U.S. DEPARTMENT OF ENERGY | Office of Science

DOE/SC-CM-17-001

FY 2017 Second Quarter Performance Metric: Develop and Implement Global Crop-Planting Date Triggers for the ACME Model

March 2017

DISCLAIMER

This report was prepared as an account of work sponsored by the U.S. Government. Neither the United States nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

Contents

1.0 Product Definition 1
2.0 Product Documentation 1
3.0 Detailed Report 1
4.0 Results and Discussion 5
5.0 References 9

Figures

Figure 1. Top: Distribution of crops in ALM. Bottom: Global distribution of crops circa 2000 based on Ramankutty et al. (2008). 2
Figure 2. Decision tree for seasonality determination. 3
Figure 3. Four month sum of P:PET ratio. 4
Figure 4. Seasonality map. 5
Figure 5. Month of planting for maize (top), soybean, (middle) and spring wheat (bottom). 6
Figure 6. Left: Difference in plant day between ALM and the Crop Calendar Data set. Right: Difference in plant month between ALM and MIRCA2000 data set. 7
Figure 7. Standard deviation of plant day (days) for maize (top) and soybean (bottom). 8
Figure 8. Left: Earliest plant month in ALM using new planting date calculator. Right: Latest plant month using new planting date calculator. 8

Tables

Table 1. Temperature threshold to trigger planting date. 4

1.0 Product Definition

Climate and weather conditions are among the key drivers of crop suitability and productivity in a region. The influence of climate and weather on the growing season determine the amount of time crops spend in each growth phase, which in turn impacts productivity and, more importantly, yields. Precipitation and temperature are responsible for 30% of the variability in crop yields (Lobell and Field, 2007). Planting date can also have a strong influence on yields (Deryng et al., 2011; Drewniak et al., 2013; Waongo et al., 2015), with earlier planting generally resulting in higher yields (Choi et al., 2017). Crop models are sensitive to planting date: for example, early planting results in higher yield for soybean crops because cooler spring temperatures slow crop development and allow an extended growing season (Drewniak et al., 2013). Furthermore, planting date is changing. Maize planting date in the Midwest U.S. is now two weeks earlier than just a few decades ago (Kucharik, 2006), which has resulted in a 19-53% increase in yields across many U.S. states (Kucharik, 2008). Although this trend is the result of improved genotypes (Kucharik, 2006) rather than early spring warming, longer growing seasons caused by future climate change could also drive early planting decisions. The Accelerated Climate Model for Energy (ACME) Land Model (ALM) does include temperature thresholds to define crop planting dates, but the application is limited to mid-latitudes. A more robust metric that includes other climate factors (i.e., precipitation) is added to improve the predicted timing of crop planting and will also allow global crop production.

2.0 Product Documentation

Crop models need an accurate method to predict plant date to allow these models to: 1) capture changes in crop management to adapt to climate change, 2) accurately model the timing of crop phenology, and 3) improve crop simulated influences on carbon, nutrient, energy, and water cycles. Climate plays a strong role governing planting date (Choi et al., 2017). Previous studies have used climate as a predictor for planting date (Deryng et al., 2011; Waha et al., 2012; Waongo et al., 2014), although other factors besides climate influence a farmer's decision to plant (e.g. workability, economics, culture) (Iizumi and Ramankutty, 2014). Climate as a plant date predictor has more advantages than the use of fixed plant dates. For example, crop expansion and other changes in land use due to changing temperature conditions, new drought or cold tolerant crop hybrids and cultivars, and increased food demands can be accommodated without additional inputs. As such, a new methodology to implement predictive planting date based on climate inputs is added to the Accelerated Climate Model for Energy (ACME) Land Model (ALM). The model considers two main sources of climate data important for planting: precipitation and temperature. The new ALM model is compared with observations to test its ability to capture planting dates globally.

