Modelling impacts of climate change on wheat yields in England and Wales: assessing drought risks

G.M. Richter *, M.A. Semenov

Agriculture and Environment Division, Rothamsted Research, Harpenden, Herts AL5 2JQ, UK

Received 24 July 2003; received in revised form 12 May 2004; accepted 1 June 2004

Abstract

With global warming, evapotranspiration (ET) is likely to increase and, with more variable rainfall, droughts could occur more often. Our objective was to evaluate the impact of climate change on drought indicators and yield of winter wheat in England and Wales. We used the crop simulation model *Sirius* to assess the effect of changing climate on maximum soil moisture deficit (SMD_{max}), drought-related reduction of potential yield (YR_{dr}) and wheat yields. Climate scenarios were based on the output from the Hadley Centre Climate Model (HadCM2) and were constructed by using a stochastic weather generator (LARS-WG). Weather was generated for the baseline (1960–1990) and future (2020s and 2050s) periods at representative sites in the UK using two types of scenarios: (1) those incorporating only mean changes in climate variables and (2) those incorporating changes in means and variance. Probability distributions were derived from multiple simulations using representative weather, soil types and sowing dates. SMD_{max} is likely to increase in the future, especially on shallow soils, and the probability of YR_{dr} exceeding 25% will increase by 10% until the 2050s. However, average wheat yields are likely to increase by 1.2 to 2 t/ha (15–23%) by the 2050s because of a CO_{2}-related increase in radiation use efficiency (RUE). Grain yields are likely to be less variable but the probability of the annual coefficient of variation (CV) exceeding 15% remains the same. Changes in the variance of weather variables will have little effect on grain yields. Ignoring genetic improvement in varieties, yields are predicted to increase more until the 2020s than in the following 30 years. A
sensitivity analysis for crop growth parameters suggests that further yield gains (1 t/ha) are possible with new varieties that increase the grain filling period.

© 2004 Elsevier Ltd. All rights reserved.

Keywords: Climate change; Crop modelling; Soil water availability; Weather generator; Wheat

1. Introduction

The HadCM2 climate model predicts for the southeast of the United Kingdom (UK) that the annual average temperature will increase by 0.9 to 2.3 °C by the 2050s (Hulme and Jenkins, 1998). Together with the likely decrease in summer precipitation, rising potential evaporation could accentuate the risk of drought for key crops in the UK. Elevated atmospheric CO₂ concentrations, [CO₂], primarily enhance CO₂ diffusion into the leaf and increase the photosynthetic rate of C3-plants over a wide range of radiation intensities, despite decreasing stomatal conductance (Lawlor and Mitchell, 1991). Elevated [CO₂] and temperatures affect plant growth and the water balance in a complex way, sometimes compensating for drought, sometimes aggravating it (Kimball et al., 2002). This raises the question of appropriate model complexity. Wheat models incorporating the positive interaction between [CO₂] and drought simulated experimental observations slightly better than simpler models (Mitchell et al., 2001b). However, the interaction between [CO₂] and water use efficiency (WUE) is weak. First, the response of radiation use efficiency (RUE) to [CO₂] in controlled environment experiments was similar for droughted and well-watered crops (Mitchell et al., 2001a). Second, the observed response of WUE to [CO₂] and drought was inconsistent (Rodriguez et al., 2001). In experiments with Free Air CO₂ Enrichment (FACE) there is only limited feedback between WUE and [CO₂] (Kimball et al., 2002). More complex models had little advantage over simpler models when applied to field data describing drought effects (Ewert et al., 2002) and simple models did better when comparing simulations with observed regional data (Mitchell et al., 2001c). In conclusion, elevated [CO₂] mainly causes an increase in RUE (Rodriguez et al., 2001; Kimball et al., 2002).

On the regional scale, the variability of weather, soils and management need to be superimposed and tested for their relative impacts. Weather needs to be generated, which includes changes in climatic variability, as predicted by general circulation models (GCMs). Introducing changes in variability may have profound impacts on the predictions of crop yield in areas with inherent water shortage (Semenov and Porter, 1994; Mearns et al., 1997; Porter and Semenov, 1999). For the UK, it is not known whether increasing variance in temperature and more variable duration of dry and wet spells will have a significant impact on the yield distribution. Furthermore, available soil water is a major factor limiting production: 25% of wheat is grown on droughty soils that are low in available water capacity (AWC) (MAFF, 1999) and drought-related yield losses can range between 2 and 4.5 t/ha (Foulkes et al., 2002). For management decisions in the future it is
necessary to know which sites will be the most vulnerable to climate variability. For the adaptation of agriculture it is necessary to know which areas and soils should be taken out of wheat production. Finally, varieties respond differently to drought (Foulkes et al., 2001) and one can select for the most appropriate variety trait to mitigate water stress.

