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Regional Variations of Optimal Sowing Dates of Maize for the Southwestern U.S.

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REGIONAL VARIATIONS OF OPTIMAL SOWING DATES OF MAIZE FOR THE SOUTHWESTERN U.S.

B. Myoung, S. H. Kim, J. Kim, M. C. Kafatos

ABSTRACT. *Sowing date (SD) is sensitive to regional climate characteristics; thus, it is critical to systematically examine the effects of SD on crop yields for various temperature regimes. We performed a sensitivity study of SD for maize in the southwestern U.S. using the regionally extended version of the Agricultural Production Systems sIMulator (APSIM) model. The model was run utilizing North American Regional Reanalysis at a 32 km resolution from 1991 to 2011, with an irrigation threshold at 95% of the soil water-holding capacity. Two types of SD optimizations maximizing yield potential (Y_p), varying spatially or interannually, revealed that the optimal SD varies according to regional climate characteristics and depends on the base temperature climatology during the growing season. For cool regions at high elevations (e.g., northern California and northern Nevada) and in coastal areas, earlier sowing results in higher Y_p, allowing longer growing seasons. In these regions, yearly varying of SD to reduce the negative effects of springtime cold events can also enhance Y_p significantly. In low-elevation warm regions (e.g., southern Central Valley, southern California, and southwestern Arizona), the length of the growing season rarely impacts Y_p, and early planting is crucial to avoid adverse impacts of extremely hot conditions in the summer. For transitional regions (e.g., the southern Great Basin in Nevada and the Colorado River basin in Arizona), high Y_p can be obtained in a short growing season due to the optimal temperature range of the growing season. Thus, for the transitional regions, SD optimization does not have much impact on Y_p.*

Keywords. *APSIM modeling, Climate variability, Growing season, Maize, Southwestern U.S., Sowing date, Temperature, Yield potential.*

Climate change and its variations are critical challenges for securing a worldwide food supply (Rosenzweig and Parry, 1994; Parry et al., 2005; Fischer et al., 2005; Lobell et al., 2008). A number of general circulation models (GCMs) project a rapid increase in the global mean temperature (0.2°C per decade) in the coming decades, with substantial variations according to regions and seasons (IPCC, 2007). However, the impacts of such changes on agriculture have not yet been well established (Lobell and Field, 2007; Kucharik, 2008). Understanding the impacts of temperature variations on crops is important in assessing the impacts of climate change on crop production at regional scales. Recently, actual yield (Y_a), yield potential (Y_p), and yield gap (Y_p minus Y_a) parameters have been widely used to assess food security (Van Ittersum and Cassman, 2013; Kim et al., 2016). While Y_a is affected by various factors (e.g., climate, water, soil type, nutrition, pest/disease, and genotypes), Y_p is determined only by climate variables such as solar radiation and temperature, with non-limiting nutrients and water and controlled biotic stresses (Evans, 1993). Therefore, not only Y_a but also Y_p can be substantially affected by temperature change and variability (Lobell et al., 2009; Van Ittersum and Cassman, 2013).

One of the key factors affecting crop yields, both Y_p and Y_a, is the sowing date and associated length of the growing season (Otegui et al., 1995, 1996; Sarvari, 2005). The importance of the growing season can be understood in the context in which plants sense temperature on a daily basis and require a minimum amount of accumulated daily temperature to complete each developmental phase (Atwell et al., 1999). Thus, warmer climates enable crops to grow faster so that they can promptly complete the development phases. This indicates that the length of the crop growing season for photosynthesis and grain filling processes and, subsequently, crop production will be reduced. This pattern is supported by some previous studies (e.g., Tubiello et al., 2000; Olesen, 2005; Porter, 2005; Liu et al., 2010; Liu et al., 2013), suggesting that warming trends tend to reduce maize production by shortening the length of the growing season, unless other management factors, including sowing dates and/or genotypes, are properly controlled for. Therefore, earlier planting dates under warmer conditions can induce higher yields because the resulting longer growing season allows plants to have more time to grow and accumulate biomass

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during the period favorable to plant growth (Kucharik, 2006). In fact, earlier planting in warmer climate conditions was reported to enhance maize yields in regions such as northern China (Liu et al., 2012, 2013) and the Great Plains of the U.S. (Kucharik, 2006). However, such studies are limited to a number of locations and short periods, which are insufficient for understanding the optimal sowing timing under various regional climate conditions. Thus, a careful examination of the relationship between sowing date and maize yield at regional scales is of great importance in developing plans for adapting agricultural practices to future climate change.

Maize, one of the major crops in the southwestern U.S. (SWUS), is widely planted in California and Arizona. Due to the latitudinally and longitudinally elongated complex topography of the SWUS region, which includes various land cover types including deserts, semi-arid regions, agricultural areas, large urban centers, mountains, and coastlines, the USDA-recommended maize sowing dates in the SWUS span a relatively long period, from March 10 to July 15 (USDA, 2010), depending on location. However, unlike the Midwestern Corn Belt (Southworth et al., 2000; Bruns and Abbas, 2006; Grassini et al., 2009), records of maize sowing dates are largely unavailable for the SWUS at either the farm or county level. This may be one of the reasons why previous studies of sowing dates in the SWUS are rarely found. In cases like these, process-based crop models, such as the Agricultural Production Systems sIMulator (APSIM; Keating et al., 2003), are useful tools in evaluating the responses of agricultural systems to variations in sowing dates (e.g., Hansen and Indeje, 2004; Lee et al., 2011; Kim et al., 2016). Process-based crop models have been widely used for simulating and estimating maize Y_p at various spatial ranges in the recent past (Chauhan et al., 2013; Mastrorilli et al., 2003; Lv et al., 2015).

