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Simulation of phenological development of wheat and maize at the global scale

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ABSTRACT

Aim: To derive location-specific parameters that reflect the geographic differences among cultivars in vernalization requirements, sensitivity to day length (photoperiod) and temperature, which can be used to simulate phenological development of wheat and maize at the global scale.

Location: Global

Methods: Based on crop calendar observations and literature describing the large-scale patterns of cultivar phenological characteristics, we developed algorithms to compute location-specific parameters to represent this large-scale pattern. Vernalization requirements were related to winter duration and coldness, sensitivity to day length was assumed to be represented by the minimum and maximum day lengths occurring at a location, and sensitivity to temperature was related to temperature conditions during the vegetative development phase of the crop.

Results: Application of the derived location-specific parameters resulted in high agreement between simulated and observed lengths of the cropping period. Agreement was especially high for wheat, with mean absolute errors of less than three weeks. In the main maize cropping regions, cropping periods were over- and underestimated by 0.5 to 1.5 months. We also found that interannual variability in simulated wheat harvest dates, was more realistic when accounting for photoperiod effects.

Main conclusions: The presented methodology provides a good basis for modelling phenological cultivar characteristics at the global scale. We show that current global patterns of growing season length as described in cropping calendars can be largely reproduced by phenology models if location-specific parameters are derived from temperature and day length indicators. Maize growing seasons cannot be modelled as good as wheat growing seasons, especially in warm regions. Our method to compute parameters for phenology models from temperature and day length offers opportunities to improve the simulation of crop productivity by crop simulation models developed for large spatial areas and for long-term climate impact projections that account for adaptation in variety selection.

Keywords: Agricultural management, crop calendars, global crop modelling, global harvest dates, phenology, cultivar/variety characteristics

INTRODUCTION

The phenological development of crops determines the duration and timing of essential periods for crop growth and thus the quality and quantity of crop yields to a large extent (Porter & Semenov, 2005). In the scientific literature it is well established that temperature (directly and in case of winter cultivars also indirectly via vernalization requirements) and day length (also referred to as photoperiod) are the main components determining crop development. Development rate shows a positive linear correlation to temperature (Slafer & Rawson, 1994). Vernalization is the influence of cold temperatures on the timing of flowering (Raven *et al.*, 2005): development is delayed as long as the plant has not experienced sufficient days with vernalizing temperatures (Miralles & Slafer, 1999). Finally, photoperiodism is the response to a change in the proportions of light and darkness in a 24-hour cycle. For long-day plants (e.g. wheat) development accelerates when photoperiod increases, for short-day plants (e.g. maize) development accelerates when photoperiod decreases (Raven *et al.*, 2005). Moreover, crop development will be synchronized among years due to photoperiodism, buffering the impact of interannual variability in weather conditions (Hay & Kirby, 1991; Gouesnard *et al.*, 2002; Craufurd & Wheeler, 2009). Crops like wheat and maize are cultivated in a wide range of environments (Gouesnard *et al.*, 2002; Trethowan *et al.*, 2006). This is possible due to a variety of cultivars that respond differently to temperature and photoperiod and farmers can therefore choose a cultivar that is well adapted to local temperature and photoperiod conditions (Olesen *et al.*, 2012).

Observed climatic warming has resulted in changes in crop phenology, which is described for Europe (Menzel *et al.*, 2006), China (He *et al.*, 2015), and the US (Twine & Kucharik, 2009), with associated consequences for crop productivity. To assess the impact of climate change on crop productivity, crop simulation models are suitable tools. The accuracy of simulated crop yield is determined to a large extent by the accuracy of the phenological module of the model (Wheeler *et al.*, 2000). Moreover, potential adaptations of farmers to climate change through cultivar and sowing date selection should be considered within climate change impact assessments (Olesen *et* *al.*, 2012). Accordingly, static crop calendars, e.g. based on observations, should not be used as input for adaptation or climate impact studies.

Given the widely reported sensitivity of crops to photoperiod, its role as key determination of crop adaptation to local conditions, and its synchronizing function, it seems important to consider its effects in phenological modules of crop models (Craufurd & Wheeler, 2009). Vernalization is often but not always considered in field scale (Asseng *et al.*, 2013) and global scale (Rosenzweig *et al.*, 2014) wheat models, while photoperiodism is covered by many field scale models for wheat (Asseng *et al.*, 2013) and maize (Bassu *et al.*, 2014) but typically not in global scale models (Rosenzweig *et al.*, 2014). One reason is certainly the lack of information required to parameterize photoperiodism and vernalization responses of crops in phenology models applied at global scale. Consequences of omitting photoperiodism and vernalization relations for phenology simulations, e.g. on the interannual variability of the length of the simulated cropping periods, have not evaluated at the global scale to date.

As stated above, farmers choose cultivars adapted to local conditions, but also as adaptation strategy to changing climatic conditions. Most global crop growth models use climate data to define sowing dates (see e.g. Waha *et al.*, 2012), thus accounting for possible adaptation strategies. However, to date, equivalent methods to define model parameters necessary to account for cultivar selection as adaptation strategy are lacking for the global scale. This limits simulation of phenological development and consequently hinders simulation of accurate crop yields and variety-related adaptation strategies, especially within climate impact assessments.

The objectives of this study were therefore: (1) to compare phenology models differing with regard to consideration of vernalization and/or photoperiod responses, (2) develop algorithms to define location-specific crop variety parameters for these phenology models; and (3) to investigate the interannual variability in simulated growing period lengths based on the different phenology models. Wheat and maize are used as example crops accounting for approximately 30% of the total harvested global crop area (FAO, 2012). We thus hypothesize that farmers' selection of crop varieties is mainly aiming to optimize the growing period as defined by local climatic conditions and that the parameters for phenology models can be derived from simple climatic indicators.

The outcomes of this study can help to improve simulations of crop phenology in crop growth models applied at large spatial areas. This will make an important contribution to climate impact studies on global crop productivity.

METHODS

Phenological model AFRCWHEAT2

To simulate phenological development of wheat and maize we used the well-established concept of heat units as implemented in the model AFRCWHEAT2 (Weir *et al.*, 1984; Porter, 1993; Ewert *et al.*, 1996). Daily temperature ($T_{i,}$, °C) is accumulated above a base temperature ($T_{\mathrm{b},}$, °C), resulting in a heat unit sum (HU_{sum}, °Cd) until the required heat units from emergence to physiological maturity (HU_{req}, °Cd) are reached. The increment in heat units is modified by the effects of photoperiod (photoperiod factor, P_{f_i}, -), and in case of winter wheat by the effects of vernalization (vernalization factor, V_{f_i}, -). The crop is harvested when the heat unit sum accumulated for the period since sowing HU_{sum} becomes equal or larger than HU_{req}:

$$HU_{\mathrm{sum}} = \sum_{i=1}^{N}(T_i - T_{\mathrm{b}}) \times P_{\mathrm{f}_i} \times V_{\mathrm{f}_i} \qquad \text{if } HU_{\mathrm{sum}} \leq HU_{\mathrm{req}} \qquad \text{(Eq. 1)}$$

with N the simulated length of the cropping period in days. The simulation of maize was in addition stopped when temperatures dropped continuously below the base temperature. Further details on the phenology model and the required parameters are provided in Appendix S1 in the Supporting Information.

Data

Datasets of observed cropping periods

Global dataset MIRCA2000

To derive regression parameters for estimating heat unit requirements and to test how well application of the obtained regression equations at global scale could reproduce spatial patterns of observed phenology, we used the global dataset MIRCA2000 (Portmann *et al.*, 2010). MIRCA2000 reports monthly growing areas of 24 irrigated and rainfed crops at a spatial resolution of 5' × 5' for the period around the year 2000. The data were aggregated to the resolution of the weather data used in this study (30' × 30').

Up to five possible cropping periods per grid cell are indicated in MIRCA2000, reflecting different cultivars of wheat and multiple-cropping systems with maize. For each grid cell, the cropping period with the maximum reported area was selected for this study. We assumed that sowing was at the first day of the reported sowing month, also applied by Portmann *et al.* (2010), and harvest at the last day of the reported harvest month. Day of emergence was set equal to the sowing date and the harvest date was assumed to correspond with physiological maturity.

A dataset similar to MIRCA2000 was developed by Sacks *et al.* (2010) but they did not differentiate between rainfed and irrigated crops. Since cropping periods often differ between irrigated and rainfed crops we used MIRCA2000 for this study.

Point observations of winter wheat harvest dates

Information on the interannual variability of harvest dates was derived from the Pan European Phenology Database (PEP725) which provides time series of harvest dates of winter wheat observed for several European countries (PEP725 Pan European Phenology Data). From this database we first selected countries that had data available for at least 10 successive years. Next we selected within these countries only locations with at least 5 observations within a 10 year period (the 10 year period was kept constant per country).

Photoperiod and temperature

Daily photoperiod (P_i, h d^{-1}) was calculated based on latitude and day of the year (Monteith and Unsworth, (1990) and monthly mean temperature data on a 30' × 30' resolution was extracted from the Climate Research Unit (TS3.0 dataset, Mitchell & Jones, 2005), using linear interpolation to obtain daily temperature values.

