Shifts in comparative advantages for maize, oat and wheat cropping under climate change in Europe


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Climate change is anticipated to affect European agriculture, including the risk of emerging or re-emerging feed and food hazards. Indirectly, climate change may influence such hazards (e.g. the occurrence of mycotoxins) due to geographic shifts in the distribution of major cereal cropping systems and the consequences this may have for crop rotations. This paper analyses the impact of climate on cropping shares of maize, oat and wheat on a 50-km square grid across Europe (45–65°N) and provides model-based estimates of the changes in cropping shares in response to changes in temperature and precipitation as projected for the time period around 2040 by two regional climate models (RCM) with a moderate and a strong climate change signal, respectively. The projected cropping shares are based on the output from the two RCMs and on algorithms derived for the relation between meteorological data and observed cropping shares of maize, oat and wheat. The observed cropping shares show a south-to-north gradient, where maize had its maximum at 45–55°N, oat had its maximum at 55–65°N, and wheat was more evenly distributed along the latitudes in Europe. Under the projected climate changes, there was a general increase in maize cropping shares, whereas for oat no areas showed distinct increases. For wheat, the projected changes indicated a tendency towards higher cropping shares in the northern parts and lower cropping shares in the southern parts of the study area. The present modelling approach represents a simplification of factors determining the distribution of cereal crops, and also some uncertainties in the data basis were apparent. A promising way of future model improvement could be through a systematic analysis and inclusion of other variables, such as key soil properties and socio-economic conditions, influencing the comparative advantages of specific crops.

Keywords: cereals; climate change; crop distribution; model; simulation; temperature

Introduction

The emergence or re-emergence of feed and food hazards like deoxynivalenol in wheat, aflatoxin in maize, and T-2 and HT-2 in oat (Miraglia et al. 2009; van der Fels-Klerx et al. 2012) is indirectly impacted by the cropping pattern of the respective cereals. Predicting the occurrence of such mycotoxins in European cereal production by application of mycotoxin forecast models (e.g. Schaafsma and Hooker 2007) therefore requires information on the cropping shares of specific crops.

Cropping patterns are determined by a complex set of impacts with a high spatio-temporal variability, including socio-economic conditions, climate, soil properties or terrain constraints (Britz et al. 2011). Among these factors, climate change is anticipated to have a major impact on European agriculture and land use (Olesen and Bindi 2002; Hermans et al. 2010; Tirado et al. 2010). In northern Europe, growing conditions for agricultural crops are expected to improve, primarily due to longer growing seasons under elevated temperature (Maracchi et al. 2005; Betts et al. 2011; Olesen et al. 2011). Thus, the biophysical suitability for many crops expands northwards, and in northern Europe the longer growing season will increase the productivity of some crop species (Falloon and Betts 2010). On the other hand, cropping systems in southern Europe may decrease in productivity due to projected increases in droughts and heatwaves (Olesen and Bindi 2002; Trnka et al. 2011).

Over time, a wide range of climate change scenarios for Europe have been described, providing estimates of annual and seasonal changes in weather variables like temperature and precipitation (e.g. Betts et al. 2011;
Materials and methods

The approach pursued was to model observed cropping shares with special attention to the effects of temperature, temperature sums and precipitation. Based on the developed models, the consequences of climate changes predicted by two RCMs for around 2040 were calculated and visualised for the three selected cereals, i.e., maize, oat and wheat.

Data collection and geographical delineation

Data on the extent of maize (Zea mays L.), oat (Avena sativa L.) and wheat (Triticum aestivum L.) cultivation were collected from inventory statistics representing NUTS level 1, 2 or 3 (NUTS: Nomenclature of Territorial Units for Statistics) in 25 European countries at latitudes between 45 and 65°N (AT, BE, CH, CZ, DE, DK, EE, FI, FO, FR, HU, IE, IT, LI, LT, LU, LV, NL, NO, PL, RO, SE, SI, SK and UK; as defined by the ISO 3166-1-alpha-2 code). Data were obtained from Eurostat, national and regional statistical databases, and from research partners in individual countries and did not distinguish grain and silage maize, or spring and winter wheat. The cropping shares were calculated as the area of each crop in relation to total cultivated area (i.e., corresponding to the sum of CORINE Land Cover classes 211, 212, 213, 221, 222, 223, 231, 241, 242, 243 and 244; Bossard et al. 2000), excluding areas with permanent and semi-permanent grasslands. Initially, data were averaged for two observation periods representing 1990–1999 and 2000–2008, but for most subsequent analyses, the average for the whole period (1990–2008) was used. Occasionally, datasets were available only for one of the two periods, which were then used also to represent the average of both periods.

