Climate-driven simulation of global crop sowing dates

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ABSTRACT

Aim To simulate the sowing dates of 11 major annual crops at the global scale at high spatial resolution, based on climatic conditions and crop-specific temperature requirements.

Location Global.

Methods Sowing dates under rainfed conditions are simulated deterministically based on a set of rules depending on crop- and climate-specific characteristics. We assume that farmers base their timing of sowing on experiences with past precipitation and temperature conditions, with the intra-annual variability being especially important. The start of the growing period is assumed to be dependent either on the onset of the wet season or on the exceeding of a crop-specific temperature threshold for emergence. To validate our methodology, a global data set of observed monthly growing periods (MIRCA2000) is used.

Results We show simulated sowing dates for 11 major field crops world-wide and give rules for determining their sowing dates in a specific climatic region. For all simulated crops, except for rapeseed and cassava, in at least 50% of the grid cells and on at least 60% of the cultivated area, the difference between simulated and observed sowing dates is less than 1 month. Deviations of more than 5 months occur in regions characterized by multiple-cropping systems, in tropical regions which, despite seasonality, have favourable conditions throughout the year, and in countries with large climatic gradients.

Main conclusions Sowing dates under rainfed conditions for various annual crops can be satisfactorily estimated from climatic conditions for large parts of the earth. Our methodology is globally applicable, and therefore suitable for simulating sowing dates as input for crop growth models applied at the global scale and taking climate change into account.

Keywords

Agricultural management, crop calendars, global crop modelling, global sowing dates, major field crops, planting dates, temperature and precipitation seasonality.

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INTRODUCTION

In addition to soil characteristics, the suitability of a region for agricultural production is largely determined by climate. Precipitation controls the availability of water in rainfed and to some extent in irrigated production systems, temperature controls the length and timing of the various phenological stages on one hand and the productivity of crops on the other hand (Larcher, 1995; Porter & Semenov, 2005), and available radiation controls, via energy supply, the photosynthetic rate (Larcher, 1995). Furthermore, low temperatures and inadequate soil water availability during germination lead to low emergence rates and poor stand establishment, due to seed and seedling diseases, as shown, for example, in sugar beet (Jaggard & Qi, 2006) and soybean (Tanner & Hume, 1978), leading to low yield levels. To maximize or optimize production, farmers therefore aim to select suitable cropping periods, crops and management strategies.

With climate change, climatic conditions during the growing period will change (Burke *et al.*, 2009). Both mean and extreme temperatures are expected to increase for large parts of the earth with rising CO_2 concentrations (Yonetani & Gordon, 2001). To cope with these changing climatic conditions, adaptation strategies are required, e.g. changing the timing of sowing (Rosenzweig & Parry, 1994; Tubiello *et al.*, 2000).

Crop growth models are suitable tools for the quantitative assessment of future global crop productivity. They are increasingly applied at global scale (e.g. Bondeau *et al.*, 2007; Liu *et al.* 2007; Parry *et al.* 2004; Stehfest *et al.* 2007; Tao *et al.* 2009). Key inputs for crop growth models are weather data and information on management strategies, e.g. the choice of crop types, varieties and sowing dates. Future weather data for global application of crop growth models are usually provided by global circulation models (GCMs). It can be assumed that farmers will adapt sowing dates to changes in climatic conditions and therefore current sowing date patterns (Portmann *et al.*, 2008; Sacks *et al.*, 2010) will change over time. To adequately simulate sowing dates for future climatic conditions, it is necessary to understand the role of climate in the determination of sowing dates.

Different approaches are applied in existing crop models to determine current and future sowing dates. Crop models such as LPJmL (Bondeau *et al.*, 2007) identify sowing dates from climate data and crop water and temperature requirements for sowing. Another approach is to optimize sowing dates using the crop model by selecting the date which leads to the highest crop yield, a method applied, for example, in DayCent (Stehfest *et al.*, 2007), or by selecting the optimal growing period based on pre-defined crop-specific requirements, as in GAEZ (Fischer *et al.*, 2002). Finally, pre-defined sowing dates based on observations have been used, e.g. in the Global Crop Water Model (GCWM) (Siebert & Döll, 2008) and in GEPIC (Liu *et al.*, 2007).

In contrast to pre-defined sowing dates, determining sowing dates from climate data, as well as the optimization of sowing dates, provides the opportunity to simulate changing sowing dates under future climatic conditions. However, outcomes of the optimization method are largely dependent on the crop model used, adding extra uncertainties to the outcomes. The calculation procedure currently applied in LPJmL (Bondeau *et al.*, 2007) is not applicable for all crops in different climatic regions and has only been evaluated for temperate cereals. Therefore, our aims are to: (1) describe an improved method to identify sowing dates within a suitable cropping window, based on climate data and crop-specific requirements at global scale, and (2) evaluate the agreement with global observations of sowing dates. Non-climatic reasons for the timing of sowing, such as the demand for a particular agricultural product during a certain period or the availability of labour and fertilizer, are not considered in the simulations of sowing dates. The outcomes of our analysis will be: (1) a set of rules to determine the start of the growing period for major crops in different climates; (2) an evaluation of the importance of climate in determining sowing dates; and (3) maps of simulated global patterns of sowing dates. Our outcomes will lead to improved simulation of crop phenology at the global scale, which will make an important contribution to estimates of carbon and water fluxes in dynamic global vegetation models. Furthermore, sowing dates in suitable cropping windows under future climatic conditions can be estimated, and are likely to improve integrated assessments of global crop productivity under climate change.

MATERIALS AND METHODS

Input climate data

Monthly data of temperature, precipitation and number of wet days on a 0.5° × 0.5° resolution are based on a data set compiled by the Climatic Research Unit (Mitchell & Jones, 2005). A weather generator distributes monthly precipitation to observed number of wet days, which are distributed over the month taking into account the transition probabilities between wet and dry phases (Geng *et al.*, 1986). Daily mean temperatures are obtained by linear interpolation between monthly mean temperatures.

