Global Ecology and Biogeography A Journal of Macroecology

RESEARCH PAPER

Crop planting dates: an analysis of global patterns

William J. Sacks[1]*, Delphine Deryng[2], Jonathan A. Foley[3] and Navin Ramankutty[2]

[1]*Center for Sustainability and the Global Environment (SAGE), University of Wisconsin-Madison, USA,* [2]*Department of Geography, McGill University, Canada,* [3]*Institute on the Environment (IonE), University of Minnesota, USA*

*Correspondence: William Sacks, SAGE, 1710 University Avenue, Madison, WI 53726, USA. E-mail: wsacks@gmail.com

ABSTRACT

Aim To assemble a data set of global crop planting and harvesting dates for 19 major crops, explore spatial relationships between planting date and climate for two of them, and compare our analysis with a review of the literature on factors that drive decisions on planting dates.

Location Global.

Methods We digitized and georeferenced existing data on crop planting and harvesting dates from six sources. We then examined relationships between planting dates and temperature, precipitation and potential evapotranspiration using 30-year average climatologies from the Climatic Research Unit, University of East Anglia (CRU CL 2.0).

Results We present global planting date patterns for maize, spring wheat and winter wheat (our full, publicly available data set contains planting and harvesting dates for 19 major crops). Maize planting in the northern mid-latitudes generally occurs in April and May. Daily average air temperatures are usually *c.* 12–17 °C at the time of maize planting in these regions, although soil moisture often determines planting date more directly than does temperature. Maize planting dates vary more widely in tropical regions. Spring wheat is usually planted at cooler temperatures than maize, between *c.* 8 and 14 °C in temperate regions. Winter wheat is generally planted in September and October in the northern mid-latitudes.

Main conclusions In temperate regions, spatial patterns of maize and spring wheat planting dates can be predicted reasonably well by assuming a fixed temperature at planting. However, planting dates in lower latitudes and planting dates of winter wheat are more difficult to predict from climate alone. In part this is because planting dates may be chosen to ensure a favourable climate during a critical growth stage, such as flowering, rather than to ensure an optimal climate early in the crop's growth. The lack of predictability is also due to the pervasive influence of technological and socio-economic factors on planting dates.

Keywords

Agricultural management, crop calendars, crop modelling, global agricultural systems, harvesting dates, maize, phenology, planting dates, spring wheat, winter wheat.

INTRODUCTION

Over the next few decades, the world's farmers will face the challenging task of increasing food production to keep up with growing population, growing per-capita consumption and the use of agricultural products as biofuels. Climate change, and the associated increases in climatic variability, will compound this challenge, especially in developing countries (Parry *et al.*, 2004). One strategy that farmers can use to maintain or increase crop yields in the face of a changing climate is to adjust planting dates (Lauer *et al.*, 1999). In order to predict how farmers might respond to climate change, it would help to know when they currently plant their crops in different regions of the world. This knowledge becomes even more important if we hope to actively design strategies for adaptation. However, there is little published literature concerning planting dates around the world.

Croplands cover *c.* 12% of the earth's ice-free land surface (Ramankutty *et al.*, 2008). Thus, in addition to their obvious importance for food production, croplands also influence global cycles of carbon, water and energy. Realizing this, many groups have recently begun to develop global models of agricultural systems (e.g. Bondeau *et al.*, 2007; Osborne *et al.*, 2007; Stehfest *et al.*, 2007). These models simulate the effects of climate on crop growth and yield as well as the effects of agricultural management on the earth's climate system.

These global crop models also require knowledge of planting and harvesting dates. Simulations of crop yields, or of the effects of croplands on energy and water balances, depend on the timing of planting and harvest (Twine *et al.*, 2004). Crop models that are designed for application at a single location generally require the user to specify the planting and harvesting dates there (e.g. the EPIC model; Sharpley & Williams, 1990). However, direct specification of these dates has not been possible for models run at a global scale. Thus, many of these global models assume a relationship between climate and planting dates. For example, Bondeau *et al.* (2007) assume that maize grown in temperate latitudes is planted when average temperatures reach 14 °C. Stehfest *et al.* (2007) use an optimization approach that prescribes the month of planting to be that which maximizes annual yields. But the question of whether these climatically determined planting dates can accurately characterize actual planting dates has not been extensively tested, due to a lack of a suitable observational data set.

A common source of global phenology observations is satellite remote sensing (e.g. Zhang *et al.*, 2006). These global data sets generally have a spatial resolution of 1 km or greater. In many parts of the world, this resolution is too coarse to completely separate natural from managed lands, and especially to separate the contribution of different crops. Even in the relatively homogenous US Corn Belt, the phenology signal of a single 1-km grid cell will often be composed of both corn and soybeans, which differ in their planting dates by about 2 weeks. An alternative means to characterize the growing seasons of croplands has been to compile observations from knowledgeable observers around the world (e.g. USDA, 2006; FAO, 2007). Most such compilations have a few deficiencies: (1) each one focuses on particular areas of the world, but neglects others, (2) they generally present only national-level averages, and (3) they present the data only in graphical format, making direct input into a global crop model impossible.

We have produced a comprehensive data set of global crop planting and harvesting dates by combining the data from FAO (2007) and USDA (2006), digitizing and georeferencing them. We have further added sub-national data for the United States, Russia, Ukraine, India and Australia. In all, this data set includes about 1300 observations of planting and harvesting dates. In addition to presenting aspects of the data set here, we have also made the full data set freely available at http://www.sage.wisc.edu. In this paper, we present and discuss only the planting date observations, but the full data set includes harvesting dates as well.

Portmann *et al.* (2010) recently performed a similar compilation of global planting and harvesting date observations as part of their MIRCA2000 data set. Our data set and MIRCA2000 are complementary, the main differences being as follows.

1. MIRCA2000 presents separate data for irrigated and rainfed crops in each region; we present the dominant cropping patterns for each crop, without regard to whether the crop is mostly irrigated or rainfed.

2. The two primary data sources are the same for our data and for rainfed crops in MIRCA2000, but there are some differences in sources of sub-national data.

3. Our data set presents the full range of the planting and harvesting periods in each region, maintaining the temporal resolution of the underlying source data; MIRCA2000 just presents the typical start and end month of the growing season.

Planting dates can change over time, due to changes in climate as well as changes in technological and socio-economic factors (Kucharik, 2006). To capture some of these dynamics, we have explored spatial relationships between planting date and climate for maize, spring wheat and winter wheat. These relationships with climate can also be useful for estimating planting dates in regions where there are no observations. But climate alone cannot fully explain farmers' choices about when to plant their crops. Therefore, in addition to presenting relationships with climate we also present a review of case studies from around the world that describe factors – climatic and non-climatic – that drive planting date decisions.

METHODS

Compilation of crop calendar observations

We compiled observations of crop planting and harvesting dates from six sources (Table 1). These sources present ranges of typical planting and harvesting dates, categorized by crop and region. Most of the original data were assembled by the United Nations Food and Agriculture Organization (FAO) or the United States Department of Agriculture (USDA) – and in particular, by personnel with expertise in a given region. Most data were specified at the national level, but we used sub-national data for the United States, Russia, Ukraine, India, Australia and a few other large countries. In general, the observations gave typical planting and harvesting dates for the 1990s or early 2000s.