Computation of location-specific phenological parameter values

For the computation of the location-specific phenological parameter values, we assumed (i) that location-specific parameters represent cultivars that are best adapted to local climatic and photoperiodic conditions and (ii) that farmers base their cultivar selection on experiences with climatic conditions in previous years, using exponentially weighted moving averages of monthly temperatures ($\overline{T_{m,y}}$, °C, see Appendix S2). These location-specific parameters can be applied to regions currently not used for the cultivation of the crop and to estimate how crop cultivar selection may change under climate change.

Vernalization requirements of winter wheat cultivars

Ewert *et al.* (1996) indicated that both the effectiveness of temperature on the vernalization process and the vernalization requirements are different among winter cultivars. Because of data scarcity we assumed however equal temperature effectiveness for all cultivars and only varied the vernalization requirements (V_{sat} and V_{b}, d, see Appendix S1) to characterize cultivars.

Due to the exposure of winter wheat to vernalizing temperatures tolerance to below-freezing temperatures is built up. Once the vernalization requirements are met the tolerance gradually disappears (Mahfoozi *et al.*, 2001). Vernalization requirements of cultivars grown at locations with a long and cold winter are higher than of cultivars grown at locations with milder winters (Iwaki *et al.*, 2001). Therefore, we used the temperatures of the five coldest months of the year to characterize winter duration and coldness, assuming that in winter wheat growing regions the frost-period is at most five months long. By considering the five coldest months separately, influences of possible relatively warm months were minimized (Appendix S3). We excluded higher latitudes regions where MIRCA2000 indicated a sowing date during spring time, since this sowing date suggests use of spring wheat cultivars.

Photoperiodism sensitivity

To simulate differences among wheat and maize cultivars with respect to photoperiod, we adapted P_{opt} values to local conditions as described below, while P_{b} was kept constant among the cultivars, using values from literature (see Table S1, Appendix S1).

<u>Wheat</u>

Wheat cultivars originating from high latitudes (e.g. UK or Finland) are true photoperiod sensitive cultivars (Worland *et al.*, 1994), while modern cultivars grown in lower latitudes such as in the Mediterranean region and north Africa are photoperiod insensitive (Ortiz Ferrara *et al.*, 1998). Miralles and Slafer (1999) indicated that for wheat cultivars with different sensitivities to photoperiod optimum photoperiod differs significantly, ranging from ca. 15 to 21 h d^{-1}. For Argentinean wheat cultivars the optimum photoperiod was found to be 13.4 h d^{-1} (Miralles *et al.*, 2007), which approximately coincides with the maximum photoperiod (P_{max}, h d^{-1}, i.e. P at December 21$^{\mathrm{st}}$) on average in the main wheat growing area in Argentina. We characterized sensitivity to photoperiod by setting P_{opt} to the location-specific P_{max}, i.e. P at June 21st and December 21st in the northern and southern hemisphere, respectively.

<u>Maize</u>

The difference in photoperiod between two successive days is smaller at lower latitudes than at higher latitudes. It is therefore plausible that tropical cultivars of short-day plants like maize are most sensitive to photoperiod (Summerfield *et al.*, 1997). Indeed, maize cultivars adapted to temperate regions (i.e. cool, long-day environments) show lower or no photoperiod sensitivity in comparison with tropical cultivars (Bonhomme *et al.*, 1994; Birch *et al.*, 1998). Similar to wheat cultivars, also maize cultivars differ in their optimum photoperiod (Birch *et al.*, 1998). Rood and Major (1980) found optimum photoperiods varying from < 14 h d^{-1} to 24 h d^{-1}. Location-specific P_{opt} values for maize were established as follows:

$$P_{opt} = \max\left(0, P_{max} \times \left(1 - \frac{1}{P_{max} - P_{min}}\right)\right) \qquad \text{(Eq. 2)}$$

where P_{min} (h d^{-1}) is the minimum photoperiod possible on a certain location, i.e. P at December 21st and June 21st in the northern and southern hemisphere, respectively.

Heat units required from emergence to maturity

Heat units from emergence to maturity (HU_{req}, °Cd) could not be derived from literature in a general fashion applicable to global-scale studies, because estimates from case studies are model specific, depending on whether sensitivity to photoperiod and vernalization was considered and depending on which parameters were used to describe this sensitivity. We therefore estimate HU_{req} with linear regression models between HU_{req} calculated by using observed MIRCA2000 crop calendar data as dependent variable and as independent variable available heat units during an estimated vegetative cropping period ($HU_{sum\ veg-period}$, °Cd), in line with Bignon (1990). Due to the spatial resolution of MIRCA2000, sowing dates are also reported in grid cells which are too cold for growing maize. We therefore excluded grid cells with $HU_{sum\ year}$ < 750 °Cd from the regression analysis. To account for differences between temperate and tropical maize cultivars, we calculated separate linear regression models for maize cultivars grown in warm regions ($HU_{sum\ year} \geq 3000$ °Cd) and for maize cultivars grown in cold regions ($HU_{sum\ year} < 3000$ °Cd).

Regression models were established separately for a thermal model, taking into account only temperature effects and a photo-thermal model, taking into account temperature effects combined with photoperiod effects, including the cultivar differences as described above. For winter wheat two additional regression models were distinguished: temperature effects combined with vernalization effects (vernal-thermal model) and temperature effects combined with vernalization and photoperiod effects (vernal-photo-thermal model). For these calculations, it was assumed, that wheat and maize are sensitive to photoperiod until flowering and winter wheat was assumed to be sensitive to vernalization until V_{sat} requirements are met. To calculate available heat units during the vegetative cropping period ($HU_{sum\ veg-period}$, °Cd) we assumed a vegetative period from May to July in the northern and November to January in the southern hemisphere for maize and from March to June in the northern and September to December in the southern hemisphere for wheat, respectively. Regression parameters and R^2 are shown in Table 1 for each of the models.

TABLE 1

Assessment of different phenological models

Assessment of regression model skill

Three area-weighted indices of agreement were computed to assess the degree of agreement between simulated and observed cropping period lengths: the mean absolute error (MAE, month), the root mean square error (RMSE, month), and the Willmott coefficient of agreement (W, dimensionless, ranging from 0 to 1, with 1 showing perfect agreement) (Willmott, 1982). MAE and RMSE indicate the global average error between simulations and observations. In addition, W is a relative measure for the differences (Willmott, 1982).

$$\mathrm{MAE} = \frac{\sum_{i=1}^{N} |O_i - S_i| \times A_i}{\sum_{i=1}^{N} A_i} \quad \text{(Eq. 3)}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (O_i - S_i)^2 \times A_i}{\sum_{i=1}^{N} A_i}} \quad \text{(Eq. 4)}$$

$$\mathrm{W} = 1 - \frac{\sum_{i=1}^{N} (O_i - S_i)^2 \times A_i}{\sum_{i=1}^{N} (|S_i - \bar{O}| + |O_i - \bar{O}|)^2 \times A_i} \quad \text{(Eq. 5)}$$

where S_i (months) is the simulated and O_i (months) the observed length of the cropping period in spatial unit i, $\bar{O}$(months) the mean observed length of the cropping period based on all spatial units, A_i (ha) the cultivated area of the crop in spatial unit i, and N (-) the number of spatial units.

Comparison of simulated interannual variability in harvest dates

To assess if accounting for the effects of photoperiod and vernalization results in less interannual variability in the length of simulated wheat cropping periods than simulation of phenology based on thermal requirements only, we used the different phenology models (thermal, photo-thermal, vernal-thermal, vernal-photo-thermal) that were parameterized with location-specific parameters derived from the linear regression analysis, to simulate the lengths of the cropping period for the period 1996 to 2005. As an indicator for interannual variability we calculated for each grid cell and model the differences between the latest and earliest of the simulated harvest dates in that period.

To compare the interannual variability in observed and simulated harvest dates we calculated per location selected from the PEP725 database the standard deviation of the observed harvest dates (Fig. S2, Appendix S4). Next we calculated the country average of these standard deviations and the average standard deviations of simulated harvest dates from the different models.

RESULTS

Calculated phenological model parameters

Vernalization requirements

For cultivars grown in large parts of Russia, Western Europe, the northern USA, and north-east Asia the maximum possible required duration of exposure to vernalizing temperatures were computed. South of these regions lower vernalization requirements were simulated (Fig. 1).

FIGURE 1

Heat units required from emergence to maturity

The simulated heat units that are required for the phenological development from emergence to maturity show a clear trend from north to south: southern regions grow varieties that require more heat units from emergence to maturity than the varieties in northern regions (Fig. 2 shows the HU_{req} for the vernal-photo-thermal wheat model and the photo-thermal maize model). The range in HU_{req} is larger for wheat than for maize.

FIGURE 2

Comparison of simulated and observed cropping periods

Wheat

For wheat, the agreement between observed and simulated cropping periods was in the same range for the different phenological models (Table 2), with the vernal-thermal model giving the highest and the photo-thermal the lowest agreement. The mean simulated lengths of the cropping periods were in the same range as the observed mean; the spatial heterogeneity was slightly lower in the simulated cropping periods in comparison with the observed cropping periods. Agreement between observed and simulated lengths of cropping periods of countries with large wheat cropping areas, such as Russia, Canada, and Turkey, was high (Fig. 3(a) gives results of the vernal-photo-thermal model, scatterplots for the other models look similar and are not shown).

