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Evolution of rain and photoperiod limitations on the soybean growing season in Brazil: The rise (and possible fall) of double-cropping systems

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ABSTRACT

Over the course of a few decades, soybeans in Brazil evolved from being a localized crop, with planting suitable only in regions with long photoperiods, to being the most cultivated crop countrywide. This happened thanks to the development of varieties that allowed changes in the planting calendar, permitting both cultivation in lower latitudes and the adoption of modern double-cropping systems. Here we develop a spatial dataset of Brazilian soy planting-window estimates for rainfed single and double cropping as a function of time during the period 1974–2012 by combining estimates of two important historical limitations: photoperiod and duration and timing of the rainy season. We apply the same methods to future climate estimates to investigate a possible contraction in the area of double cropping due to changes in the rainy season with global change. The resulting dataset agrees with time-invariant official agricultural zoning and optimal yield experiments and provides unprecedented spatial and temporal information on the soy growing season in Brazil. Analysis of the evolution of planting limitations shows that the relaxation of photoperiod limitations gradually made double cropping possible in central–northern Brazil in the 1980s by lengthening the planting window and allowing farmers to make use of a larger portion of the rainy season. Due to these developments, there were 20 Mha potentially suitable for double cropping in 2012, and this potential has been increasingly exploited. Under the constraints of current widely used crop varieties, we predict that climate change poses a severe threat to this potential, causing area reductions of ~17% in central Brazil and 61% in the MATOPIBA region, known as the world's newest agricultural frontier.

1. Introduction

The timing of agricultural management is a determinant factor of agricultural production. Planting dates influence the environmental conditions that crops are subject to, and planting multiple times in a year can drastically change total output (Ray and Foley, 2013). Crop management information is therefore very important for large-scale assessments that depend on crop–climate relationships, such as crop modeling studies (Jones et al., 2016). Although several efforts have been made to compile data on common planting and harvesting dates (Sacks et al., 2010; Portmann et al., 2010), such management practices are known to vary considerably over time due to climatic, socio-economic and technological factors (Kucharik, 2006; Sacks et al., 2010; Ray et al., 2015). Estimating management practices such as planting windows and cropping frequency based on their relationships to climate can be a useful approach (e.g. Stehfest et al., 2007; Waha et al., 2012), but these relationships also change as new technologies present farmers new management options.

A clear example where these relationships have changed over time due to technology is the Brazilian soybean. Brazil produced over 30% of the world's soybeans in 2016, and was the second largest producer (CONAB, 2016; USDA, 2017). The planted area totaled 30 Mha that year, spanning latitudes from 30°S to 2°S. However, until the 1970s most of Brazil's land was deemed unsuitable for soybean cultivation, since early varieties were limited by their sensitivity to short photoperiods.

The soybean (*Glycine max* L. Merr.) flowers earlier when days are shorter. With soybean varieties available before the 1970–80s, flowering occurred much too soon in latitudes below 15°S, where the maximum photoperiod is less than 12.9 h, and the short vegetative period led to short plants and very low yields (Carpentieri-Pípolo et al., 2002, more detailed explanation in Section 2.2.1). This characteristic effectively hindered cultivation of those varieties in low latitudes, and the crop was limited to the southern, extratropical parts of Brazil (Destro, 2001).

During the 1960s, several factors favored an expansion in soybean

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cultivation towards central Brazil (latitudes in the range of 10°S–20°S), including rising world soybean prices, low land prices and government incentives for infrastructure (Gavioli, 2013). The acid soils, pest conditions and, most importantly, short photoperiods were challenges to the varieties of that time. But the region also had several attractive conditions, especially a stable rainy season and vast expanses of flat soil suitable for mechanized agriculture (Spehar, 1994; Almeida et al., 1999; Schnepf et al., 2001).

These advantages favored the development of varieties adapted to that region. The first significant research developments in soybean breeding started in the late 1960s at universities and public research institutions, where several photoperiod-tolerant but low-yielding varieties were developed. In the 1970s, the Brazilian government invested heavily in agricultural research. Embrapa (Empresa Brasileira de Pesquisa Agropecuária), currently the largest Brazilian government agricultural research and development agency, was created in 1973, and a branch with the specific goal of developing tropical soybeans started operating in 1975 (Pessôa and Bonelli, 1997). Embrapa and several other research institutions, especially universities, cooperated towards the goal of creating soybean varieties and systems adapted to the conditions of central Brazil while increasing the productivity of the crop (Almeida et al. 1999; Santos et al., 2016).

This effort led, in the beginning of the 1980s, to the release of varieties that were both combine-harvestable and relatively productive under the relatively short days of central Brazil. The possibility of planting in that vast region, where land was cheaper, created a continuous demand for better-adapted varieties (Viana et al., 2013). Later work produced varieties even less sensitive to photoperiod and improved yields under different environmental conditions (Spehar, 1994; Gavioli, 2013). These developments also had the effect of "flexibilizing" planting dates; that is, the new varieties allowed for more flexible planting dates as compared to older varieties. These developments eventually led to irrigated winter soybeans being cultivated in some northern states (Carpentieri-Pípolo et al., 2002). In addition, breeding work that focused on the dependence of crop cycle length on temperature and photoperiod produced varieties with a wide range of cycle length options under different environments (Alliprandini et al., 2009; Cavassim et al., 2013).