3.0 Detailed Report

The Accelerated Climate Model for Energy (ACME) is a fully coupled Earth System Model (ESM) developed by the U.S. Department of Energy (DOE) to simulate the atmosphere, ocean, and land. ACME shares lineage with the Community Earth System Model (CESM) v1.2, and thus the ACME Land Model (ALM) v0 is based on the Community Land Model (CLM4.5). The crop model in ALM (Levis et al., 2012) consists of three crop types: maize, soybean, and spring wheat. Crop phenology and allocation

dynamics depend on thermal degree-days that determine the growth phase of each crop. ALM v1 has fertilizer, retranslocation, soybean nitrogen fixation, dynamic roots, grain harvest, and yields from Drewniak et al. (2013). Crops are grown in separate soil columns from natural vegetation and each other to avoid competition for resources that are available to crops from management (i.e., fertilizer and irrigation). Plant date in ALM is determined by temperature thresholds. This has an undesired effect of restricting crops to temperate latitudes (between 30°N and 30°S) because temperature thresholds are not appropriate for use in tropical zones. This limits the area where crops are grown to a much smaller region than observed (Figure 1). Tropical regions typically have temperature ranges that can support crop production year-round; however, the growing season in many areas of the tropics and sub-tropics is limited by water availability. In these regions, precipitation should be considered when establishing planting date. Therefore, a new scheme that takes into account temperature and precipitation seasonality is applied to determine plant date. The more robust plant date in ALM meets two requirements: 1) the planting trigger functions globally, and 2) the plant date can change over time.

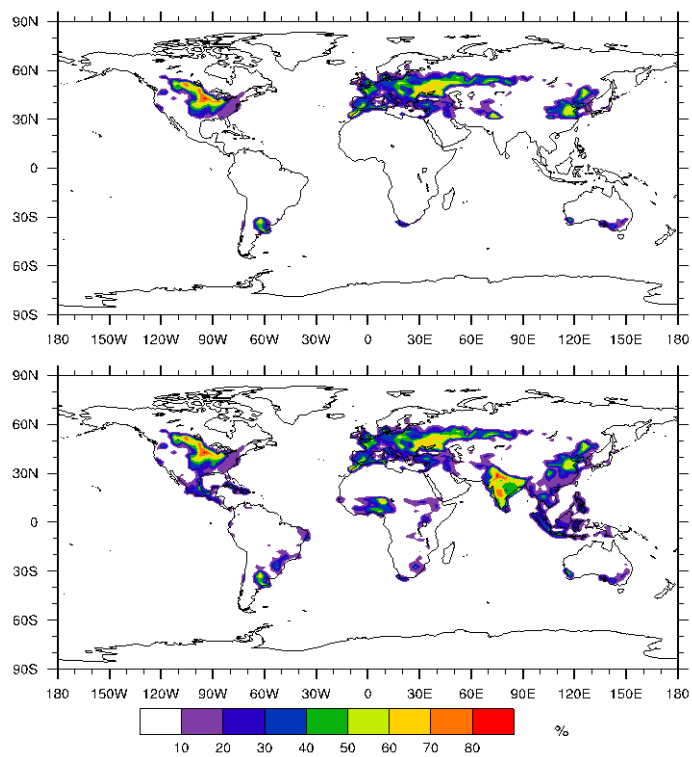


Figure 1. Top: Distribution of crops in ALM. Bottom: Global distribution of crops circa 2000 based on Ramankutty et al. (2008).

