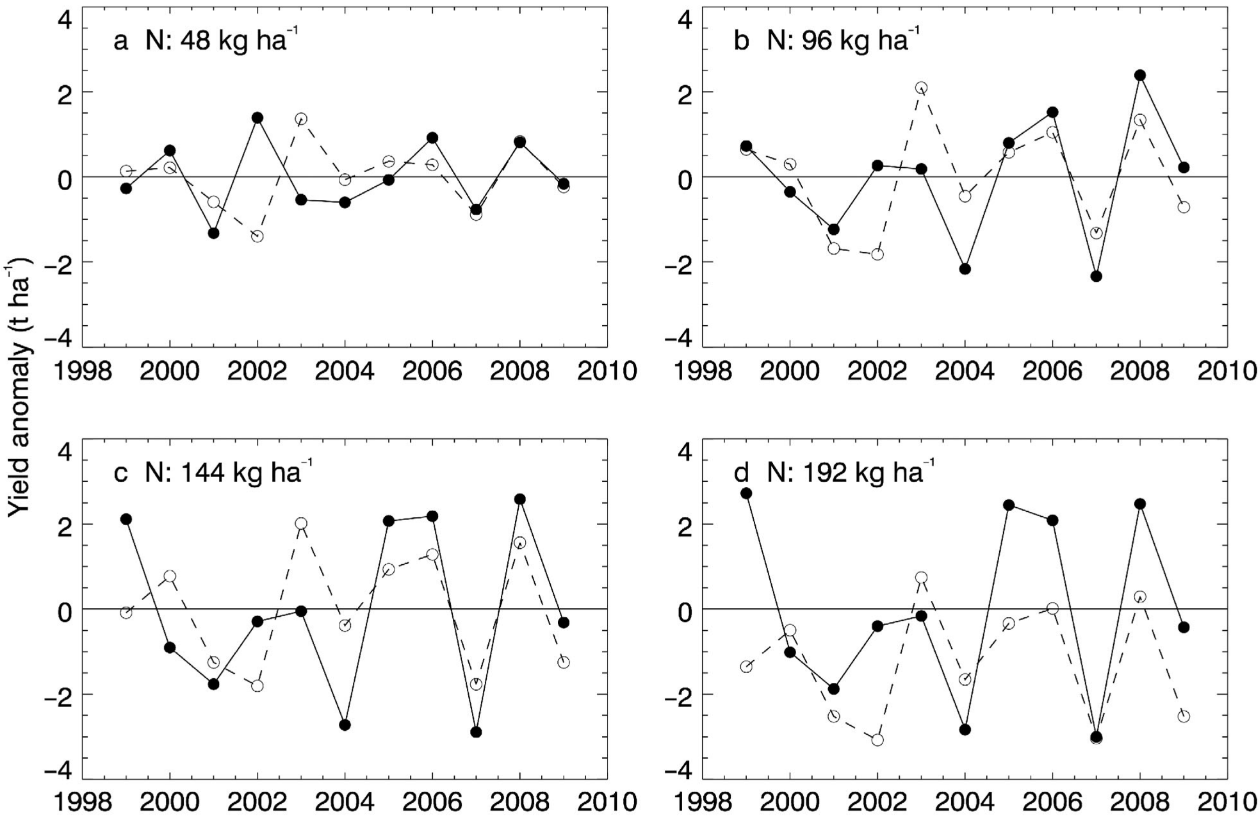

Fig. 3. Yield anomalies in winter wheat yield responses to 4 different amounts of nitrogen (N) fertiliser (a: 48, b: 96, c: 144 and d: 192 kg ha^{-1}) during 1999–2009. Simulated (●) and observed (○) data are shown

(EE) in the 2020s; 1.6°C (NS) and 3.0°C (WM) in the 2050s; and 2.3°C (NS) and 4.6°C (SE) in the 2080s. Corresponding mean daily minimum temperature increased by between 0.8°C (NE, NI, NS and YH regions) and 1.8°C (SE) in the 2020s; 1.8°C (NI and NS) and 3.0°C (SE) in the 2050s; and 2.9°C (SE) and 4.5°C (SE) in the 2080s. The rate of increases in both 30 yr mean maximum and minimum temperatures shows similar trends through the 3 time periods, and was greatest in the northern UK region. Temperature differences from the baseline also increased with time period, and as a result climatic uncertainties increase in the future.

Fig. 5 shows the changes from baseline in 30 yr mean precipitation during the 3 time periods. The UKCP09 projections suggest an annually wetter future UK climate than the baseline. Changes range from 5.5% (EE region) to 24.9% (SE) in the 2020s; −0.2% (EE) to 21.6% (NE) in the 2050s; and −3.4% (SW) to 25.3% (ES) in the 2080s. In the 2080s, reductions in annual precipitation occur in southern parts of the UK (notably in the SW, SE, Wa, EM and WM regions). The 30 yr mean precipitation changes are mostly dominated by winter-time changes. According to UKCP09 (Jenkins et al. 2009), precipitation decreases of between 10 and 30% are likely in summer in the UK, and increases of between 10 and 30% in winter (depending on regions) during the 2080s.

Wheat is able to grow under various environmental conditions; from temperate, high rainfall to dry and from warm, humid to dry, cold areas. However, wheat requires optimal temperatures for proper development and growth. In particular, winter-type wheat has a strong response to vernalisation in its early development (Harrison & Butterfield 1996) and requires a period of cold weather to flower, and cardinal temperatures (minimum, maximum and optimum for growth) for photosynthesis, and grain filling. Fig. 6 shows 30 yr averaged monthly temperatures of baseline and 2080s in 4 regions (NS, YH, EE and SW). According to the CERES-Wheat model, winter wheat requires temperatures between −5 and 15°C with an optimum temperature range of 0 to 7°C for vernalisation, and between 0 and 45°C with an optimum temperature range of 16 to 35°C for grain filling (Evans et al. 1975, Hoogenboom et al. 2004). In the