The objective of the current study was to quantify the impact of climate change on wheat production in the UK. We assessed the probability of drought by displaying the indices of soil moisture depletion (SMD) and drought-related reduction of potential yields (YRd), and, ultimately, we determined the distribution of simulated yields. The variability of simulated yields was related, first, to regional variations in soil AWC and weather, and second, to the choice of weather scenario and parameters. We finally investigated via modelling some management and breeding options to mitigate the impact of rising temperatures on accelerated senescence.

2. Materials and methods

2.1. Modelling wheat response to climate change

The impact of changing weather patterns on wheat production is simulated with the mechanistic model Sirius, which simulates grain yields from biomass accumulation until anthesis and during grain filling. The simulation of anthesis date, growth rate and the decline of green leaf area (GLA) during grain fill are therefore important for its accuracy. Sirius was validated for field experiments over a wide range of yields (4–10 t/ha) including drought effects (Jamieson et al., 1998a,b). Anthesis dates were well predicted (root mean square deviation, 3.8–4.9 days), and for 17 out of 21 cases in New Zealand and the UK simulated versus observed yields were close to the 1:1-line (RMSD = 0.9 t/ha; Jamieson et al., 1998b).

Sirius also described wheat growth under elevated [CO₂] in the FACE experiment at Maricopa (Kimball et al., 1999), incorporating the response of RUE to fraction of diffuse radiation, [CO₂] and temperature (Jamieson et al., 2000). Grain yields for four N×[CO₂] treatments in two years were predicted with less bias and RMSD than a more complex model. As one of the wheat models tested for regional climate impact assessment (Mitchell et al., 2001b) it performed better than the other models on a range of statistical parameters for biomass, grain yield and water use efficiency (Ewert et al., 2002). Sirius was also more robust in simulating on-farms yields in southern Spain and extrapolating them to future climate conditions (water×temperature×[CO₂]).

2.1.1. Water balance and drought stress

In Sirius, light interception, RUE and plant phenology are controlled by specific drought stress factors (Jamieson et al., 1998a) based on a general water stress factor, Fws. The actual evapotranspiration (ET) depends on relative soil water content (rSWC), and Fws is defined as the ET-ratio (actual ET/potential ET), which decreases curvilinearly once rSWC is smaller than 0.5. Potential ET is usually calculated
according to the Penman–Monteith method. However, a simplified equation (Priestley and Taylor, 1972), based only on temperature and radiation data, was used for the UK, because daily wind run and humidity data were not generally available in the observed and generated weather data. Estimates of daily potential ET compared well with available ET (grass) data derived with the standard Penman–Monteith method.

2.1.2. Crop development and growth

The phenology of winter wheat is modelled as a function of accumulated thermal time and additionally determined by the varieties’ vernalization requirements, day-length responses and the final leaf number on the main stem. Drought accelerates plant development when $F_{ws}$ exceeds 0.7, reaching its maximum of 1.5 when $F_{ws}$ reaches 0.4 (Jamieson et al., 1998a). Vernalization is crucial for the prediction of anthesis and it is modelled using a new vernalization response function (Brooking and Jamieson, 2002).

Biomass production is calculated as the product of intercepted photosynthetically active radiation and RUE. Radiation interception is related to green leaf area index, GLAI, via Beer’s law, and GLAI is derived from the number of leaves (Jamieson et al., 1998a). Drought affects GLAI by reducing the leaf expansion rate proportional to $F_{ws}$, and by accelerating senescence once $F_{ws}$ is smaller than 0.33. Grain yield is the sum of dry matter production after anthesis, which is allocated exclusively to the grain, and carbohydrates translocated from the vegetative biomass to the grain, which is assumed to be 25% of biomass at anthesis.

2.1.3. Response of RUE to elevated [CO$_2$] and temperature

RUE is a function of water availability, temperature and carbon dioxide concentration. It is a variety-specific trait and decreases with the ET-ratio (Jamieson et al., 1998a). This approach was expanded by assuming that RUE increases linearly with increasing [CO$_2$] so that doubling [CO$_2$] from 350 to 700 µmol/mol increases RUE by 30% (Jamieson et al., 2000). In Sirius it is assumed that there is no interaction between CO$_2$ concentration and drought. The implemented response of RUE to elevated [CO$_2$] corresponds to the average published response for C3 plants growing under FACE conditions (Kimball et al., 2002). RUE is also modelled as an inverse quadratic function of the average air temperature with the optimum at 18 °C and decreasing to zero at 38 °C.

2.1.4. Model calibration and evaluation

Sirius was calibrated and evaluated for wheat varieties defined as the UK reference crop (cv. Mercia and Consort) using experiments at three sites run during 1993–1997. The sites represent different regions in England: Rosemaund (RM, West Midlands), Sutton Bonnington (SB, East Midlands) and Boxworth (BW, East Anglia). The soils were described as silty clay loam (RM), sandy clay loam over marl (SB) and clay loam over clay or chalk (BW). They covered AWC in the range 160–225 mm. The crop data included approximately 20 observations for each year quantifying phenology, GLAI, accumulated total biomass, water-soluble carbohydrates, and grain yield (HGCA, 1998; HGCA, 2000).
Two crop parameters were calibrated to account for the differences in current varieties compared with earlier ones. (1) The response of vernalisation rate to temperature and its intercept at 0 °C was optimised to match the anthesis dates observed in 1993–1995. (2) Relative growth rate of GLAI in response to thermal time (1/Cd) was optimised to match observed GLAI in the years with sufficient moisture (1993–94). We adjusted the thermal time for emergence to match the initial course of observed GLAI.