The new planting algorithm is calculated in three parts: 1) establish the type of climate seasonality that exists in a grid cell, 2) determine a plant month based on that seasonality (i.e., warm season or wet season), and 3) determine the plant day (i.e., temperature or precipitation thresholds). The type of seasonality of a region can be determined by monthly coefficients of variation (CV) of temperature and precipitation (Waha et al., 2012). The CV is calculated for each year (*j*) by:

$$CV_j = \frac{\sigma_j}{\mu_j} \qquad \text{Eq. 1}$$

where the standard deviation (σ) of temperature or precipitation and the annual mean temperature or precipitation (μ) of year j are determined by:

$$\sigma_j = \sqrt{\frac{1}{12-1} \times \sum_{m=1}^{12} \left(\overline{X}_{m,j} - \mu_j\right)^2} \qquad \text{Eq. 2}$$

$$\mu_j = \frac{1}{12} \times \sum_{m=1}^{12} \overline{X}_{m,j} \qquad \text{Eq. 3}$$

$\overline{X}_{m,j}$ is the exponential weighted moving average (ewma) temperature or precipitation of month m in year j with a weighting decrease (α) of 0.05.

$$\overline{X}_{m,j} = \alpha \times X_{m,j} + (1-\alpha) \times \overline{X}_{m,j-1} \qquad \text{Eq. 4}$$

The ewma captures past climate in order to account for farmer experiences, but gives more importance to recent experiences and less weight to past years. Precipitation seasonality occurs when the CV of precipitation is above 0.4 (Waha et al, 2012); temperature seasonality occurs when CV of temperature is at or above 0.01. The final seasonality determination for a given region can be determined using the decision tree shown in Figure 2. Some regions have both temperature and precipitation seasonality. In these cases, the presence of a cold season is the deciding factor for seasonality classification used to trigger planting. A cold season occurs if the average temperature of the coldest month is less than 10°C. In regions with a cold season, the grid cell is classified as having temperature seasonality; otherwise the grid cell has precipitation seasonality. The seasonality map is updated annually.

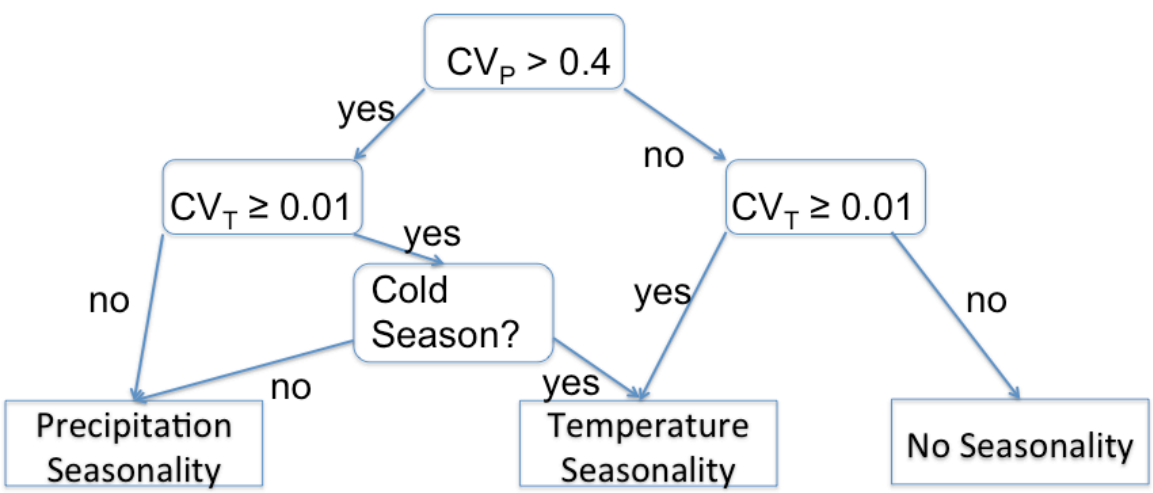


Figure 2. Decision tree for seasonality determination.

In regions with temperature seasonality, the month of planting is determined when the average monthly temperatures are above the thresholds listed in Table 1, column 2. The day of planting occurs

when the 10-day average temperature and the 10-day minimum average temperature are above the thresholds listed in Table 1, column 2 and 3, respectively. In areas with precipitation seasonality, the month of planting is determined by the largest ratio of precipitation to potential evapotranspiration (PET; see Figure 3), summed over 4 months. PET is calculated with the Penman-Monteith method (Monteith, 1965). Plant day is the first day of rain above 0.1 mm on the first month of the wet season. Areas that do not have temperature or precipitation seasonality are assigned a plant date of January 1.