The data were assigned to 1467 grid cells (Figure 1) by a GIS procedure where a 50-km square grid theme, used in the JRC-MARS meteorological database (Genovese 2004; Peltonen-Sainio et al. 2010), was applied to obtain the grid cell results. Dominating soil groups of the agricultural area within each of the grid cells (World Reference Base for Soil Resources) were extracted from the European Soil database (European Soils Bureau Network). Missing information on properties such as soil group or cultivated area caused the observations from 12 grid cells to be discarded. Further, data from grid cells representing a cultivated area less than 1000 ha (0.4% of the total grid cell area) were discarded (n = 50) to avoid any stochastic error from small-sized samples. Data from the resulting 1405 grid cells were included in the present study.

Data analysis

Prior to the data analysis, grids with no data were examined. Grids with no data were the results of either: (1) crops present, but specific data not available or accessible, or (2) crops not present (or very infrequent) and therefore no data recorded. In the first case (1) entries were handled as data not available, whereas in the second case (2) entries were given the value zero. The distinction between (1) and (2) was based on database information when available and otherwise on expert judgement. The final number of grid cells included in the subsequent analysis was 1308 for maize, 866 for oat and 1405 for wheat (i.e., including grid cells for which the value was zero).

The cropping shares of maize, oat and wheat, as well as their logarithmic and square-root transformed derivatives (Zar 1996), were analysed for the relationship to temperature regimes as represented by effective temperature sums (\(T_{\text{sum}}\)) for maize and monthly mean temperatures for oat and wheat. \(T_{\text{sum}}\) (in degree-days, °Cd) was calculated as:

\[
T_{\text{sum}} = \sum ((T_{\text{max}} + T_{\text{min}})/2 - T_{\text{base}}) + 1
\]

where \(T_{\text{max}}\) and \(T_{\text{min}}\) are the daily maximum and minimum temperatures; and \(T_{\text{base}}\) is a base temperature of 6, 8 or 10°C. \(T_{\text{sum}}\) was calculated and tested for various periods spanning from May–September. Negative contributions to \(T_{\text{sum}}\) were not included as denoted by the subscript (+) in Equation (1). For oat and wheat, respectively, the mean temperatures during 2000–2008 were calculated and visualised for the three selected cereals, i.e., maize, oat and wheat.
various periods spanning from April–August and March–August were tested as driving variables. Based on data inspection, a number of exponential, sigmoidal and peak-curve distribution models were tested to fit the cropping shares in response to temperature. Likewise, these models were applied for the response to cumulative rainfall for the periods March–May (spring) and July–August (summer) to explore effects of precipitation during growth and harvest.

Data analysis was done by fitting the non-linear models directly to the cropping shares (or their transformed derivatives) by using the Marquardt–Levenberg least squares algorithm (SigmaPlot 2000; Systat Software, Point Richmond, CA, USA). Coefficients of determination ($R^2$) were used as a measure of the goodness-of-fit and two generic best-fit models were identified, namely a sigmoidal (Equation (2)) and a Gaussian model (Equation (3)):

$$CS = a/(1 + \exp(-(x - x_0)/b))$$

$$CS = a \times \exp((-0.5 \times (x - x_0)/b)^2)$$

where $CS$ is the cropping share; $x$ is the temperature or precipitation term; and $a$, $b$ and $x_0$ are constants.

Based on the generic models for temperature and precipitation, the performance of combined multiplicative models was tested. This was done to include the possible interactions between temperature and precipitation in providing suitable cropping conditions. Precipitation variables (spring and summer) were included only if the $R^2$ and AIC (Akaike’s information criterion; Burnham and Anderson 2004) of the extended models were better than the simpler one. Evaluation of $R^2$ for models fitted to transformed cropping shares was done on the basis of back-transformed estimates to avoid potentially misleading results (Kva˚lseth 1985; Sokal and Rohlf 1995). Using this approach the best goodness-of-fit was always obtained with original rather than transformed cropping share data.