In this study, we examine the effects of temperature and sowing date on maize Y_p on interannual time scales in the SWUS region using the APSIM model. Our focus is on the following questions: (1) Do the optimal sowing dates vary in space (e.g., geographically) and/or time (e.g., interannually)? and (2) How do local climate regimes affect optimal sowing dates and Y_p in the target regions (e.g., changing the length of the growing season)? To do so, we first determine optimal sowing dates from the multiple APSIM simulations and characterize the spatial variations in terms of growing season climate conditions, such as temperature. Due to the wide variations in climate regimes in the SWUS related to its complex topography and atmospheric circulations (e.g., the North American Monsoon, NAM) during a particular growing season, the result will elucidate the variations in the optimal sowing dates for maize according to local temperature variability. Second, we compare the optimal sowing date simulation with fixed sowing date simulations for verifying impacts of sowing date optimization on Y_p. Third, we investigate the effects of year-to-year temperature variations on sowing date and Y_p. By understanding the agricultural system in the SWUS based on agricultural model simulations, this study is expected to contribute to improved understanding of the optimal sowing dates for maximizing maize yields in the SWUS for various climate conditions.

Data and Methods

The ApsimRegions model (Stack and Kafatos, 2013), the regionally extended version of the APSIM model, was run at a total of 958 grid points in the SWUS region, including California (CA), Nevada (NV), and Arizona (AZ) at 32 km spatial resolution over a 21-year period from 1991 to 2011 (Kim et al., 2016). The input data included the daily maximum and minimum temperatures (T_{max} and T_{min}, respectively), surface insolation, and precipitation from North American Regional Reanalysis (Mesinger et al., 2006; http://www.esrl.noaa.gov/psd/) at 32 km spatial and 3 h temporal resolutions. The generic type of maize selected in this study was Pioneer 3273. Although application of a single cultivar type across such a large region is to some extent far from realistic, it is methodologically acceptable considering that the aim of this study is to examine impacts of climate on sowing date optimization and yield at a regional scale. The soil type at each grid point was specified based on HC27, a generic soil profile database, at a 9 km horizontal resolution (HarvestChoice, 2010; Koo and Dimes, 2013). Irrigation was set to maintain the soil moisture content at the 95% level of the soil water-holding capacity. In order to isolate the effects of climate on maize yield, all management practices except sowing date were fixed in all simulations. Detailed descriptions of the model and its calibration and validation are given by Kim et al. (2016). With this model setup, maize yield is simulated without nutrient, water, and pest/disease stresses and, thus, is considered yield potential (Y_p).

The threshold for irrigation used in this study, 95% of the soil water-holding capacity, was set to minimize impacts of precipitation on Y_p because much of the farmland in the SWUS region is heavily irrigated, especially during the growing season. A sensitivity study suggested that the effects of solar radiation on Y_p are minimal during warm seasons, except in some coastal regions (Kim et al., 2016). Thus, the simulated maize yield is most sensitive to the averages and the variability of temperature during the growing season.

As mentioned previously, crop development is more likely dependent on accumulated temperature (called "thermal time") than on physical time. Thermal time is a summation of daily mean temperature and has units of degree-days (°C day) (Atwell et al., 1999). In the APSIM model, thermal time is used to drive phenological growth and canopy development, and the duration of each of the eleven crop stages (except for sowing to germination, which is driven by soil moisture) is determined by the accumulation of thermal time (Keating et al., 2003). Figure 1 displays daily thermal time in response to air temperature in the APSIM maize module (https://www.apsim.info/Documentation/Model,CropandSoil/CropModuleDocumentation/Maize.aspx), with the optimum temperature at 34°C. Note that the thermal time becomes zero with air temperatures less than 0°C and greater than 44°C. In the model, daily thermal time was computed based on the eight averaged 3 h average air temperatures, which are interpolated from T_{max} and T_{min} (Jones and Kiniry, 1986).

To investigate the impact of sowing date on maize Y_p, three sets of model experiments with different sowing dates were performed (table 1). In optimization 1 (Opt1), the

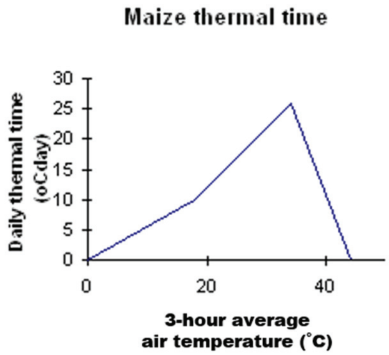

Figure 1. Daily thermal time in response to air temperature in the APSIM maize module with the optimum temperature at 34°C. Thermal time is zero with air temperatures less than 0°C or greater than 44°C.

model was run at each grid point with sowing dates separated by 7 days from March 1 to July 1, resulting in 17 simulations of varying sowing dates. The optimal sowing date for each grid point was then selected as the date that yields the maximum Y_p for each year (hereafter, the annual optimal sowing date). Hence, the annual optimal sowing date varies from year to year at each given grid point. In optimization 2 (Opt2), we first defined the time-invariant optimal sowing date at each grid point as the median of the annual optimal sowing dates for the 21 years in Opt1. The optimal sowing date defined in this way varies only spatially, i.e., each grid point is assigned its own unique sowing date over the 21-year period (hereafter, the spatial optimal sowing date). The last experiment was performed with a fixed sowing date (Fix) of May 1 at every grid point for every year (hereafter, the fixed May 1st sowing date).

Once a sowing date (hereafter, SD) is given with the input data (e.g., T_{max}, T_{min}, surface insolation, and precipitation), the APSIM model simulates the harvest date (hereafter, HD) and Y_p at each grid point. In the APSIM maize module, HD is the date when a whole plant dies due to various stresses from water, heat/cold, and nutrition during the growing season (https://www.apsim.info/Documentation/Model,CropandSoil/CropModuleDocumentation/Maize.aspx). The length of the growing season (hereafter, LGS), defined as the period from SD to HD, was then calculated. Note that, while the individual SD of Opt1 is different from that of Opt2, the 21-year average SD of Opt1 is identical to that of Opt2 by the definition of the sowing date for Opt2 (see the previous paragraph). However, HD, LGS, and Y_p, and their 21-year averages for Opt1 are different from those of Opt2. This feature may be obtained from the nonlinear developmental processes of maize during the changed weather conditions associated with the different SD in individual years (Porter and Semenov, 2005). We examined and compared the spatial variations of the optimal SD, LGS, and Y_p and the relationship of these variables to local temperatures. We also investigated how interannual temperature variability is associated with SD and Y_p by correlation analysis, with an emphasis on geographical differences.

Table 1. Descriptions of the three experimental simulations.