Deterministic simulation of sowing dates

Sowing dates, averaged over the period from 1998 to 2002, were simulated deterministically, based on a set of rules depending on crop and climate characteristics. Sowing dates were simulated for 11 major field crops (wheat, rice, maize, millet, pulses, sugar beet, cassava, sunflower, soybean, groundnut and rapeseed) under rainfed conditions. We did not consider irrigated systems, because if irrigation is applied, sowing dates are strongly determined by the availability of irrigation water (e.g. melting glaciers upstream) and labour, factors not considered in the methodology.

We assumed that farmers base the timing of their sowing on experiences with past weather conditions: e.g. in southern India, farmers use a planting window for rainfed groundnut based on experiences of about 20 years (Gadgil *et al.*, 2002), in the African Sahel, knowledge for decision making is influenced by previous generations' observations (Nyong *et al.*, 2007), while farmers in the south-eastern USA are expected to adapt their management to changes in climatic conditions within 10 years (Easterling *et al.*, 2003). In order to be able to use a generic rule across the earth we represented the experiences of farmers with past weather conditions by exponential weighted moving average climatology. This gave a higher importance to the monthly climate data from the most recent years than the monthly climate data from less recent years for the calculation of the average monthly climate data. Consequently, the month of sowing is determined by past climatic conditions, whereas the actual sowing date within that month is simulated based on the daily temperature and precipitation conditions from the specific year. Figure 1 shows a schematic overview of the methodology followed.

Determination of seasonality types

We assumed that the timing of sowing is dependent on precipitation and temperature conditions, with the intra-annual vari-

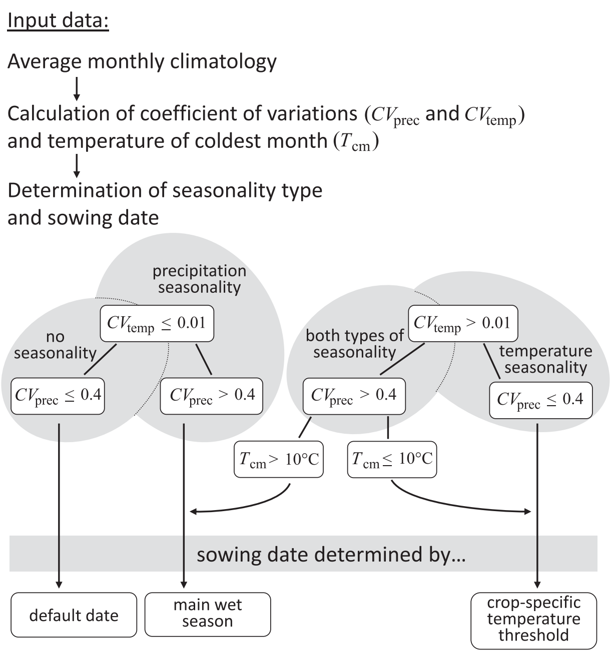

Figure 1 Procedure to determine seasonality type and sowing date. Annual variation coefficients for precipitation (CV_{prec}) and temperature (CV_{temp}) are calculated from past monthly climate data. T_{cm} is temperature of the coldest month.

ability of precipitation and temperature being especially important. Precipitation and temperature seasonality of each location are characterized by the annual variation coefficients for precipitation (CV_{prec}) and temperature (CV_{temp}), calculated from past monthly climate data. To prevent interference from negative temperatures if expressed in °C, temperatures are converted to kelvin. The variation coefficients are calculated as the ratio of the standard deviation to the mean:

$$CV_j = \frac{\sigma_j}{\mu_j}$$

with

$$\sigma_j = \sqrt{\frac{1}{12-1} \times \sum\nolimits_{m=1}^{12} (\bar{X}_{m,j} - \mu_j)^2}, \mu_j = \frac{1}{12} \times \sum\nolimits_{m=1}^{12} \bar{X}_{m,j}, \text{and}$$
$$\bar{X}_{m,j} = \alpha \times X_{m,j} + (1-\alpha) \times \bar{X}_{m,j-1}$$

where $X_{m,j}$ is the mean temperature (K) or precipitation (mm) of month m in year j, $\bar{X}_{m,j}$ the exponential weighted moving average temperature or precipitation of month m in year j, μ_j the annual mean temperature or precipitation in year j, σ_j the standard deviation of temperature or precipitation in year j, and α the coefficient representing the degree of weighting decrease (with a value of 0.05). The calculation was initialized by $\bar{X}_{m,j=1} = X_{m,j=1}$.

Variation coefficients are commonly used to distinguish different seasonality types (Walsh & Lawler, 1981; Jackson, 1989; Hulme, 1992). Walsh & Lawler (1981) provided a classification scheme for characterizing the precipitation pattern of a certain region based on the value of CV_{prec} and suggested describing a region with a CV_{prec} exceeding 0.4 as 'rather seasonal' or 'seasonal'. We could not find such a value for CV_{temp} in the literature; however, in order to simulate a reasonable global distribution of temperate and tropical regions, we assumed temperature seasonality if CV_{temp} exceeds 0.01. Accordingly, four seasonality types can be distinguished: (1) no temperature and no precipitation seasonality, (2) precipitation seasonality, (3) temperature seasonality, and (4) temperature and precipitation seasonality.

In situations with a combined temperature and precipitation seasonality, we additionally considered the mean temperature of the coldest month. If the mean temperature of the coldest month exceeded 10 °C, we assumed absence of a cold season, i.e. the risk of occurrence of frost is negligible, which is in line with the definition of Fischer *et al.* (2002). Consequently, temperatures are high enough to sow year-round, therefore precipitation seasonality is determining the timing of sowing. If the mean temperature of the coldest month is equal to or below 10 °C, we assumed temperature seasonality to be determining the timing of sowing.

Determination of the start of the growing period

The growing period is the period between sowing and harvesting of a crop. We applied specific rules per seasonality type to simulate sowing dates (Fig. 1). In regions with no seasonality in precipitation and temperature conditions, crops can be sown at any moment and we assigned a default date as sowing date (1 January, for technical reasons).