TABLE 2

Maize

For maize, agreement between observed and simulated cropping periods was slightly higher based on the thermal model than based on the photo-thermal model but both were lower than for wheat. The simulated cropping periods underestimated the observed cropping period on average by approximately one week; also the spatial heterogeneity in cropping period was underestimated by the simulations (Table 2). The scatterplot (Fig. 3(b) for the photo-thermal model) indicates that in countries situated in warmer regions, e.g. Mexico and Nigeria, the lengths of the cropping period were overestimated, while in cooler regions, e.g. the USA and Russia, the lengths of the cropping period were underestimated.

FIGURE 3

Comparison of simulated interannual variability in harvest dates

As indication for the interannual variability in simulated harvest dates we calculated per gridcell the differences between the latest and earliest of the 10 simulated harvest dates. For comparison we plotted in Fig. 4 the cumulative frequency distributions of these differences per model. The initially steeper slopes of the vernal-photo-thermal and photo-thermal model for wheat in Fig. 4(a) indicate that accounting for especially photoperiodism results in less variability in harvest dates among years. Accounting for vernalization reduced only slightly the interannual variability in harvest dates. We also mapped the spatial distribution of the difference between the latest and earliest of the simulated harvest dates of the thermal (Fig. 5(a)) and vernal-photo-thermal model (Fig. 5(b)) in the period 1996 till 2005. To quantify the interannual variability in temperature conditions the coefficient of variation of the available $HU_{\mathrm{sum\ veg-period}}$ within the same period was calculated (Fig. 5(c)). The maps indicate that especially in areas with high interannual variability in temperature conditions, combined with cultivars sensitive to photoperiod, e.g. north-eastern USA, north and western Europe, interannual variability in harvest dates decreases due to inclusion of photoperiod effects.

For maize we found that including the effects of photoperiodism only slightly changed the interannual variability of simulated harvest dates (Fig. 4(b)).

FIGURES 4 AND 5

A direct quantitative comparison between the interannual variability in observed and simulated wheat harvest dates was not possible due to various reasons. First of all, the spatial scale of the observed and simulated harvest dates differed (point vs. 0.5° × 0.5° resolution). Secondly, besides variation in observed harvest dates due to variation in interannual weather conditions, it is likely that in the real-world observations additional variation occurs due to several other factors, e.g. delay in harvesting due to unfavourable soil conditions or lack of machinery for timely harvesting. Despite these differences, the values in Table 3 show that for 4 out of the 6 countries interannual variability in harvest dates was simulated more in line with observed variations with models including photoperiod in comparison with thermal-only models.

TABLE 3

DISCUSSION

Comparison of simulated and observed cropping periods at the global scale

We present in this study an evaluation of the effects of including photoperiod and temperature (directly and indirectly) effects in crop phenology simulations for the global scale. We developed algorithms to compute location-specific parameter values that account for differences among cultivars in vernalization requirements and sensitivity to photoperiod and temperature. Accounting for photoperiod and vernalization effects in the phenology model decreases the spatial heterogeneity of heat units required from emergence to physiological maturity for wheat, a result in line with Miralles and Slafer (1999) who reported that differences in development rate among wheat cultivars mainly originate from differences in sensitivity to photoperiod and vernalization requirements.

The accuracy of simulated cropping period lengths did not improve if the phenology models accounted for the effects of photoperiod and/or vernalization (Table 2). However, accounting for effects of photoperiod and vernalization decreased the simulated interannual variability in lengths of cropping periods, especially for wheat (Fig. 4). As such, we concluded from the comparison to the PEP725 data set that the interannual variability in wheat harvest dates was likely simulated more realistically by the models including photoperiod. The comparison is complicated, however, by not accounting for the variability in sowing dates in the simulations. Still, we consider the reduced variability in cropping periods make a strong case for considering photoperiod in phenology models which are applied for large spatial areas. For maize we could not determine whether including photoperiodism has added value, because there is no observational data set as PEP725 for maize available for tropical regions. Also growing seasons in the tropics are often determined by non-climatic factors that a comparison is deemed to be difficult here.

The indices of agreement (Table 2) and the scatterplots (Fig. 3) indicated that in general, agreement between simulations and observations was higher for wheat than for maize. This reduced agreement despite good fits of the regression models for maize especially in the cooler regions (Table 1) can be explained by the differences in harvest seasons between wheat and maize. In temperate regions, wheat is normally harvested during the warmest period of the year, while maize is harvested in autumn, when temperatures approach the base temperature of maize. As a consequence, an equal over- or underestimation of the heat unit requirements leads to higher deviations in simulated harvest dates for maize than for wheat.

Calculated vernalization requirements

The pattern of simulated vernalization requirements (Fig. 1) corresponds with information found in the literature, e.g. in the south-eastern border of the Australian wheat belt winter wheat is grown, while in rest of the belt spring wheat is grown (Fisher, 1999). Also the low computed vernalization requirements for wheat in west Asia (e.g. Yemen and Saudi Arabia) and north Africa are in line with results of previous studies (see e.g. Ortiz Ferrara *et al.*, 1998). Kato and Yokoyama (1992) determined vernalization requirements of traditional cultivars originating from various countries. They found vernalization requirements of approximately 31 days for landraces originating from western Turkey, Italy, and Greece; 35 days for landraces from Afghanistan, Pakistan, Nepal, and Bhutan; 56 days for landraces from Georgia, east Turkey, and north and east Iran; 28 days for landraces from Armenia; and 7 and 14 days for landraces from Egypt and Ethiopia. This pattern is reflected in our results and builds trust in the relatively simple relationship between vernalization days and temperatures of the coldest 5 months of the year.

Simulated interannual variability in harvest dates

To evaluate the effect of vernalization and photoperiod on the interannual variability of harvest dates we compared time series of harvest dates, simulated with different phenology models, to observations from six European countries (Table 3). We found that in particular the consideration of photoperiod resulted in a decrease of the interannual variability of winter wheat harvest dates. However, the mean standard deviation of simulated winter wheat harvest dates was even smaller when using the photo-thermal-model or the vernal-photo-thermal model as compared to the observations, in particular for the two countries where most of the observations were obtained (Germany and Slovakia). An explanation for this difference could be that the observations were collected by a network of voluntary observers so that observation errors (e.g. due to confusion of crops, data handling, low frequency of field visits) in the observation dataset are likely. It is very difficult to distinguish "true" from potentially "wrong" observations but the corresponding outliers may contribute substantially to the standard deviation in the observed harvest dates. Therefore, standard deviation of harvest days is likely overestimated in the observations.

The small differences in interannual variability of simulated maize harvest dates between the thermal- and photo-thermal model, is a consequence of low sensitivity to photoperiod in areas with high interannual variability in temperature conditions (e.g. western Europe), while cultivars with high sensitivity to photoperiod are grown in areas with lower interannual variability in temperature conditions (tropical regions).

Practical implications of our research

Our approach yields two major advantages to large-scale crop modelling studies. Firstly, the simple but robust relationship between cultivar parameters that determine the length of the growing period and simple climatic indicators allow for out-scaling of crop cultivar parameters to areas currently not used for cultivation of these crops. This is important to inform simulations of gridded crop models that feed data to economic land use models (Müller & Robertson, 2014). Secondly, our approach also allows for assessing possible changes in cultivar choice under climate change, as crop cultivar parameters can be derived from climatic indicators and can thus inform climate adaptation studies and provide information that cannot be derived from observed cropping calendars (see Appendix S5 for a comparison between growing periods lengths simulated for future climatic conditions based on non-adapted inputs and inputs based on our methodology). Moreover, our methodology can be applied in combination with the methodology developed by Waha *et al.* (2012) to determine sowing dates using climatic data, to be independent of fixed cropping calendars such as MIRCA2000 or Sacks *et al.* (2010).

Limitations of our methodology and directions for further research

Only two datasets (Portmann *et al.*, 2010; Sacks *et al.*, 2010), with roughly the same data sources, report on global sowing and harvest dates but only Portmann *et al.* (2010) distinguish between irrigated and rainfed crops. Literature reporting reasonable ranges of observed HU_{req} across the world is not available and case studies are difficult to compare, given differences in underlying phenology models. Calibration of the different phenology models was therefore carried out for HU_{req} values based on the dataset of Portmann *et al.* (2010) and evaluation how well the global scale application of the regression equations shown in Table 1 reproduced the spatial pattern in observed crop phenology was done with the same dataset. Being aware of this limitation, we still found it valid to test whether observed patterns of harvest dates could be reproduced when cultivar-specific parameters are computed based on average climatic conditions only. Clearly, we did not aim to evaluate the concept of heat units itself but our methodology to compute location-specific cultivar parameters used within the heat unit concept.