Most data were obtained in graphical format, with bars spanning the typical planting and harvesting dates for a region. We digitized the start and end dates for planting and harvesting from these graphs using DigitizeIt (version 1.5.7; available via http://www.digitizeit.de); we then computed the mean planting and harvesting dates from these ranges. In this paper, we mainly present the mean planting dates, but the ranges of both planting and harvesting dates are available in our full data set.

We compiled data for 19 crops (Table 2), which occupy 71% of the world's crop area (Monfreda *et al.*, 2008). The number of

Table 1 Sources of crop calendar data, ordered approximately from greatest to smallest area coverage.

Source	Areas covered
FAO (2007)*	Many countries, with an emphasis on developing countries, especially Africa. Mostly national-level data, but some large countries are divided into two or three regions
USDA (2006)*†	Many countries, with an emphasis on Europe, Asia and North America. Mostly national-level data, but some large countries are divided into two regions
USDA-FAS (2008)‡	High-resolution, sub-national data for Russia and Ukraine. National-level data for Argentina, Côte d'Ivoire, Ethiopia, Iran, Iraq, Kenya, Nigeria, Somalia, Syria, Tanzania, Turkey and Zimbabwe
USDA-NASS (1997)	State-level data for the United States
IMD-AGRIMET (2008)	Very high-resolution, district-level data for India
USDA-FAS (2003)	State-level data for Australia

*In the case of disagreements between USDA (2006) and FAO (2007), priority was usually given to USDA (2006); but in a few cases, we either gave priority to FAO (2007) or averaged the data from these two sources. This decision was made based on the spatial resolution of the two sources, the stated source of the observation in the FAO (2007) data set, and how recently the observation was updated in the USDA (2006) data set. (We used data from FAO, 2007) for cotton in Uzbekistan, rice in Japan, South Korea, Indonesia and Malaysia, and winter wheat and barley in Algeria, Morocco and Tunisia. We averaged the two sources for maize, rice and winter wheat in Argentina, winter wheat in South Africa, maize in eastern South Africa, and second season maize in central and southern Brazil. In all other cases, we gave priority to USDA, 2006).
†We used the latest updates available from USDA (2006), as of November, 2007. However, in some cases, the only data available were from the original 1994 report; in these cases, where there were no updates available, we used the original 1994 data.
‡In the case of disagreements between national-level data from USDA-FAS (2008) and either FAO (2007) or USDA (2006), priority was given to FAO (2007) or USDA (2006).

data points per crop ranges from 10 to nearly 200. In this paper, we present data only for maize and wheat, but data for the other crops are available as Supporting Information (Figs S1 & S2 in Supporting Information), as well as in our full data set.

For wheat, as well as barley and oats in the full data set, we divided the observations into winter and spring varieties. Winter wheat requires cold winter temperatures for vernalization. It is planted in the autumn, begins to grow before the winter sets in, becomes dormant during the winter and then resumes growth the following spring. Spring wheat does not have a vernalization requirement. Like many other crops, it grows continuously from planting to harvest, without a dormant period. Spring wheat is grown both where temperatures never get cold enough for vernalization, and where the winters are so severe that a dormant wheat plant would be killed.

Some observations were explicitly labelled 'winter wheat' or 'spring wheat', and likewise for barley and oats. For wheat, barley and oat observations lacking an explicit label, we classified them as 'winter cereals' if they fitted the characteristic winter grain pattern of planting shortly before the coldest time of year (according to the average climate of the region, as described below). Observations that did not fit this pattern were classified as 'spring cereals'. (However, we made an exception for wheat in Australia, which we classified as 'spring wheat', as that is the dominant wheat type grown there; D. L. Liu, e-mail communication, 19 March, 2009). We acknowledge that, in tropical and subtropical regions, this scheme could lead to the classification of some spring types as winter cereals. Ideally, we would also have included a minimum temperature threshold to distinguish between winter and spring cereal-growing regions, as winter varieties require cold temperatures for vernalization. However, we were not able to identify a robust threshold, perhaps in part because vernalization requirements can differ between cultivars. Misclassifications should not have a large effect on the climatic relationships presented in this paper (e.g. Figs 4, 7 & 8), because our climatic filters exclude most questionable regions (see 'Delineation of temperature and precipitation-limited regions', below). But we caution that our data set should not be used to determine which regions actually grow winter versus spring cereals.

For some other crops, including maize, we compiled observations for the second season in a double-cropping system as well as for the main season. We only present the main season of maize in this paper, but data for the second season are available as Supporting Information (Figs S1 & S2) as well as in our full data set.

Calculation of climate variables and summary statistics

In addition to compiling crop calendar data, we also computed relationships between planting dates and climate. To do this, we used monthly climatologies of temperature, precipitation and sunshine fraction for the years 1961–90, from the Climatic Research Unit, University of East Anglia (the CRU CL 2.0 data set; New *et al.*, 2002). These data are available at 10′ spatial resolution; we interpolated them to 5′ resolution to match the resolution of the crop maps (described below). To compute quantities such as the temperature at planting, we linearly interpolated these monthly climatologies to daily values.

For each crop calendar observation, we computed weighted spatial means and standard deviations of temperature, precipitation and sunshine fraction over the region for which the observation applied. The weighting was done based on the harvested area of the given crop, using the 5′ resolution crop maps produced by Monfreda *et al.* (2008). For large regions where a crop

Table 2 Crops for which we have compiled crop calendar observations, along with: the number of observations for each crop; the percentage of the world's harvested area (HA) of that crop for which we have observations (based on Monfreda *et al.*, 2008); and the amount of harvested area for which we have data at a sub-national resolution (expressed as a percentage of the area for which we have any data).

Crop	No. of obs.	HA (%)*	Sub-national (%)†
Barley	103	84	35
Winter	53	57	12
Spring	50	39	58
Cassava	17	45	70
Cotton	65	76	48
Groundnuts	40	57	50
Maize	192	88	63
Main season	165	88	63
Second season	27	15	52
Millet	73	74	41
Oats	61	44	69
Winter	15	10	75
Spring	46	34	67
Potatoes	60	13	26
Pulses	34	11	25
Rapeseed (winter)	10	66	0.3
Rice	183	82	48
Main season	146	81	48
Second season	37	47	57
Rye (winter)	40	69	42
Sorghum	115	83	51
Main season	102	80	48
Second season	13	11	85
Soybeans	51	92	75
Sugarbeet	29	68	14
Sunflower	18	66	6
Sweet potatoes	21	17	56
Wheat	173	76	52
Winter	138	54	43
Spring	35	32	60
Yams	13	92	0

*For crops that are split into multiple categories (e.g. winter and spring, or main season and second season), percentage HA for each category is calculated as (HA for which we have observations in this category)/(total HA of this crop) × 100. For example, the denominator for winter wheat is the same as the denominator for all wheat combined.

†Sub-national sometimes means we have data at the state/province level (or even higher resolution); but sometimes it simply means that a country is divided into two or three large regions.

is only grown in part of the region, this weighting ensures that the climate averages apply to the area in which the crop is actually grown. However, the Monfreda *et al.* (2008) data set combines winter and spring wheat in a single map (and similarly for barley and oats). Thus, in weighting the climate data we were not able to distinguish between the harvested area of winter wheat versus spring wheat. This could lead to incorrect weightings in regions that grow substantial amounts of both winter and spring wheat.