In regions with precipitation seasonality, we assumed that farmers sow at the onset of the main wet season. The precipitation-to-potential-evapotranspiration ratio is used to characterize the wetness of months, as suggested by Thornthwaite (1948). Potential evapotranspiration is calculated using the Priestley–Taylor equations (Priestley & Taylor, 1972), with a value of 1.391 for the Priestley–Taylor coefficient (Gerten *et al.*, 2004). As a region may experience two or more wet seasons, the main wet season is identified by the largest sum of monthly precipitation-to-potential-evapotranspiration ratios of four consecutive months; 4 months was selected because the length of that period captures the length of the growing period of the majority of the simulated crops. Crops are sown at the first wet day in the main wet season of the simulation year, i.e. with a daily precipitation higher than 0.1 mm, which is in line with the definition of New *et al.* (1999).

In regions with temperature seasonality, the onset of the growing period depends on temperature. Crop emergence is related to temperature; accordingly, sowing starts when daily average temperatures exceed a certain threshold (Larcher, 1995). Crop varieties such as winter wheat and winter rapeseed require vernalizing temperatures and are therefore sown in autumn. Accordingly, for those crops, temperatures should fall below a crop-specific temperature threshold (Table 1). To be certain to fulfil vernalization requirements, crop-specific temperature thresholds are set around optimum vernalization temperatures, which resembles the practice applied by farmers in southern

Table 1 Crop-specific temperature thresholds for sowing.

Crop	Base temperature for emergence found in literature			Temperature used in this study (°C)
	Reference	Temperature (°C)	Range (°C)	
Cassava	Hillocks & Thresh (2002)	16	12–17	22
	Keating & Evenson (1979)	12–17		
Groundnut	Angus *et al.* (1980)	13.3	8–13.3	15
	Mohamed *et al.* (1988)	8–11.5		
	Prasad *et al.* (2006)	11–13		
Maize	Birch *et al.* (1998)	8	8–12.8	14
	Coffman (1923)	10		
	Grubben & Partohardjono (1996)	10		
	Kiniry *et al.* (1995)	12.8		
	Pan *et al.* (1999)	10		
	Warrington & Kanemasu (1983)	9		
Millet	Garcia-Huidobro *et al.* (1982)	10–12	7.7–13.5	12
	Grubben & Partohardjono (1996)	12		
	Kamkar *et al.* (2006)	7.7–9.9		
	Mohamed *et al.* (1988)	8–13.5		
Pulses	Angus *et al.* (1980) – field pea	1.4	1.4–11	10
	Angus *et al.* (1980) – cowpea	11		
	Angus *et al.* (1980) – mungbean	10.8		
Rice	Rehm & Espig (1991)	10	10–19	18
	Yoshida (1977)	16–19		
Soybean	Angus *et al.* (1980)	9.9	5–10	13
	Tanner & Hume (1978)	10		
	Whigham & Minor (1978)	5		
Spring rapeseed	Angus *et al.* (1980)	2.6	1–2.6	5
	Booth & Gunstone (2004)	2		
	Vigil *et al.* (1997)	1		
Spring wheat	Addae & Pearson (1992)	0.4	0.4–2.8	5
	Del Pozo *et al.* (1987)	2		
	Khah *et al.* (1986)	1.9		
	Kiniry *et al.* (1995)	2.8		
Sugar beet	Jaggard & Qi (2006)	3	3–4	8
	Rehm & Espig (1991)	4		
Sunflower	Angus *et al.* (1980)	7.9	3.3–7.9	13
	Khalifa *et al.* (2000)	3.3–6.7		
Winter rapeseed*				17
Winter wheat*				12

*Winter wheat and winter rapeseed are sown in autumn, as both crops have to be exposed to vernalizing temperatures. Their base temperatures for emergence have been selected around the optimum vernalization temperatures.

Europe for example (Harrison *et al.*, 2000). Earlier research, i.e. the analysis of Sacks *et al.* (2010) on crop planting dates, showed that temperatures at which sowing usually begins vary among crops, but are rather uniform or in the same range for a given crop throughout large regions. For simplicity, we assumed that one crop-specific temperature threshold is applicable globally. The sowing month is the month in which mean monthly temperatures of the past ($\overline{X}_{m,j}$) exceed (or fall below) the temperature threshold. In addition, typical daily temperatures of the preceding month are checked. If the typical daily temperature of the last day of this preceding month already exceeds (or falls below) the temperature threshold, this month is selected as the sowing month. Typical daily temperatures are computed by linearly interpolating the mean monthly temperatures of the past ($\overline{X}_{m,j}$). Next, daily average temperature data of the simulated year determine the specific date of sowing in the sowing month, in order to consider the climatic specificity of the simulated year.

We derived the temperature thresholds, for non-vernalizing crops only, by decreasing and increasing the temperature thresholds given by Bondeau *et al.* (2007) for sowing by –4 °C to +8 °C and selected the temperature thresholds that resulted in an optimal agreement between observed and simulated sowing dates in regions with temperature seasonality. The resulting temperature thresholds for sowing are plausible when compared with base temperatures for emergence found in the literature

(Table 1). Although our temperature thresholds are slightly higher or at the top end of the range of base temperatures found, temperatures just above these base temperatures for emergence will result in retarded emergence (Jaggard & Qi, 2006).

Procedure to validate the methodology

Data set of observed growing periods: MIRCA2000

To validate our methodology, the global data set of observed growing areas and growing periods, MIRCA2000 (Portmann *et al*., 2008) at a spatial resolution of 0.5° × 0.5° and a temporal resolution of 1 month was used. Monthly data in MIRCA2000 were converted to daily data following the approach of Portmann *et al*. (2010), by assuming that the growing period starts at the first day of the month reported in MIRCA2000. The data set includes 26 annual and perennial crops and covers the time period between 1998 and 2002. For most countries, MIRCA2000 was derived from national statistics. For China, India, the USA, Brazil, Argentina, Indonesia, and Australia, subnational information was used as well, mainly from the Global Information and Early Warning System on food and agriculture (FAO-GIEWS) and from the United States Department of Agriculture (USDA). Based on the extent of cropland, derived from satellite-based remote sensing information and national statistics (Ramankutty *et al*., 2008), the growing area combined with the growing period of each crop was distributed to grid cells at a spatial resolution of 5′ × 5′, which were finally aggregated to grid cells of 0.5° × 0.5° (Portmann *et al*., 2008). Sacks *et al*. (2010) recently compiled a similar data set of crop planting dates, also using cropping calendars from FAO-GIEWS and USDA. MIRCA2000, in contrast, distinguishes between rainfed and irrigated crops, which allows a comparison of sowing dates for rainfed crops only.