To evaluate the quality of the model outputs, statistical performance indicators were calculated including the modelling efficiency (MEF) and the mean absolute error relative to the observed mean ($r$MAE) (Mayer and Butler 1993):

$$\text{MEF} = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y})^2}$$

$$r\text{MAE} = \frac{1}{n} \sum \frac{|y_i - \hat{y}_i|}{\bar{y}_i}$$

Figure 1. Overview of NUTS (lines) and grid cells (squares) applied in the present data compilation of cropping shares. The percentage of the total cultivated area in each grid cell is indicated by colour codes.
Table 1. Descriptive statistics of dominant soil groups and percentage of cropping shares of maize, oat and wheat in 50 × 50 km grid cells.

<table>
<thead>
<tr>
<th>Dominant soil group in the grid cell</th>
<th>Grid cells (n)</th>
<th>Cultivated area (ha, millions)</th>
<th>Percentage of the dominant soil group in grid cells</th>
<th>Mean cropping share (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arenosols</td>
<td>18</td>
<td>2.0</td>
<td>46 ± 14</td>
<td>Maize: 4 ± 8, Oat: 3 ± 5, Wheat: 15 ± 7</td>
</tr>
<tr>
<td>Cambisols</td>
<td>450</td>
<td>50.6</td>
<td>67 ± 18</td>
<td>Maize: 7 ± 8, Oat: 2 ± 3, Wheat: 10 ± 6</td>
</tr>
<tr>
<td>Chernozems</td>
<td>33</td>
<td>5.0</td>
<td>86 ± 16</td>
<td>Maize: 20 ± 9, Oat: 0 ± 0, Wheat: 18 ± 4</td>
</tr>
<tr>
<td>Fluvisolos</td>
<td>51</td>
<td>5.1</td>
<td>55 ± 21</td>
<td>Maize: 7 ± 8, Oat: 2 ± 8, Wheat: 12 ± 8</td>
</tr>
<tr>
<td>Gleysoils</td>
<td>73</td>
<td>5.7</td>
<td>58 ± 19</td>
<td>Maize: 1 ± 2, Oat: 2 ± 5, Wheat: 7 ± 7</td>
</tr>
<tr>
<td>Histosols</td>
<td>27</td>
<td>1.2</td>
<td>62 ± 23</td>
<td>Maize: 3 ± 4, Oat: 1 ± 1, Wheat: 3 ± 4</td>
</tr>
<tr>
<td>Lithosols</td>
<td>38</td>
<td>0.6</td>
<td>66 ± 18</td>
<td>Maize: 1 ± 6, Oat: 5 ± 4, Wheat: 6 ± 5</td>
</tr>
<tr>
<td>Luvisols</td>
<td>300</td>
<td>42.1</td>
<td>55 ± 16</td>
<td>Maize: 5 ± 6, Oat: 1 ± 0, Wheat: 4 ± 8</td>
</tr>
<tr>
<td>Phaeozems</td>
<td>33</td>
<td>4.8</td>
<td>55 ± 18</td>
<td>Maize: 21 ± 8, Oat: n.a., Wheat: 15 ± 3</td>
</tr>
<tr>
<td>Podzols</td>
<td>281</td>
<td>13.8</td>
<td>71 ± 22</td>
<td>Maize: 1 ± 3, Oat: 6 ± 6, Wheat: 4 ± 5</td>
</tr>
<tr>
<td>Regosols</td>
<td>28</td>
<td>0.4</td>
<td>79 ± 18</td>
<td>Maize: 0 ± 1, Oat: 4 ± 2, Wheat: 6 ± 4</td>
</tr>
<tr>
<td>Rendzinas</td>
<td>24</td>
<td>2.8</td>
<td>51 ± 15</td>
<td>Maize: 6 ± 6, Oat: 0 ± 0, Wheat: 16 ± 9</td>
</tr>
<tr>
<td>Podzoluvlisols</td>
<td>42</td>
<td>5.7</td>
<td>50 ± 13</td>
<td>Maize: 2 ± 2, Oat: 3 ± 6, Wheat: 11 ± 7</td>
</tr>
</tbody>
</table>

Notes: values are mean ± standard deviation (SD).

aData are not included for seven grid cells representing solitary dominant soil groups (Andosol, Kastanozem, Planosol, Ranker, Solonchak, Solonetz and Vertisol). For descriptions of individual soil groups, see European Soils Bureau Network (2005).

b n.a., Not available, but likely less than 1%.

where \( y_i \) is the individual cropping share observations; \( \bar{y}_i \) is the individual cropping share simulations; and \( \bar{y} \) is the mean of the cropping share observations.