The output variables of simulation, anthesis date, GLAI and grain yield, were evaluated on the whole set of experimental data (three sites, five years) including the subset of calibration. The Sirius response to drought was evaluated using a wide range of yields from rain-shelter experiments (4–8 t/ha; 1986), Broadbalk long-term experiment (4.5–11 t/ha; 1975–2000) at Rothamsted, and on-farm field trials on sandy soils (3.5–7 t/ha; 1990–1996) (Richter et al., 2002).

2.2. Weather sites

For each of the major regions in England and Wales, data from three weather stations were assessed for completeness and length of weather records. Thirty years of data were selected to represent the variation of local weather records in correct statistical site parameters (mean, standard deviation for temperature, rainfall, and radiation). These are essential for the generation of future weather. For the simulation minimum and maximum daily air temperature (°C), rainfall (mm) and global radiation (MJ m⁻²) were needed. In case where radiation data were missing, global radiation was derived from sunshine duration. Table 1 summarises the characteristics of the sites finally selected. There are obvious west–east and south–north gradients of precipitation and temperature. The long-term average annual climatic water balance (CWB), defined as the difference between average annual precipitation and potential ET, ranged from +317 to −46 mm. For individual years, deficits below −200 mm were calculated for sites in central and eastern England (Oxford, Cambridge, and Leeming).

Table 1
Selected weather stations for the different regions in England and Wales; climatic water balance (CWB) equals rain minus potential ET (grass)²

<table>
<thead>
<tr>
<th>Region</th>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Altitude m asl.</th>
<th>T (°C)</th>
<th>Rain mm</th>
<th>CWB mm</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wales</td>
<td>Aberportha</td>
<td>52.13</td>
<td>−4.57</td>
<td>133</td>
<td>9.5</td>
<td>851</td>
<td>118</td>
<td>1961–1990</td>
</tr>
<tr>
<td>S West</td>
<td>Lyneham</td>
<td>51.5</td>
<td>−1.98</td>
<td>145</td>
<td>9.6</td>
<td>724</td>
<td>85</td>
<td>1971–1990</td>
</tr>
<tr>
<td>S East</td>
<td>Oxford</td>
<td>51.77</td>
<td>−1.27</td>
<td>63</td>
<td>10.2</td>
<td>601</td>
<td>−46</td>
<td>1971–1990</td>
</tr>
<tr>
<td>E Anglia</td>
<td>Cambridge</td>
<td>52.2</td>
<td>0.13</td>
<td>26</td>
<td>9.8</td>
<td>553</td>
<td>44</td>
<td>1961–1990</td>
</tr>
<tr>
<td>W Mid</td>
<td>Shawbury</td>
<td>52.8</td>
<td>−2.68</td>
<td>72</td>
<td>9.0</td>
<td>653</td>
<td>89</td>
<td>1961–1990</td>
</tr>
<tr>
<td>E Mid</td>
<td>Sutton Bon.</td>
<td>52.8</td>
<td>−1.25</td>
<td>48</td>
<td>9.3</td>
<td>614</td>
<td>88</td>
<td>1961–1990</td>
</tr>
<tr>
<td>N West</td>
<td>Ringwaya</td>
<td>53.35</td>
<td>−2.27</td>
<td>75</td>
<td>9.5</td>
<td>821</td>
<td>156</td>
<td>1961–1990</td>
</tr>
<tr>
<td>N East</td>
<td>Leeming</td>
<td>54.3</td>
<td>−1.53</td>
<td>32</td>
<td>9.2</td>
<td>623</td>
<td>8</td>
<td>1965–1995</td>
</tr>
<tr>
<td>North</td>
<td>Carlisle</td>
<td>54.93</td>
<td>−2.95</td>
<td>26</td>
<td>8.9</td>
<td>834</td>
<td>292</td>
<td>1961–1988</td>
</tr>
</tbody>
</table>