MIRCA2000 distinguishes up to five possible growing periods per grid cell, reflecting different varieties of wheat, rice and cassava and/or multiple-cropping systems of maize and rice, but for most crops only one growing period per year is reported. For wheat, spring varieties and winter varieties are distinguished; for rice a number of growing periods are distinguished, i.e. for upland rice, deepwater rice and paddy rice, with up to three growing periods for paddy rice (Portmann *et al*., 2010). For cassava, an early and a late ripening variety with different sowing dates are distinguished.

In contrast, we assumed only one growing period per year in single-cropping systems. For wheat and rapeseed, we distinguished between spring and winter varieties: in regions with suitable climatic conditions for both varieties, the winter variety has been selected. If daily average temperatures exceed 12 °C (17 °C for rapeseed) year round or drop below that threshold before 15 September (Northern Hemisphere) or before 31 March (Southern Hemisphere), the spring variety was selected. As MIRCA2000 reports several growing periods for some crops, it was difficult to select the most suitable growing period for comparison. Consequently, we selected the best corresponding growing period, indicating the reasonableness of the simulated sowing dates but not their representativeness. Portmann *et al*. (2010) reported several uncertainties and limitations of MIRCA2000: data gaps and uncertainties in the underlying national census data, the lack of subnational data for some larger countries and therefore neglect of possible effects on growing periods due to climatic gradients, and the fact that very complex cultivation systems, in which more than one crop is grown on the same field at the same time, could not be represented adequately. These constraints, as well as the temporal resolution of 1 month of MIRCA2000 should be taken into account when assessing the comparison between observed and simulated sowing dates.

Methodology for comparing observed and simulated sowing dates

To assess the degree of agreement between simulated and observed sowing dates, two indices of agreement were calculated for each crop: the mean absolute error (*ME*) and the Willmott coefficient of agreement (*W*) (Willmott, 1982):

$$ME = \frac{\sum_{i=1}^{N} |S_i - O_i| \times A_i}{\sum_{i=1}^{N} A_i} \quad W = 1 - \frac{\sum_{i=1}^{N} (S_i - O_i)^2 \times A_i}{\sum_{i=1}^{N} \left(|S_i - \bar{O}| + |O_i - \bar{O}|\right)^2 \times A_i}$$

where S_i is the simulated and O_i the observed sowing date (day of year) in grid cell i, $\bar{O}$ the mean observed sowing date (day of year), A_i the cultivated area (ha) of the crop in grid cell i, and N the number of grid cells.

Indices are area-weighted, so the agreement in the main growing areas of a crop is considered more important than the agreement in areas where the crop is grown on smaller areas. *W* is dimensionless, ranging from 0 to 1, with 1 showing perfect agreement. *ME* indicates the global average error between simulations and observations, *W* additionally considers systematic differences between simulations and observations (Willmott, 1982). In addition to the two indices of agreement, we calculated the cumulative frequency distribution of the mean absolute error in days between the observed and simulated sowing dates, to show the frequency of grid cells and of cultivated area below a certain threshold.

RESULTS

We show the global distribution of seasonality types (Fig. 2) as well as sowing dates simulated with the presented methodology and the comparison with observed sowing dates from MIRCA2000 (Figs S1–S11 in Supporting Information). To assess these results, we performed a sensitivity analysis of crop yields on sowing dates (see Fig. S12). Regions without seasonality are not considered in the evaluation of results, because sowing dates do not substantially affect crop yield there, as indicated by the sensitivity analysis (Figure S12).

Seasonality types

The spatial pattern of the calculated seasonality types (Fig. 2) resembles the distribution of various climates across the earth.

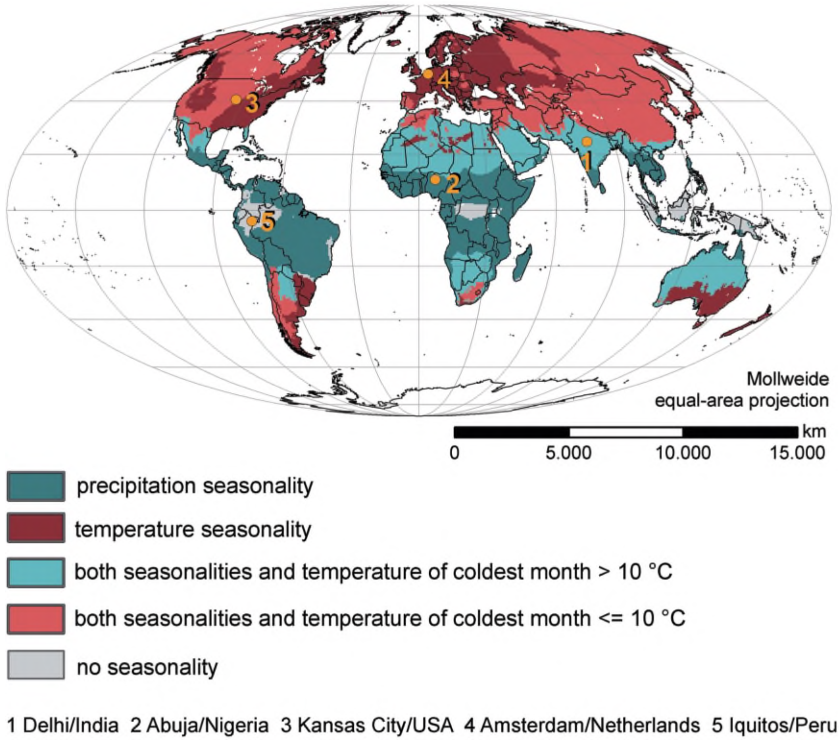

Figure 2 Global distribution of seasonality types. Seasonality types are based on the annual patterns of precipitation and temperature. For each seasonality type one example region is marked.