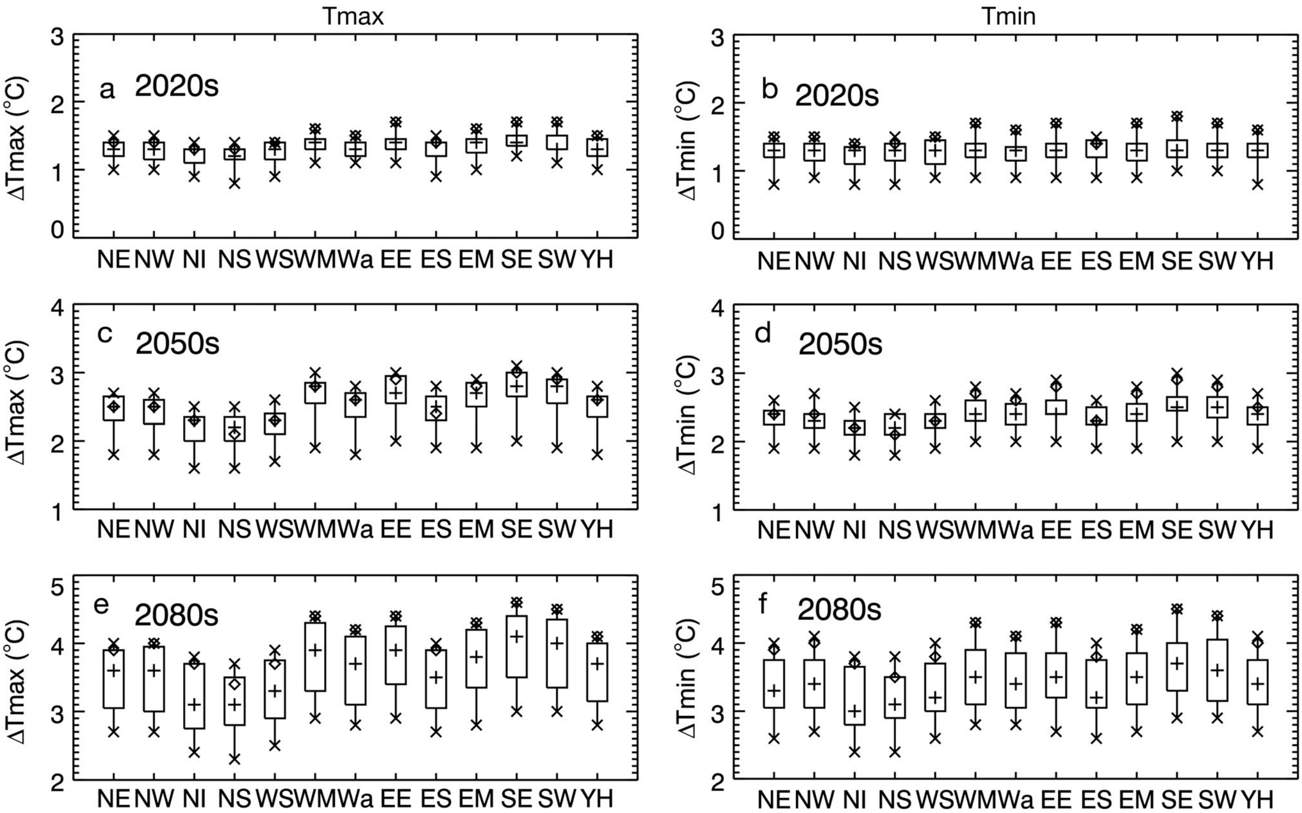

Fig. 4. Changes in 30 yr mean maximum and minimum temperature (Tmax, and Tmin) from baseline scenarios (1971–2000) in the 13 main administrative regions during (a,b) 2010–2039, (c,d) 2040–2069 and (e,f) 2070–2099. Box: 25th and 75th percentiles; (×) maximum and minimum values of 11 regional climate model ensembles. Median value of the entire ensemble (+) and the value of the unperturbed simulation (◇) are also shown. See Table 1 for region abbreviations

2080s, warmer winter temperatures are projected to cause a reduced duration within the optimal temperature range for vernalisation. This reduction varied regionally and ranged from the lowest decrease in duration of 1 mo (NS region) to the greatest decrease of 3 mo (YH), assuming a fixed sowing date.

Under a baseline climate, a few regions did not reach the lower optimal temperature range for grain filling in June to August. In the 2080s, monthly mean temperatures are projected to increase toward the optimal grain-filling temperature range but not to exceed it. As such, climate change has a relatively small impact on grain-filling duration, especially when compared to other development periods, such as maturity duration. It is possible that extreme temperature events may lead to yield decreases depending on their frequency, intensity and persistence; however, we cannot analyse how winter wheat will respond to extreme weather here, because we only used 30 yr averaged temperatures and precipitation. For this reason, further study focusing on extreme weather events would be useful.

3.3. Sensitivity of yield to climate change

Fig. 7 shows the sensitivity of potential yield to temperature (maximum and minimum), precipitation and CO_2 relative to the baseline climate using the unperturbed RCM simulation.

Increases in temperature alone improved grain yields compared to the baseline in 9 administrative regions (mostly in the north), whilst yields showed declines in more southerly regions (WM, Wa, SE and SW). In the latter southerly regions, the rate of development and grain filling generally showed an increase, resulting in lower eventual yields. Also, minimum temperature during winter-time is projected to increase (Jenkins et al. 2009) which may lead to decreases in optimal vernalisation duration, and thus reduce yields (Southworth et al. 2002).

For example, in the SW region, warmer winter temperatures are projected to cause reduced duration within the optimal temperature range for vernalisation (Fig. 6), with approximately 4 mo being within this range during the baseline period and increases

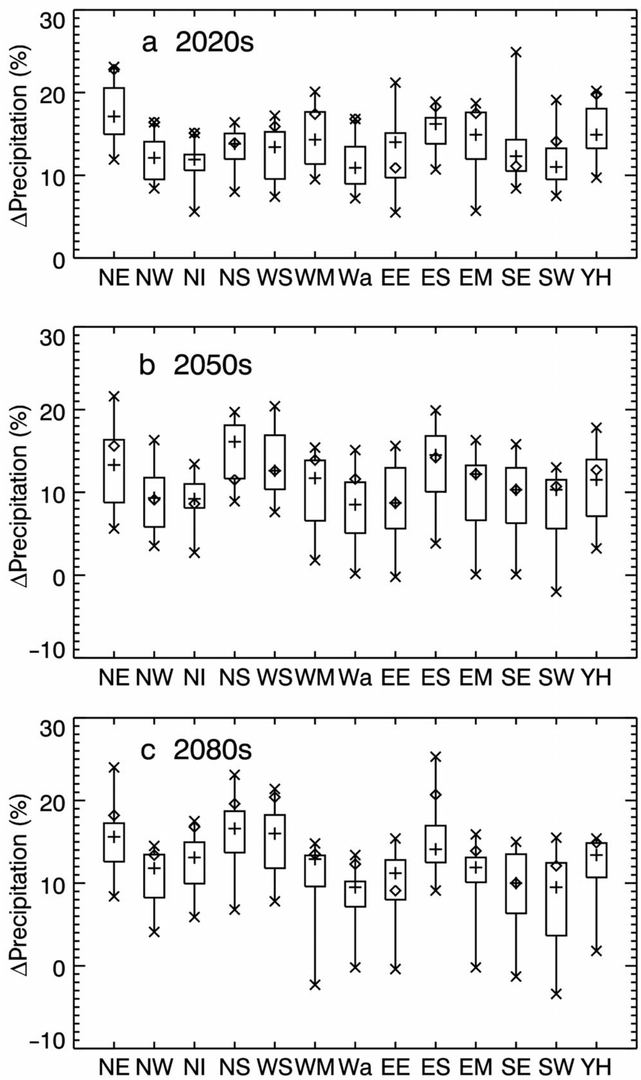

Fig. 5. Same as Fig. 4, but for changes in 30 yr mean precipitation from baseline scenarios