Further model validation parameters were calculated from regression analysis of observed versus simulated data plots, including the paired t-test (Mayer and Butler 1993), the significance of the correlation coefficient, and the simultaneous F-test for unit slope and zero intercept as explicitly outlined by Haefner (2005). Finally, box plots of residuals were evaluated for each of the major soil groups, operationally defined as Cambisols, Luvisols, Podzols and Other soils (cf. Table 1).

Climate change and cropping share projections

Meteorological data on monthly basis (precipitation \( P \), \( T_{\text{sum}} \), \( T_{\text{min}} \) and \( T_{\text{max}} \)) were obtained from each grid cell from 50 years of synthetic daily data generated by the LARS weather generator (LARS-WG) using 1976–2005 as baseline and 2031–2050 to estimate projected effects of climate change around 2040. LARS-WG is a stochastic weather generator based on the series approach (Racsko et al. 1991). The baseline data were taken from observed daily meteorological data for 1976–2005 that had been interpolated onto a 50-km regular square grid across Europe. These data were extracted from the JRC-MARS meteorological database, which includes data from more than 5000 meteorological stations (Peltonen-Sainio et al. 2010). The LARS-WG was calibrated for each of the grids in the observational data, and change parameters for 2040 were obtained by deriving changes in parameters from the selected RCM for the respective control period (1976–2005) and the scenario period (2031–2050). Climate model data were extracted from the ENSEMBLES database, which includes projected climate changes for different combinations of global and regional climate models, all based on the A1B emission scenario of the Intergovernmental Panel on Climate Change (IPCC) (van der Linden and Mitchell 2009). The A1B emission scenario represents a mid-range scenario for greenhouse gas emissions in the IPCC Special Report on Emission scenarios (SRES) (Nakicenovic et al. 2000). Results from two RCM runs were used, namely the KNMI RACMO2 model (Royal Netherlands Meteorological Institute) and the HC HADRM3Q0 model (Hadley Centre Met Office). The first model (KNMI) has a moderate climate signal and a good performance to predict the present-day climate, whereas the second model (HC) has a stronger climate change signal (both in temperature and precipitation) thereby spanning the range of possible climate change scenarios (Christensen et al. 2010).

Cropping share projections were based on the algorithms derived for maize, oat and wheat, and the climate data derived from the KNMI and HC models. Monthly averages of the data generated with the LARS-WG on temperature, effective temperature sums and average summarised monthly precipitation were applied at grid scale, and used in the calculations of cropping shares in the different scenarios.
Results

Distribution of cropping shares

Data compiled for the present analysis of cropping shares represented a cultivated area of 140 million ha distributed over 1405 grids and including 13 dominant soil groups (Table 1). Descriptive statistics showed that wheat was the most versatile of the crops, i.e., it showed a significant cropping share (e.g. >5%) on more soil groups (10) than oat (two) and maize (six). The soils with the highest relative occurrence of wheat and maize were Chernozems, Phaeozems and Rendzinas; these soil groups were at the same time characterised by the virtual absence of oat. In contrast, the most suitable soils for oat were Podzols, Lithosols and Regosols; these soils had the lowest combined cropping share of maize and wheat.

The distribution of cropping shares was consistent with a south-to-north gradient, where maize had its maximum in south (45–55°N), oat had its maximum in north (55–65°N), and wheat was more evenly distributed across latitudes in Europe (Figure 2). Further, changes in cropping shares between the two observation periods (1990–1999 and 2000–2008) pointed at systematic or preponderant tendencies for increases in maize cropping shares at 50 to 57°N and increases in wheat cropping shares at 57 to 65°N, while at other latitudes increases and decreases tended to level out (Figure 3).

Relation of cropping shares to temperature and precipitation

For the maize data, $T_{\text{sum}}$ with $T_{\text{base}}$ of 6, 8 and 10°C gave similar quality of model fits to the cropping shares. Best fits were consistently obtained with sigmoidal models and a slight decrease in $R^2$ was observed by increasing the $T_{\text{sum}}$ period, e.g., from May–July ($R^2=0.63$) to May–September ($R^2=0.61$). For the further modelling, a $T_{\text{base}}$ of 10°C and $T_{\text{sum}}$ from May–July were applied (Figure 4A). A number of potential outliers ($n=15$) were identified with maize cropping shares of >13% for a resulting $T_{\text{sum}}$ of <400°Cd (Figure 4A). These data were related to mountainous regions, where temperatures in the valleys could be different from the grid cell average. Yet, as evaluated by Cook’s distance, the data could not be excluded as influential outliers (Bollen and Jackman 1990) and they were kept in the dataset, increasing the three model parameters by about 4%.