These combined factors eventually allowed farmers to plant multiple crops in a single year, leading to the modern prevalence of double-cropping systems (Correa and Schmidt, 2014). Planting a second crop such as maize or cotton after soybeans in the same field, the so-called *safrinha* crop, increases the profitability of land and is associated with higher economic development in Brazil (Arvor et al., 2012; VanWey et al., 2013). These systems are dependent on a rainy season that is long enough to accommodate both crop cycles. To make maximum use of the rainy season, farmers tend to plant the soybeans as early as possible. Although this leads to suboptimal yield from the soybean crop, the profits of the second crop and the higher prices that can be achieved by harvesting earlier can render double cropping an attractive option for farmers (Flaskerud and Johnson, 2000; Borchers et al., 2014).

Soybean planting and harvesting dates are a complex function of time because of the particularities of the relationship between climate and planting dates for double-cropping systems, the great improvements to photoperiod limitations, the interaction between the rainy season timing and the photoperiod, and the interannual variation of the rainy season. This is especially true as double-cropping systems, which were uncommon in the 1990s, became increasingly common over time, such that now 58% of all Brazilian maize is produced as a second crop. Most modeling studies oversimplify this complexity by not considering double-cropping systems and using either a planting date fixed in time and space (e.g. Oliveira et al., 2013), time-invariant maps of global planting dates (e.g. Ray et al., 2015) or date optimization schemes for single-cropping systems (e.g. Rosenzweig et al., 2014).

Here we develop a dataset of estimated planting and harvesting windows for single and double cropping as a function of time during the period 1974–2012. First, we estimate the photoperiod limitations of soybean varieties planted in Brazil in each year based on the spatial distribution of soybean harvested area. Then, combining this information with gridded precipitation data, we derive yearly estimates of the soybean planting window on a 1° × 1° grid for both single- and double-cropping systems. Although available observational data does not allow proper validation that photoperiod and rainy season duration and timing are the most important limiting factors, the resulting dataset compares well with available countrywide planting-date assessments and recommendations. This dataset provides insight into the influence of technological improvements on planting limitations, and the role of those technological improvements in the rise of double-cropping systems. The dataset can also be used as input data for crop models. We also apply the same methods to outputs from Earth System Models (ESMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al., 2012) to assess the possible impacts of future climate change on soybean double cropping in Brazil.

2. Data and methods

2.1. Gridded soybean area dataset

A Brazil-wide, spatially explicit dataset of soybean harvested area (km^2) in a 1 km × 1 km grid was developed using a methodology similar to the one used by Dias et al. (2016), which used the Global Forest Cover (GFC) dataset for tree cover (Hansen et al., 2013) to perform a spatial disaggregation of Brazilian census data for land use from 1940 to 2012, including harvested areas and yields of soybeans. The version used here has minor modifications with respect to data periods and applies less filtering to ensure pixel by pixel consistency across years for locations where census tracts changed. It covers the study period beginning at the 1974 harvest and ending at the 2012 harvest. Before 1974, census data were not available every year. A more detailed description of the dataset's development can be found in Appendix A.

2.2. Planting limitations

Soybean planting suitability varies with many environmental factors, such as total solar radiation, in-season precipitation, temperatures and complex genotype–environment interactions (Hu and Wiatrak, 2012; Junior et al., 2017), in addition to economic factors such as soybean prices and farmers' propensity to take risks (Boyer et al., 2015). Here we assume that these factors influence the planting decision only inside a broad planting window defined by (i) the rainy season, which is a large-scale limiting factor for planting in Brazil (Waha et al., 2012), especially for double-cropping systems (Spangler et al., 2017); and (ii) photoperiod, which influences plant development and was a strong constraint on expansion of Brazilian soybean agriculture in its earlier years (Spehar, 1994). Frost is only indirectly considered, as the methodology for the photoperiod limitations imposed does not allow planting of the first crop in the winter, and possible effects on the second crop during its final development stages were not considered. All parameters were chosen to be conservative in the sense that they should give the broadest estimates of the planting window at each location. We also considered limitations created by the appropriate phytosanitary legislation enacted in the periods and regions where they were in effect.

2.2.1. Photoperiod limitations

The development cycle of the soybean plant can be divided into two periods: vegetative and reproductive. During the vegetative period, the plant grows in mass and height, allocating the products of photosynthesis to roots, stems and leaves. The first flowers mark the beginning of the reproductive period, when products of photosynthesis are mostly (exclusively, in some varieties) allocated to the reproductive organs. While actual grain filling happens in the reproductive period,