to temperatures, largely within the optimal range for all ensemble members by the 2080s. In the SW region, June to August temperatures also increased toward the optimal range for grain filling but did not exceed it, which may partly explain the relatively small impact of climate change on grain filling (Fig. 6). In addition, the relatively small future reduction in grain-filling duration (see Fig. 8) in this region may therefore explain the low sensitivity of yield changes to higher future temperatures. Since yields in the SW region did not show a strong response to changes in N-fertilisation rate (see Section 3.5.1 and Fig. 11), it seems unlikely that N stress was a key factor in determining future yields in this region.

Leaf area index (LAI) is also an important crop growth index for maximum dry matter production of cultivated crops. For the 2080s period, compared to the baseline climate, LAI generally decreased throughout all growth periods over the UK, mainly due to higher temperatures without considering the influence of altered N-fertilisation, or water and pest stresses. At the stage of terminal spikelet, LAI decreased between approximately 40% (NS and SW regions) and 70% (NW and YH). However, by the beginning of grain filling and in some regions (NS, WS, and ES), LAI recovered to some extent, showing smaller decreases of around 10% compared to baseline. Decreases in LAI in the 2080s relative to the baseline were generally similar or little improved in the other regions (WM, Wa, EE and EM). However, LAI in the SW region decreased from 40% at the stage of terminal spikelet to 70% at the beginning of grain filling, showing a different trend to that observed in other regions (Fig. 7b). Therefore, future LAI decreases may have been a significant factor in determining overall reductions in potential grain yield for southern regions, due to temperature increases beyond critical maximum values.

Applying only precipitation changes relative to the baseline decreased yields by approximately 10% in 7 regions; small positive yield changes occurred elsewhere. Crop yield responses to increased CO_2 concentration were always positive (in agreement with Tubiello et al. 2007), with yield increases of over 20% projected for the central, middle and eastern parts of the UK, compared to yields under baseline CO_2 concentrations (347 ppm). Temperature changes rather than precipitation changes appear to give the greatest regionally varying changes in yield.

These results suggest that temperature increases could have a larger impact on potential winter wheat yields in the UK than projected precipitation changes in the future. Elevated CO_2 concentration could potentially partially compensate for any decreases in potential yield due to future projected temperature and rainfall changes, as found by Ghaffari et al. (2002). In particular, the decrease in potential yield is reduced due to the beneficial effects of elevated CO_2 in southern and western regions (Wa and SW).

3.4. Impacts of climate change on UK winter wheat

3.4.1. Development changes

Our study suggests that the rate of winter wheat development over the UK may accelerate in the future, compared to the baseline period. This was a robust result across all members of the regional