Experiment	Name	Description
Opt1	Annual optimal sowing date	Sowing date varies both grid-to-grid and year-to-year.
Opt2	Spatial optimal sowing date	Sowing date varies only grid-to-grid.
Fix	Fixed May 1st sowing date	Sowing date fixed (May 1) at every grid point for every year.

Results and Discussion

Climatology of the Annual Optimal Sowing Date Simulations (OPT1)

The 21-year median SD of the annual optimal sowing date experiment (Opt1) shows substantial geographical variations (fig. 2a). The SD is as early as March (blue grids) in low-elevation regions, such as the Central Valley, southern CA, coastal regions, and the Sonoran desert, whereas it is one month later, in April (green grids), in high-elevation regions, such as the northern CA mountainous regions, the Sierra Nevada, and northern/central NV. The earlier optimal SD in the low-elevation regions in comparison to the high-elevation regions is likely due to relatively warm springs in the low-elevation regions. Note that maize yield simulations were unsuccessful at some grid cells in the highest elevation areas of the Sierra Nevada (white grid cells), probably due to an extremely cold environment. These grid cells were not included in the analyses below. Four additional white grid cells in CA and NV indicate large lake areas for which no simulation results were available as well.

Similar spatial variations are found in the HD (fig. 2b), illustrating a dramatic difference between the low-elevation and high-elevation regions. The HD is as early as June, July, or August (or as late as September and partial October) in the low-elevation regions (or high-elevation regions). Accordingly, the LGS (fig. 2c) also reveals similar geographical variations, with longer LGS in high-elevation regions (more than 170 days) versus shorter LGS in low-elevation regions (90 to 160 days), except the coastal regions. The coastal regions are characterized by very long growing seasons (180 to 270 days) resulting from the early SDs (e.g., March) and late HDs (e.g., August to October) shown in figures 2a and 2b, respectively.

On the other hand, a unique characteristic of the combinations of SD, HD, and LGS is found in the transition regions between the low-elevation regions and the high-elevation regions in the southern part of AZ and the southwestern part of the Great Basin in NV. The optimal SD is late (May or June; orange and dark red grid cells in fig. 2a), and the HD is also late (September; orange grid cells in fig. 2b). Hence, in these regions, the LGS is relatively short (mostly 120 to 170 days) compared to the LGS in the high-elevation regions and coastal regions (fig. 2c).

These geographical variations of the optimal SD, HD, and LGS are primarily attributed to different responses of maize growth to the various temperature ranges within the study domain, which is subjected to spatial differences in thermal time and its accumulation. Generally, in the low-elevation regions (except the coastal regions), an early SD is beneficial due to the warm spring, and an early HD is also beneficial due to the extremely hot summer (hereafter, low-elevation warm regions). In contrast, in high-elevation regions, a late SD is preferred due to the cold spring, but a late HD is pre-

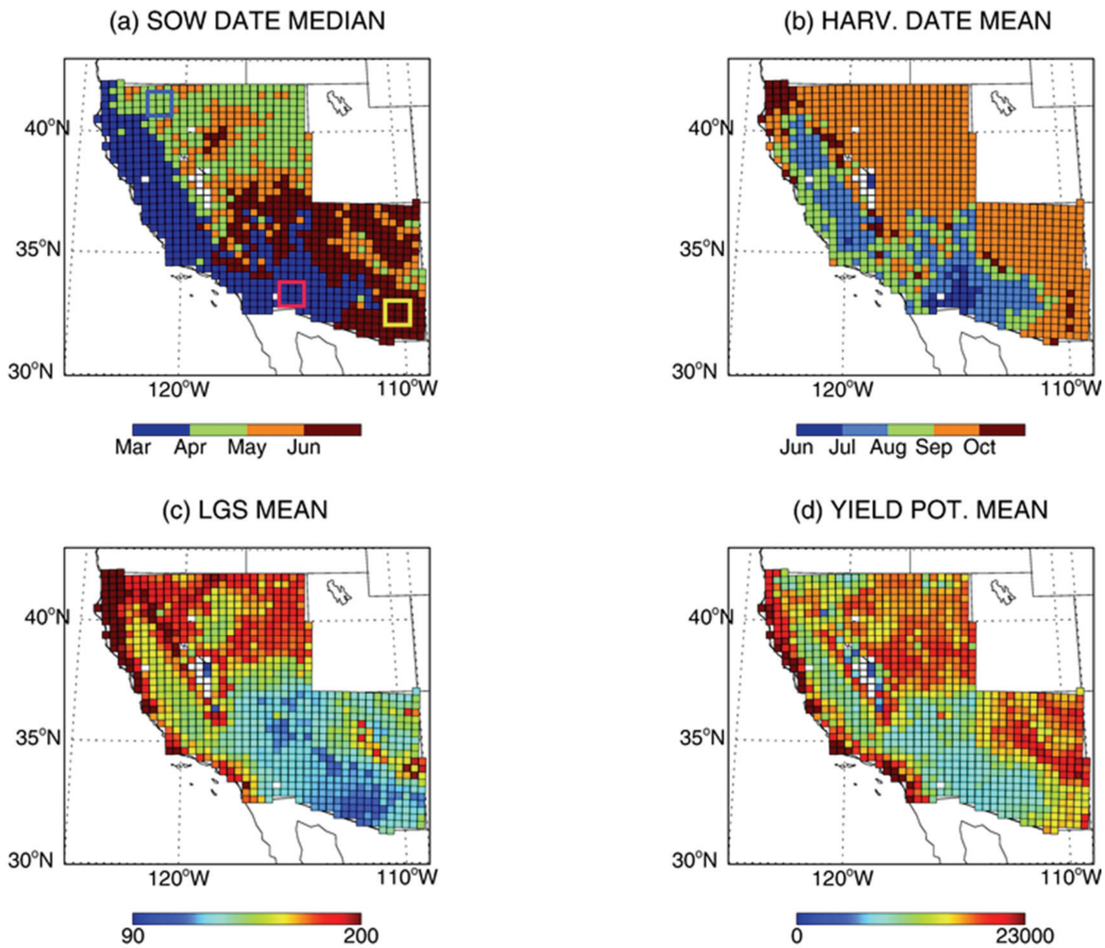

Figure 2. The 21-year medians of the annual optimal sowing date experiment (Opt1): (a) sowing date, (b) harvest date, (c) length of growing season, and (d) yield potential. Units are days in (c) and kg ha^{-1} in (d). White grid cells indicate either unsuccessful simulations or large lake areas. Three colored boxes (1.5° longitude × 1° latitude each) in (a) represent the three selected areas used in figure 3.

ferred due to the cool summer conditions, resulting in delayed maize development until serious cold events start negatively affecting the growth (hereafter, high-elevation cool regions). In the transitional regions, a late SD is optimal in order to take full advantage of the maximized thermal time in moderately hot summers for maize growth (hereafter, transitional regions).