² Coastal location.
2.3. Generating climate change scenarios

The climate change scenarios were constructed from the daily HadCM2 output for the land grid boxes (2.5° latitude × 3.75° longitude). This was done without spatial downscaling, as no robust procedure was available to downscale variability parameters. Daily data for the appropriate grid boxes from the control and perturbed integrations of the HadCM2 runs were used to calculate the parameters of scenario files. These are changes in daily precipitation intensities, changes in duration of wet and dry spells, changes in daily temperature means and variances and changes in monthly mean radiation. These changes were then applied to the site parameters previously calculated from the observed daily data at each site using LARS-WG (Semenov and Barrow, 1997). The perturbed parameters were used to generate 35 years of synthetic daily weather data. Two types of scenarios were constructed: (1) scenarios incorporating changes in means values only, and (2) scenarios incorporating changes in both mean and variability. For the climate change impact assessment work three time periods were considered as scenarios: 1961–1990 (baseline), 2005–2034 (2020s) and 2035–2064 (2050s). The LARS-WG generates four variables, namely, precipitation, minimum and maximum temperatures, and solar radiation (Semenov and Barrow, 1997; Semenov et al., 1998). LARS-WG is based on modelling of dry and wet periods; precipitation is modelled independently for each wet day. The temperature and radiation are conditioned on wet or dry status of the day (see also Semenov and Barrow, 1997). Semi-empirical distributions were used for precipitation, duration of wet and dry spells and radiation (Semenov et al., 1998), which are more flexible for representing local weather conditions.

We selected the scenario of medium-high CO₂ emission without sulphur dioxide emission (Johns et al., 1997). [CO₂] increases from 334 µmol/mol (equivalent to ppmv, used hereafter) (1961–1990) to 447 ppmv in the 2020s and 554 ppmv in the 2050s. The 2020s scenario was generated using the parameters derived for the 2050s and a scaling factor of 0.5 assuming a linear change of main weather parameters. Weather was also generated for two sites of the major growing regions (Shawbury, Sutton Bonnington, Table 1) using the appropriate ensemble means published by Hulme and Jenkins (1998) to compare different precipitation scenarios and the effect of weather variability on crop yield.

2.4. Selecting soil profiles

The Soil Map of England and Wales (scale 1:250,000) was used to identify all soil types suitable for wheat cultivation (SSEW, 1983). From the Regional Bulletins (SSEW, 1984; No. 10–15) we derived the regional distribution of these soil types and land-use (% wheat per county). About 85% of the arable land was classified as suitable for wheat, which corresponds to approximately 4.7 million hectares, about 2.5 times the area actually sown.

Soil profile data, stratification, and available water capacity (AWC) were taken from the Soil Survey Bulletins (SSEW, 1984) or the relevant Soil Survey Records for the counties (Hollis, 1978; Palmer, 1982). Soil series were grouped into five major
classes according to AWC (Table 2), and for each region the most frequently observed series were selected to represent the respective AWC class. Based on the observed wheat area in each region and AWC class, 23% of the 2 million hectares were classified as soils likely to result in water stress effects on wheat (80–120 mm AWC). This is similar to the estimate for soils causing drought damage in wheat, even during an average year (Foulkes et al., 2001). The tabulated weighting factors were used to construct the regional scenarios.

2.5. Management scenarios

The simulations were done using three different sowing dates representing the lower quartile, the mean, and upper quartile of sowing dates (21 September, 11 October, 31 October). Surprisingly, crops were not sown earlier in the south compared with the north of the country. Weighting factors were selected according to the soil distribution in the regions (Table 2) to represent the spatial variation of AWC in the model realisation. The following varietal parameters were tested as mitigation options under varying environmental conditions: (a) thermal time to anthesis, by varying the phyllochron (standard 90°C days) by ±15% and (b) thermal time for grain filling (standard 650°C days) by ±100°C days.

2.6. Drought indices and yield response

Sirius simulates the development of soil moisture deficit up to its seasonal maximum, SMD$_\text{max}$, which is displayed for soils of sufficient AWC. The ratio of SMD$_\text{max}$ /AWC defines the relative soil moisture depletion for all soils of the region (rSMD$_\text{max}$). It can be related to thresholds of moisture depletion beyond which plant growth and senescence are affected. In addition, a drought-related reduction factor of potential yield ($YR_{dl}$) is defined as the ratio of water-limited yield and potential
yield \((Y_{w1}/Y_{pot})\). \(YR_{dr}\) can be calculated from yields simulated with and without water-limitation, and probability distributions of \(YR_{dr}\) are calculated from multiple simulations (realisations of weather by soil AWC classes by sowing quartiles) for each of the chosen scenarios.

Probability distribution functions of drought indices and yields were constructed. Weighted averages for wheat yields in different parts of England and Wales were calculated using sowing dates and soil distribution data (Table 2). The differences between the means were tested using ANOVA and \(t\) tests. Differences between distributions were tested with the Kolmogorov–Smirnoff and \(\chi^2\) test for maximum difference. The residual maximum likelihood (REML; GENSTAT, 2001) was calculated for the variance components of soil–climate interaction, avoiding the downward bias introduced by a fixed number of soils and replicates.

3. Results

3.1. Model evaluation

The calibration of the phenological parameters confirmed that the variety Mercia had a weak response of vernalisation rate to temperature, which is about 60% lower than that for Avalon earlier. In comparison with the observations (1993–1995), anthesis date was predicted a little too early (mean difference – 2.5 d). The overall root mean square error (RMSE) compared well with earlier evaluations (4.1 d). For 1996 the model predictions were impaired by cold and dry weather (MD = 11 d; Richter et al., 2001), which may have caused the model to underestimate crop temperatures. The measured LAI was simulated with great precision in the years 1993 and 1994 (overall RMSE 1.17).