Similarly, in presenting histograms and summary statistics of climate variables, we weighted the mean for each region by the total harvested area of the crop in that region. (As for the weighting described above, however, we were not able to distinguish between the harvested area of winter wheat versus spring wheat in weighting these observations.) This weighting prevents the results from being dominated by areas where we have many small-scale observations (e.g. India). For the purposes of showing planting date distributions and correlations between planting dates and climate, we assumed that the mean planting date applied everywhere within a region. In reality, of course, planting dates vary within each region, but we did not have enough information to specify these intra-regional variations. Without this information, we also could not determine, for example, the variability in temperature at planting within a given region, so we only use the mean values for each region.

We also computed climatologies of potential evapotranspiration (PET) for each region, using the Priestley–Taylor equation with $\alpha = 1.26$ (Priestley & Taylor, 1972). We estimated net radiation in this equation as a function of solar geometry, sunshine fraction and temperature, similarly to Ramankutty *et al.* (2002). We specified a constant albedo of 0.2 (this is a typical value for soil albedo, which we chose because we were most interested in values of PET outside the growing season). The temperature and sunshine fraction values used to calculate PET were weighted spatial averages over the given region, interpolated to daily temporal resolution.

Delineation of temperature and precipitation-limited regions

In order to examine relationships between planting date and temperature, we used criteria to distinguish between regions whose planting dates are likely to be governed by temperature ('temperature-limited' regions) and those whose planting dates are unlikely to be governed by temperature (Fig. 1). The purpose of this was simply to exclude the latter from our analyses of planting date–temperature relationships. For maize and spring wheat, we considered a region to be temperature-limited if the average monthly temperature of its coldest month is less than 10 °C (this threshold corresponds to the delineation of frost-free regions in the FAO's GAEZ analysis; Fischer *et al.*, 2002). We further excluded Pakistan and Iraq from the maize analyses because they were outliers, with temperatures at planting > 30 °C. For winter wheat, our main goal was to exclude from our analyses regions that may have been misclassified as winter wheat-growing, despite actually growing spring wheat varieties because of their warm winter temperatures. (For consistency, we still refer to the regions included in our analyses as 'temperature-limited'.) To accomplish this, we considered a winter wheat-growing region to be temperature-limited if the average monthly temperature of its coldest month is less than 4 °C (Fig. 1c). This threshold corresponds to a typical base temperature for growing degree accumulation in simulation models of winter wheat (e.g. Blue *et al.*, 1990).

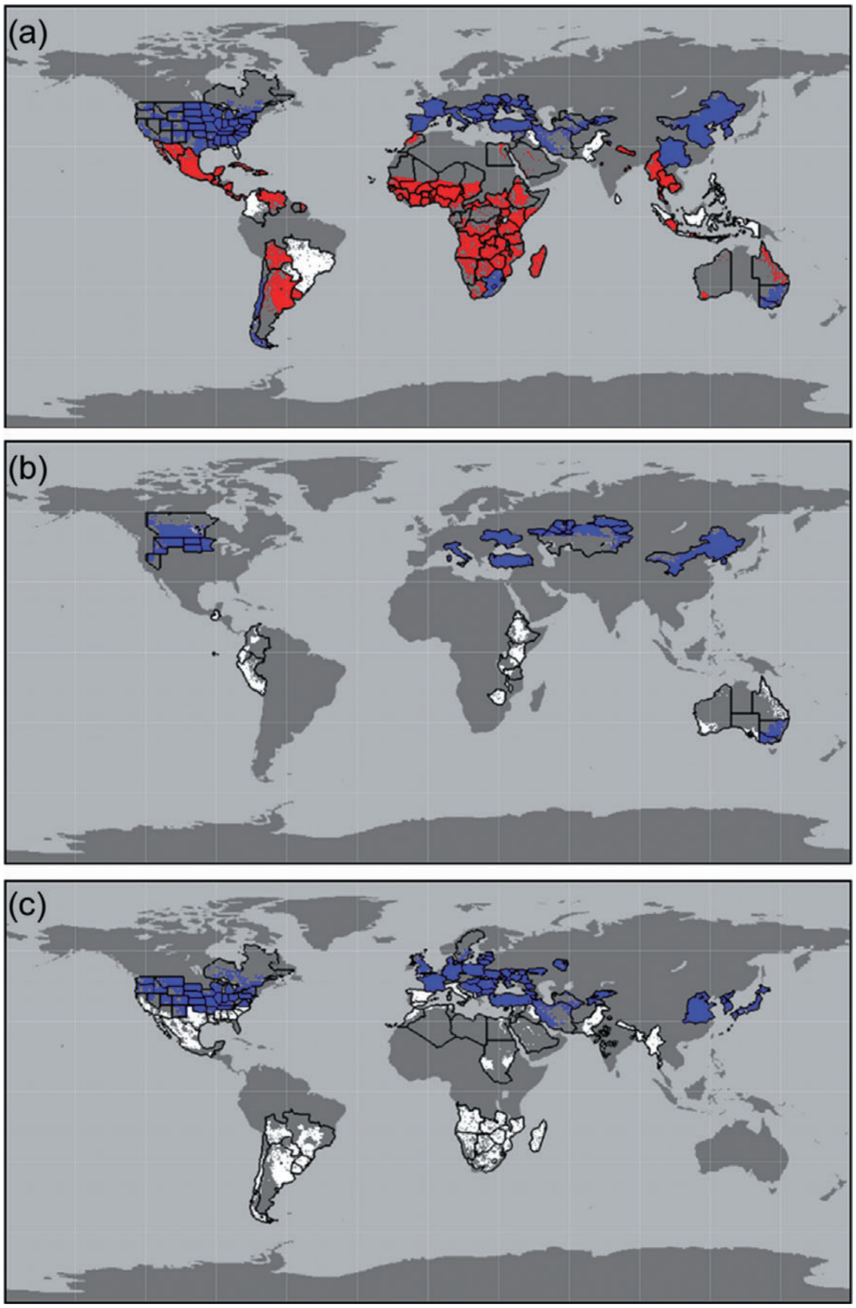

Figure 1 (a) Division of maize-growing regions into temperature-limited (blue), precipitation-limited (red) and neither temperature nor precipitation-limited (white). (b) Division of spring wheat-growing regions into temperature-limited (blue) and non-temperature-limited (white). (c) Same as (b), but for winter wheat. Grey indicates lack of crop calendar observations for the given crop, or that the crop is not grown there (according to Monfreda *et al.*, 2008). Black lines delineate the regions for which we have crop calendar observations.

Similarly, to examine relationships between maize planting date and precipitation, we separated maize-growing regions into those for which planting dates are likely to be governed by the seasonality of precipitation ('precipitation-limited' regions) and those for which planting dates are unlikely to be governed by the seasonality of precipitation (Fig. 1a). We considered a maize-growing region to be precipitation-limited if there is some day when precipitation is less than half of PET (using average monthly precipitation interpolated to daily values, and daily computed values of PET, as described above). However, we did not allow a region to be classified as both temperature and precipitation-limited. We assumed that temperature limitation takes priority, since farmers have more means to alleviate precipitation limitation (e.g. irrigation) than temperature limitation. (This explains, for example, why maize in California is grown in the warm, dry season, and not the cool, wet season.)