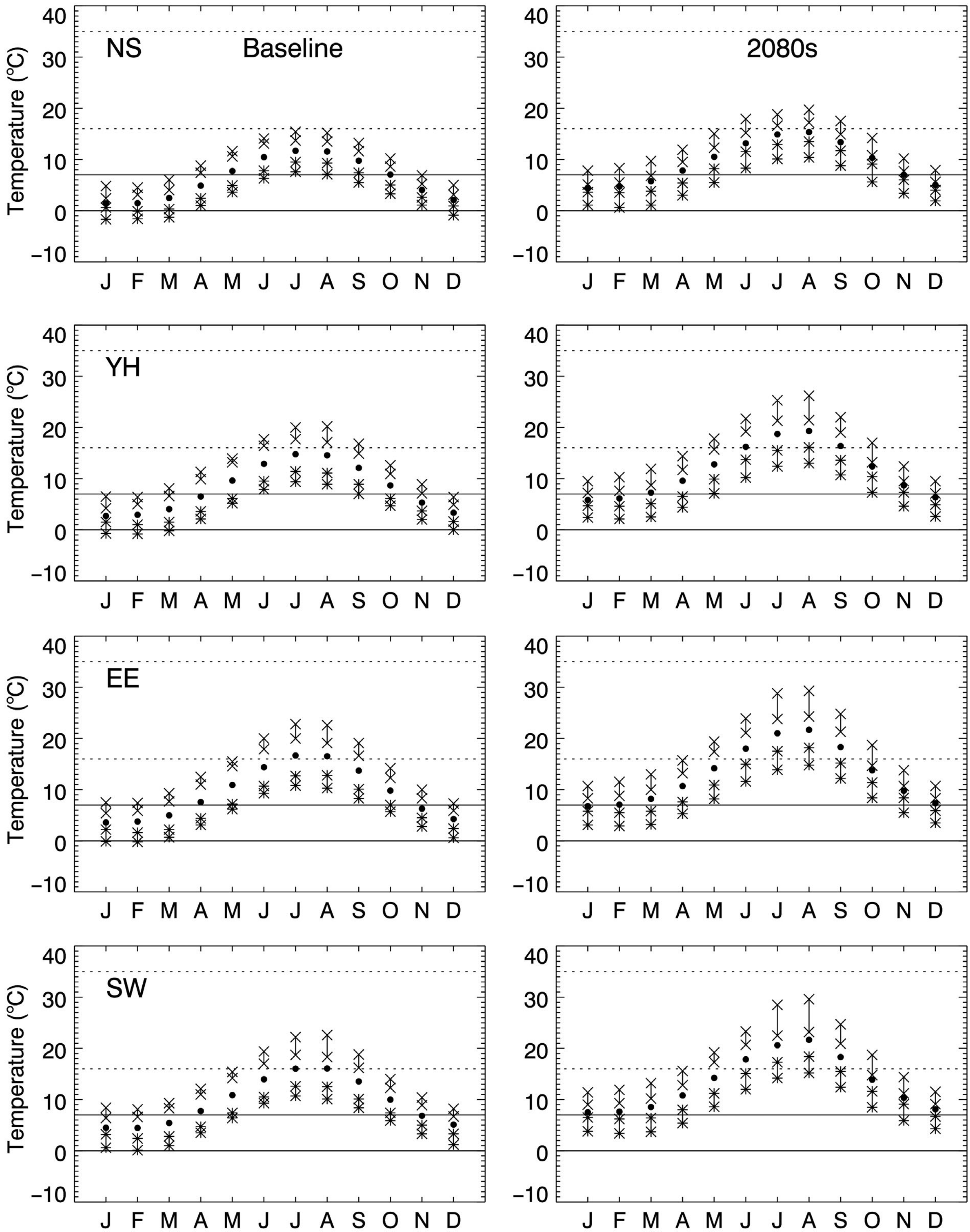

Fig. 6. Thirty-year mean monthly temperatures of (left column) baseline (1971–2000) and (right column) the 2080s (2070–2099) in 4 regions. (×) and (✳): maximum (upper) and minimum (lower) values of maximum and minimum temperature in the 11 regional climate model (RCM) ensembles, respectively. (●): Averaged mean temperature of the 11 RCM ensembles. Solid lines: upper (0°C) and lower (7°C) optimal temperatures of vernalisation; dotted lines: upper (16°C) and lower (35°C) optimal temperatures of grain filling, respectively. See Table 1 for region abbreviations

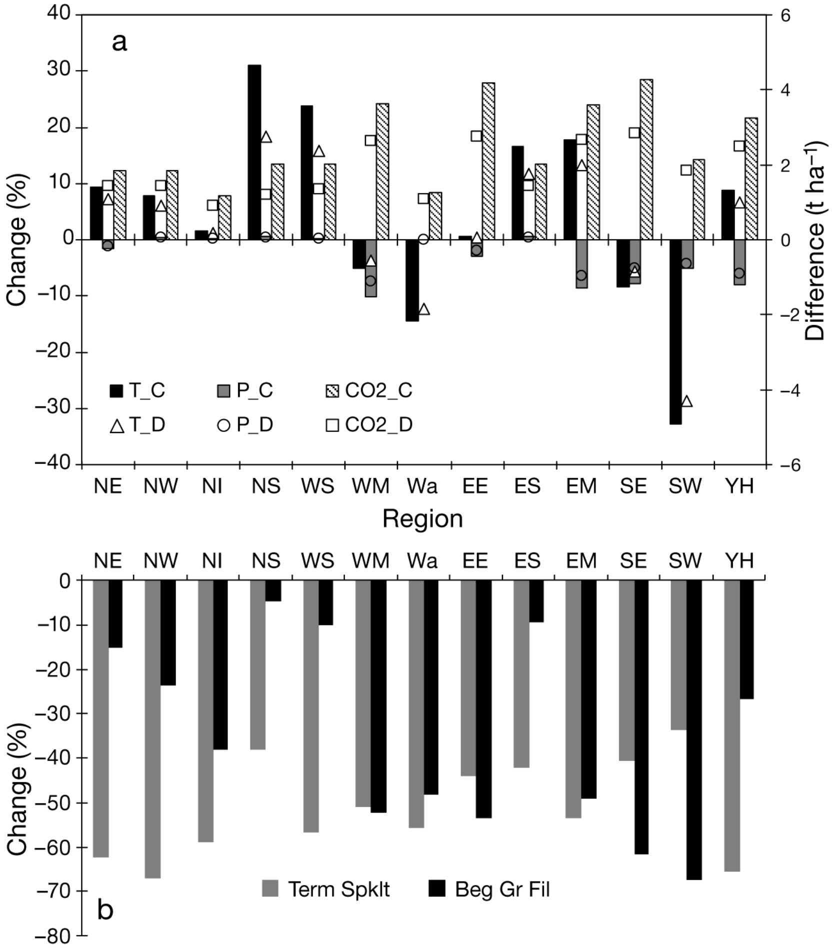

Fig. 7. (a) Relative changes and differences in winter wheat yield in response to altering individual climate variables using the unperturbed simulation. T_C (relative change) and T_D (absolute difference) are maximum, minimum temperature (2080s) + precipitation, CO_2 (baseline). P_C (change) and P_D (difference) are precipitation (2080s) + maximum and minimum temperature, CO_2 (baseline). CO2_C (change) and CO2_D (difference) are CO_2 (2080s) + maximum, minimum temperature, precipitation (baseline). (b) Changes in leaf area index (LAI) in response to maximum and minimum temperature (2080s) + precipitation and CO_2 (baseline) using the unperturbed simulation. Term Spklt: terminal spikelet stage, Beg Gr Fil: beginning of grain-filling stage. See Table 1 for region abbreviations

model ensemble, although the magnitude of acceleration varied. The flowering season advances for all future time-slices when compared to the baseline (Fig. 8). Reductions in time to flowering ranged between 4 d (Wa region) and 15 d (NS) in the 2020s; 12 d (NI, Wa and EE) and 23 d (NS and ES) in the 2050s; and 16 d (EE) and 34 d (NS) by the 2080s. The heading date of winter wheat is governed primarily by temperature, and earlier heading or flowering dates mostly indicate higher temperatures in the spring (Hu et al. 2005). As the heading date shortened in our simulations, the maturity duration also decreased from 10 d to 2 mo (data not shown). This is in agreement with previous studies (Harrision & Butterfield 2000, Tubiello et al. 2000, Trnka et al. 2004). Particularly large decreases in heading and physiological maturity occurred in northern regions of the UK (NS, ES and WS). Other authors have found the rate of physiological maturity to be more sensitive to increases in temperature than the rate of heading (Brown & Rosenberg 1997, Tubiello at al. 2000). They reported that temperature increases mostly accelerated phenological development for all crops, and specifically shortened the time to maturity.

Grain filling plays a critical role in determining final yield because grain dry weight increases rapidly during this period. It has therefore been suggested that high temperatures during grain filling may reduce the grain growth period, which may impact on the photosynthetic phase, and thus the source of carbon may become limiting (Richards 1996, Wheeler et al. 1996b). The rate of grain filling increased in the future and as such the duration of grain filling was reduced compared to baseline, with decreases ranging from a few days in the 2020s to 1 mo in the 2080s. Although changes varied across the 11 RCMs, the grain-filling duration decreased consistently with time (Fig. 8). However, the grain-filling duration in the future declined less than maturity duration.