Based on these calibrations, Sirius predicted the average grain yields at all three sites in Central and East England very well (MD = 0.17; RMSE = 1.3 t/ha). The yields in these field experiments had little variation (7.3–10 t/ha) and the mean of all growth variables were closely simulated (Richter et al., 2001). In drought experiments the greater range of yields was well simulated (RMSE = 1.54 t/ha). The model had an overall positive bias (MD = –1.11 t/ha), which was largest in those “on-farm trials” with irrigation and in wet years (up to 2.7 t/ha), whereas the drought response was simulated closely (±0.4 t/ha). For the long-term field data (1975–1999) the deviation from the observed and the model bias were smaller (RMSE = 1.14 t/ha; MD = –0.72 t/ha). The analysis of weather data revealed that the model overestimated yields by about 1.5 t/ha in those years when pest pressure (aphids) was highest (Richter et al., 2002).

3.2. Distribution of drought indices

The scenario simulations for a typical soil of wheat production (180 mm of AWC) show that the distribution of SMD\(_{max}\) is likely to shift to higher moisture depletion in the 2050s. Even with more rainfall being predicted for the future, average SMD\(_{max}\)
are predicted to increase by about 20 mm due to greater ET as a consequence of elevated temperature. Small SMD may generally disappear. The regional simulations of moisture deficit confirmed past observations: on average the SMD_{max} were smaller in the west and north than in eastern and southern areas during the past (Fig. 1; baseline scenario). In the future (2050s) these differences are likely to decrease because changes are larger in the western parts of the country. SMD_{max} is likely to increase by only 5–10% in the east and 15–30% in the west of England. It is predicted to increase most in the southwest (~30 mm; 30% at Plymouth, 25% at Lyneham) and only marginally in East Anglia (5% at Cambridge).

For a comprehensive regional estimate of moisture deficit all soils need to be accounted for. As an example, the cumulative probability distribution of the relative soil moisture deficit (rSMD_{max}), simulated for all soil classes in the West Midlands, is shown in Fig. 2. It is representative for those areas with a greater change of SMD. The probability of exceeding a threshold of 0.7 (start of enhanced senescence) will increase by about 10%, and distributions are likely to shift towards complete depletion of AWC (value of 1) in the future. By the 2050s, wheat crops are expected to mature faster, and crops in the west and east could become more similar. However, the time of SMD occurrence has an impact on yield reduction, and because of earlier anthesis (see below) the crop may escape drought effects.

3.3. Drought-related reduction of potential yield

Simulations of potential and water-limited yields were compared for three regions: the West and East Midlands and East Anglia, which represent about 50% of the total wheat area. For example, in the West Midlands, the probability of YR_{dr}
exceeding 25% will double to about 0.10 (Fig. 3). In large parts of England (East Midlands, East Anglia) the overall drought impact on potential yield is predicted to differ little between baseline and future scenarios. There, the overall risk of yield losses greater than 25% is likely to remain at a probability of 0.10, partly because shallow, droughty soils are not so widely distributed (Table 2). The predicted change in moisture deficit is also smaller in eastern locations (Fig. 1). A comparison of predicted yields for wheat grown on shallow soils in the west and eastern regions highlights these findings. For shallow soils, the probability of yield loss greater than 25% could more than double to 0.22 in West Midlands by the 2050s. Soils of low AWC are likely to suffer greater yield loss not once every 10 but once every five years. In the East Midlands changes are less severe on shallow soils and YRdr remains at a similar probability distribution for past and future. Only yield losses smaller than 15% are likely to occur more frequently in the future. By the 2050s western and eastern regions of England are likely to face similar drought risks because of droughty soils and more variable and increasing seasonal moisture deficit in the west.

3.4. Scenario simulations of wheat yield

Simulations of yields, based on past and future weather scenarios, integrate all processes with respect to the interaction of climate variables and crop growth. First, increasing temperatures are predicted to accelerate plant development: anthesis may occur two to three weeks earlier in the 2050s, at the end of May instead of mid June.
as at present. The period of grain filling is predicted to be less affected; representative simulations revealed that it may be shortened by elevated temperature by up to two days. This is less than the predictive precision and its variation on dry soils, which may be as much as five or even 10 days. Second, the total number of leaves will increase from an average of 13 to 16 because of milder winters and earlier beginning of the growing season. The effect of sowing date on the final number of leaves will remain the same, increasing it by 5 leaves between earliest and latest sowing.