We assumed in this study that cultivar selection is made only based on local photoperiod and temperature conditions. The choice of farmers to grow a certain cultivar with specific characteristics is, however, also dependent on numerous other reasons, including production system specifics such as multiple-cropping systems that require cultivars with a specific cropping period length (Tao *et al.*, 2014), the demand for specific cultivars for quality reasons, such as durum wheat in Italy (Dettori *et al.*, 2011), or to avoid pests and diseases (Kouressy *et al.*, 2008). Currently this complex system of cultivar choice is not well understood and therefore we could not include these factors in our methodology. Insights in the complex issues of cultivar choice will help to improve simulation of crop phenology for large spatial areas, but could also assist in improving studies related to possible adaptation measures to climate change, see e.g. Olesen *et al.* (2012). Finally the interaction of simulated sowing dates (see e.g. Waha *et al.*, 2012) with simulated cultivar traits, including the effects of irrigation, needs further evaluation as e.g. soil temperature warming.

Our approach allows for deriving parameters for wheat phenology models with good accuracy, but for maize the approach has larger limitations. This can be due to a more complex phenological response to temperature in maize (Kumudini *et al.*, 2014) too simple assumptions on the development phase that is sensitive to photoperiod (Birch *et al.*, 1998), as well as to overestimating the effect of photoperiod in tropical regions where longest and shortest days are not very different (see equation 2 and Table 1). These limitations for maize need to be considered when employing the approach and we suggest using the thermal model for maize. However, the thermal model approach may still be a valid alternative to assuming static variety distributions in long-term climate impact assessments or even simpler temperature based response functions (Rosenzweig *et al.*, 2014)

A limitation of MIRCA2000 was the temporal resolution of a month. By assuming sowing to be on the first day and harvest to be on the last day, it is likely that we have overestimated the simulated and observed growing periods, possibly with two months. To further improve the simulation of crop phenology for the globe we therefore stress continuously expanding datasets such as MIRCA2000 over time and including more spatial detail. Moreover, to make it possible to understand the complex system of cultivar choice, we stress the importance of collection of cultivar characteristics, including timing of vulnerable stages such as anthesis, and cultivar use for as much as possible (contrasting) locations.

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BIOSKETCH

We concentrate in our research on simulation of crop growth at large spatial areas, because it helps us in understanding challenges such as which regions have largest potential to increase crop production and which regions will be most vulnerable to climate change.

Author contribution: L.vB., E.S., C.M., and F.E. conceived the idea of computing location-specific parameter values to account for cultivar differences at global scale. All authors were involved in developing the methodology and discussing the model outputs. L.vB wrote the model code, ran the models, and prepared the manuscript and the supporting material. All authors were involved in reviewing and editing the manuscript.

TABLES

Table 1

Coefficients of determination from the linear regression analysis with the available heat units during an estimated vegetative cropping period ($HU_{\text{sum veg-period}}$), as well as the accompanying equations to compute location-specific HU_{req} values based on $HU_{\text{sum veg-period}}$. The regression models were applied at global scale with the same set of parameters.

For maize we estimated the vegetative period from May to July in the northern and November to January in the southern hemisphere; for wheat from March to June in the northern and September to December in the southern hemisphere). For maize we distinguished between warm and cold regions using $HU_{\text{sum year}}$ (we considered a location to be warm if $HU_{\text{sum year}} \geq$ 3000 °Cd, if $HU_{\text{sum year}} < 3000$ °Cd we considered it to be cold).

Crop	Equations to calculate HU_{req}	R^2
	Thermal model	$HU_{\text{sum veg-period}}$
Spring wheat	$HU_{\text{req}} = 1.06 \times HU_{\text{sum veg-period}} + 815.08$	0.75
Winter wheat	$HU_{\text{req}} = 1.18 \times HU_{\text{sum veg-period}} + 941.45$	0.45
Maize	warm region: $HU_{\text{req}} = 1.4 \times HU_{\text{sum veg-period}} + 399.66$ cold region: $HU_{\text{req}} = 1.82 \times HU_{\text{sum veg-period}} - 150.51$	0.44 0.92
	Photo-thermal model	
Spring wheat	$HU_{\text{req}} = 0.91 \times HU_{\text{sum veg-period}} + 775.27$	0.64
Winter wheat	$HU_{\text{req}} = 0.66 \times HU_{\text{sum veg-period}} + 1126.49$	0.26
Maize	warm region: $HU_{\text{req}} = 1.06 \times HU_{\text{sum veg-period}} + 145.04$ cold region: $HU_{\text{req}} = 1.52 \times HU_{\text{sum veg-period}} - 72.08$	0.35 0.91
	Vernal-thermal model	
Winter wheat	$HU_{\text{req}} = 0.99 \times HU_{\text{sum veg-period}} + 811.52$	0.44
	Vernal-photo-thermal model	
Winter wheat	$HU_{\text{req}} = 0.87 \times HU_{\text{sum veg-period}} + 907.47$	0.36

Table 2

Area weighted means, coefficient of variation of spatial distribution, and indices of agreement between simulated and observed cropping periods for wheat and maize.

Crop	Mean (months)*	Coefficient of variation (-)	Mean absolute error (months)*	Root mean square error (months)*	Willmott coefficient of agreement (-)
Observations					
Wheat	8.7	3.8	–	–	–
Maize	5.7	2.1	–	–	–
Thermal model					
Wheat	8.6	3.6	0.73	0.92	0.97
Maize	5.5	2.1	0.75	0.92	0.54
Photo-thermal model					
Wheat	8.7	3.6	0.77	0.96	0.97
Maize	5.5	2.1	0.89	1.03	0.42
Vernal-thermal model					
Wheat	8.7	3.7	0.66	0.82	0.98
Vernal-photo-thermal model					
Wheat	9.0	3.6	0.75	0.97	0.97

*Recalculation from days to months is done by assuming an equal amount of days per month (i.e. 365/12 = 30.42 days per month)

Table 3

Observed winter wheat data specifications and standard deviation of observed and simulated harvest dates of winter wheat. Fig. S2 shows the locations of the observations.

Country	Time period observations	Total number of observations	Number of locations with ≥ 5 years of observations	Standard deviation observed and simulated harvest dates (d)				
				Observations	Thermal model	Photo-thermal model	Vernal-thermal model	Vernal-photo-thermal model
Austria	1996 - 2005	178	24	8.08	13.81	10.00	11.01	9.20
Belgium	1989 - 1998	95	13	7.61	10.98	4.98	9.14	5.09
Croatia	1996 - 2005	40	4	9.28	8.33	5.11	6.92	5.04
Czech Republic	2001 - 2010	20	2	6.20	10.22	6.05	8.77	6.45
Germany	1995 - 2004	11560	1352	8.70	10.85	5.44	10.47	5.82
Slovakia	2000 - 2009	456	56	8.98	9.14	5.66	7.43	5.81

FIGURE LEGENDS

Fig. 1 Simulated location-specific vernalization requirements (i.e. required duration of exposure to vernalizing temperatures, $V_{sat,}$ d) for winter wheat, using the Mollweide projection.

Fig. 2. Simulated location-specific heat units from emergence to maturity (HU_{req}, °Cd) for (a) the vernal-photo-thermal wheat model and (b) photo-thermal maize model, using the Mollweide projection. Patterns reflect that varieties with high heat unit requirements are grown in warm locations and varieties with low heat unit requirements are grown in cooler locations.

Fig. 3 Scatterplots of observed versus simulated cropping periods per spatial unit of MIRCA2000 for: (a) wheat, based on the vernal-photo-thermal model;(b) maize, based on the photo-thermal model. The solid line represents the 1:1 line; The radius of the circles is proportional to the cultivated area of the crop in the corresponding spatial unit.

Fig. 4 Relative cumulative frequency distributions of the differences between the latest and earliest of the simulated harvest dates in the period 1996 to 2005 for: (a) wheat and (b) maize. The lines indicate the different models used to simulate the length of the cropping period. The arrows in the wheat plot indicate that if phenological development is simulated including photoperiod effects, in 75% of the grid cells the differences between the latest and earliest simulated harvest dates within the 10 year period is at most 18 days, while for the thermal model this is at most 26 days.

Fig. 5 Differences between latest and earliest of the simulated wheat harvest dates in the period 1996 to 2005 for the: (a) thermal model and (b) vernal-photo-thermal model; (c) coefficient of variation of the available heat units during the estimated vegetative cropping period ($HU_{\mathrm{sum\ veg-period}}$) in the period 1996 to 2005 for wheat (Mollweide projection). The coefficient of variation is used to characterize interannual variability in temperature conditions: regions with high coefficients of variation are characterized by high interannual variability in temperature conditions.