Detailed explanations are shown in figure 3, which displays daily time series of the 21-year mean temperature and accumulated thermal time (ATT) of three selected areas indicated by 1.5° longitude × 1° latitude boxes in figure 2a. The three areas represent three distinctively different maize climate regimes: area 1 (red box) is among the low-elevation warm regions, area 2 (blue box) is among the high-elevation cool regions, and area 3 (yellow box) is among the transitional regions. Note that the time series are shown only for the 21-year average optimal growing season (i.e., from the average optimal sowing date to the average optimal harvest date) specified for each area.

As expected, for area 1 (red line in fig. 3a), maize grows through warm spring and extremely hot summer seasons ranging between 20°C and 34°C. When substantial interannual variability of T_{max} and T_{min} is considered in the area, maize is likely to experience frequent heat stress events between June and August, so an early harvest is needed to prevent permanent damage to the plants by heat stress in the middle of summer, e.g., end of July as shown in figure 2b. This speculation is supported by the high percentage of 3 h

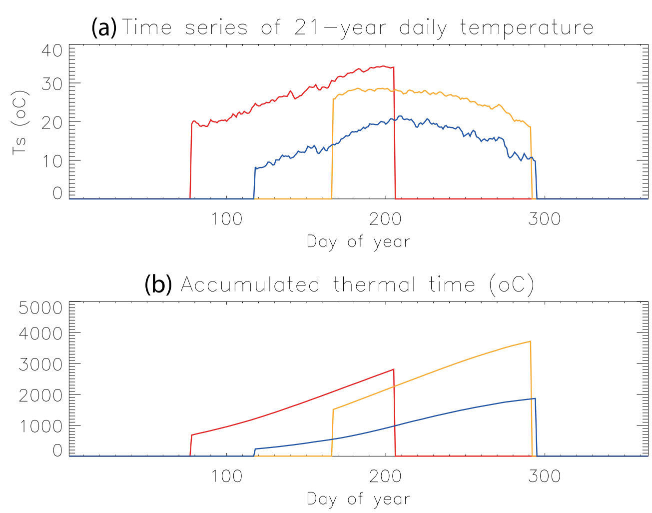

Figure 3. Daily time series of the 21-year mean (a) air temperature and (b) accumulated thermal time of three selected areas indicated in figure 2a: area 1 (red), area 2 (blue), and area 3 (yellow). The time series are shown only for the 21-year average optimal growing season (i.e., from the median optimal sowing date in fig. 2a to the median optimal harvest date in fig. 2b) specified for each area. Units are °C.

average temperatures exceeding 40°C from June to August; such periods are rare or short in the other areas (not shown). These characteristics of the local climate of area 1 appear to be responsible for the early optimal SDs and HDs.

In the high-elevation cool region, area 2 (blue line), maize grows through cold springs and cool summers ranging from 7°C to 20°C. A possible reason for the late optimal SD in April and not in March may be the negative impact of cold stress on maize growth after planting. However, maize in this area rarely experiences heat stress due to cool summer climate conditions, and instead normally requires a sufficient photoperiod and thermal time for production. This may explain why there is a longer growing season in this region than in any other region within the study domain (fig. 2c).

For area 3 (yellow line), the growing season temperature varies between 19°C and 31°C and, unlike area 2, the growing season includes the mid-summer period. In this temperature range, thermal time is maximized (fig. 1), and the prompt accumulation of thermal time in certain periods tends to result in fast development of maize for yield in a relatively short time. This is why LGS is short in the transitional regions. In area 3, the cooling trend after June may be linked with the development of NAM that typically affects southeastern AZ from July through September (Higgins et al., 1997, 1998; Kim et al., 2005; Mitchell et al., 2002; Mo and Juang, 2003). Development of NAM also implies less frequent extreme temperature events (e.g., heat waves) that can stress plants and can sometimes affect crop maturation and can cause crop failure. Owing to these summer climate characteristics, the optimal SD in area 3 is delayed to about the 145th day of a year so that plants can take advantage of the moderately hot summer climate for fast development.

The time series of ATT in the three selected areas (fig. 3b) are consistent with the descriptions above. As expected, the increasing trends of ATT in areas 1 and 3 (red and yellow lines, respectively) are much steeper than in area 2 (blue line), showing warmer conditions than area 2 in the growing season. In comparing areas 1 and 3, it is clear that the magnitude of ATT in area 3 during the growing season is much larger than in area 1 because of the later start of the growing season. Meanwhile, it is noteworthy that the ATT differences between HD and SD are similar in these three areas (about 1600°C to 2250°C), although the magnitudes of ATT on SD or HD are much more variant by geographical area. This result is consistent with the fact that completing the eleven crop stages for yield in APSIM is determined by a certain amount of accumulated thermal time. Therefore, area 2 requires a longer period for maize production than the other two areas. This feature makes Y_p sensitive to LGS in the high-elevation cool regions, including area 2, which will be described below.

Ultimately, Y_p of Opt1 (fig. 2d) also shows strong regional contrasts, with high Y_p in the high-elevation cool regions and low Y_p in the low-elevation warm regions. In general, larger (smaller) Y_p in the high-elevation cool (low-elevation warm) regions is associated with longer (shorter) LGS. This is confirmed by the statistically significant positive correlation between LGS and Y_p (r = 0.69) among the grid points of the high-elevation cool regions and low-elevation warm regions, shown in figure 4a. A high correlation is also found among the grid points of the transitional regions (r = 0.62) in figure 4b. These results highlight the positive LGS-Y_p linkages in space.