Oat and wheat cropping shares showed a peak-curve distribution in response to mean monthly temperatures (Figure 4B and C) with the three-parameter Gaussian model (Equation (3)) as the marginally best. For oat, an increase in the period for calculating mean temperatures from April–August successively decreased $R^2$ from 0.54 to 0.30, whereas for wheat

Figure 2. Cropping shares (percentage of agricultural area) of maize, oat and wheat at latitudes between 45 and 65°N in Europe (average of two observation periods from 1990–1999 and 2000–2008).

Figure 3. Changes in observed maize, oat and wheat cropping shares (percentage points) between the two observation periods (1990–1999 and 2000–2008) for latitudes between 45 and 65°N. Positive values signify a higher cropping share in 2000–2008 than in 1990–1999.
there was a varying effect of increasing the period for calculating mean temperatures, and the best model fit ($R^2 = 0.30$) was observed for temperature in March–August.

For both oat and wheat the data distribution at a given temperature interval was characterised by cropping shares ranging from almost zero to a temperature-dependent maximum. Hence, the maximum of cropping shares as a function of mean temperatures could essentially be contained within a peak-curve (Equation (3)) that was visually fitted by manipulation of the three model parameters $a$, $x_0$ and $b$ (Figures 4B and C; derived model parameters are available as “Supplementary material”).

Cumulated precipitation in spring and summer showed no systematic relationship to the cropping shares of maize, which at least partly could be due to irrigation. Thus, cropping shares from zero to 32% were generally scattered within a precipitation window ranging from 50 to 300 mm in spring (Figure 4D) and 50 to 200 mm in summer (data not shown).

For oat, the cropping shares followed a trend related to cumulated precipitation in spring that was modelled by Equation (3) with a goodness-of-fit of $R^2 = 0.31$ (Figure 4E). Cumulated precipitation in summer showed no systematic relationship to the oat cropping shares (data not shown) and was not pursued in further modelling.

Wheat cropping shares, showed a peak-curve distribution in response to precipitation both in spring (Figure 4F) and summer (data not shown). Yet, the goodness-of-fit was poor ($R^2 = 0.07$) for both periods and, as for oat, the data were rather contained within a peak-curve as visually fitted by manipulation of the model parameters (Figures 4E and F; derived model parameters are available as “Supplementary material”).

**Combined models and deviance measures**

Combined models using temperature and precipitation as drivers were pursued for oat and wheat, whereas
for maize, the derived effective temperature sum model was used directly:

$$\text{CS}_{\text{maize}} = 29.5/(1 + \exp(- (T_{\text{sum}} - 671.2)/105.7))$$

(6)

where \(\text{CS}_{\text{maize}}\) is the cropping share of maize (%); and \(T_{\text{sum}}\) is the temperature sum (°Cd, base 10°C) in May–July. The resulting modelling efficiency was 0.63 and \(r\)MAE was 0.54 (Table 2).

For oat, a combined multiplicative model including temperature and precipitation performed slightly better \(R^2 = 0.55\), and had a lower AIC, than the model based on temperature alone. The resulting parameterisation yielded the algorithm:

$$\text{CS}_{\text{oat}} = (2.23 \times \exp(-0.5 \times ((T_4 - 2.44)/(2.27)^2))) \times (8.68 \times \exp(-0.5 \times ((P_3 + 79.43)/91.86)^2))$$

(7)

where \(\text{CS}_{\text{oat}}\) is the cropping share of oat (%); \(T_4\) is the mean temperature (°C) in April; and \(P_3\) is the cumulated precipitation (mm) in March. For this model MEF was 0.55 and \(r\)MAE was 0.59 (Table 2).