Thus, if a region would be classified as both temperature- and precipitation-limited, we considered it to be temperature-limited, including it in our analyses of relationships with temperature but not in our analyses of relationships with precipitation.

RESULTS AND DISCUSSION

Maps of planting and harvesting dates for all 19 crops (Table 2) are available as Supporting Information (Figs S1 & S2). All of these maps, as well as additional data (e.g. the start and end of the planting and harvesting periods in each region, in addition to the mean dates) and figures like Fig. 5 for all crops and regions, can be obtained from http://www.sage.wisc.edu. Here we only present planting date patterns for maize, spring wheat and winter wheat.

Maize

Maize planting in the northern mid-latitudes generally occurs in April and May, with cooler regions planting later than warmer regions. Maize planting dates vary more widely in tropical and southern mid-latitude regions, where two neighbouring countries can often have very different planting dates (Fig. 2a).

In temperature-limited regions, maize planting tends to occur when daily average air temperatures reach between 12 and 17 °C (Figs 3 & 4a). The weighted median temperature at planting in these regions is 15.8 °C, but there is some spatial variability in this relationship. For instance, maize is generally planted at cooler temperatures in western and southern Europe (includes Albania, Bulgaria, France, Italy, Macedonia, Spain and the former Yugoslavia; weighted median temperature at planting = 12.1 °C) than in the United States (weighted median temperature at planting = 15.4°C) (Fig. 3).

Illinois presents a typical example of planting patterns in northern mid-latitude regions. There, farmers plant maize in late April and throughout the month of May. The average air temperature in the middle of this planting period is *c.* 16 °C (Fig. 5a). One constraint on this planting date is that maize cannot germinate below a soil temperature of *c.* 10 °C (Nafziger, 2003a). But the water content of the soil can be more important than its temperature. Farmers need to wait for the soil to dry out enough to avoid undue soil compaction and 'mudding in' of the crop (Nafziger, 2003a). Thus, air temperature is rarely a direct determinant of maize planting date in temperate regions, but is rather an index of when soils are warm enough, and more importantly dry enough, to drive a tractor over them without causing too much soil compaction. This indirect effect of air temperature, mediated by soil moisture, may partly explain why planting temperatures are generally warmer in North America than in Europe: more snowfall in North America could mean that higher air temperatures are required to dry the soil sufficiently for farmers to plant their crops.

In precipitation-limited regions, planting generally occurs around the start of the rainy season. In particular, maize is usually planted when monthly average precipitation reaches 80–140 mm month^{-1} (Fig. 6a). These precipitation rates typically correspond to times when precipitation is between about 0.5 × PET and 0.9 × PET (Fig. 6b); this ratio of precipitation to PET can be a better proxy for soil moisture than is precipitation alone. However, there is considerable spread in these relationships between planting date and precipitation. To some extent, admittedly, this spread overemphasizes the difference between regions. In many of these precipitation-limited regions, there is a rapid increase in precipitation rates at the start of the rainy season. Thus, a large difference in precipitation at planting between two regions could translate into a relatively small difference in planting dates. Nevertheless, there seems to be more variability in farm management between, as well as within, precipitation-limited regions, than there is for temperature-limited regions.

In northern Nigeria, for example, maize is generally planted in May and June, coinciding with the start of the rainy season there (Fig. 5b). But a more detailed study of part of this region showed that, even within small areas, planting dates could vary substantially between farmers (Weber *et al.*, 1995). Some farmers planted in early to mid June, once the rains were well established, according to the recommended practice. Many others, though, planted in May. The latter group had an increased risk of crop failure and the subsequent need to replant. However, they were apparently willing to take on this risk in order to achieve early food availability, reduced pest problems and, importantly, greater nitrogen supply through capturing the flush of nitrogen that often comes with the early rains. Jagtap & Abamu (2003) therefore hypothesized that earlier planting may be most beneficial for farmers who use few or no inorganic fertilizers, whereas later planting may be better for farmers who use more fertilizers, and so do not rely on the early flush of soil nitrogen.

Maize planting times in Nigeria are also partly driven by the climate later in the season. Planting in June allows flowering to occur during the rainy period. If this key crop growth stage occurred later, there would be risk of drought stress (Kamara *et al.*, 2009). This consideration affects planting decisions in other regions as well. In all cereals, the crop is most sensitive to drought stress during flowering, but this is especially true for maize (Heisey & Edmeades, 1999). Thus, although some global models predict planting date based on conditions at the time of planting (e.g. Bondeau *et al.*, 2007), in reality the expected conditions later in the season can be more important. However, for crops that are photoperiod sensitive, the flowering date may be less dependent on the planting date. Tropical maize cultivars tend to be photoperiod sensitive, whereas temperate cultivars are generally not (Major & Kiniry, 1991).

When farmers plant based on the rains, they often use different indicators of the start of the rainy season from those an agronomist might use. For example, Mutiso (1996) found that most farmers in a region of south-eastern Kenya used traditional knowledge systems to determine when to start land preparation and planting. The main indicators these farmers used were: budding of certain trees, high temperatures and relative humidity, animal behaviour, wind direction and the smell of rain.