Table 1. Temperature threshold to trigger planting date. Base temperature is the minimum daily temperature for a crop to grow. Planting date is triggered when the average monthly temperature is above the average temperature to trigger planting (from Waha et al., 2012) and the monthly average minimum temperature is above the minimum temperature for growth.

Crop	Base temperature for growth (°C)	Average temperature to trigger planting (°C) (Waha et al., 2012)	Minimum temperature for growth (°C)
Corn	8	14	6
S. Wheat	0	5	0
Soybean	10	13	6

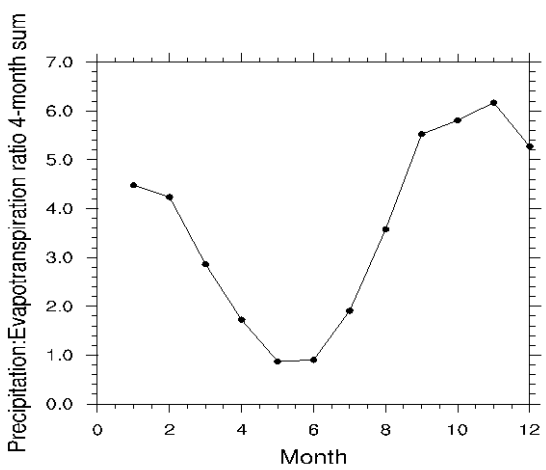


Figure 3. Four-month sum of P:PET ratio. In this grid cell example, planting would occur in November.

The new plant date methodology in ALM functions globally, allows the plant date to evolve with changes in local climate, and easily accommodates changes in land use because potential plant dates can be calculated in grid cells where crops are currently not grown, thereby requiring no additional external inputs.

4.0 Results and Discussion

The new plant date scheme is tested with the three crops growing in CLM: corn, soybean, and spring wheat. The model is run offline for 20 years (from 1972-1991) using atmospheric data forcing from Qian et al., (2006). The generated seasonality map is shown in Figure 4. Results are consistent with Waha et al. (2012); most temperate regions are classified as temperature seasonal and tropical regions are mostly precipitation seasonal. Some regions in the Amazon, Central Africa, and Indonesia do not have seasonality. Western U.S. and large parts of Europe and Asia have both temperature and precipitation seasonality, but have a cold season. Parts of the subtropics also have both temperature and precipitation seasonality, but are classified as precipitation seasonal because they do not have a cold season.