For wheat, a multiplicative model including temperature and precipitation in both spring and summer showed the best goodness-of-fit \((R^2 = 0.44)\) and the lowest AIC. Thus, the resulting parameterisation yielded:

$$\text{CS}_{\text{wheat}} = (5.33 \times \exp(-0.5 \times ((T_{3-8} - 13.63)/(2.88)^2))) \times (4.26 \times \exp(-0.5 \times ((P_{3-5} - 118.85)/114.37)^2))) \times (4.26 \times \exp(-0.5 \times ((P_{7-8} + 487.23)/319.50)^2)))$$

(8)

where \(\text{CS}_{\text{wheat}}\) is the cropping share of wheat; \(T_{3-8}\) is the mean temperature (°C) in March–August; \(P_{3-5}\) is the cumulated precipitation (mm) in March–May; and \(P_{7-8}\) is the cumulated precipitation (mm) in July–August. For the combined model MEF was 0.44 and \(r\)MAE was 0.43 (Table 2).

Analysis of observed versus predicted cropping shares demonstrated a strong and significant correlation (Table 2). Likewise, the paired \(t\)-tests for differences were non-significant and only for oat the simultaneous \(F\)-test indicated potential bias \((p < 0.05; \text{Table 2})\). However, modelling efficiencies were reasonably low \((0.44–0.63)\) and \(r\)MAE were higher than generally acceptable \((e.g. \text{rMAE} < 0.3; \text{Adam et al. 2011})\). Box plots of residuals (Figure 5) showed a similar pattern for individual soil groups, which indicated a lack of systematic deviations caused by soil groups. Rather, the model validation data indicated that for all soil groups the derived models tended to under-predict at high cropping shares and over-predict at low cropping shares.

**Comparison of observed, baseline and projected cropping shares**

The observed, baseline and projected cropping shares of maize, oat and wheat are shown in Figures 6–8.
Disregarding the areas with no data, the observed low maize cropping shares in Scandinavia, the UK and the Baltic countries were adequately reproduced for the baseline climate data (Figure 6). Also the high cropping shares in Hungary, Romania and northern Italy were reproduced well. However, the maize cropping shares in the coastal area covering western Germany and the Benelux countries seemed to be underpredicted, whereas cropping shares in France generally were over-predicted by the baseline model. The effects of projected climate changes indicated an overall increase in maize cropping shares, which notably for the HC model extended northwards into Denmark, Sweden and Finland. However, there were considerable differences in projected cropping shares according to the two climate projections (KNMI and HC), as exemplified by the results for Germany and Poland. These variations were directly linked to the differences in the temperature signal between the two climate projections.

Observed cropping shares of oat showed the major occurrence to be confined to southern Finland, Sweden and Norway (Figure 7). The baseline scenario, derived from the temperature and precipitation model, also pointed at a major distribution in northern Europe, but the model failed to reproduce the low cropping shares for oat cropping in Sweden and Norway. This was interpreted as the result of inappropriate agricultural soil conditions since these regions are characterised by hilly plateaus mantled by moraine-derived material (Fullerton 1954). Further, the model only partially reproduced the area with maximum oat cropping shares in south-western Finland. Projections made with the two climate change scenarios (notably HC) suggested a lower cropping share of oat in the southern part of Scandinavia and Finland, whereas no area was characterised by marked increases in the cropping share of oat.

Cropping shares of wheat (Figure 8) in Scandinavia, Finland and the Baltic countries were reasonably well reproduced for the baseline climate data, although some areas were under-predicted (e.g. Denmark and southern Finland). Also for the eastern European countries (Czech Republic, Slovakia, Slovenia, Hungary and Romania) there was a concordance between observed and baseline-modelled cropping shares. However, the modelled baseline cropping shares failed to reproduce the areas with very high observed wheat share in mid-Germany, northern France and eastern England. For the projected climate change scenarios there was a tendency to higher wheat cropping shares in Scandinavia, Finland and the Baltic

Figure 6. Maps of maize cropping shares (percentage of agricultural area) observed during 1990–2008 (upper left), modelled for baseline climate data from 1976–2005 (upper right), and modelled for projected climate change around 2040 according to the KNMI projections (lower left) and the HC projections (lower right).
Figure 7. Maps of oat cropping shares (percentage of agricultural area) observed during 1990–2008 (upper left), modelled for baseline climate data from 1976–2005 (upper right), and modelled for projected climate change around 2040 according to the KNMI projections (lower left) and the HC projections (lower right).