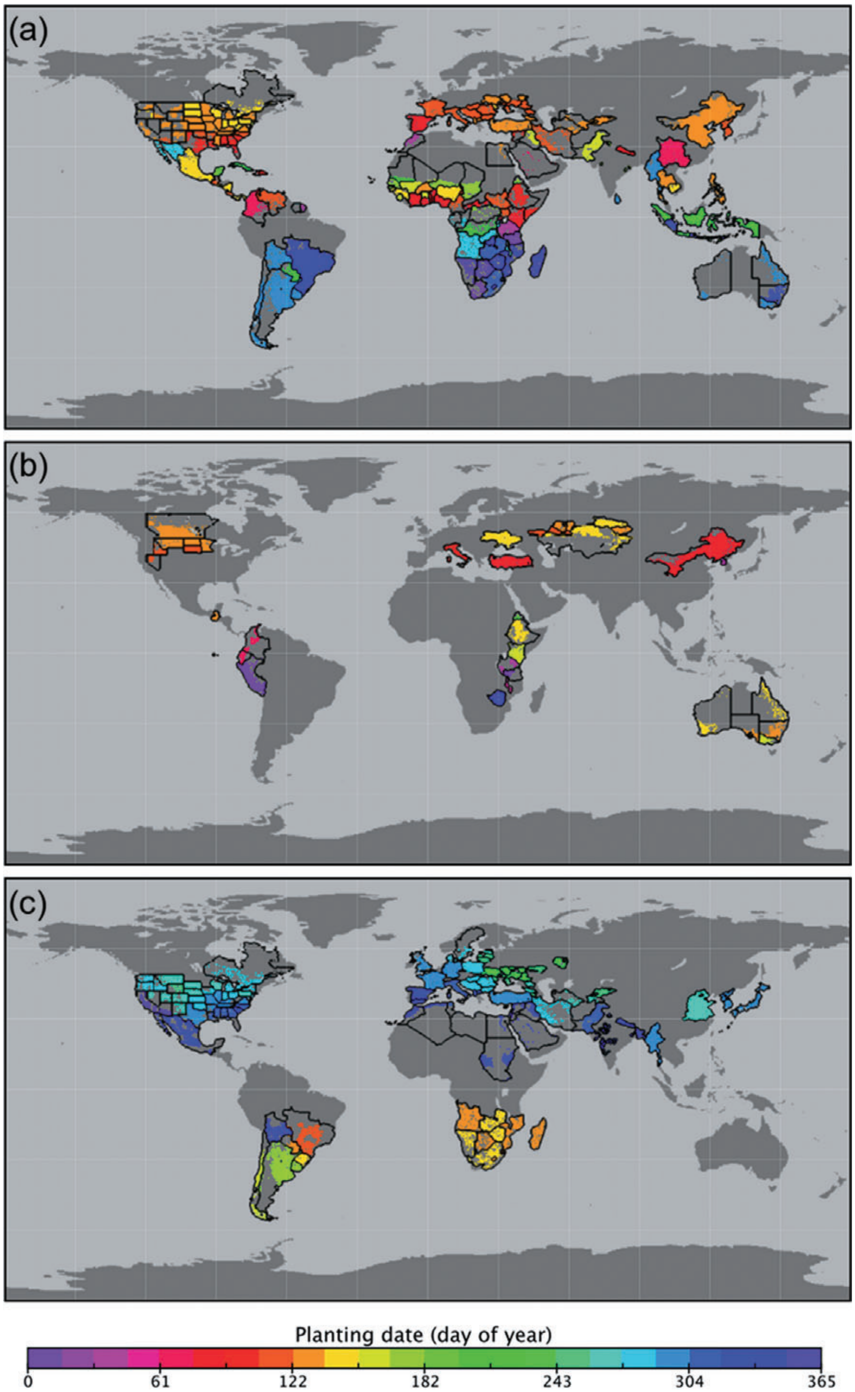

Figure 2 Maps of typical crop planting dates for (a) maize, (b) spring wheat and (c) winter wheat. Grey indicates lack of crop calendar observations for the given crop, or that the crop is not grown there (according to Monfreda *et al*., 2008). Black lines delineate the regions for which we have crop calendar observations.

These traditional knowledge systems are important to acknowledge if we are interested in predicting how farmers might respond to climatic changes. With climate change, the relationships between these indicators and climate might shift, confounding simple predictive relationships based on precipitation alone.

In addition to climatic factors, other agronomic factors also influence planting date decisions, especially in precipitation-limited regions. In Kenya, for instance, the timing of rain onset is one factor influencing planting date. But planting dates can differ between farms due to a number of other factors. Farmers who use their own tractors or oxen are able to plant earlier than those who rent tractors. In addition, farmers with larger families can plant earlier because of the greater availability of labour. Finally, farmers plant about a week earlier if they are planning to grow a second crop after the main maize crop (Hassan, 1996). Similarly, farmers in Swaziland generally plant maize around the start of the rainy season. However, these farmers often face delays from a shortage of working tractors in the country. Those who use government tractors must reserve them ahead of time

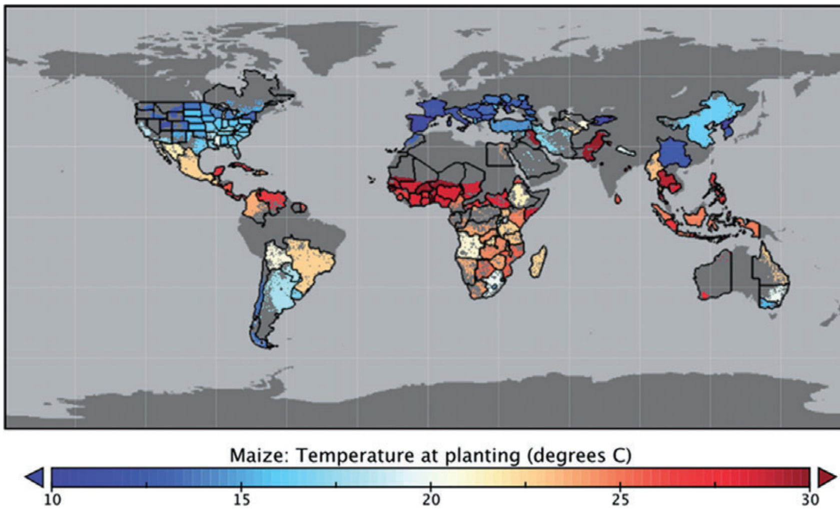

Figure 3 Average temperature at which maize is planted. For each region, we computed a single value, which is the average across time (1961–90) and space of the temperature on the mean planting date in that region. In averaging across space, we weighted the temperature of each grid cell by the harvested area of maize in that grid cell.

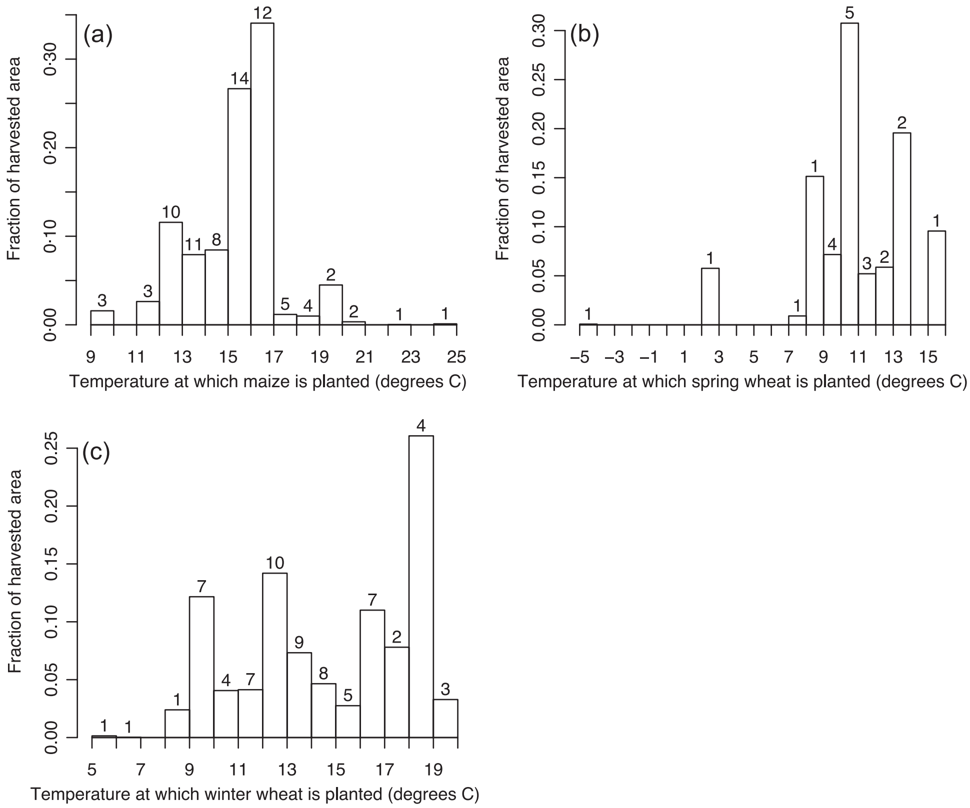

Figure 4 (a) Distribution of the average temperature at which maize is planted in temperature-limited regions (see text for the definition of 'temperature-limited'). As in Fig. 3, we computed a single average temperature at planting for each region. Each regional average was then weighted by the total harvested area of maize in that region. The numbers above the bars show the count of observations in each bin, ignoring harvested area. (b) Same as (a), but for spring wheat. (c) Same as (a), but for winter wheat, which is defined as 'temperature-limited' where the average monthly temperature of the coldest month is less than 4 °C.

for a particular date, leaving them unable to respond to unexpected weather patterns. In addition, a payment is required to use these government tractors early in the season. Finally, difficulties in obtaining seed and fertilizer can lead to further planting delays (Rauniyar & Goode, 1992; Rukandema *et al.*, 2008). These factors and others like them can prevent farmers from responding optimally to climate.