In order to further investigate the importance of LGS for Y_p, we examined the interannual relationship between LGS and Y_p at each grid point. The grid points that have one or more zero-yield years were omitted in this correlation analysis. Figure 4c shows that Y_p is strongly and positively correlated with LGS year-to-year (red colors) in most of the study domain, except the extremely hot south-central regions, such as the Sonoran Desert. This result emphasizes the interannual link between Y_p and LGS. The importance of LGS for yield has been widely reported in previous literature (Kucharik, 2006, 2008; Liu et al., 2012, 2013). Most of these studies focused on maize growth and yield in cool environments. As pointed out previously in this study and in other studies, the positive relationship is because a considerable number of warm days and photosynthetic periods are required for growth, maturity, and production of maize in cool climate regions during the growing period, so a longer growing season is beneficial for yields (Kucharik, 2006, 2008; Sacks and Kucharik, 2011). Consistent with the results of these previous studies, the results of our study indicate that, on an interannual time scale, the LGS-Y_p linkage is pronounced in cool climate regions but weak in extremely hot regions. In an effort to correlate planting date trends to maize yield trends in the Corn Belt of the central U.S., Kucharik (2008) pointed out that early planting is more beneficial for yield in the northwestern parts than in the southeastern parts of the Corn Belt, where vegetation growth is more limited by low temperature. In warm or hot climate regions, LGS is relatively short (fig. 2c) and rarely varies year-to-year because the fast accumulation of thermal time allows for quick development of maize. Therefore, variations in LGS are less important for maize growth and production in warm or hot climate regions than in cool or cold climate regions.

On the other hand, high yields are attained in the transitional regions despite a relatively short LGS (figs. 2c and 2d). Figure 4d shows the yield efficiency, which is defined as the ratio of Y_p to LGS (= Y_p/LGS) at each grid point. We did not find any specific elevation ranges linked with high yield efficiency (not shown). Rather, specific ecoregions based on U.S. Environmental Protection Agency (EPA) Level III (ftp://ftp.epa.gov/wed/ecoregions/us/Eco_Level_III_US.pdf) show that ecoregions with yield efficiency greater than 100 kg ha^{-1} d^{-1} include Central California Foothills and Coastal Mountains (ecoregion 6), Southern California/Northern Baja Coast (ecoregion 85), Central Basin and Range (ecoregion 13), Arizona/New Mexico Plateau (ecoregion 22), Arizona/New Mexico Mountains (ecoregion 23), and Madrean Archipelago (ecoregion 79). The high yield efficiency for these regions is attributed to the optimal summer climate (not too hot and not too cold) for maize growth, as described above. The coastal regions, in the same manner, have mild climate despite the low elevations, which ultimately contributes to high yield efficiency.

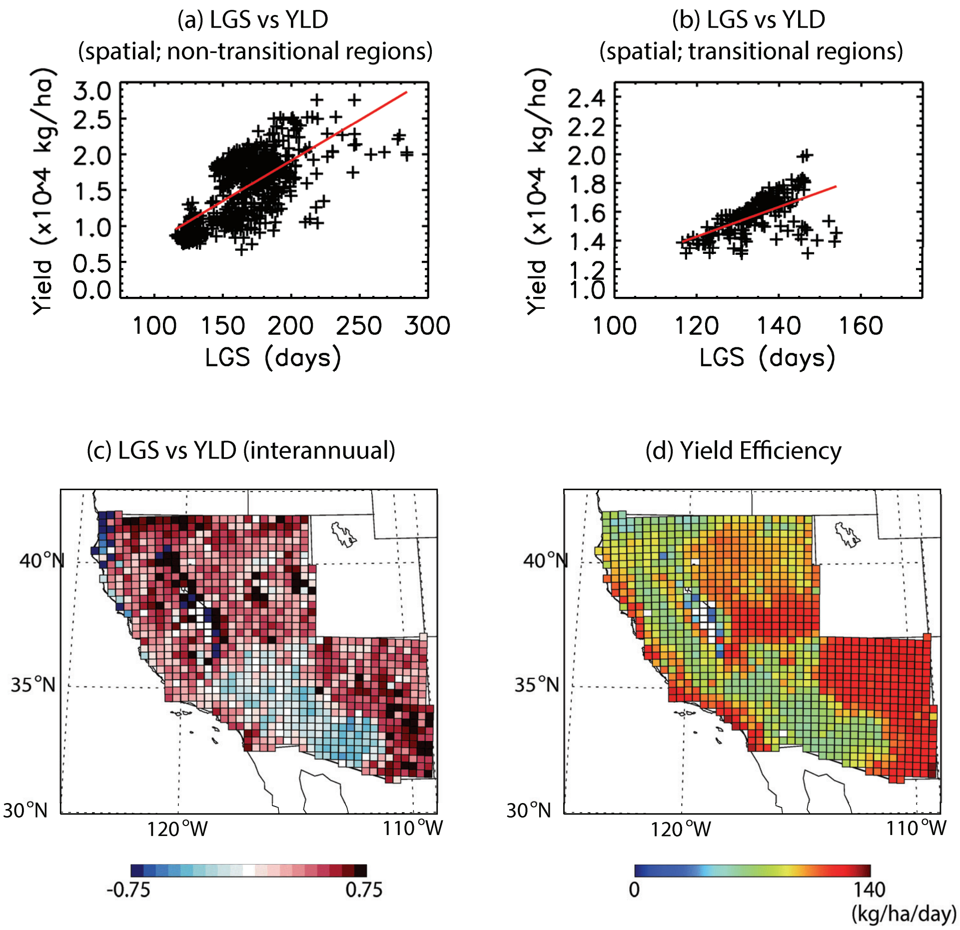

Figure 4. Scatter plot between 21-year mean length of growing season and yield potential (a) among the grids of the high-elevation cool regions and low-elevation warm regions and (b) among the grids of the transitional regions. Red lines indicate least-squares regression lines. (c) Correlation map on interannual time scales between annual length of growing season and yield potential at each grid. (d) Yield efficiency, which is defined as the ratio of yield potential to the length of the growing season (= Y_p/LGS) at each grid. Unit is kg ha^{-1} d^{-1}.