Locations around the equator in the humid tropics are characterized by a lack of seasonality in both temperature and precipitation (e.g. Iquitos, Peru). The semi-humid tropics, with dry and wet seasons, are characterized by precipitation seasonality only (e.g. Abuja, Nigeria). The temperate zones in the humid middle latitudes with warm summers and cool winters are characterized by temperature seasonality (e.g. Amsterdam, the Netherlands). In locations with precipitation seasonality and a distinct cold season (e.g. Kansas City, USA), low temperatures limit the growing period of crops and sowing dates are simulated based on temperature. If a cold season is absent in a location with precipitation seasonality (e.g. Delhi, India), sowing dates are simulated based on precipitation. Figure 3 shows annual variations in temperature and precipitation for five locations and Fig. 2 indicates their location.

Comparison of observed and simulated sowing dates

Figures S1–S11 show simulated and observed sowing dates, as well as the deviations per crop. As a condensed overview, Fig. 4 shows the cumulative frequency distribution of the mean absolute error between observations and simulations for all crops, for all grid cells combined, and separately for the two rules.

Figure 4 and the difference maps (Figs S1a–S11a) indicate close agreement for rice, millet, sugar beet, sunflower, soybean and groundnut globally, as well as close agreement for pulses in regions where temperature seasonality determines sowing dates. Figure 4 shows that for all crops except rapeseed and cassava, in at least 50% of the grid cells and on at least 60% of the cultivated area the error between simulations and observations is less than 1 month. Even in regions where simulated sowing dates deviate from observed sowing dates by 1 month, the results from the sensitivity analysis suggest that this range hardly affects computed crop yields from a global dynamic vegetation and crop model (Fig. S12), if they fall within a suitable growing period (e.g. the main wet season or spring season).

Poor agreement, with differences between simulations and observations of more than 5 months, is found for wheat in Russia, for maize and cassava in Southeast Asia and China (and in East Africa for maize), for pulses in Southeast Asia, India, West and East Africa, the south-east region of Brazil and southern Australia, for groundnut in India and Indonesia, and for rapeseed in northern India, southern Australia and southern Europe. Deviations are also large for crops growing in the southern part of the Democratic Republic of Congo, in Indo-China and in regions around the equator.

Table 2 shows both *ME* and *W* for each crop for all cells where the crop is grown and differentiated for the rules to determine sowing date. The *ME* for all cells is less than 2 months, with the exception of pulses. For wheat (without Russia), rice, millet, sugar beet and sunflower, the agreement is even closer, with a difference of at most 1 month between simulations and observations. The *W* values are high, and show close agreement between simulations and observations ($W > 0.8$) with the exception of pulses. Both indices show closer agreement for pulses, groundnut, sunflower and rapeseed in regions where sowing dates are determined by the temperature threshold than in regions where the onset of the main wet season determines sowing date. In contrast, both indices show closest agreement for millet in regions where sowing dates are determined by the onset of the wet season.

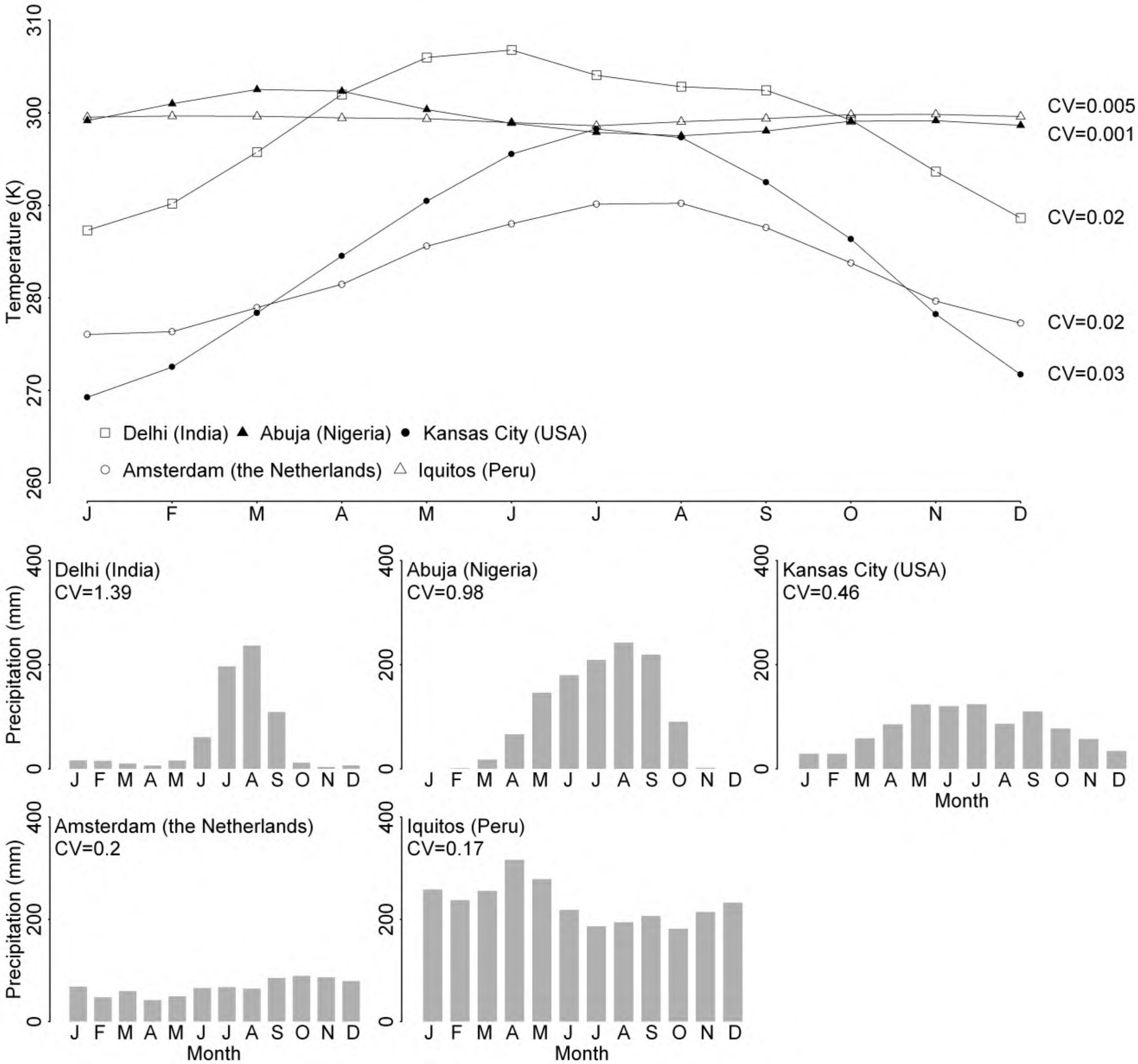

Figure 3 Annual variations in temperature (above) and precipitation (below) for five locations.