Thus, in the mid-latitudes, many of the spatial patterns in maize planting dates can be explained by temperature at planting. In lower latitudes, the relationship between climate and

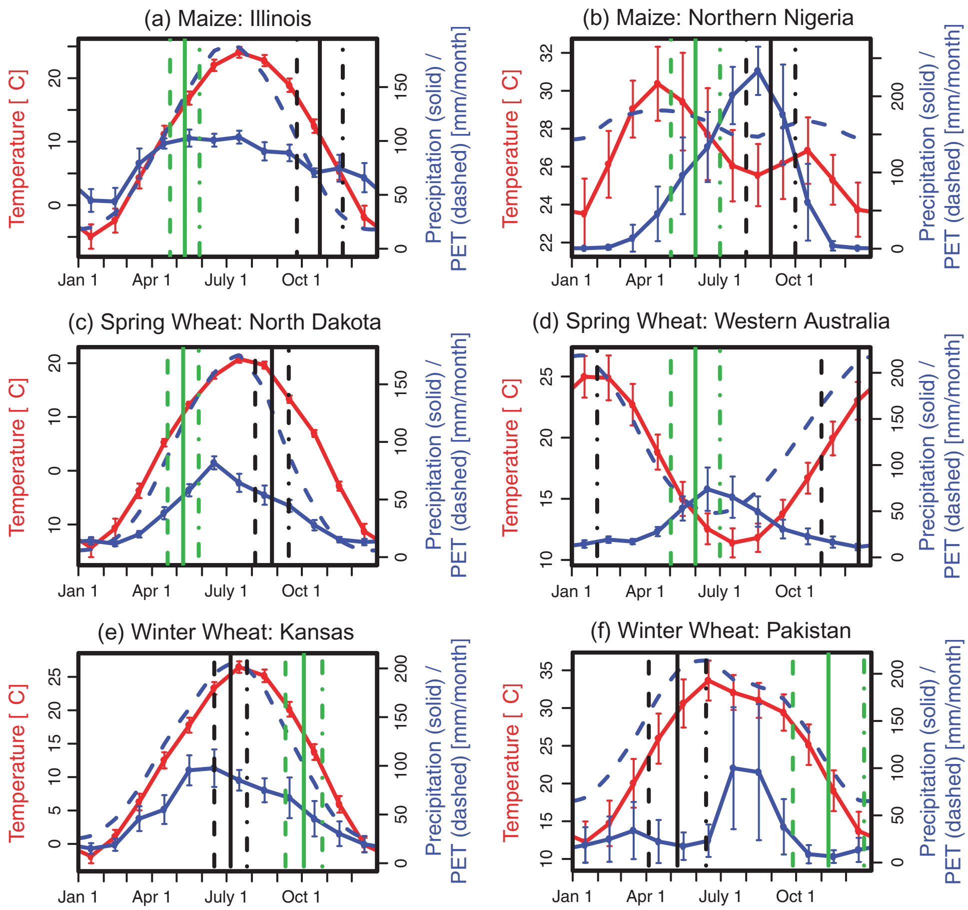

Figure 5 Planting and harvesting dates for select regions, along with average patterns of temperature, precipitation and potential evapotranspiration (PET). Vertical green lines show typical planting dates (mean and range); vertical black lines show typical harvesting dates. The red curves show climatological average temperatures for each month, the solid blue curves climatological average precipitation, and the dashed blue curves climatological average PET. The climatological averages are averages across time (1961–90) and space, with each grid cell weighted by the given crop's harvested area in that grid cell. The error bars give spatial weighted standard deviations. (a) Maize in Illinois (USA). (b) Maize in northern Nigeria. (c) Spring wheat in North Dakota (USA). (d) Spring wheat in Western Australia. (e) Winter wheat in Kansas (USA). (f) Winter wheat in Pakistan.

planting date is less clear, although precipitation at planting or precipitation/PET at planting can explain some general patterns. However, these climatic relationships can mask the true drivers of planting decisions. In the mid-latitudes, temperature may simply be a proxy for when soils are dry enough to plant. In precipitation-limited regions, the timing of the rainy season places a broad constraint on planting dates, but agronomic, socioeconomic and cultural factors can shift planting dates by a month or more from what might be expected based on climate alone. And, in many regions, the most important climatic consideration is ensuring a favourable climate at key crop development stages later in the season, such as during flowering.

Spring wheat

Spring wheat planting in the northern mid-latitudes, like maize planting, generally occurs in April and May (Fig. 2b). But spring wheat tends to be grown in higher-latitude, cooler regions than maize, and for a given climate, spring wheat is generally planted earlier than maize. For example, in US states where both crops are grown, spring wheat is planted 1–4 weeks earlier than maize. Thus, spring wheat tends to be planted at cooler temperatures than maize – generally between 8 and 14 °C in temperature-limited regions, with a weighted median temperature at planting of 10.9 °C (Fig. 4b; cf. Fig. 4a).

The earlier planting of spring wheat, as compared to maize, agrees with recommendations that spring wheat should be planted as early as possible, as long as the time of greatest frost risk has passed and soils are not too wet (e.g. Smith, 1995). This is not just to ensure a longer growing season. Rather, late planting can result in heat stress during sensitive crop development stages, such as the start of the reproductive growth period (Smith, 1995). North Dakota represents a typical spring wheat-growing region, where winter temperatures are generally too cold to grow winter wheat. There, spring wheat is planted between mid-April and late May, corresponding to average daily air temperatures between 6 and 14 °C (Fig. 5c).

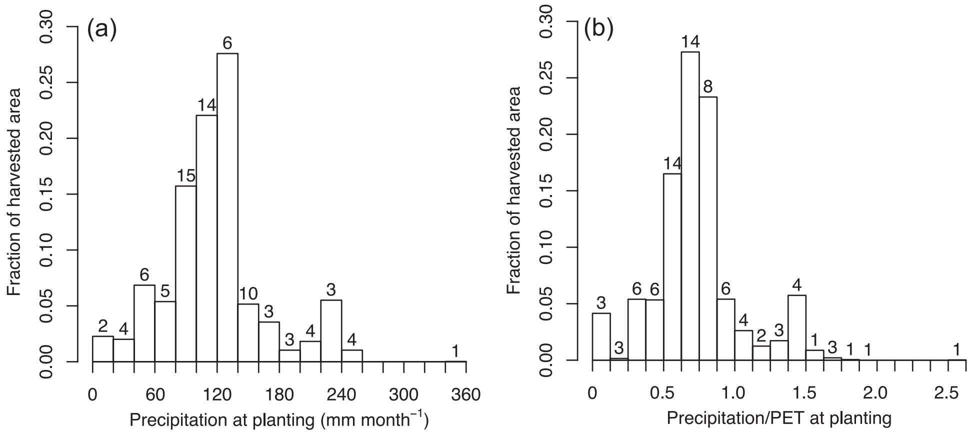

Figure 6 Distributions of (a) the average monthly precipitation rate at which maize is planted in precipitation-limited regions and (b) the average precipitation/potential evapotranspiration (PET) at planting in precipitation-limited regions. See text for the definition of 'precipitation-limited'. We computed a single average precipitation (or precipitation/PET) value for each region. Each regional average was then weighted by the total harvested area of maize in that region. The numbers above the bars show the count of observations in each bin, ignoring harvested area.