Impacts of Sowing Date Optimizations on Yield Potential

In order to examine the potential impacts of SD on Y_p, we calculated the Y_p differences between the spatial optimal sowing date experiment (Opt2) and the May 1st sowing date experiment (Fix), as shown in figure 5a, and between the annual optimal sowing date experiment (Opt1) and the spatial optimal sowing date experiment (Opt2), as shown in figure 5b. The former differences represent the effects of spatial (i.e., geographical) optimization, while the latter differences represent the effects of temporal (i.e., interannual) optimization. In figure 5a, significant Y_p increases (>100%) in Opt2 occur in most of the low-elevation warm regions and more prominently in the southern Central Valley and Sonoran De-

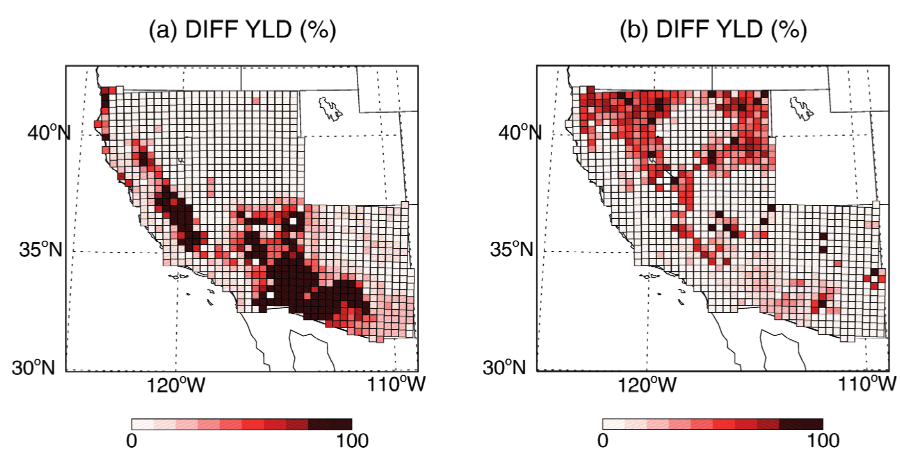

Figure 5. Yield potential differences (a) between the spatial optimal sowing date experiment and the May 1st sowing date experiment (Opt2 minus Fix) and (b) between the annual optimal sowing date experiment and the spatial optimal sowing date experiment (Opt1 minus Opt2). Units are percentage.

sert areas. Because the Y_p in these regions is greatly affected by hot summer temperatures, planting early, e.g., in March (fig. 2a) instead of in May, is crucial for high yields. Increased Y_p is also pronounced in some of the northern coastal regions. Planting on May 1 in those coastal regions would shift the harvest date to late fall (e.g., October or November), which would increase the chances of exposure to cold events, eventually diminishing Y_p.

For the differences between Opt1 and Opt2 (fig. 5b), increased Y_p is noticeable in the high-elevation cool regions. The Y_p increases typically range between 50% and 80%. These Y_p increases simultaneously occur with delayed HD (fig. 6a) and a longer growing season (fig. 6b), indicating that interannual optimization of SD enhances Y_p by increasing LGS.

When maize is planted on the same day every year (e.g., the spatial optimal sowing date), maize growth and production often seem to fail in the high-elevation cool regions. Figure 6c displays the ratio (in percentage) of "no yield" years out of the total 21 years for Opt2. The frequency of maize production failure in those regions varies from 35% to 80%, while "no yield" years are rarely found in the other regions. In the high-elevation cool regions where cold events (e.g., less than 0°C) sometimes impair maize development in early and late growing season (Kim et al., 2016), the frequency of cold events could increase in certain years and seriously damage the plants. Therefore, planting at a fixed date every year in such regions, even though the SD is spatially optimized, results in a high risk to maize production in abnormally cold springs and/or cold autumns and could result in no yield. As such, the interannual optimization of the sowing date to avoid cold events (e.g., early planting in a warm spring or late planting in a cold spring) is crucial in high-elevation cool regions for maize yield enhancement.

Figures 5 and 6 emphasize the regional differences in sowing date optimization methods. The high-elevation cool regions are more likely to experience a yield benefit from the interannual optimization of avoiding negative impacts of cold events, while the low-elevation warm regions experience a yield benefit from spatial optimization (i.e., early planting preferred) to avoid the impact of hot events. However, the mild climate regions, such as the coastal regions and transitional regions, receive little or no benefit from ei-her interannual or spatial optimization, as shown by the little increase of Y_p in figures 5a and 5b. In these regions, the base climate temperature is ideal for maize growth during the growing season, as compared to the other regions, so yields are less sensitive to sowing date variations than in the other regions.

Effect of Temperatures on Sowing Date, Harvest Date, and Yields

To explore the effects of temperature on SD and Y_p, we defined the sowing period minimum temperature (hereafter, T_{min_Sow}) as the average T_{min} for the period from -20 days to +20 days from the median SD shown in figure 2a (41 days total) at each grid point. Similarly, the harvest period T_{max} (hereafter, T_{max_Harv}) was defined as the average T_{max} for the period from -40 days to the median HD shown in figure 2b (41 days total). We then computed interannual correlation coefficients of T_{min_Sow} (T_{max_Harv}) with the annual optimal SD (HD), which are shown in figure 7a (fig. 7c). Interannual correlation coefficients of T_{min_Sow} (T_{max_Harv}) with Y_p are shown in figure 7b (fig. 7d). We chose the 41-day window because the results of different time windows (e.g., 20-day and 60-day windows) for T_{min} and T_{max} showed similar correlation patterns in space but slightly reduced magnitudes.

While negative correlations between T_{min_Sow} and the optimal SD are pervasive in the SWUS, statistically significant negative correlations are concentrated in the high-elevation cool regions, such as northern CA and northern Sierra Nevada (fig. 7a). A negative sign indicates that the optimal SD is earlier in years with warmer sowing periods. In these regions, T_{min_Sow} is strongly linked with Y_p values with positive signs (fig. 7b). Therefore, the combined results of figures 7a and 7b suggest that advanced sowing dates in warmer sowing periods enhance the yield potential by lengthening the growing season in the high-elevation cool regions. This argument is supported by positive correlations between LGS and T_{min_Sow} in these regions (not shown).