The annual wheat yields in the regions are likely to increase overall and decrease in variation (CV), comparing the simulations for the baseline (1961–1990) and future (2050s) scenarios. The effect of sowing date on the variance of yields is diminished, and so is the combined effect of sowing date and soil type. Annual yields in Cambridgeshire (East Anglia), for example, are likely to rise by almost 2 t/ha and, on average, annual CVs are more likely to be lower, dropping from 11% to 9%. The frequency of the CV of annual yields exceeding 10% drops from 50% to 35% (Fig. 4). However, the probability of the CV of average annual yields exceeding 14% remains similar (~18 vs. 20%). Smaller yields in dry years are usually simulated for soils with less AWC, and the drought-related yield loss can exceed 50% of the maximum obtainable yield. For the West Midlands an increase of the average annual CV is predicted and maximum annual variation of yields may be as high as 30%, equivalent to a drought-related yield loss of more than 5 t/ha.

3.4.1. Impact of climate scenario inputs

Distributions of wheat yields were calculated for several types of scenarios generated for the 2050s. Yields were simulated using weather inputs generated from parameters derived by Semenov and Barrow (1997) and compared with predictions
based on scenarios derived from the mean changes published in the “UKCIP98” data set (Hulme and Jenkins, 1998). We further distinguish inputs derived from changes in means only (“means”) or changes in means and variance (“stochastic”). Differences in yield distribution introduced by weather inputs generated under these different assumptions are small for the 2050s (~0.2 t/ha) compared with the increase of mean yields (1.6 t/ha) from the baseline scenario in the West Midlands (Fig. 5). Changing the variance of weather inputs was almost neutral. However, the fraction of yields less than 6 t/ha produced on shallow, droughty soils may increase by about 3% under more variable weather. In the East Midlands the response of mean yields to different weather inputs is equally small (0.23 t/ha). The maximum difference of yields generated from different weather inputs were significant (Kolmogorov–Smirnoff-test; p<0.001). The more appropriate REML-method revealed that there is no significant impact on yield prediction introduced by the scenarios selected.

Another question was whether the response of current varieties to climate change is likely to be dynamic and leaves room for mitigation. Simulated scenarios for the 2020s and 2050s show that in comparison with the baseline yields are likely to increase more during the next 30 years than thereafter in spite of [CO₂] and temperature increasing linearly. Under the MH-scenario, mean yields in the West Midlands may increase from 8 t/ha now to 8.9 t/ha by the 2020s and not much further until the 2050s (9.2 t/ha). For the East Midlands it is predicted that the average yield will increase from a lower level (7.5 t/ha) slightly more (8.6 t/ha), finally reaching 9.1 t/ha by the 2050s. In general, the average yield increase is likely to slow down to less than half of the initial increase. This shows that the compensating effect of rising [CO₂] on growth will diminish in comparison with the negative effects of higher ET and limited soil water availability. This conclusion is supported by the analysis of variability. In
the West Midlands yields are predicted to become less variable by the 2020s (CV of 10% compared with 13% in the baseline scenario) but may be more variable again by the 2050s. In the East Midlands variation is predicted to decrease continually. If climate scenarios with higher temperatures were selected (Hulme et al., 2002), evaporation would further increase by the 2050s, yields could become even more limited by available soil water, and yield uncertainty could rise.

3.4.2. Impact of soil variability

Yields will become increasingly limited by soil properties, as shown for the West Midlands, where YR_{d,r} on shallow and sandy soils may substantially increase (see 3.3). On such soil series (Clifton, Whimple), average yields are predicted to rise by between 0.7 and 1.1 t/ha by the 2020s but may decrease thereafter. Overall, the inter-annual variations of yields decline with increasing soil water storage, and CVs in the baseline scenario are usually larger in the East Midland (11–18%) than in the West Midland region (10–15%). Under future scenarios the change in yield variation is not the same in the East and West Midlands. First, by the 2020s, the CV decreases in the West (Shawbury) but then increases in general to the initial level of variation (13%). Yield variation on shallow soils (Whimple) or clay soils (Clifton) low in AWC is likely to be above the variation simulated for the baseline scenario. Under the weather expected for the future, variation of yields is predicted to decrease by 1 to 2% in East Midlands. On droughty soils in the East yields may remain slightly lower than in the West and their variation, though higher is predicted to decrease by the 2050s (12–15%).
3.4.3. Distribution of regional yields

Mean yields are expected to increase in all regions (1.2–2 t/ha). The variability of yield within a region is strongly affected by the variation of weather inputs as we could show for sites with an identical or similar distribution of soils. For example, mean yields within the Southwest region are predicted to differ by 0.8 t/ha. This is similar to the differences in the past but also to differences between regions. Average yields are predicted to increase equally by 1.3 t/ha. The variation of yields in coastal (Plymouth) and inland areas (Lyneham), however, is greatly different and represents the variability in local weather. In the coastal location, future yield distributions are more peaked (mean CV 8%; range 5 t/ha) than in the inland location (CV 12%; range 7 t/ha). A similar response is predicted for the distributions of yields in the West Midlands and Northwest (Fig. 6), where similar soil distributions were used for the scenarios (Table 2, % shallow soils). In the Northwest yields are less variable than in the West Midlands because its higher regional rainfall (Table 1) will prevent shallow soils from drying out.