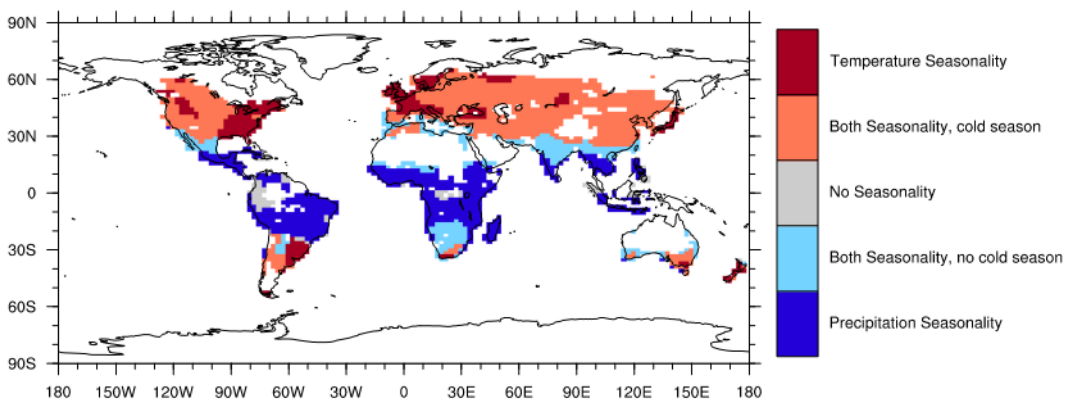
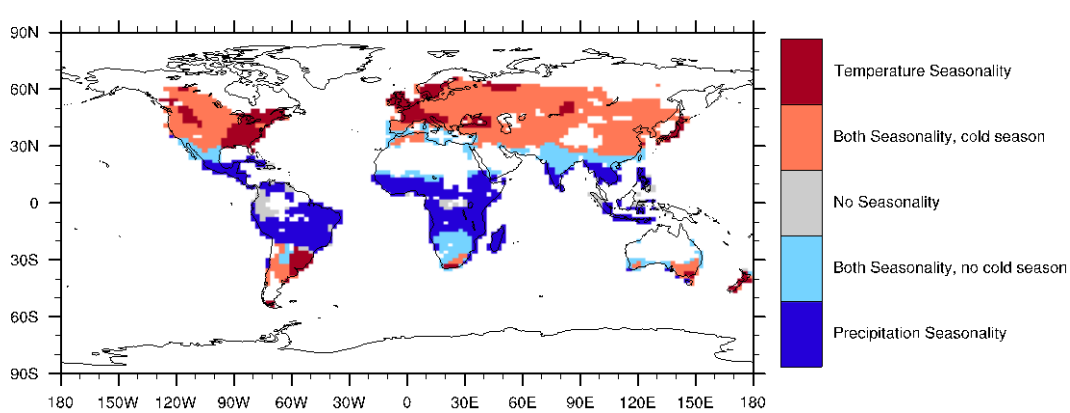


Figure 4. Seasonality map.

The ALM-predicted plant month is shown in Figure 5. In general, for temperature seasonality-dominated areas, planting occurs during the spring. For the northern mid-latitudes, this is usually in April or May, and in the southern mid-latitudes planting occurs in October or November. In the tropics, where precipitation seasonality dictates planting, crops are planted during June in the Northern Hemisphere. In the Southern Hemisphere tropics, crops are planted starting in autumn for regions in South America and Africa, but can be as late as January or February.



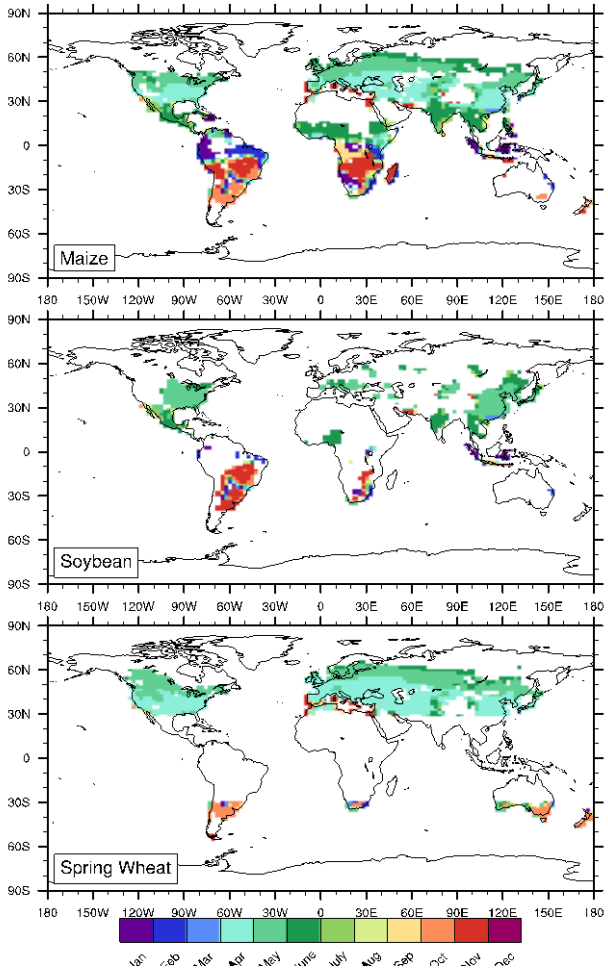


Figure 5. Month of planting for maize (top), soybean (middle), and spring wheat (bottom).