Generally, development rates (heading, maturity and grain-filling duration) were rapidly reduced over the UK, particularly over the west and north of the country, because the rate of development in CERES-Wheat responds to a positive linear function of temperature.

3.4.2. Yield changes

Fig. 9 shows the changes in potential yield during the 3 future periods under elevated CO_2 concentrations and future projected climate change. We generally find that climate change positively affects final yield, which is agreement with a previous study based on the earlier UKCIP02 climate change scenarios (Hulme et al. 2002). However, across the en-

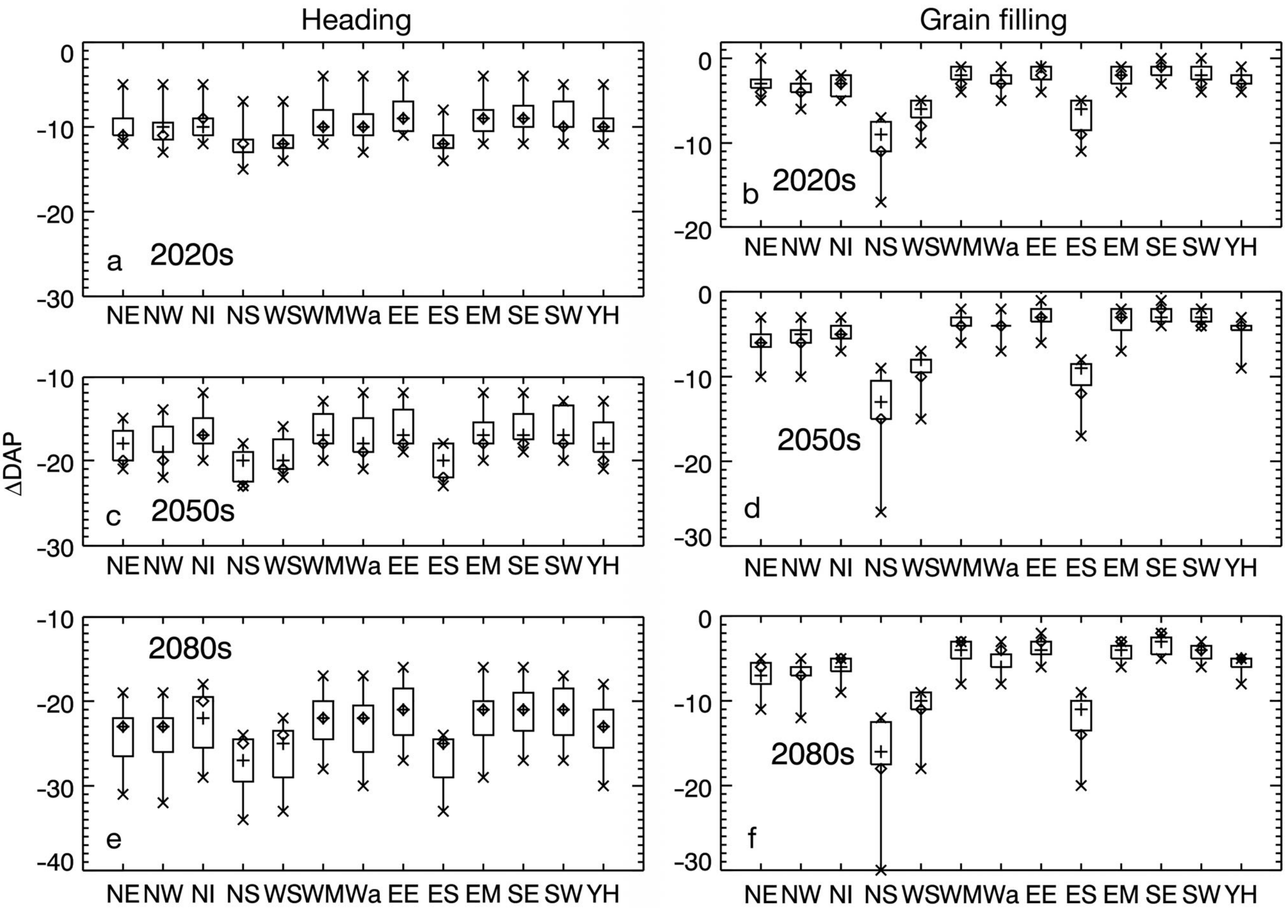

Fig. 8. Same as Fig. 4, but for change in days after planting (DAP) of heading date from baseline scenarios and for differences in grain-filling duration of winter wheat from baseline scenarios. Sowing date is 10 Oct (intermediate) and nitrogen application is supplied at 200 kg ha^{-1} yr^{-1} ('medium' application)

semble, the range of yield changes was large, suggesting that this result is less robust than the impact of climate change on accelerating crop development, which shortened growing seasons and reduced yields in southern regions. Uncertainty in projected yields also increases with time, being greatest in the 2080s. This is not unexpected as the range of uncertainty in the climate model output also increases with time.

Both controlled environment experiments (Wheeler et al. 1996a, Dijkstra et al. 1999) and modelling simulations (Ghaffari et al. 2002, Southworth et al. 2002) have shown positive impacts of climate change on winter wheat. These studies suggested that the combination of warmer winters and elevated atmospheric CO_2 increased rates of photosynthesis and water-use efficiency, resulting in increased plant biomass and crop yields.

There was considerable regional variation in projected yield changes, with increases projected for the north and Scotland and decreases for the south and west. From the RCM ensemble members, the highest regional rates of increase in yields were 39.6% (WM region) in the 2020s; 30.6% (NE) in the 2050s; and 65% (NS) in the 2080s relative to baseline conditions. The highest regional rates of decrease in yield during the 3 periods were 16.8% (SW region) in the 2020s; 32.9% (SW) in the 2050s; and 35.2% (NI) in the 2080s. Differences between regions were generally greater in the 2080s compared to the 2050s (and 2020s), reflecting greater uncertainty in overall UK yields by the end of the century.