These findings can be generalised with respect to the effect of weather in coastal versus inland sites. The probability distributions for past and future yields peak more strongly in the western regions (Fig. 6). With a few exceptions the yield distributions are negatively tailed and will be more skewed in the future. Yields above 10 t/ha are likely to occur in those areas where mild and moist weather will predominate, such as the coastal areas of the English Southwest and Wales. For Wales, highest average yields were actually observed in the past but its relative importance for the UK is small (Table 2). Strongly peaked, non-skewed distributions can be interpreted as high yield certainty, usually expressed in a low coefficient of variation (CV <10%). This ignores any negative effects of rain such as the increase of diseases (Landau et al., 1998). In the central and eastern regions (rain shadow), yield distributions are wider and yield uncertainty in the past was slightly greater (CV 12–15%). CVs are predicted to decrease under future climate scenario.

Yield distributions and their changes in the central and eastern regions of England are more affected by the quality of the soil. For the baseline scenario, average yield was 7.8 t/ha (7.1–8.1 t/ha) which is predicted to increase to 9.2 t/ha (8.5–9.5 t/ha) by the 2050s. Although summers are going to be drier (Fig. 1), the greatest relative increase of yields in Central and East England (19–23%) are likely to be sustained by deep soils, high in AWC. This is especially apparent in Oxfordshire where the distribution of yields is strongly peaked (Fig. 6, South East) in spite of the CWB being negative (Table 1) and SMD increasing (Fig. 1).

4. Discussion

The Sirius simulation model was used to assess the effect of climate change on future wheat yields, to analyse the risk of drought and assess mitigation strategies. It was chosen because we believe that the main effects of climate change on yields are due to (a) accelerated development and higher growth rates due to rising temperatures, (b) increased RUE proportional to rising [CO₂] under moderate temperatures,
and (c) shortage of water limiting several processes. Sirius does not take into account the direct interaction between water use and [CO2] in the atmosphere, which seems justified because of inconsistent experimental results (Rodríguez et al., 2001; Kimball et al., 2002).

Sirius was validated for most of the UK, and the current yield estimates for the baseline scenario (7.2–8.1 t/ha) compare well to the observed (see 3.1). The average regional yields (baseline) also compare well with the maximum of observed regional yields for the early 1990s (7.1–8.1 t/ha). The model can describe a wide range of variation due to drought but not the relatively small annual variation for short, site-specific (Richter et al., 2001) and regional series (Mitchell et al., 2001c). However, it may overestimate regional yields in the South and West, because it neglects the negative impacts of rain and wetness, such as the greater risk of diseases (Landau et al., 1998).
Indicators of drought considered are SMD\textsubscript{max} and YR\textsubscript{dr}, and “soil droughtiness” is often referred to as the seasonal SMD (SSEW, 1984). The mean and probability distribution of regional SMD\textsubscript{max} are good indicators for increasing seasonal ET. The predictions are in line with recent observations of SMD increasing during the 1990s, which was the warmest decade of the 20th century in South Central UK (Limbrick et al., 2000). Effects on yield depend, however, on crop type and the time at which conditions change relative to crop development. Winter wheat is more likely to escape the water deficit than spring cereals because of early development. For maize the probability of crucial stress periods doubled in well-drained (dry) compared to a poorly drained (wet) soil (Dale and Daniels, 1995).

The timing of stress during crucial development periods is reflected in YR\textsubscript{dr}, which will remain greater in the east than in the west of the UK. In the west, however, changes are likely to be greater, doubling the probability of exceeding 25% loss, which may occur once in 10 years instead of once in 20 years. On soils with low AWC, yield losses of about 50% could occur once in 30 years. Across the whole region such yield uncertainty will occur only once in 50 or 100 years, almost negligible compared with the yield loss in drier regions such as southern Europe (Porter and Semenov, 1999).

For the Midland regions the average yields of wheat are predicted to increase by 0.1t/ha for every extra unit of AWC, slightly stronger in the future than in the baseline scenario (Fig. 7). Lack of AWC will diminish the returns in response to climate change benefits. If soils are shallow then AWC may decrease to less than 100 mm. Below this point, the model predicts that available water will have a much greater impact on yields, and average yields could drop by 30% (dashed line; Fig. 7). Fur-

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig7.png}
\caption{Relationship between mean yields per AWC of soil series in the West and East of the Midlands; \'{} baseline, ■ future scenario (2050s); open symbols (◇,□) and hatched lines describe model response to soil degradation reducing the AWC.}
\end{figure}
ther, the CV of yields in such soils will double to 30% and 50% depending on the climate. Simulation scenarios for sugar beet confirm that yields will become more variable at lower AWC (Richter et al., 2002). These scenarios are highly relevant at the catchment scale because in some regions 50% of the arable area consists of soils with an AWC of only 80 mm (Richter et al., 2002). Furthermore, erosion and compaction have degraded many upland soils, which is not reflected in the mapped soil information (Table 2) and is not included in the regional distribution (Fig. 6). In spite of the importance for many risk assessments, there is a lack of up-to-date, quantitative, spatial information on rooting depth and the distribution of shallow soils; such information is urgently needed for future analysis.