FIGURES

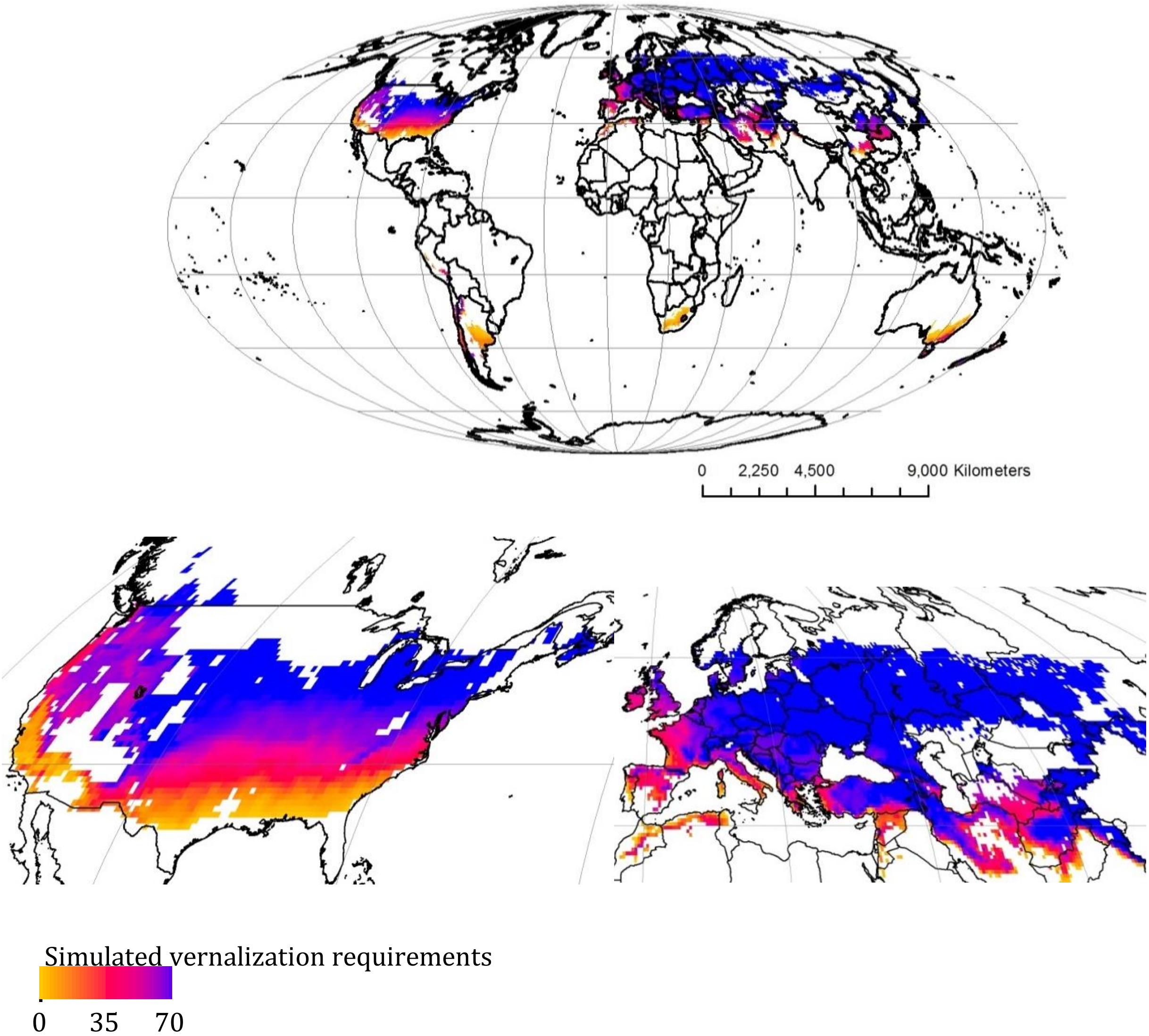

Figure 1

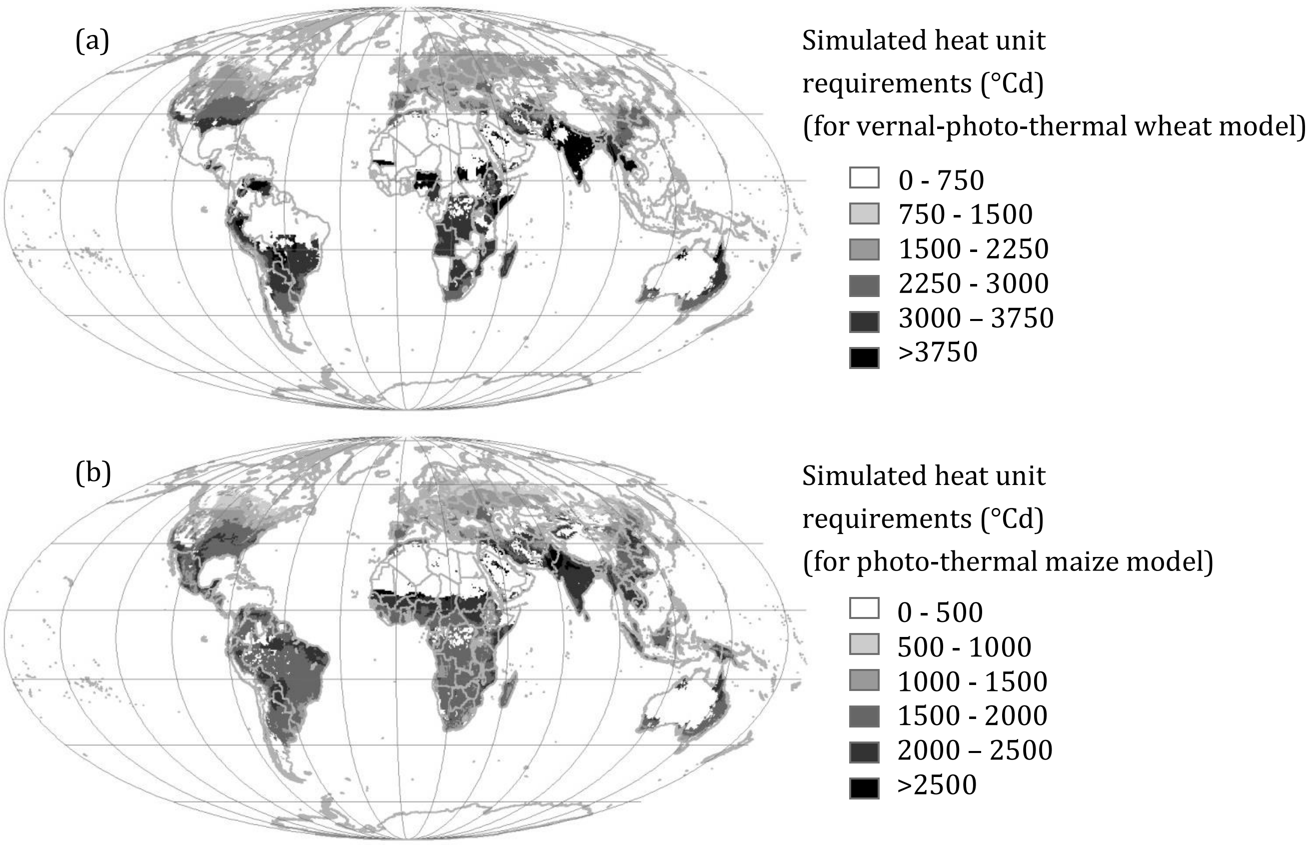
(a)
Simulated heat unit requirements (°Cd)
(for vernal-photo-thermal wheat model)
0 - 750
750 - 1500
1500 - 2250
2250 - 3000
3000 – 3750
>3750
(b)
Simulated heat unit requirements (°Cd)
(for photo-thermal maize model)
0 - 500
500 - 1000
1000 - 1500
1500 - 2000
2000 – 2500
>2500

Figure 2

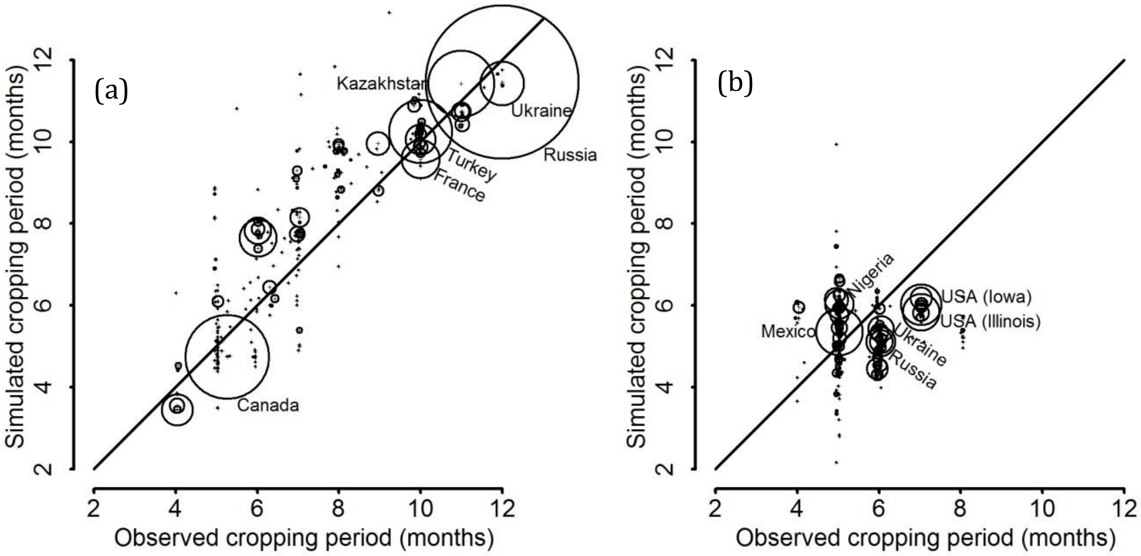
(a)
Kazakhstan
Ukraine
Russia
Turkey
France
Canada
Simulated cropping period (months)
Observed cropping period (months)
(b)
Nigeria
USA (Iowa)
USA (Illinois)
Mexico
Ukraine
Russia
Simulated cropping period (months)
Observed cropping period (months)