In low-elevation warm regions, the optimal SD is less sensitive to T_{min_Sow} (fig. 7a) than in high-elevation cool regions, but Y_p is positively linked with T_{min_Sow}, except in the Sonoran Desert area (fig. 7b). One possible explanation for this is that extremely cold T_{min} at night in the desert environment may adversely influence maize growth and yields, although temperature variations in the sowing period do not explicitly affect the sowing date in these regions (Kim et al.,

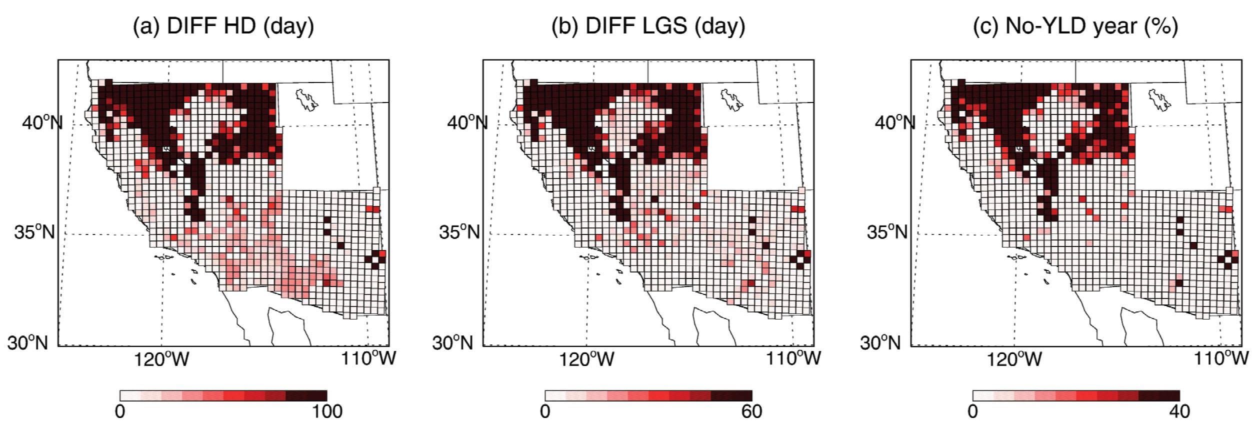

Figure 6. Differences (in days) between the annual optimal sowing date experiment (Opt1) and the spatial optimal sowing date experiment (Opt2) for (a) harvest date and (b) length of growing season. (c) The ratio (in percentage) of "no yield" years out of the total 21 years for the spatial optimal sowing date experiment (Opt2).

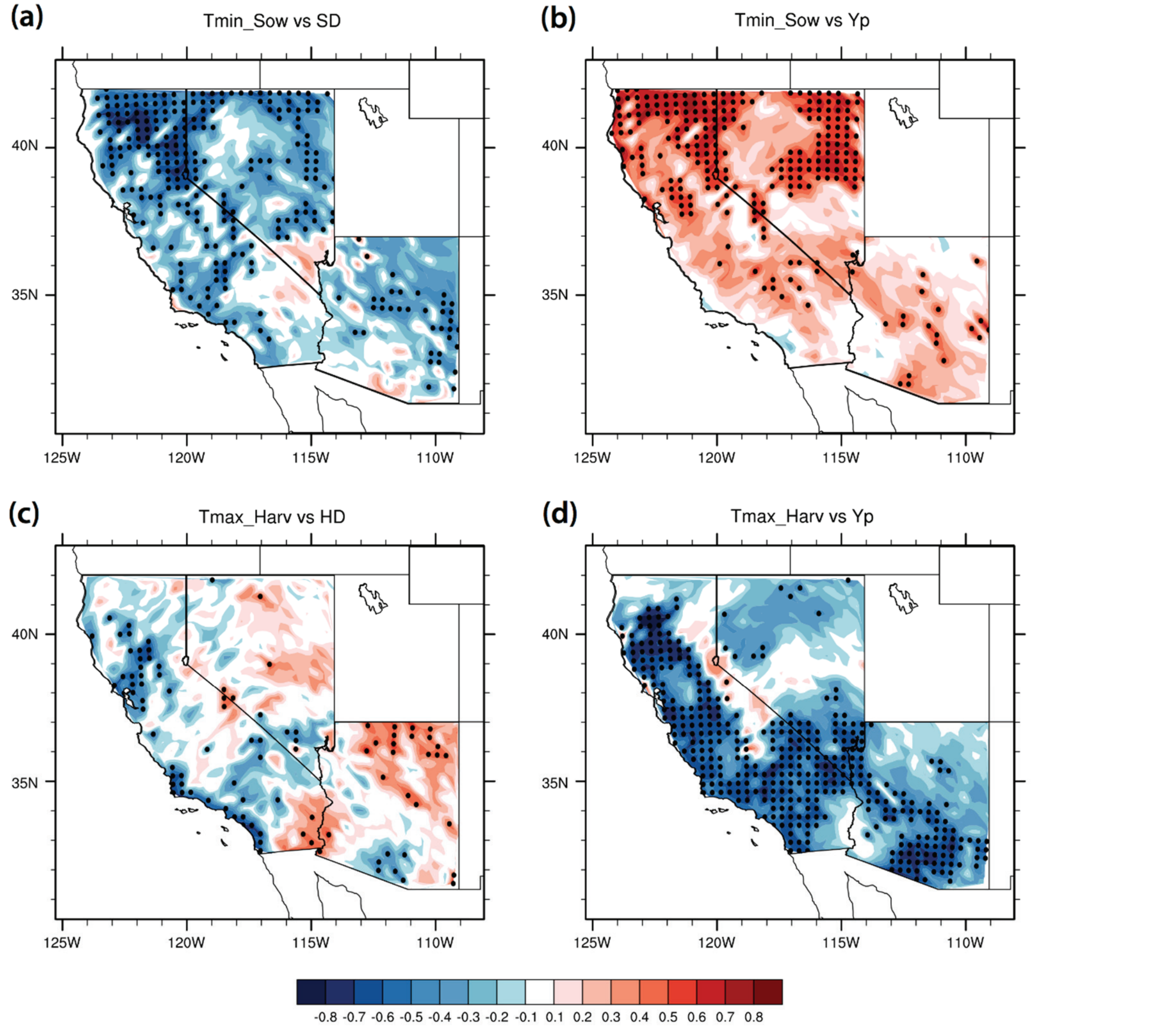

Figure 7. The 21-year interannual correlations of average minimum air temperature during the sowing period (T_{min_Sow}, see text) with (a) the annual optimal sowing date and (b) yield potential; (c) and (d) are the same correlations but of average maximum air temperature during the harvest period (T_{max_Harv}, see text) with (c) the yearly varying optimal harvest date and with (d) yield potential. Black dots indicate statistically significant correlations at the 95% confidence level.