Global estimates of plant dates are generally consistent with observations (Figure 6). ALM planting dates in the U.S. are earlier than the Crop Calendar Data set, but later than the MIRCA2000 data, although these differences are small and generally less than a month. In some regions, the observational data sets differ in plant date, and ALM tends to predict in the middle of the observations (e.g., U.S., parts of Europe and Asia, and South America for maize, and in the U.S. and South America for soybean). Spring wheat is the exception since spring wheat is only differentiated in the Crop Calendar Data set and not in the MIRCA2000 data (which includes both spring and winter wheat).

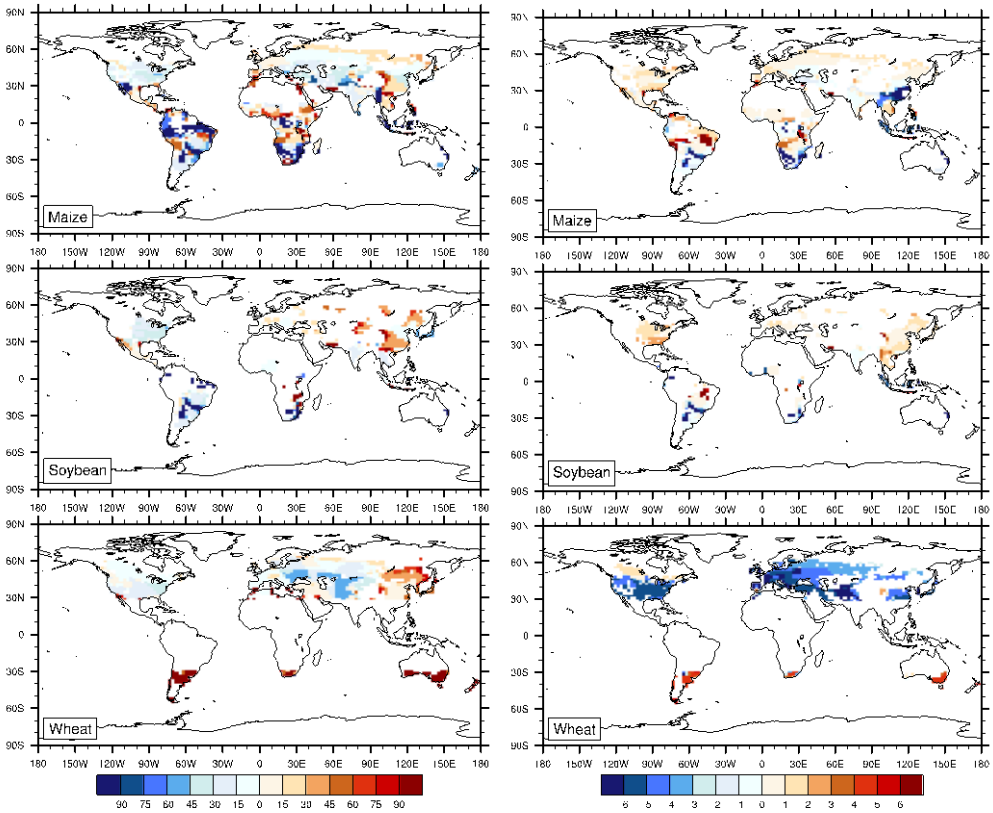


Figure 6. Left: Difference in plant day between ALM and the Crop Calendar Data set (Sacks et al., 2010). Right: Difference in plant month between ALM and MIRCA2000 data set (Portman et al., 2008).