DISCUSSION

Non-climatic reasons can considerably affect the timing of sowing. They arise from social attitudes and customs, religious traditions and the demand for certain agricultural products (Gill, 1991). In addition, agronomic practices, technological changes and farm size can influence the timing of sowing. Depending on crop rotation, sowing can be affected by the harvest of the preceding crop (Dennett, 1999), and available labour and machinery, depending on farm size, determine whether sowing can be completed in the desired time period (Kucharik, 2006). The timing of sowing may also be influenced by the weather later in the growing season, e.g. in order to avoid possible dry spells during certain stages of crop development that are relatively sensitive to drought stress. Information on these technological and socio-economic conditions and their influence on the timing of sowing is scarce at the global scale and has therefore not been considered in this study. The results of our study (Figs 4 & S1–S11) show, however, that close agreement between simulated and observed sowing dates for large parts of the earth for wheat, rice, millet, soybean, sugar beet and sunflower, as well as for pulses and maize in temperate regions, can be realized based on climatic conditions only. For most crops, the disagreement between simulated and observed sowing dates is only 1 month or less for the largest part of the global total cropping area (Fig. 4b). At least 80% of the global cropping area displays a disagreement of less than 2 months (except for rapeseed, Fig. 4b). However, some regions show mediocre or poor agreement between simulated and observed sowing dates. The agreement is especially poor in tropical regions, where, despite a

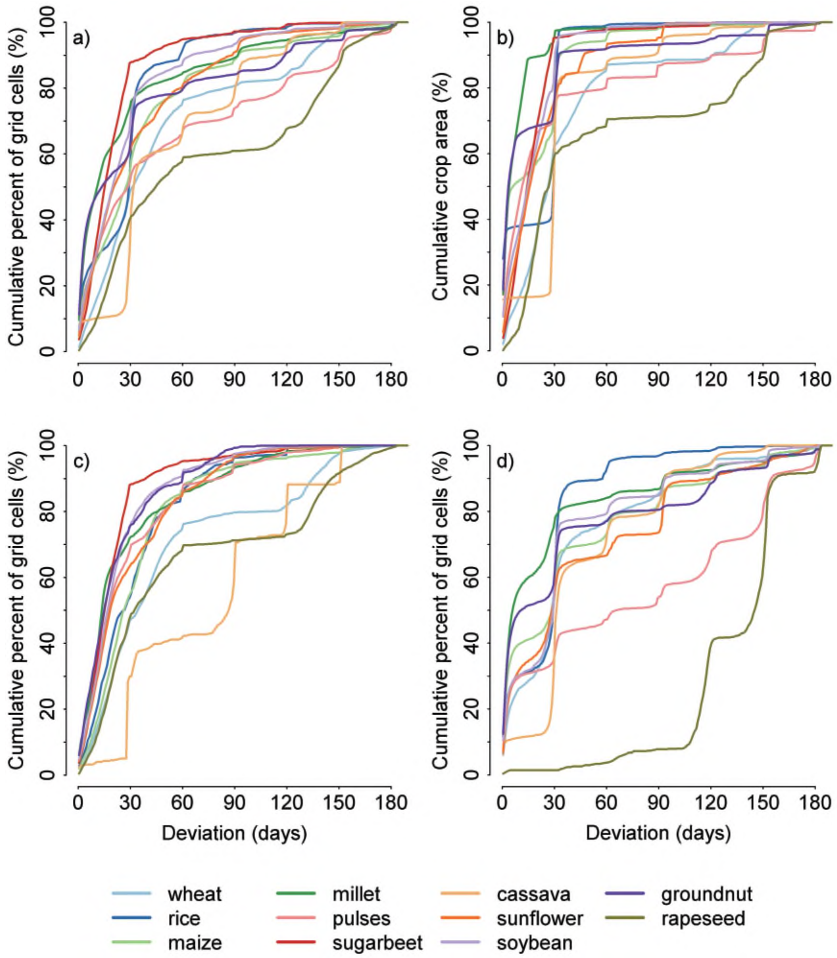

Figure 4 Cumulative percentage of grid cells (or crop area in a grid cell) with certain differences between observed and simulated sowing date. Deviations are shown for: (a) all grid cells, (b) crop area of all grid cells, (c) grid cells where sowing dates are determined by a temperature threshold, and (d) grid cells where sowing dates are determined by the onset of the main wet season. Grid cells with a crop area smaller than 0.001% of the grid cell area are not considered in the calculations. Curves are only shown if the number of grid cells in which a specific rule to determine the sowing date for a specific crop is applied exceeds 1% of all grid cells.

Table 2 Indices of agreement between simulated sowing dates and observed sowing dates.

	Mean absolute error (days)			Willmott coefficient (dimensionless)			% of all cells	
		Sowing date determined by:			Sowing date determined by:			
	All cells	Main wet season	Temp. threshold	All cells	Main wet season	Temp. threshold	Main wet season	Temp. threshold
Wheat	44 (30*)	37 (37*)	45 (**30***)	0.88 (0.96*)	0.9 (0.9*)	0.88 (**0.96***)	18 (22*)	82 (78*)
Rice	24	**22**	23	0.92	0.92	**0.94**	82	18
Maize	34	38	**32**	0.89	**0.89**	0.87	48	52
Millet	15	**14**	33	0.91	**0.95**	0.86	63	37
Pulses	69	79	**37**	0.63	0.62	**0.84**	50	50
Sugar beet	18		**18**	0.81		**0.71**	1	99
Cassava	48	**48**	51	0.93	0.93	**0.96**	83	17
Sunflower	25	43	**22**	0.93	0.88	**0.93**	25	75
Soybean	34	36	**33**	0.95	**0.94**	0.93	32	68
Groundnut	31	33	**19**	0.84	0.82	**0.97**	81	19
Rapeseed	54	133	**39**	0.85	0.14	**0.91**	16	84

*Indices of agreement without Russia.
Bold values indicate which rule determining sowing date results in a closer agreement. Indices of agreement are only shown if the number of cells in which a specific rule for determining the sowing date is applied is > 1% of all cells. Grid cells with a crop area smaller than 0.001% of the grid area are not considered in the calculations.

possible seasonality, climatic conditions are favourable throughout the year, and in regions characterized by multiple-cropping systems. Furthermore, agreement is poor in temperate regions, where both spring and winter varieties of wheat and rapeseed are grown, and in regions where observations are lacking or have been replaced or adjusted in MIRCA2000.