In contrast to the rate of reduction in heading and maturity duration, decreases in grain-filling period showed little sensitivity to warmer future temperatures (Fig. 8). As a result, this small reduction in grain-filling duration may explain the low yield decreases due to increased temperature. According to a field experiment under temperature gradient tunnels with winter wheat cultivar Hereward (Wheeler et al. 1996b), the maximum rates of grain filling per ear during the grain-filling period occurred at 16°C

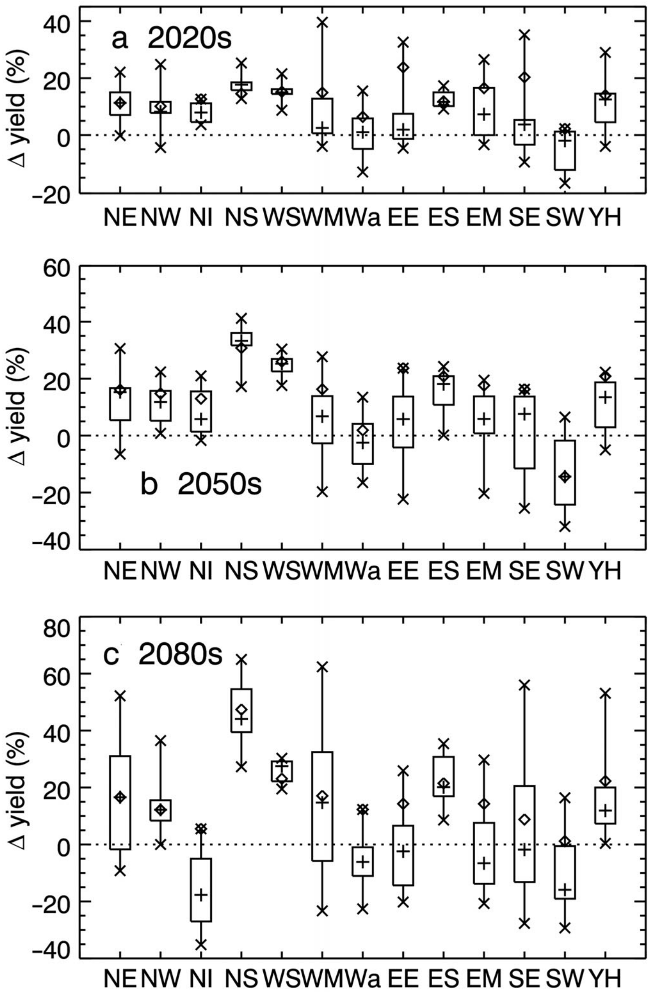

Fig. 9. Same as Figs. 4, 5 & 8, but for change in winter wheat yield from baseline scenarios

under ambient CO_2 concentrations (380 ppm) and at 18°C under doubled CO_2 concentrations (684 ppm). Wheeler et al. (1996b) also found that the rate of increase in grain dry weight per ear was 2.0 mg d^{-1} greater per 1°C increase in temperature, but that the number of grains per ear was similar at both normal and doubled CO_2 concentrations, as CO_2 enrichment did not affect the duration of grain filling.

Our simulations suggest that overall, UK winter wheat yield and production in the future will likely increase by the end of the 21st century, even though temporal and spatial uncertainty is considerable (Table 5, Fig. 9). For example, certain regions experienced strong decreases (>15%) in production during the later time-slice. This is presumably because of the well-known initial improvement in cool or temperate region yields for moderate warming and downturns in yield for stronger warming—the timing and sign of yield response will depend on the location (IPCC 2007, Gornall et al. 2010). However, changes to crop management may be needed to sufficiently fulfil vernalisation and maturity requirements, which also affect overall yield.

3.5. Impact of management practices on winter wheat yields

3.5.1. Temporal and spatial yield distribution

Figs. 10 & 11 show the temporal and spatial yield variation of changes (%) in sowing date and N-fertiliser application quantities over the UK using the unperturbed climate model simulation.

Table 5. UK winter wheat production and changes compared to the baseline using the unperturbed climate simulation. Observed data calculated using yield and area from the Defra cereal and oilseed production survey (Defra 2010). Simulated data calculated using area from the Defra cereal and oilseed production survey (Defra 2010) and mean potential yields for 3 different sowing dates (early, intermediate and late; see Table 4) without any loss. SC: Scotland. See Table 1 for other region abbreviations

Region	Observed (10^3 t) 1999–2009	Simulated						
		Baseline	2020s		2050s		2080s	
			Production (10^3 t)	Change (%)	Production (10^3 t)	Change (%)	Production (10^3 t)	Change (%)
SC (NS, WS, ES)	795	976	1145	17	1225	25	1290	32
NE	523	844	898	6	938	11	972	15
NW	177	365	383	5	394	8	403	10
NI	58	98	106	9	106	8	106	9
WM	1154	1810	1997	10	1997	10	2028	12
Wa	104	197	206	5	195	−1	192	−2
EE	1321	1882	2226	18	2226	18	2281	21
EM	4010	5841	6584	13	6584	13	6782	16
SE	1888	2517	2904	15	2831	13	2759	10
SW	2852	4837	4874	1	4188	−13	4079	−16
YH	1912	2903	3162	9	3304	14	3446	19
UK total	**14794**	**22270**	**24485**	**10**	**23988**	**8**	**24338**	**9**