Figure 7 shows the standard deviation of plant day in days for maize and soybean. ALM tends to plant on the first day of the month. In regions with temperature seasonality, this is because the month of planting is defined with the same temperature threshold (Table 1) as the average daily 10-day temperature requirement, so the temperature threshold is generally already met on the first day of the month. For precipitation seasonality, this is likely the result of a bias toward drizzle in the model. However, variability in plant date can range from a week to several months. The largest variability in plant date occurs in grid cells that may shift between two different seasonalities. The earliest and latest plant month is shown in Figure 8. The largest differences between plant date occur along transition gradients between temperature and precipitation seasonalities (southern U.S., Europe, South America, and South Africa).

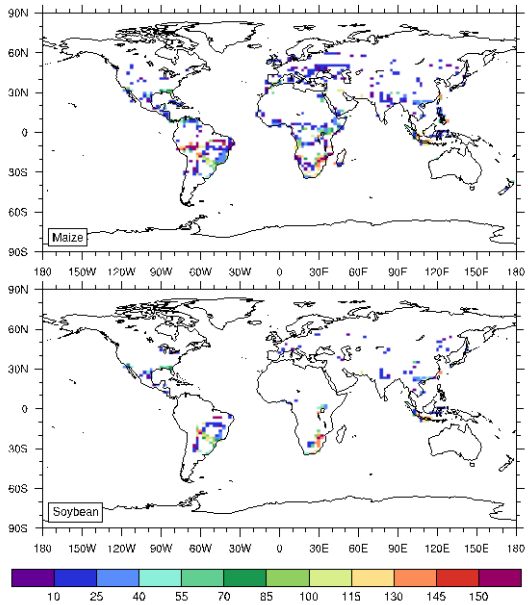


Figure 7. Standard deviation of plant day (days) for maize (top) and soybean (bottom).

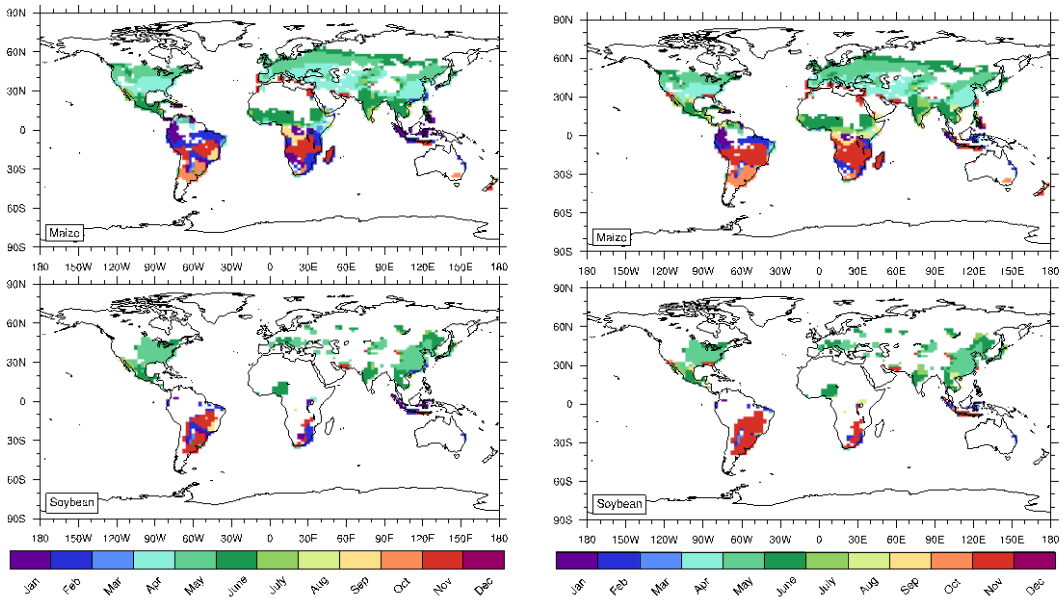


Figure 8. Left: Earliest plant month in ALM using new planting date calculator. Right: Latest plant month using new planting date calculator.