Figure 8. Maps of wheat cropping shares (percentage of agricultural area) observed during 1990–2008 (upper left), modelled for baseline climate data from 1976–2005 (upper right), and modelled for projected climate change around 2040 according to the KNMI projections (lower left) and the HC projections (lower right).
countries, whereas the southern parts of the study area (e.g. France, Hungary and Romania) were characterised by reductions in the wheat area. This tendency was stronger for the projected changes by the HC model as compared with those of the KNMI model.

Discussion

Modelling approach

The present modelling approach was based on an empirical association between land use and weather data in Europe between 45 and 65°N. The approach aimed to capture major drivers of the system behaviour in a simple model, but some uncertainties in the available data were apparent. Land-use data were obtained at different NUTS classification levels (1, 2 and 3), based on current availability from national or regional statistical institutes, and therefore the accuracy of the 50-km square grid results varied due to differences in data availability at various NUTS scales, different sizes of NUTS regions, and the number of years with land-use data. Also, the applied grid cells often covered more than one NUTS region, and the value of the grid was then estimated as a weighted average based on agricultural area of the represented NUTS regions within the grid cell. This adds some uncertainty to the specific land use within each grid cell. Further, observations of maize, oat and wheat cropping shares during the period 1990–2008 were coupled to baseline climatic data for the period 1976–2005. This asynchrony may have created an imprecision in the model input, but it was probably of minor importance since the land-use data covered a central part of the climatic period. Another minor deficiency in our approach was that we omitted the differential effects of future elevated CO2 concentrations on C3 (wheat and oat) and C4 (maize) crops (Ainsworth and Rogers 2007; Tubiello et al. 2007) which could change the relative competitiveness in favour of C3 crops. However, also other differential developments in breeding and agricultural technologies could cause shifts in crop performance over time.

The present modelling approach may represent an over-simplification of the factors determining the distribution of cereal crops, as indicated by the tendency of under-prediction of high cropping shares and over-prediction of low cropping shares. Thus, one or more additional variables probably should have been included to improve the modelling efficiency. One option in the present data analysis was to include the soil group. Yet, assignment of soil groups to the 1405 grids was done according to the dominant soil group, which on average represented only 46–79% of the cultivated area in the individual grid cells (Table 1). Therefore, there was an unknown association between soil group and the observed occurrence of specific crops in the grid cells. When analysed, residuals for operationally defined soil groups showed a similar distribution indicating a minor contribution from soil group as an explanatory variable. This lack of correspondence may be partially due to a lack of proper representation of the soil groups on which the crops are actually grown, and to an inability of the employed soil classification to represent the important soil conditions for growing specific crops. The difficulty of incorporating soil properties in modelling approaches has been discussed by, for example, Hazeu et al. (2010). A possible way forward to improve the current modelling could be to analyse and include (instead of soil groups) such candidate properties as topsoil C content or rooting depth which may be better linked to crop requirements.

One general observation, however, from the present analyses of cropping shares related to soil groups was that soil groups with the highest shares of maize and wheat had the lowest shares of oat and vice versa. This reflected that poorer soils are frequently assigned to oat because more valuable crops are grown on the better soils, and oats perform relatively better on poor soils.

Projected changes in cropping patterns

Several studies have addressed the effects of climate change on potential or actual yields of crops like maize, wheat, and others (e.g. Ewert et al. 2005; Supit et al. 2010; Olesen et al. 2011). Relatively fewer studies have addressed future distribution of production areas for specific crops – the Rhine basin study by Rötter et al. (1995) being an early exception. Also, Tuck et al. (2006) modelled the potential distribution of bioenergy crops in Europe, including maize, oat and wheat. This approach was based on whether or not each crop could grow in individual grid cells (as influenced by different climate change scenarios) according to crop-specific critical limits for temperature and precipitation. Conclusions from this study (Tuck et al. 2006) were that the suitability for production of maize extended northwards, whereas the current distribution of oat at 55–64°N was maintained.

Based on a recent exploratory assessment, Hermans et al. (2010) indicated that increased agricultural productivity would generally reduce the area of agricultural land needed to meet the future European demand for food and feed. As projected for 2050, this production would concentrate in regions of northwestern Europe, and, for example, one-third of the demand for wheat would be supplied by France (Hermans et al. 2010). Thus, in addition to effects of climate change, the development of European crop production may be subject to influences of various factors including future developments in demography,
technology and global demand for agricultural produce (Hermans et al. 2010). Indeed, it has been suggested that the potential impacts of climate change are relatively small as compared with the projected productivity increases from technological developments (Ewert et al. 2005; Hermans et al. 2010). Thus, our basic assumption, that current relationships between climate conditions and comparative cropping advantages are similar under climate change, would be challenged in particular by changes in socio-economic conditions that are not correlated with changes in climate.