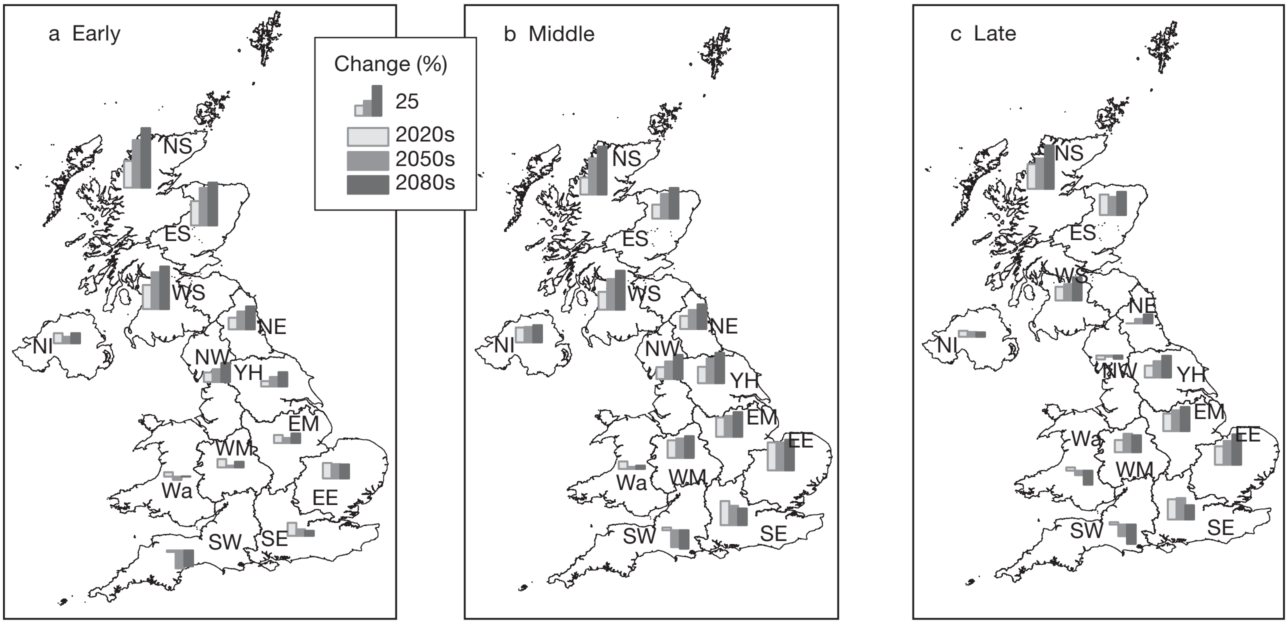

Fig. 10. Temporal and spatial variation of changes in winter wheat yield over the UK, based on the unperturbed simulation with different sowing dates (a: 10 Sep, b: 10 Oct and c: 10 Nov). See Table 1 for region abbreviations

Irrespective of sowing date, yield changes due to climate change showed some degree of spatial variability. Negative effects were clearly shown on yield over the southwest of England (Fig. 10). Effects were positive in most other regions, especially over Scotland for example, with increases exceeding 25%. Percentage increases in yield resulting from later sowing dates appear to be greater over eastern rather than western UK regions. Part of this may be due to our expression of results as a percentage resulting from very small yields during the baseline climate for middle and late sowings over eastern regions. Presumably, the relatively warm baseline in these regions meant that later sowing dates were not beneficial here. The largest absolute yields were predicted under the early sowing dates for all 3 time periods (Table 6).

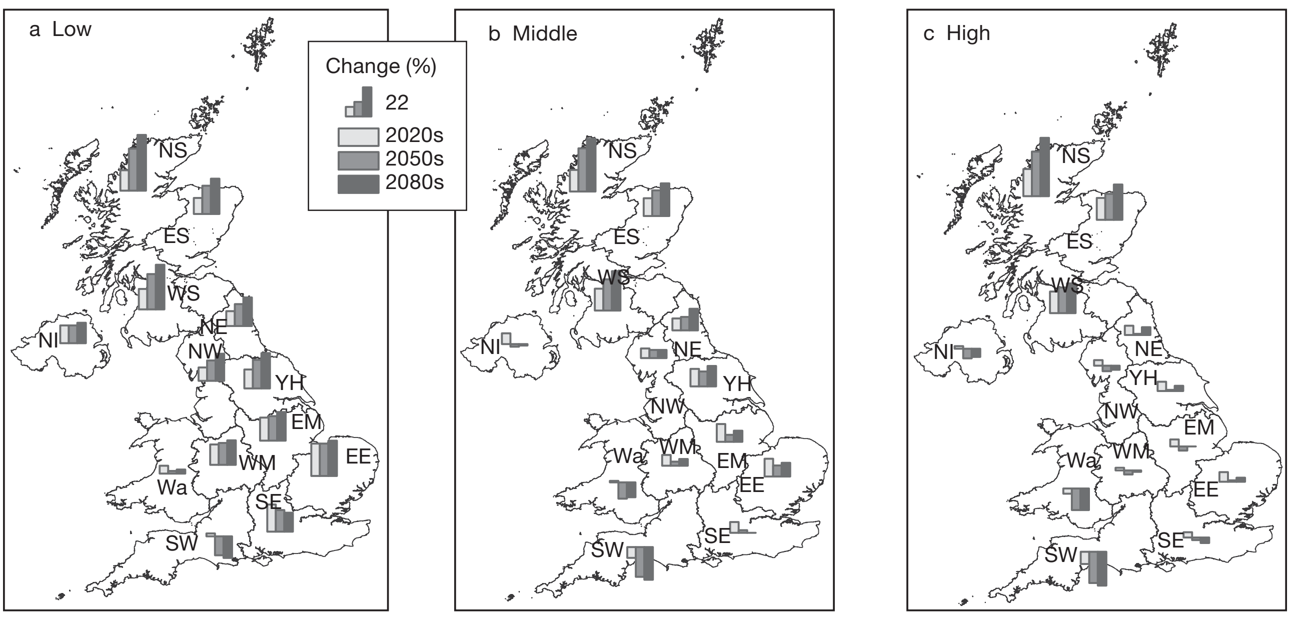

Fig. 11. Same as Fig. 10, but for different amounts of nitrogen fertiliser (a: 150, b: 200 and c: 250 kg ha^{-1})

Table 6. Regional distribution of winter wheat yields using the unperturbed climate simulation (t ha^{-1}). Sowing date: Early: 10 Sep, intermediate: 10 Oct, Late: 10 Nov. See Table 1 for region abbreviations

Region	Baseline (1971–2000)			2020s			2050s			2080s		
	Early	Intermediate	Late	Early	Intermediate	Late	Early	Intermediate	Late	Early	Intermediate	Late
NE	12.7	11.8	13.2	13.9	13.1	13.3	14.6	13.7	13.8	15.1	14.3	14.2
NW	12.6	11.7	13.4	13.6	12.9	13.0	14.0	13.5	13.3	14.6	14.1	13.0
NI	12.7	11.6	12.4	13.8	13.0	13.0	13.5	13.1	12.9	13.8	13.3	12.9
NS	8.7	8.9	9.4	10.7	10.2	11.4	12.3	11.6	11.8	13.1	12.5	12.9
WS	10.0	10.0	11.3	12.0	11.5	12.6	13.1	12.6	12.8	13.6	13.2	13.4
WM	13.1	10.9	10.7	14.1	12.6	11.8	13.3	12.7	12.3	13.8	12.9	12.2
Wa	13.6	12.7	13.1	14.1	13.5	13.5	13.3	12.9	12.7	13.7	13.1	11.6
EE	11.9	9.8	9.6	13.5	12.2	11.1	13.4	12.1	11.5	13.3	12.4	12.0
ES	10.4	10.6	11.4	12.5	11.9	13.4	13.7	12.8	13.2	14.2	13.4	13.6
EM	13.3	11.1	11.0	14.2	13.0	12.6	13.8	13.1	12.9	14.3	13.5	13.2
SE	12.0	9.9	9.2	13.4	11.9	10.8	12.7	11.5	10.9	12.6	11.3	10.4
SW	14.2	13.1	12.8	14.0	13.4	13.0	12.1	11.2	11.5	12.3	11.0	10.6
YH	13.5	11.5	11.9	14.1	13.1	13.1	14.5	13.9	13.6	15.1	14.5	14.1

Yield changes associated with different rates of N-fertiliser application for the 3 future periods are shown in Fig. 11. With lower amounts of N-fertiliser, yields generally improved over the UK, except in the southwest and Wales. These improvements though were clearly absent over almost all English regions with the greater N-fertiliser applications. It is only in Scotland that climate change-induced yield increases were retained for all 3 levels of N-fertilisation.