In the wheat belt of Western Australia, as in a few other regions, frost risk is low, so wheat planting dates are determined more by precipitation than by temperature (Fig. 5d). However, as in temperature-limited regions, the climate at planting is less important than the climate later in the season. The optimal planting time is the time that will lead to relatively low moisture stress during flowering and grain filling, by taking advantage of the cooler temperatures and greater moisture availability of the austral winter. Changing agronomic practices also affect wheat planting dates in Western Australia: farmers can sow their fields earlier today than a few decades ago thanks to herbicides and minimum tillage technology (Kerr *et al.*, 1992; Stephens & Lyons, 1998).

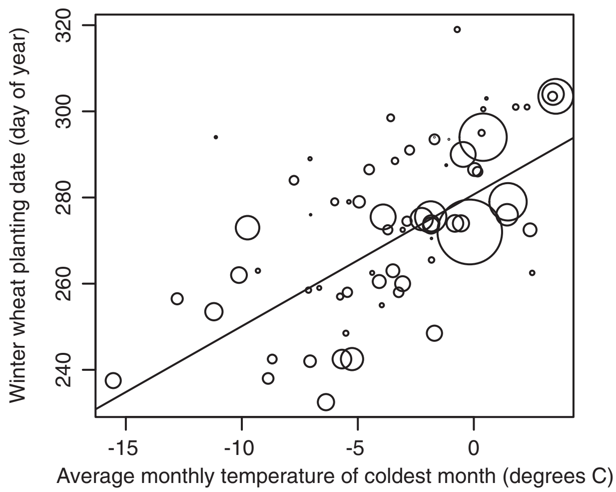

Figure 7 Relationship between mean winter wheat planting date and average monthly temperature of the coldest month, in temperature-limited regions (defined as regions where the average monthly temperature of the coldest month is less than 4 °C; note that this criterion only includes regions in the Northern Hemisphere). Each circle indicates a single region; the area of the circle is proportional to the harvested area of wheat in that region. The solid line shows a weighted linear regression; its equation is $y = 3.06x + 281$ ($R^2 = 0.49$).

Winter wheat

Winter wheat in the northern mid-latitudes is generally planted in September and October (Fig. 2c). In Kansas, for example, the dominant winter wheat-growing state in the US, winter wheat is planted between mid-September and late October (Fig. 5e). Regions with cold winters generally plant earlier than those with warmer winters (Fig. 7). Note that, for this and other climatic relationships, we considered only temperature-limited regions, as defined above.

Farmers choose winter wheat planting dates to ensure a proper amount of growth before winter dormancy sets in. Thus, the growing degree day (GDD) accumulation between planting and the onset of cold temperatures is an important climatic factor (e.g. Blue *et al.*, 1990). However, this factor varies between different winter wheat-growing regions (Fig. 8). The temperature at planting also varies between different wheat-growing regions, from about 9–19°C (Fig. 4c). In general, winter wheat planting dates are less easily predicted from climate alone than are the planting dates of spring crops.

Winter wheat yields decline if the crop is planted too early or too late. Unlike many spring crops, early planting does not necessarily give an advantage to winter wheat. One of the major risks of early planting is an increased vulnerability to insects and viral infection. In much of the US, for example, farmers wait to plant winter wheat until the risk of hessian fly infestation has subsided. Since the flies cannot survive freezing temperatures, this means waiting to plant until after the first frost (Nafziger, 2003b; Johnson, 2008). The threats posed by insects, viruses and weeds are also decreased by waiting to plant until after other grasses have died – thus avoiding a 'green bridge' between other

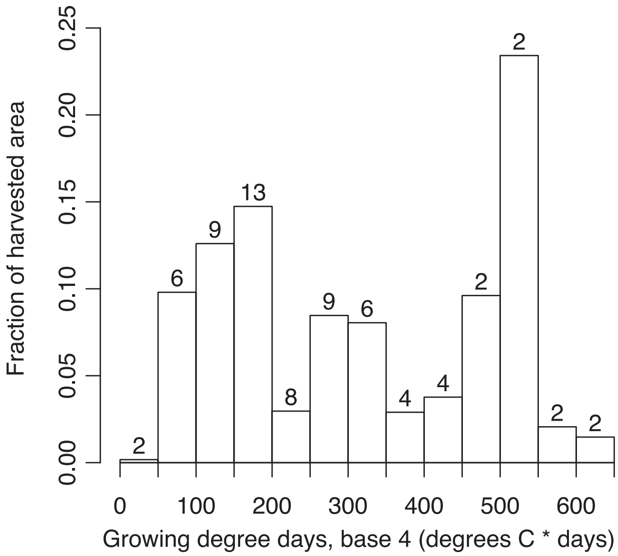

Figure 8 Distribution of the average growing degree day accumulation (GDD, base 4 °C) from the time of winter wheat planting until the time when climatological average temperatures fall below 4 °C, in temperature-limited regions (defined as regions where the average monthly temperature of the coldest month is less than 4 °C). We computed a single average GDD value for each region. Each regional average was then weighted by the total harvested area of wheat in that region. The numbers above the bars show the count of observations in each bin, ignoring harvested area.

hosts and the emerging winter wheat (Wibberley, 1989; Wiersma *et al*., 2006). Another problem with early planting of winter wheat is that high temperatures can have adverse effects on the germination and early development of the crop (Smith, 1995). Finally, early planting can lead to excessive autumn growth. One problem associated with this is too much soil water depletion in the autumn, which in turn can lead to more freeze injury in the spring, since dry soils cool down more than wet soils (Klein *et al*., 2008).

Late planting of winter wheat is also detrimental to yields. Late planting does not allow enough time for crop growth before dormancy sets in. This can result in insufficient root growth, making the plants more susceptible to drought and winter injury (Hammon *et al*., 1999). In addition, late planting can prevent the crop from achieving full vernalization prior to dormancy (Wiersma *et al*., 2006). Thus, winter wheat planting dates are based on hitting the optimal window that avoids most of the problems of both too-early and too-late planting. This optimal window is determined by a complex set of interactions between climatic and biological factors. In general, though, the optimal window will be earlier in cooler regions; this explains the relationship seen in Fig. 7.