Figure 3

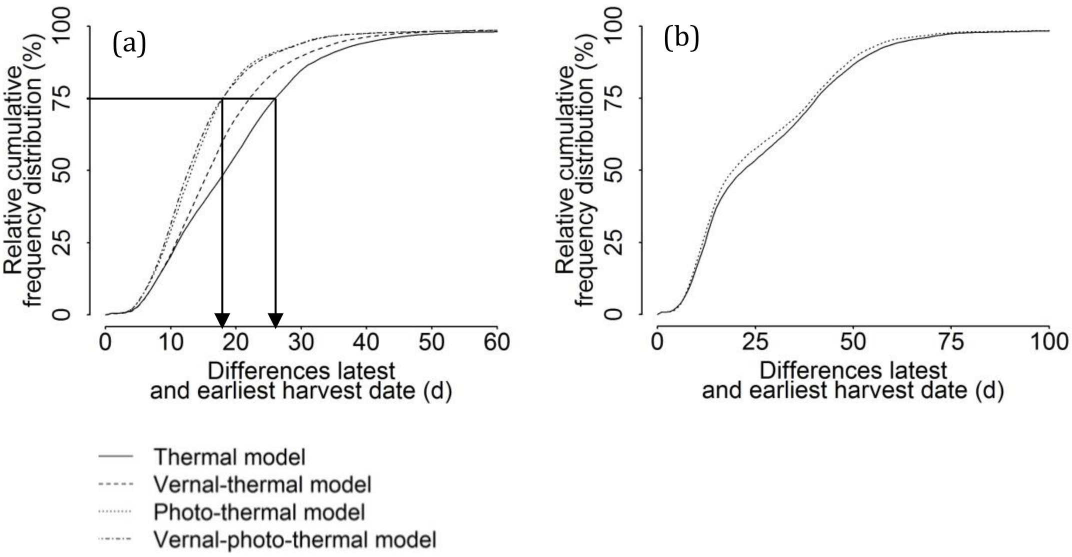
(a)
Relative cumulative frequency distribution (%)
0
25
50
75
100
0
10
20
30
40
50
60
Differences latest and earliest harvest date (d)
(b)
Relative cumulative frequency distribution (%)
0
25
50
75
100
0
25
50
75
100
Differences latest and earliest harvest date (d)
Thermal model
Vernal-thermal model
Photo-thermal model
Vernal-photo-thermal model

Figure 4

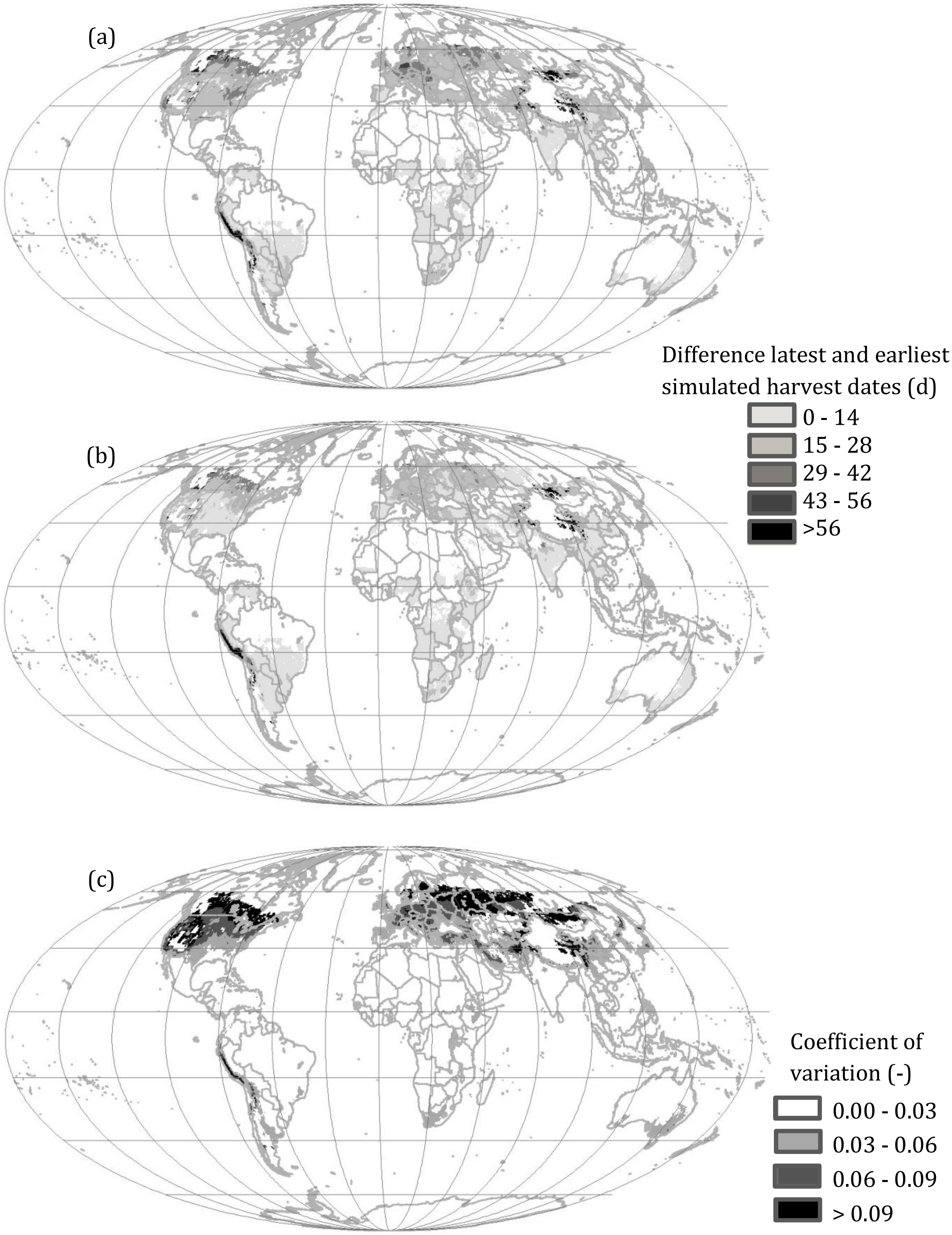
(a)
(b)
(c)
Difference latest and earliest simulated harvest dates (d)
0 - 14
15 - 28
29 - 42
43 - 56
>56
Coefficient of variation (-)
0.00 - 0.03
0.03 - 0.06
0.06 - 0.09
> 0.09

Figure 5

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1: Detailed description of the AFRCWHEAT2 model
Appendix S2: Calculation of the exponentially weighted moving averages of monthly temperatures
Appendix S3: Detailed description of the computation of the location-specific parameters
Appendix S4: Locations selected from the PEP725 database
Appendix S5: Simulated wheat growing period lengths for current (year 2000) and future climatic conditions

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APPENDIX S1 CALCULATIONS OF PHOTOPERIOD AND VERNALIZATION FACTOR

The increment in heat units (main Eq. 1) is modified by the effects of photoperiod (photoperiod factor, P_{f_i}, -), and in case of winter wheat by the effects of vernalization (vernalization factor, V_{f_i}, -), both as applied in the AFRCWHEAT2 model (Porter, 1993; Ewert *et al.*, 1996).

The photoperiod factor (P_{f_i}, -) for day i is calculated as follows:

$P_{\mathrm{f}_i} = \frac{P_i - P_\mathrm{b}}{P_\mathrm{opt} - P_\mathrm{b}}$ if $P_\mathrm{b} \le P_i \le P_\mathrm{opt}$ (for wheat) (Eq. A1)

if $P_\mathrm{opt} \le P_i \le P_\mathrm{b}$ (for maize)

$P_{\mathrm{f}_i} = 1$ if $P_i > P_\mathrm{opt}$ (for wheat) (Eq. A2)

if $P_i < P_\mathrm{opt}$ (for maize)

$P_{\mathrm{f}_i} = 0$ if $P_i < P_\mathrm{b}$ (for wheat) (Eq. A3)

with P_i (h d^{-1}) the daily photoperiod, P_b (h d^{-1}) base photoperiod (i.e. the longest (shortest) photoperiod below (above) which no further photoperiod-induced delay in long-day (short-day) plants is observed), P_opt (h d^{-1}) optimum photoperiod (i.e. the shortest (longest) photoperiod above (below) which no photoperiod-induced delay in long-day (short-day) plants is observed). (Fig. S1a and see Table S1 for the values).