3.5.2. Coefficient of variation

The coefficient of variation (CV%) in yield is a good indicator of variability and reliability of potential yields. Increases in CV% generally indicate a more unstable and high risk of production variability (Ghaffari et al. 2002, Hulme et al. 2002, Yao et al. 2007). The CV% values calculated in the present study indicate that later sowing dates increase instability and yield risk over the UK (Fig. 12a) during the 2050s and 2080s. Late sowings may lead to heat stress during later heading dates, smaller final leaf numbers and reduced dry matter yields due to shortening grain filling under climate change (Wheeler et al. 2000, Ghaffari et al. 2002, Southworth et al. 2002). The instability and risk of yield (as assessed by CV) generally increased in the future when high N-fertiliser amounts were applied (Fig. 13b). In field experiments, the acclimation of wheat photosynthesis decreased at temperatures 4°C above ambient with high N supply (Mitchell et al. 1993, Martínez-Carrasco et al. 2005). Thus, excess N-fertilisation may have a negative effect on yields (Karing et al. 1999). However, this negative effect may have arisen from the date of application, which was held constant for all future time-slices. A more realistic scenario would be to bring forward application dates for later time-slices as a consequence of changes in crop development rate.

4. CONCLUSIONS

Our study assessed the potential impact of climate change on future 21st century UK winter wheat yields using output from a PPE of Met Office RCM

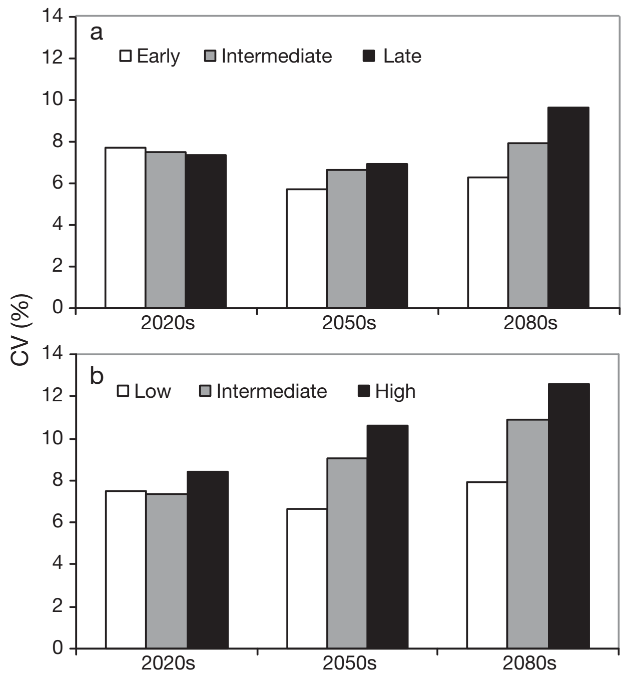

Fig. 12. Coefficient of variation (CV) in yield change over the UK for different (a) sowing dates (early: 10 Sep; intermediate: 10 Oct; late: 10 Nov) and (b) nitrogen fertiliser applications (low: 150; intermediate: 200; high: 250 kg ha^{-1} yr^{-1}) during the 3 future periods

simulations that had contributed to the UKCP09 findings that fed into the CERES-Wheat crop model.

Future changes in temperature and precipitation varied spatially across the UK and generally increased with time. Uncertainties in changes relative to the present day also became greater towards the year 2100. However, despite these uncertainties, our sensitivity analyses of climate variables on future winter wheat yield in the UK generally indicated positive impacts from climate change. Increases in temperature and atmospheric CO_2 concentrations appear to contribute positive impacts on potential yield, greater than from increases in precipitation. Our simulations also found that a faster rate of winter wheat development (heading and maturity) is likely compared to baseline climate conditions (1971–2000).

Impacts of adjustments in sowing dates and N-fertilisation on yield were also examined. Earlier sowing generally appears to be more beneficial in future over the UK and larger yield increases were simulated over the southwest and Scotland. Later sowing dates were also associated with increased yield instability and risk to production. Smaller N-fertiliser applications appear to increase future yields over almost all UK regions. Large N applications, above current levels used, appear to have little future benefit. Analysis of inter-annual yield variability also indicates that although overall yield is likely to be greater in future, volatility of yield and the risk of a poor yield is also likely increase. This risk increase is greater for late sowings and high N-fertiliser applications.

In the absence of CO_2 fertilisation, yield decreases may appear likely in some regions, possibly due to winter temperatures becoming less optimal for wheat development, shorter growing seasons and less efficient vernalisation, which is required to initiate bud formation.

For stable winter wheat production under future climate change, we suggest that new management systems, including new varieties such as high-temperature-tolerant varieties, may need to be adopted (Gornall et al. 2010).

Finally, for this assessment, some uncertainties or limitations should be mentioned. The CERES-Wheat model in the present study simulates only positive feedbacks from the physiological effects of increased atmospheric CO_2 concentrations on crop growth and water use (Rosenzweig et al. 1994). Also, the rate of development is determined by only temperature and day length (Jones et al. 2003). In addition, changes in inter-annual variability and the impact of extreme weather events and pests and diseases are not considered. Water stress may occur during the growing season depending on the environment in which the crop is grown. The most critical phase for water deficit is from double ridge to anthesis (FAO 2002). However, this water stress was not considered, and further study is required based on appropriate genotypes. Also, CERES-Wheat can only represent current agricultural technology and practices, not potential future improvements such as new varieties and management systems (Yao et al. 2007).

Climate model projections based on plausible scenarios are the most appropriate means of assessing climate change impacts. However, it is necessary to consider uncertainties in future emissions pathways, natural climate variability and modelling uncertainty when projecting future climate change (Murphy et al. 2007).

Acknowledgements. We are grateful to the curators of the e-RA Database at Rothamsted Research, Harpenden for supplying the Broadbalk wheat data and meteorological data for 2002–2006. P.F., R.B., J.G. and R.C. were supported by the Joint DECC and Defra Integrated Climate Programme – DECC/Defra (GA01101).

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