The new plant date methodology in the ALM crop model predicts planting date based on climate metrics of temperature and precipitation. The scheme compares well with observations. In addition to providing a more robust planting method that can evolve with changes in local and regional climate, the new plant date scheme allows crops to expand away from the temperate zones, to be modeled globally. Furthermore, because the method requires no additional inputs, adding new cropland to grid cells is a straightforward task. The next steps for this work are to look at the response in yield and growing season from this new development and explore how future climate will influence changes in plant date.

5.0 References

Deryng, D, WJ Sacks, CC Barford, and N Ramankutty. 2011. "Simulating the effects of climate and agriculture management practices on global crop yield." *Global Biogeochemical Cycles* 25, doi:10.1029/2009GB003765.

Drewniak, BA, J Song, J Prell, VR Kotamarthi, and R Jacob. 2013. "Modeling agriculture in the Community Land Model." *Geoscientific Model Development* 6: 495-515.

Iizumi, T, and N Ramankutty. 2015. "How do weather and climate influence cropping area and intensity?" *Global Food Security* 4: 46-50.

Kucharik, CJ. 2006. "A multidecadal trend of earlier corn planting in the central USA." *Agronomy Journal* 98: 1544-1550.

Kucharik, CJ. 2008. "Contribution of plant date trends to increased maize yields in the Central United States." *Agronomy Journal* 100(2): 328-336.

Levis, S, GB Bonan, E Kluzek, PE Thornton, A Jones, WJ Sacks, and CJ Kucharik. 2012. "Interactive Crop Management in the Community Earth System Model (CESM1): seasonal influences on land-atmosphere fluxes." *Journal of Climate* 25, doi:10.1175/JCLI-D-11-00446.1.

Lobell, DB, and CB Field. 2007. "Global scale climate-crop yield relationships and the impacts of recent warming." *Environmental Research Letters* 2, doi:10.1088/1748-9326/2/1/014002.

Monteith, JL. 1965. Evaporation and the environment. In the movement of water in living organisms, *XIXth Symposium. Society for Experimental Biology*, Swansea, Cambridge University Press, 205-234.

Portman,FT, S Siebert, and P Doll. 2010. "MIRCA2000-Global monthly irrigated and rainfed crop areas around the year 2000: a new high-resolution data set for agricultural and hydrological modeling." *Global Biogeochemical Cycles* 24: GB1011.

Qian, T, A Dai, KE Trenberth, and KW Oleson. 2006. "Simulation of global land surface conditions from 1948 to 2004. Part 1: Forcing data and evaluations." *Journal of Hydrometeorology* 7: 953-975.

Ramankutty, N, A Evan, C Monfreda, and JA Foley. 2008, "Farming the planet. Part 1: The geographic distribution of global agricultural lands in the year 2000." *Global Biogeochemical Cycles* 22, doi:10.1029/2007GB002952.

Sacks, WJ, D Deryng, JA Foley, and R Ramankutty. 2010. "Crop planting dates: an analysis of global patterns." *Global Ecology and Biogeography* 19: 607-620.

Waha, K, LGJ van Bussel, C Müller, and A Bondeau. 2012. "Climate-driven simulation of global crop sowing dates." *Global Ecology and Biogeography* 12(2): 247-259.

Waongo, M, P Laux, SB Traoré, M Sanon, and H Kunstmann. 2014. "A crop model and fuzzy rule based approach for optimizing maize planting dates in Burkina Faso, West Africa." *Journal of Applied Meteorology and Climatology* 53: 598-613.

Waongo, M, P Laux, and H Kunstmann. 2015. "Adaptation to climate change: The impacts of optimized planting dates on attainable maize yields under rainfed conditions in Burkina Faso." *Agricultural and Forest Meteorology* 205: 23-39.

U.S. DEPARTMENT OF
ENERGY

Office of Science