To assess the impact of variable soil, climate, etc. on simulated distributions of drought indices and yield, we have to distinguish the mean response from probabilities of extremes and exceeding thresholds in the scenarios. To assess means of regional yields it is adequate to simulate crop–climate interactions for different soil types separately and weight their spatial contribution (Richter, 1999; Brooks et al., 2000). Long-term weighted means, as determined here, were similar to those without weighting, possibly because soil types have little effect on inter-annual yield variations (Olesen et al., 2000). In our simulations, yield distributions were dominated by climatic variation. However, it is important to know where yields are likely to exceed a threshold and economic margin, such as 25% or even 50% yield loss, so that these impacts can be mitigated at the regional or even farm level.

Our analysis included some special aspects of climate change scenarios: the inclusion of change in variance and the response dynamics. Tested for two major regions in the UK, a change in variance in the future climate scenarios did not affect wheat production significantly. The method of generating daily weather inputs changed the distribution of yields only marginally. The additional change in length of dry and wet spells and change in variance of monthly precipitation slightly skewed the distribution towards low yields in the region with more vulnerable soils (West Midlands). Different drought patterns generated by reducing summer precipitation by 15% (Hulme and Jenkins, 1998) did not alter wheat yields and their distributions from those simulated with higher summer precipitation (Fig. 5). This confirms that winter wheat escapes summer drought. This may change, however, with more warming and less summer precipitation as predicted by different and more recent scenarios (Hulme et al., 2002; IPCC, 2001). Great uncertainty exists with respect to summer precipitation, which may or may not decrease by up to 30% (Hulme et al., 2002; p. 24).

In spite of generally increasing yields, the scenarios suggest the need for mitigation options to make better use of available resources. Mean yields were predicted to increase more in the first 30 years compared with the next, in spite of assuming a linear change in climatic variables. Furthermore, the sharp drop of probability towards higher yields (Fig. 6) could be a sign of reaching the regional yield potential, which is characteristic for the current variety. We hypothesised that the current variety may have reached its yield potential and therefore we analysed the sensitivity of crop parameters describing phenological response. Parameters associated with earlier dates of anthesis increased average yields by only 1%, and by 2% on soils with
low AWC and in dry regions. Crop parameters related to the length of grain filling, assimilate availability and remobilization of stem reserves are thought to be important (Reynolds et al., 1999; de la Vega et al., 2002). A sensitivity analysis showed that yields responded almost linearly to delayed maturation and senescence. If grain filling is prolonged by 100 °Cd, wheat yields are likely to increase by another 1 t/ha in deep soils under the weather of the 2050s, less in droughty soils (<0.8 t/ha). The advantage of varieties with late maturation may disappear under still higher summer temperatures and evaporation. Varieties with a higher rate of grain filling may be better yielding in warm-dry climate (Santiveri et al., 2002).

Finally, some yield-limiting conditions such as high temperatures around and after anthesis, which limit grain numbers and grain filling, were not included in the model. For scenarios under HadCM2 this seemed justified because heat-induced sink limitation is likely to be more important under continental and southern European conditions (Ferris et al., 2000). However, scenarios based on newer climate change predictions (IPCC, 2001) suggest that summer temperatures across most of the southern UK are likely to further increase (Hulme et al., 2002), and heat resistance may become an important trait for new varieties. Our assessment may be optimistic because we ignored negative impacts of wetness during and after anthesis, related to the occurrence of pest and diseases (Harrington et al., 2001; Smyrnioudis et al., 2000).

In conclusion, in spite of a predicted increase of drought in the future, compensating effects of rising CO₂ are likely to be stronger than the effect of water shortage in England and Wales. The uncertainty of estimated wheat yields is not increased when considering the CV and the probability of below average yields. However, dry years may cause substantial reductions in grain yield on droughty soils more frequently. Breeding and selecting varieties as well as other management practices to maintain the GLAI longer may further increase future yields by 1 t/ha. More analysis is needed as new scenarios with a wider range of precipitation become available.

Acknowledgement

This work was funded by the UK Department of Environment, Food and Rural Affairs (DEFRA Project No CC0336). Rothamsted Research receives grant-aided support from the Biotechnology and Biological Sciences Research Council of the UK. We are indebted to ADAS Boxworth and Wolverhampton for making the growth data of their wheat experiments available for validation. We thank Rowan Mitchell for his contribution to this work and Margaret Glendining for her careful reading of the manuscript.

References


MAFF, 1999. CAP reform: potential for effects on environmental impact of farming. Report for the Ministry of Agriculture, Food and Fisheries, MAFF (ACD) by the Agricultural Development and Advisory Service (ADAS) and Central Science Laboratory (CSL).