Our projections of changes in cropping shares support the general notion that cropping conditions in northern Europe may improve in response to climate change. Yet, although milder winters may enable an increased cultivation of winter crops at northern latitudes, the risk of poor overwintering may affect the actual cropping area. Thus, for the current production of rye and wheat in Finland, Peltonen-Sainio et al. (2011) found that overwintering damage, and associated yield losses, fluctuated on a year-to-year basis and that the severity of winter damage was associated negatively with the area sown in the following year. Such causal relationships may prevail under future climate change as weather variation and extreme events are projected to become more pronounced (Mastrandrea et al. 2011; Olesen et al. 2011). Trnka et al. (2011) showed that projected climate changes for a number of environmental zones in Europe might lead to deteriorating agroclimatic conditions due to increased drought stress and shortening of the active growing season. These negative impacts would be most pronounced in southern, eastern and central Europe (Trnka et al. 2011).

The projected northward expansions of wheat and maize cropping shares into northern Scandinavia and Finland are conditional on the suitability of the soil and terrain for cultivation of arable crops. Since some of the areas in Norway and Sweden, into which cereals might be expanding, are located in hilly regions (Fullerton 1954), the prospective area for expansion of cereal cropping may be much smaller than indicated in Figures 7 and 8.

**Perspectives**

The current study on cropping shares supplements and concurs with other studies which show that the areas for cultivation of major cereal crops will most likely shift northwards under projected climate change. This effect is most pronounced and well documented for maize (Kenny et al. 1993; Olesen et al. 2007). The results presented here show that by 2040 the cropping share with maize in England, southern Scandinavia and the Baltic countries may increase to 4–20%, the uncertainty mainly depending on the model used for climate change projections. There is a similar uncertainty in the projections for change in the projected relative area cultivated with oat. This shows the need for a better quantification of the uncertainty in climate change projections to address likely changes in agricultural land use. For a crop like oat that for biophysical reasons can also be grown further south than the current cultivation range, there is also a need to better understand the broader range of factors affecting the area of its cultivation. As indicated by the inverse relationship between cropping of oat versus maize and wheat, these factors likely include competition from a market perspective.

Wheat is grown under a wider range of climatic conditions than maize and oat. However, also for this crop there is a shift of the suitable cropping region towards northeast farther into Scandinavia and Finland. Under severe climate change, projected by the HC model, the area cropped with wheat would decline in parts of France and Hungary by about 50% as compared with the baseline scenario. This is in agreement with other studies showing that these regions would be at particular risk of losing suitability for rainfed crop production under climate change (Olesen et al. 2011; Trnka et al. 2011). Correspondingly, in a number of crop simulation studies, wheat has shown a decrease in grain yield with increasing temperatures due to earlier dates of maturity and a resulting decrease in the duration of the grain-filling period (Wolf et al. 1996). However, recent developments in wheat yields in Europe have shown that yield reductions from warming can at least in some regions be balanced by the gains obtained from plant breeding (Brisson et al. 2010).

**Conclusions**

Changes in cropping shares of maize, oat and wheat under projected climate changes showed a contrasting pattern with northwards expansion and generally increasing cropping shares of maize, unchanged or lower cropping shares of oat (except for the most northern areas), and divergent changes in cropping patterns of wheat with increases in the northern parts and decreases in the southern parts of Europe. The present modelling approach represents a simplification and minimisation of the number of factors determining the distribution of cereal crops, but improved modelling efficiencies probably could be obtained by the addition of one or more variables representing important soil conditions required for growing specific crops. In this respect, the assignment of a dominating soil group to each grid cell apparently was too indistinct to improve the modelling results. For the future, a promising way of improvement would be through a systematic analysis of key soil properties determining
the soil suitability for growing specific crops. These can then be incorporated in a GIS environment together with crop-specific agro-climatic suitability criteria for spatial analysis of shifts in cropping shares. Such models, in turn, may contribute to improved scenario analyses of emerging or re-emerging feed and food hazards in European cereal production.

Supplementary material
Supplementary material associated with this article can be found in the online version.

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