In the sections below the most likely reasons for strong disagreements are identified in example regions. Reasons can be limitations and uncertainties in MIRCA2000, e.g. the spatial scale of MIRCA2000 or data gaps, uncertainties in our methodology, the use of one global temperature threshold for sowing temperatures, which is known to vary between regions (Sacks *et al*., 2010), or the application of specific crop management techniques, e.g. multiple-cropping systems.

Pulses and groundnuts in multiple-cropping systems

The poor agreement between simulated and observed sowing dates for pulses in Southeast Asia, India, West and East Africa, and south-east Brazil, and for groundnuts in India (Fig. S10a), originates from a mismatch in the production systems assumed. In these regions, it is common practice to grow pulses and groundnuts in multiple-cropping systems. In the south-eastern region of Brazil, with wet seasons long enough for a multiple-cropping system of maize and beans, beans are sown in combination with maize or after maize has been harvested (Woolley *et al*., 1991). In West and East Africa, cowpea is largely grown as a second crop in multiple-cropping systems with maize or cassava (in humid zones) and millet (in dry zones) (Mortimore *et al*., 1997). These patterns are reflected in MIRCA2000. In contrast, we have assumed only single-cropping systems, so that sowing of pulses and groundnut starts at the beginning of the wet season, i.e. too early in comparison to the observations. Where cowpea is grown as a single crop, as in coastal regions of East Africa (Mortimore *et al*., 1997), there is close agreement with the observed sowing dates (Fig. S5a).

The deviations in India for pulses (Fig. S5a), and for groundnut in western India (Fig. S10a), are associated with the occurrence of multiple-cropping systems. Here, cowpea is grown in mixtures with sorghum and millet (Steele & Mehra, 1980) and groundnuts may be grown in the dry season following rice, often under irrigation (Norman *et al*., 1995).

Maize in multiple-cropping systems in Southeast Asia

In Southeast Asia, as well as in China, a large number of crops may be grown on the same plot. According to Portmann *et al*. (2010), this indicates high land use intensities with multiple-cropping systems. Intensive rice and wheat production are common practice in Asia (Devendra & Thomas, 2002), and maize has a subsidiary place in some of the Asian cropping systems as a second crop following the wet-season rice crop (Norman *et al*., 1995). This rice–maize multiple-cropping system is covered by MIRCA2000, e.g. in China and Burma. As a consequence, the simulated growing period of maize starts earlier in the year than the observed growing period (Fig. S3a).

Wheat and rapeseed in temperate regions

The poor agreement for wheat and rapeseed in temperate regions of Russia, Australia, and small parts of Europe (Fig. S11a) is the result of disagreement between the simulated and observed varieties of wheat and rapeseed. In Russia, MIRCA2000 overestimates the share of winter wheat (Portmann *et al*., 2010), because the cropping calendar for Russia is partly derived from the cropping calendars from Ukraine, Norway and Romania, where mainly winter wheat is grown (Portmann *et al*., 2008). In contrast, we exclude winter wheat in Russia because temperatures drop below 12 °C before 15 September, and consequently spring wheat is simulated in Russia. This is in line with the cropping calendar from USDA, which reports, in addition to winter wheat, large areas of spring wheat in Russia (USDA, 1994). In other temperate regions the agreement between simulated and observed sowing dates is good with only 1 month deviation, and simulated sowing dates are similar to those shown in Bondeau *et al*. (2007).

For rapeseed in southern and eastern Australia, our rules simulate sowing dates in May and June (Fig. S11b), whereas MIRCA2000 reports a sowing date in December (Fig. S11c). However, in line with the simulations, West *et al*. (2001) and Robertson *et al*. (2009) confirm that rapeseed is grown as a winter crop, starting in May and June in Australia. In Europe, winter rapeseed is also the dominant cultivar due to its higher yield levels. Sowing dates of winter rapeseed in southern Europe can be extended from mid August to early September, as indicated by Booth & Gunstone (2004) and USDA (1994), which is in line with the simulated sowing dates in countries like Spain, France, Hungary, Ukraine and Romania for example (Fig. S11b). MIRCA2000, however, identifies spring rapeseed sown in May in those countries.

Cassava in multiple-cropping systems

MIRCA2000 reports that in China, Thailand and Vietnam, cassava is sown in March as an early ripening variety. In China, farmers plant cassava from February to April before the wet season starts in order to use the cover of cassava plants to avoid soil losses due to the impact of heavy rains (Yinong *et al*., 2001). Planting before the onset of the wet season may also avoid damage from pests (Evangelio, 2001). These practices explain the differences in southern China and Southeast Asia between observed and simulated sowing dates (Fig. S7a), because the simulated sowing dates are associated with the main wet season starting in May to July, not with the agronomic practices described in the literature.

Specific climatic conditions in temperate regions

Other examples of differences between observed and simulated sowing dates occur in European countries, partly in countries which are characterized by a mediterranean climate. For sugar beet, both MIRCA2000 and our simulations indicate mainly spring sowings in the Mediterranean region. However, the mediterranean climate is characterized by mild winters and winter rainfall. In those regions, sugar beet is therefore sown in autumn, avoiding the high temperatures and high evapotranspirational demand of summer (Castillo Garcia & Lopez Bellido, 1986; Rinaldi & Vonella, 2006; Elzebroek & Wind, 2008). The effect of this specific climatic condition on sowing dates is not reflected in MIRCA2000, or in our simulations.