2016). In this correlation analysis, we examined the relationship of not only T_{min} but also T_{max} in the sowing period and found that T_{min} displayed a tighter relationship than T_{max} did, implying that the minimum temperature during the sowing period is more crucial for maize development.

For the harvest period, the connection between T_{max_Harv} and the optimal HD is not pronounced in most of the study domain (fig. 7c). However, strong negative correlations of T_{max_Harv} with Y_p (fig. 7d) prevail in low-elevation warm regions, except in the Sonoran Desert. This indicates that hotter conditions during the harvest period are likely to reduce maize yield potential significantly in those regions. Because the median HD in low-elevation warm regions is in July or August (fig. 2b), this result can easily be understood with respect to the negative effect of hot summer conditions on maize yield. In contrast, the negative effect of harvest season temperature on maize yield is not obvious in most of the high-elevation cool regions and transitional regions, as shown by the small or positive correlations in figure 7d. In particular, positive correlations in the Sierra Nevada area indicate that warmer conditions during the harvest period can enhance yield potential in the coldest climate region in the study domain. These results suggest that the influences of temperature during the harvest period and Y_p differ by the timing of harvest and the corresponding climate regimes that strongly vary geographically in the study domain.

Summary and Conclusions

Using ApsimRegions crop model simulations, we tested the importance of sowing date for yield at regional scales in the SWUS by examining the 21-year median and interannual variations of sowing date, harvest date, length of growing season, and yield potential (Y_p). Furthermore, we investigated how temperature variations affect those agricultural variables and Y_p. The reasons for this study based on model simulations are, as mentioned previously, that observational datasets of sowing date, harvest dates, and yields are almost unavailable for the study region, and that model-based studies are valuable for characterizing the impacts of climate variability on agricultural products at a regional scale in current and future climate conditions (Parry et al., 2005; Rosenzweig et al., 2014). The findings of this study are unlikely to be suitable for practical applications, in particular for maize producers who are interested in the optimal planting timing. This is because the sowing date optimization method employed in this study requires accurate seasonal forecasting of temperature for the entire growing seasons, which is not possible even with state-of-art seasonal forecasting models. Another reason is that this study focused on examining impacts of local and regional climate on sowing date optimization and yield, taking the impacts of future climate changes into consideration. As this study was initially designed to improve our understanding of the sensitivity of maize yield to planting date in various climate regimes, the effects of weather, soil, and environmental conditions during planting seasons on Y_p may serve as a topic for future research.

There were distinct differences in the characteristics of maize development subjected to local temperature regimes associated with geographical variations (e.g., hot deserts, cold mountain areas, and cool coastal areas) and atmospheric circulations (e.g., NAM):

- In cool climate regions at high elevation in CA and NV and at low elevation along the southwest coast, sowing date has an important effect on Y_p through the change in the length of the growing season. In these regions, the growing season is generally long, greater than 180 days (fig. 2c). A longer growing season is more optimal for high production because it induces a higher chance for photosynthesis and grain filling processes (Otegui et al., 1995; Kucharik, 2008; Liu et al., 2013). Therefore, early planting in a warmer spring extends the length of the growing season, thereby increasing Y_p.
- In low-elevation warm southern regions in CA and AZ, including the south Central Valley, the major maize cultivation areas in the SWUS, Y_p is less likely to be affected by sowing date and length of growing season. Climatologically, while growing seasons are relatively short (less than 130 days due to the warm climate) in these regions (fig. 2c), low temperature and/or a low photoperiod are not critical limiting factors for maize development. Rather, since extremely hot summer conditions (around the harvest period) can have negative impacts on plants and yields, early planting and early harvesting are preferred for producing high yields.
- In the transitional regions between the cool climate regions and warm climate regions, relatively high Y_p values are easily attained due to the optimal temperature ranges for maize growth. The optimal sowing dates are the latest for the study domain, in May or June (fig. 2a), because maize growth is intensified in the moderately hot summer, which results in yield potential being less sensitive to sowing date. Due to these climate characteristics, high yields can be accomplished in a relatively short period in these regions, resulting in high yield efficiency (fig. 4d).

The comparison of the simulation results with various sowing dates showed that appropriate adaptation strategies for regional sowing dates can significantly enhance maize yield (fig. 5). In particular, in the low-elevation warm regions, the spatial optimization (i.e., early planting in March) is favored for high Y_p to avoid the adverse effects of hot summer temperatures, but the interannual optimization does not contribute as much as the spatial optimization to Y_p increases. On the other hand, interannual optimization tends to enhance maize Y_p in the high-elevation cool regions, where cold events in early spring frequently cause yield failure in some years. In the transitional regions, sowing date optimizations showed the least effect on Y_p.

The application of the ApsimRegions model in this study has expanded our understanding of the impacts of sowing date optimization on Y_p in the SWUS. We found that the characteristics of maize development with respect to sowing date, length of a growing season, and responses to extreme temperature events vary by region, depending on the local or regional base climate conditions and temperature variability. The spatial contrast of the LGS-Y_p relationship between cool climate regions and hot climate regions also reveals different maize growth mechanisms with varied temperature regimes. Thus, proper selection of sowing date according to local climate by region can result in significant increases in maize yield. This information is considered to be timely and useful for agricultural practitioners, especially with regard to future regional climate change associated with global climate change and its impacts on agriculture.

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