The vernalization factor is incremented daily with values between 0 and 1, depending on the daily temperature and their effectiveness for vernalization (Fig. S1b). Its calculation is split in two parts, first the vernalization effectiveness (V_{eff_i}, -) of the mean temperature of day i is determined:

$V_{\mathrm{eff}_i} = \frac{T_i - T_\mathrm{v1}}{T_\mathrm{v2} - T_\mathrm{v1}}$ if $T_\mathrm{v1} \le T_i < T_\mathrm{v2}$ (Eq. A4)

$V_{\mathrm{eff}_i} = 1$ if $T_\mathrm{v2} \le T_i \le T_\mathrm{v3}$ (Eq. A5)

$V_{\mathrm{eff}_i} = \frac{T_\mathrm{v4} - T_i}{T_\mathrm{v4} - T_\mathrm{v3}}$ if $T_\mathrm{v3} < T_i \le T_\mathrm{v4}$ (Eq. A6)

followed by the vernalization factor:

$V_\mathrm{DD} = \sum_{i=1}^{K} V_{\mathrm{eff}_i}$ (Eq. A7)

$V_{\mathrm{f}_i} = 0$ if $V_\mathrm{DD} < V_\mathrm{b}$ (Eq. A8)

$V_{\mathrm{f}_i} = \frac{V_\mathrm{DD} - V_\mathrm{b}}{V_\mathrm{sat} - V_\mathrm{b}}$ if $V_\mathrm{b} \le V_\mathrm{DD} \le V_\mathrm{sat}$ (Eq. A9)

$V_{\mathrm{f}_i} = 1$ if $V_\mathrm{DD} \ge V_\mathrm{sat}$ or $DVS > DVS_\mathrm{dr}$ (Eq. A10)

with T_i (°C) the mean temperature of day i, T_vn (°C) temperatures defining the vernalization effectiveness, V_DD the accumulated effective vernalized days, V_b the base accumulated vernalized days (d), which was assumed to be one fifth of V_sat (d), the saturated vernalization days (i.e. required duration of exposure to vernalizing temperatures) (Fig. S1c and see Table S1 for the values).

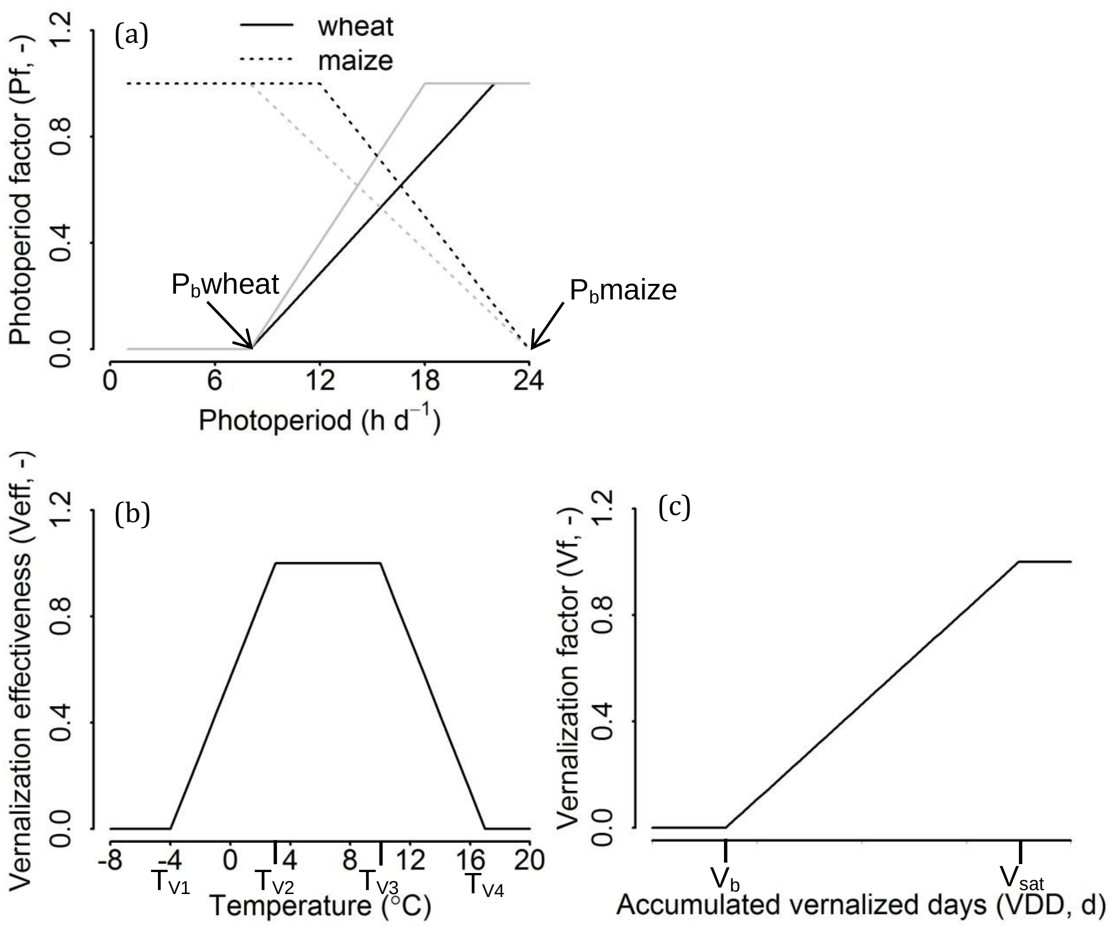

Fig. S1 (a) Effect of photoperiod on phenological development (photoperiod factor, P_{f_i}, –, ranging from 0 to 1). The solid black line indicates the response to photoperiod of a wheat cultivar from a high-latitude location; the solid grey line indicates the response of a wheat lower-latitude cultivar. The dashed black line indicates the response to photoperiod of a cultivar from a maize high-latitude location; the dashed grey line indicates the response of a maize lower-latitude cultivar; (b) daily vernalizing effectiveness (V_{eff_i}, –); (c) effect of vernalizing temperatures on phenological development (vernalization factor, V_{f_i}, –, ranging from 0 to 1); figures adapted from Ewert *et al.* (1996).

In the main text four different models are distinguished:

1. Thermal model, assuming phenological development is not influenced by photoperiod or vernalization, i.e. P_{f_i} and V_{f_i} are always 1;
2. Photo-thermal model, assuming phenological development is only influenced by photoperiod but not by vernalization, i.e. V_{f_i} is always 1 and P_{f_i} is calculated as indicated above;
3. Vernal-thermal model, assuming phenological development is P_{f_i} is always 1 and V_{f_i} is calculated as indicated above;

4. Vernal-photo-thermal model, assuming phenological development is influenced by photoperiod and vernalization, i.e. P_{f_i} and V_{f_i} are calculated as indicated above.

The ratio between HU_{sum} and HU_{req} indicates the phenological development stage of the plant (DVS, -), ranging from 0 (sowing/emergence) to 1 (harvest/physiological maturity) during the cropping period. The development scale was used to estimate the timing of the phenological stages double ridges (floral initiation) (DVS_{dr}, -) and flowering (DVS_f, -). We assumed that the rate of development of wheat and maize is sensitive to photoperiod from emergence to flowering, as indicated by Craufurd and Wheeler (2009). In addition, the rate of development of winter wheat is influenced by the effect of vernalization from emergence to the double ridge stage (Slafer & Rawson, 1994). For simplicity we assumed that all wheat cultivars are long-day plants, although some wheat cultivars behave as short-day plants (Evans, 1987) or are insensitive for photoperiod (Ortiz Ferrara *et al.*, 1998); all maize cultivars were considered short-day plants.

Table S1 lists the crop-specific parameters values for the simulation of the length of the cropping periods.

Table S1 Crop specific parameter values

Parameter	Spring wheat	Winter wheat	Maize
Base temperature (T_b,°C)	0[a]	0[a]	8[a]
Required heat units for maturity (HU_{req}, °Cd)	Location specific	Location specific	Location specific
Phenological development scale double ridge (DVS_{dr}, -)	–	0.2[b]	–
Fraction of HU_{req} when flowering occurs (DVS_f, -)	0.58[c]	0.5[c]	0.7[c]
Minimum temperature for effective vernalization (T_{v1}, °C)	–	-4[d]	–
Minimum temperature for optimal vernalization (T_{v2}, °C)	–	3[d]	–
Maximum temperature for optimal vernalization (T_{v3}, °C)	–	10[d]	–
Maximum temperature for effective vernalization (T_{v4}, °C)	–	17[d]	–
Saturated vernalization requirement (i.e. required duration of exposure to vernalizing temperatures, V_{sat} , d)	–	Location specific, from 0 till 70[e]	–
Maximum saturated vernalization requirement per month possible ($V_{sat\,max}$, d)	–	70/5 = 14 (d month^{-1})[e]	–

Base accumulated vernalized days (V_b, d)	–	$\frac{1}{5} \times V_{sat}$[f]	–
Base photoperiod (P_b, h d-1)	8	8[d]	24
Optimum photoperiod (P_{opt}, h d-1)	Location specific	Location specific	Location specific

[a]Kiniry *et al.* (1995); [b]Van Bussel *et al.* (2011); [c]Kiniry *et al.* (1995); [d]Ewert *et al.* (1996); [e]The maximum value of V_{sat} was based on a study by Baloch *et al.* (2003), they indicated that winter wheat cultivars with high vernalization requirements need at least 70 days of optimum vernalizing temperatures. We assumed an equal distribution over the five months; [f]Wang and Engel (1998).