In some regions, winter wheat is grown in rotation with a summer crop. There, winter wheat planting dates often depend on the harvesting date of the previous crop. Wheat tends to be less profitable than the summer crop, so farmers prefer to achieve an optimal harvesting date of the summer crop than to achieve an optimal planting date of winter wheat. In Pakistan, for instance, about 50% of the wheat crop is grown after either rice or cotton (Cheema *et al*., 2002) (Fig. 5f). (We classified wheat in South Asia as 'winter wheat' because it is grown in the cool, dry season; in reality, though, many of the wheat varieties grown there may be spring wheat types; Hodson & White, 2007). There, and in other parts of South Asia where wheat is double-cropped with rice, wheat is commonly planted later than the optimal time. Sometimes the late planting is due to the use of high-value, long-duration rice varieties, such as basmati rice. Late planting can also be caused by a lack of animals or machines for ploughing, or the farmers devoting their time to processing the rice before preparing the land for wheat (Hobbs & Mehla, 2003). Some of these problems can be alleviated by the adoption of no-till agriculture, which allows a shorter turn-around time between the rice harvest and the subsequent planting of wheat (Bhuiyan & Saleque, 2004).

Thus, the factors determining winter wheat planting dates tend to be more complex than those determining the planting dates of spring-planted grains. In a broad sense, winter wheat planting dates are still constrained by climate. The crop needs to experience sufficient growth before dormancy sets in, which requires planting when enough warm days remain in the year. But many other factors constrain winter wheat planting dates, from biological interactions with pests and weeds, to the harvesting date of a previous crop.

Limitations

Our crop calendar data set has a number of limitations. Many of these are based on limitations of the underlying data. First, the crop calendar observations generally apply to large geographic regions. Most observations are specified for an entire country or for a fairly large sub-national unit (e.g. a single state in the US). In reality, there are variations in planting and harvesting dates across many spatial scales. Within many of the regions for which we have data, there is probably a general north–south gradient in planting dates, following the temperature gradient. Moreover, there are small-scale variations in planting and harvesting dates, on the scale of a few kilometres or less. These are due to variations in soil properties, cultivar choice and individual farm management. The ranges in planting and harvesting dates, which are available in our full data set, capture some of this variability, but these ranges alone do not provide any information about the spatial patterns of this variability. One way to capture these spatial patterns would be to merge this crop calendar data set with a satellite-derived phenology product (e.g. Zhang *et al*., 2006).

Second, our data set does not capture any changes in time. In reality, planting dates change through time based on changes in climate as well as changes in technological and socio-economic factors. For example, corn planting dates in the central U.S. have been getting earlier by about 0.5 day year^{-1} over the last few decades, largely due to the development of cold-tolerant cultivars, improved fungicide treatments of seeds and other technological changes (Kucharik, 2006). Our observations generally refer to planting and harvesting dates in the 1990s and early 2000s, but different observations refer to slightly different years. In addition, there is a discrepancy between the years for which the crop calendar observations apply and the years for which the climate data apply (1961–90). In regions that have experienced substantial climatic changes over the last few decades, this discrepancy could lead to small errors in some of our climate statistics, such as temperature at planting.

Third, there may be some observations in our data set for which the 'main' growing season of a particular crop is actually the secondary growing season in a double-cropping system. If we had only one crop calendar for a given crop in a given region, we categorized the observation as a 'main season' crop calendar. But if this observation actually represented a subordinate growing season, this categorization could introduce some error in our climatic relationships, which were meant to characterize the main growing season of each crop.

Despite these limitations, the data set should still be useful for characterizing broad spatial patterns of crop planting and harvesting dates.

CONCLUSIONS

We compiled observations of crop planting and harvesting dates from around the world to make a single, comprehensive crop calendar data set. This data set is available via http://www.sage.wisc.edu. It contains about 1300 planting and harvesting date observations for 19 crops (Table 2). We envision this data set being used in the following ways.

1. For investigating the general question of when farmers plant their crops around the world, and what factors drive these planting decisions.

2. For global crop modelling of present-day patterns: planting and harvesting dates can be specified directly where we have observations and correlations with climate and/or spatial extrapolation can be used to fill gaps where we do not have observations.

3. For global crop modelling of future climates: correlations with climate can be used to predict future planting and harvesting dates by assuming that relationships between climate and planting dates developed using patterns across space can be transferred to changes in time.

By analysing the maize and wheat planting dates in this data set and reviewing case studies from the literature, we have found that planting decisions are often driven by factors that are much more complex than those assumed in existing global crop models (e.g. Bondeau *et al*., 2007; Osborne *et al*., 2007). Climatic thresholds such as the temperature at planting can explain some of the spatial patterns in planting dates for spring-planted crops in temperate regions. But in lower latitudes, there is considerable spread in these climatic relationships. Winter wheat planting dates are also more difficult to predict from climate alone. For winter wheat, interactions with pests and weeds, and the harvesting dates of other crops in a double-cropping system, are important determinants of planting date. Furthermore, in all areas of the world, crop planting dates may be chosen more to ensure a favourable climate later in the growing season, such as during flowering, than to ensure an optimal climate early in the crop's growth. This is especially true if there is potential for drought stress during the summer. This dependence of planting dates on the climate later in the season is important to bear in mind if we hope to predict how climate change might affect planting dates.

Finally, although climate provides broad constraints on planting dates, the exact timing of planting is often governed largely by technological and socio-economic factors. For example, farmers may have to plant later than the climatically optimal time due to shortages of tractors or labour. On the other hand, in many places, farmers can plant earlier today than in the past thanks to agronomic technologies such as no-till agriculture and improved fungicide treatments of seeds (Bhuiyan & Saleque, 2004; Kucharik, 2006). In some cases, climatic and technological factors interact to constrain planting dates. A trend towards warmer spring temperatures, for instance, may drive crop breeders to develop longer-season cultivars, which in turn could take advantage of earlier planting. It is important to consider all of these factors if we want to develop accurate models of today's agricultural practices – and even more important if we want to predict future agricultural practices. Over the next few decades, planting dates may shift at least as much due to changes in technological and socio-economic factors as they will due to changes in climate.

ACKNOWLEDGEMENTS

We thank George Allez for his untiring work compiling and digitizing much of the crop calendar data. We are also grateful to Chris Kucharik, Carol Barford, Paul West and Rachel Licker for valuable discussions that helped shaped the direction of this paper, and to Chris Kucharik, Carol Barford, Tom Osborne and an anonymous referee for their constructive comments on an earlier draft of the paper. W.J.S. was supported by a National Science Foundation Graduate Research Fellowship, D.D. by the Global Environmental and Climate Change Centre, J.F. by a National Aeronautics and Space Administration Interdisciplinary Sciences grant, and N.R. and D.D. by the US Environmental Protection Agency's Office of Atmospheric Programs and the Discovery Grants Program of the Natural Sciences and Engineering Research Council of Canada.

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SUPPORTING INFORMATION

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

Figure S1 Maps of typical planting dates for all crops listed in Table 2.
Figure S2 Maps of typical harvesting dates for all crops listed in Table 2.

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BIOSKETCH

William Sacks is an Environment and Resources PhD candidate in the Center for Sustainability and the Global Environment (SAGE) at the University of Wisconsin-Madison. His research investigates two-way interactions between agricultural management and climate. He explores these interactions through the development and application of vegetation and climate models, as well as through the analysis of regional and global data sets.

Editor: Matt McGlone