Limitations of MIRCA2000

Large differences between observed and simulated sowing dates occur in countries characterized by strong climatic gradients, associated with the size of countries (e.g. Russia, Democratic Republic of Congo, Mexico), or to large climatic variability, associated with large differences in elevation (e.g. Kenya). These gradients and variability influencing sowing dates are captured in our methodology, but not in MIRCA2000, where sowing dates for one spatial unit (country or subnational unit) are assigned to grid cells of $0.5° \times 0.5°$. An example is the large difference between observations and simulations in the southern part of the Democratic Republic of Congo, where in MIRCA2000 missing observations were replaced by the cropping calendar from the neighbouring country Rwanda (Portmann *et al*., 2008). While this procedure might be adequate for the northern parts of the Democratic Republic of Congo which are characterized by the same bimodal seasonal rainfall distribution, it is not adequate for the southern parts, where the main wet season does not start until November/December (McGregor & Nieuwolt, 1998).

Deficiencies in simulated sowing dates may strongly influence the results of applications of the sowing date algorithm, depending on the application and model used. A deviation of sowing dates by 2 or 3 months (e.g. sunflower in France, sugar beet in Spain, soybean in the northern USA, or maize in Europe; see Figs S1–S11) could already strongly affect the results of crop model applications, e.g. the assessment of crop evapotranspiration and crop virtual water content. The level of agreement per crop and region is therefore depicted in Figs S1–S11, which allows for a more detailed evaluation when to use our sowing date algorithm with caution.

CONCLUSIONS

This study presents a novel approach for deterministically simulating sowing dates under rainfed conditions for various annual field crops. We show that sowing dates for large parts of the earth can be satisfactorily estimated from climatic conditions only. Close agreement is achieved between simulated and observed sowing dates, although substantial deviations occur in: (1) tropical regions and (2) regions with high land-use intensity and multiple-cropping systems. Even if those regions show seasonality in temperature or precipitation, climatic conditions can be suitable throughout the year for crop growth. In both types of regions, climatic conditions are of minor importance for the timing of sowing, instead it is determined mainly by other criteria such as the demand for special agricultural products, availability of labour and machines, and religious and/or social traditions (Gill, 1991; Kucharik, 2006). Furthermore, certain cropping practices and crop rotations are applied in order to avoid pests and disease infestations. These agronomic practices cannot be considered in our methodology due to lack of information at the global scale. Differences between simulated and observed sowing dates in regions without precipitation and temperature seasonality have little impact on the computed crop yield in global crop growth models such as LPJmL. Sowing date deviations of 1 month or more, in locations with temperature and precipitation seasonality may lead to substantially different simulated crop yields. In the LPJmL model with the currently implemented cultivars, sowing dates simulated with the presented methodology are within the most productive cropping window for almost all locations displayed in Fig. S12. However, the interaction of sowing dates, management options, and cultivar characteristics will have to be evaluated further.

Our methodology is explicitly developed for the global scale. Climate and soil characteristics, as well as agricultural management practices, can vary considerably among regions. If applied at smaller scales, parameter values as proposed here should be adapted, e.g. the temperature threshold for sowing can show spatial variability (Sacks *et al*., 2010), and important socio-economic and technical drivers should be considered to attain higher accuracy. In addition, if reliable daily minimum and maximum temperature and precipitation data are available, rules should adapted in order to consider avoidance of damage by frost or extreme high temperatures. At the global scale, our methodology is suitable for simulating sowing dates for global crop growth models. In our methodology, we are able to apply current and future climate input data. We are therefore able to account for some possible global responses to climate change by farmers changing their sowing dates.

ACKNOWLEDGEMENTS

We would like to thank Felix Portmann and Stefan Siebert for making available the MIRCA2000 data set, as well as the LPJmL crop modelling team, Herman van Keulen and Peter Leffelaar for valuable discussions on the methodology and results. Furthermore we are grateful for the comments of two anonymous referees on a previous version of the manuscript, and to Benjamin Gaede and Alison Schlums who did the spell and grammar check. K.W. and C.M. gratefully acknowledge financial support from projects with the International Food Policy Research Institute (6012001) and the International Livestock Research Institute (81102850) funded through the German Federal Ministry for Economic Cooperation and Development.

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SUPPORTING INFORMATION

Figure S1 Analysis of sowing date patterns of wheat: (a) difference between simulated sowing dates and observed sowing dates, (b) simulated sowing date, (c) observed sowing dates according to MIRCA2000.

Figure S2 Analysis of sowing date patterns of rice: (a) difference between simulated sowing dates and observed sowing dates, (b) simulated sowing date, (c) observed sowing dates according to MIRCA2000.

Figure S3 Analysis of sowing date patterns of maize: (a) difference between simulated sowing dates and observed sowing dates, (b) simulated sowing date, (c) observed sowing dates according to MIRCA2000.

Figure S4 Analysis of sowing date patterns of millet: (a) difference between simulated sowing dates and observed sowing dates, (b) simulated sowing date, (c) observed sowing dates according to MIRCA2000.

Figure S5 Analysis of sowing date patterns of pulses: (a) difference between simulated sowing dates and observed sowing dates, (b) simulated sowing date, (c) observed sowing dates according to MIRCA2000.

Figure S6 Analysis of sowing date patterns of sugar beet: (a) difference between simulated sowing dates and observed sowing dates, (b) simulated sowing date, (c) observed sowing dates according to MIRCA2000.

Figure S7 Analysis of sowing date patterns of cassava: (a) difference between simulated sowing dates and observed sowing dates, (b) simulated sowing date, (c) observed sowing dates according to MIRCA2000.

Figure S8 Analysis of sowing date patterns of sunflower: (a) difference between simulated sowing dates and observed sowing dates, (b) simulated sowing date, (c) observed sowing dates according to MIRCA2000.

Figure S9 Analysis of sowing date patterns of soybean: (a) difference between simulated sowing dates and observed sowing dates, (b) simulated sowing date, (c) observed sowing dates according to MIRCA2000.

Figure S10 Analysis of sowing date patterns of groundnut: (a) difference between simulated sowing dates and observed sowing dates, (b) simulated sowing date, (c) observed sowing dates according to MIRCA2000.

Figure S11 Analysis of sowing date patterns of rapeseed: (a) difference between simulated sowing dates and observed sowing dates, (b) simulated sowing date, (c) observed sowing dates according to MIRCA2000.

Figure S12 Sensitivity of maize yield to sowing dates for five locations.