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Ewert, F., Porter, J. & Honermeier, B. (1996) Use of AFRCWHEAT2 to predict the development of main stem and tillers in winter triticale and winter wheat in North East Germany. *European Journal of Agronomy*, **5**, 89-103.

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Ortiz Ferrara, G., Mosaad, M. G., Mahalakshmi, V. & Rajaram, S. (1998) Photoperiod and vernalisation response of Mediterranean wheats, and implications for adaptation. *Euphytica*, **100**, 377-384.

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Van Bussel, L. G. J., Ewert, F. & Leffelaar, P. A. (2011) Effects of data aggregation on simulations of crop phenology. *Agriculture, Ecosystems & Environment*, **142**, 75-84.

Wang, E. & Engel, T. (1998) Simulation of phenological development of wheat crops. *Agricultural Systems*, **58**, 1-24.

APPENDIX S2 CALCULATION OF THE EXPONENTIALLY WEIGHTED MOVING AVERAGES OF MONTHLY TEMPERATURES

We assumed that farmers base their cultivar selection on experiences with previous year's climatic conditions. To implement this, we calculated the exponentially weighted moving average of monthly temperatures ($\overline{T_{m,y}}$), using temperatures of the same month of previous years:

$$\overline{T_{m,y}} = \alpha \times T_{m,y} + (1-\alpha) \times \overline{T_{m,y-1}} \qquad \text{(Eq. A11)}$$

where $T_{m,y}$ (°C) is the mean monthly temperature of month m in year y and α (-) a coefficient representing the degree of weighting decrease (a value of 0.05 was used). The calculation was initialised by $\overline{T_{m,y=1970}} = T_{m,y=1970}$. $\overline{T_{m,y}}$ were used to compute the location-specific parameter values for the coming year, e.g. $\overline{T_{m,y=2004}}$ was used to derive location-specific parameters for the year 2005.

Daily mean temperatures ($T_{i,}$, °C), required by the phenological model, were generated by linear interpolation between the monthly means of that specific year, e.g. $T_{m,y=2005}$ was used to simulated phenological development for the year 2005 (see Van Bussel *et al.*, 2011 for a detailed description of the linear interpolation).
The observed cropping periods from MIRCA2000 refer not to a single year but to a number of years around 2000. To evaluate our methodology we therefore used $\overline{T_{m,y=2000}}$ to derive both the location-specific parameter values and the daily mean temperatures.

Van Bussel, L. G. J., Müller, C., Van Keulen, H., Ewert, F. & Leffelaar, P. A. (2011) The effect of temporal aggregation of weather input data on crop growth models' results. *Agricultural and Forest Meteorology*, **151**, 607-619.

APPENDIX S3 SIMULATION OF THE REQUIRED VERNALIZATION DAYS

The required amount of vernalization days in year y is calculated as follows:

$$V_{\mathrm{sat},y} = \sum_{m=1}^{N} V_{\mathrm{sat},m,y} \qquad \text{(Eq. A12)}$$

with

$$V_{\mathrm{sat},m,y} = V_{\mathrm{sat\ max}} \qquad \text{if } \overline{T_{m,y-1}} \leq T_{\mathrm{v2}} \qquad \text{(Eq. A13)}$$

$$V_{\mathrm{sat},m,y} = 0 \qquad \text{if } \overline{T_{m,y-1}} \geq T_{\mathrm{v3}} \qquad \text{(Eq. A14)}$$

$$V_{\mathrm{sat},m,y} = \frac{V_{\mathrm{sat\ max}}}{T_{\mathrm{v3}}-T_{\mathrm{v2}}} \times \overline{T_{m,y-1}} \qquad \text{if } T_{\mathrm{v2}} < \overline{T_{m,y-1}} < T_{\mathrm{v3}} \qquad \text{(Eq. A15)}$$

where N (-) represents the five coldest months, $V_{\mathrm{sat\ max}}$ (d month^{-1}) the maximum possible required duration of exposure to vernalizing temperatures per month (see Table S1), $\overline{T_{m,y-1}}$ (°C) the average monthly temperature of the previous year (Appendix S3 Eq. A11), and T_{v2} and T_{v3} (°C) the minimum and maximum temperatures for optimal vernalization, respectively (Ewert *et al.*, 1996). In Eq. A12 monthly temperatures are used as input, therefore only optimal temperatures for the vernalizing process were considered in this equation. Based on Eq. A12 we computed vernalization requirements for all locations with autumn sown wheat according to MIRCA2000.

Ewert, F., Porter, J. & Honermeier, B. (1996) Use of AFRCWHEAT2 to predict the development of main stem and tillers in winter triticale and winter wheat in North East Germany. *European Journal of Agronomy*, **5**, 89-103.

APPENDIX S4 LOCATIONS SELECTED FROM THE PEP725 DATABASE

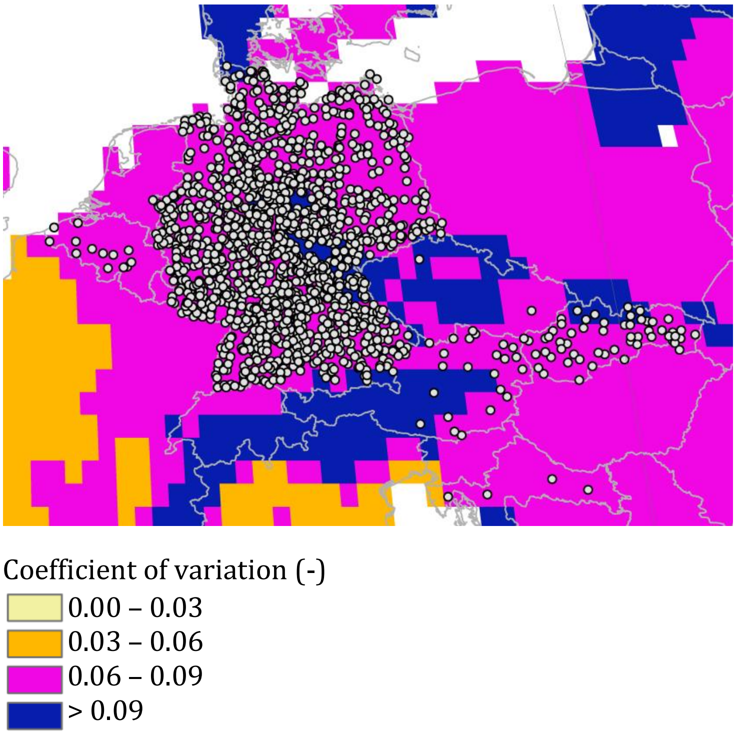

Fig. S2 Observation sites of winter wheat harvest dates. The background displays the coefficient of variation of the available heat units during the estimated vegetative cropping period ($HU_{\mathrm{sum\ veg-period}}$) in the period 1996 till 2005 for wheat (see Fig. 5(c)).

APPENDIX S5 SIMULATED WHEAT GROWING PERIOD LENGTHS FOR CURRENT (YEAR 2000) AND FUTURE CLIMATIC CONDITIONS

To demonstrate the added value of using the developed algorithms to compute location-specific phenological parameters for climate change impact studies, growing period lengths have been simulated for three locations (southern Sweden (58.25°, 14.75°), southern Italy (37.25°, 13.75°), and central Ethiopia (8.75°, 38.75°)). Weather data for the year 2000 and for future climatic conditions, represented by adding 4°C to the weather data of the year 2000, have been used. Growing season lengths for future climatic conditions have been simulated with non-adapted thermal times, which are based on climatic conditions prior to the year 2000, and for adapted thermal times, applying the developed algorithms. This has been done for two phenological models: the thermal and vernal-photo-thermal model. Sowing date was kept constant for all simulations.

In Table S2 the second and third column indicate for the year 2000 the simulated growing period lengths for the three locations resulting from the two models. Reductions in growing period lengths under climate change without adaptation to future climatic conditions and with adaptation are indicated in columns four and five, and six and seven, respectively.

If thermal times are not adapted to future climatic conditions both models simulate reductions of the growing period with 15-67 days, bearing the risk of yield reductions because of less intercepted radiation. If thermal times are adapted, the reductions range between no to 35 days reduction. These smaller reductions represent more likely lengths of growing periods between the extremes of full adaptation (second and third column) and no adaptation (fourth and fifth column).

Table S2 Simulated growing period lengths (d) for three locations for climatic conditions of the year 2000 and reductions in growing period lengths (d) for future climatic conditions, based on non-adapted and adapted thermal times.

	Climatic conditions year 2000		Future climatic conditions			
	Thermal times calculated for the year 2000		Non-adapted thermal times		Adapted thermal times	
Location/model	Thermal model	Vernal-photo-thermal model	Thermal model	Vernal-photo-thermal model	Thermal model	Vernal-photo-thermal model
Sweden	304	330	-67	-32	-35	-10
Italy	127	115	-18	-15	0	0
Ethiopia	188	168	-36	-33	-12	-10