GABRIEL MEDEIROS ABRAHÃO

SOYBEAN EXPANSION IN BRAZIL: A QUANTITATIVE ASSESSMENT OF PAST TECHNOLOGICAL AND ENVIRONMENTAL CHANGES AND IMPLICATIONS FOR FUTURE CLIMATE CHANGE

Dissertação apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Meteorologia Aplicada, para obtenção do título de *Magister Scientiae*.

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APROVADA: 26 de julho de 2016.

Dênis Antônio da Cunha

Gabrielle Ferreira Pires

Marcos Heil Costa
(Orientador)

"Irei por meu caminho sem sentir minhas dores

Sem sentir minhas dores que ficarão atrás

Irei pelas beiradas recolhendo as flores

Deste longo caminho que já não verei mais"

Pablo Neruda, *"O Rio Invisível"*

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Abstract

ABRAHÃO, Gabriel Medeiros, M. Sc., Universidade Federal de Viçosa, July, 2016, Soybean expansion in Brazil: A quantitative assessment of past technological and environmental changes and implications for future climate change. Adviser: Marcos Heil Costa.

Brazil is today the world's second largest soybean producer, and the crop is cultivated throughout the country. However, this was not always the case. The most productive soybean regions of today were deemed unsuitable for soybean planting until the 1970's, and the crop was limited to southern Brazil. The new regions were incorporated into production only after significant technological developments on soybean breeding and management practices. The expansion of soybeans into those areas represented a major change in the climate experienced by the plants, and provides important lessons on adaptation to future climate change. This work aims to overcome limitations of data on yields, area and planting dates in order to perform a large-scale quantitative assessment of the changes in climate, photoperiod and technology experienced by soybeans during the expansion, and compare them with future climate expectations. A spatially explicit dataset on soybean harvested area and yields is developed. The photoperiod limitations to the planting date of each year's varieties are estimated using the northernmost latitude where soybeans were planted. This information is combined with spatial rainy season onset and end to obtain spatial and temporal estimates of the planting window for the period 1974-2012. The estimates compare well with planting dates recommended by the literature. With the development of photoperiod-insensitive varieties, planting windows went from being limited by the photoperiod on most of soybean-producing Brazil in 1974 to be limited by the rainy season in 1984. This development also had the effect of flexibilizing planting dates, making feasible the double cropping systems common today in central Brazil. Soybeans moved to much wetter regions, as total change in average excess precipitation (P-ETC) found was 2.33 mm day^{-1} on the historical period (1974-2012). Average temperatures rose at a rate of 0.49 °C $decade^{-1}$ during the expansion, 0.29 °C $decade^{-1}$ being due to local trends, faster than the expected rate for 2013-2050 (0.35 °C $decade^{-1}$). The highest yields were also achieved in the warmer regions. Funding and coordinating agricultural R&D towards unified goals is likely to be an efficient strategy to adapt Brazilian agricultural systems to climate change, and may bring many beneficial side effects.

Resumo

ABRAHÃO, Gabriel Medeiros, M. Sc., Universidade Federal de Viçosa, Julho, 2016, Expansão da soja no Brasil: uma avaliação quantitativa de mudanças tecnológicas e ambientais passadas e implicações para mudanças climáticas futuras. Orientador: Marcos Heil Costa.

O Brasil é hoje o segundo maior produtor de soja do mundo, e a cultura é plantada por todo o país. Porém, nem sempre foi assim. As regiões atualmente mais produtivas eram consideradas inaptas para o cultivo da soja nos anos 1970, e a cultura era limitada à região Sul. As novas regiões foram incorporadas à produção apenas depois de desenvolvimentos significativos em melhoramento genético e práticas de manejo. A expansão da soja para essas áreas representou uma grande mudança no clima a que as plantas foram submetidas, e traz importantes lições sobre adaptação às mudanças climáticas futuras. O objetivo deste trabalho é superar a limitação de dados sobre área, produtividade e épocas de plantio para realizar uma avaliação quantitativa em larga escala das mudanças no clima, fotoperíodo e tecnologia da soja durante a expansão e compará-las a expectativas para o clima futuro. É desenvolvido um banco de dados espacialmente explicito de área colhida e produtividade de soja. São estimadas as limitações fotoperiódicas ao plantio das variedades de cada ano usando a latitude mais ao norte onde a soja foi colhida. Essa informação é combinada com dados espacializados de início e fim da estação chuvosa para obter estimativas espaciais e temporais da janela de plantio para o período 1974-2012. As estimativas são consideradas adequadas quando comparadas com datas de plantio recomendadas na literatura. As janelas de plantio da maior parte das regiões produtoras de soja no Brasil eram limitadas pelo fotoperíodo em 1974. Com o desenvolvimento de variedades insensíveis ao fotoperíodo, passaram a ser majoritariamente limitadas pela estação chuvosa em 1984. Esse desenvolvimento também teve o efeito de flexibilizar as datas de plantio, tornando possíveis os sistemas de dupla safra que hoje são comuns no Brasil central. O cultivo da soja se moveu para regiões bem mais chuvosas, sendo a mudança total no excesso de precipitação (P-ETC) de 2.33 mm dia^{-1} no período 1974-2012. A temperatura média aumentou a uma taxa de 0.49 °C $década^{-1}$ nesse período, sendo 0.29 °C $década^{-1}$ devido a tendências locais, mais rápido do que a taxa de aquecimento esperada para 2013-2050 (0.35 °C $década^{-1}$). As produtividades mais altas foram obtidas nas regiões mais quentes. O financiamento e principalmente a coordenação das instituições de pesquisa e desenvolvimento agrícola na direção de objetivos comuns é provavelmente uma estratégia

eficiente para adaptar os sistemas agrícolas brasileiros às mudanças climáticas, e deve trazer diversas externalidades positivas.

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1. Introduction

Brazil produced 28% of the world's soybeans in 2014, being the second largest producer (FAO 2016). However, this was not always the case. Until the 1970s most of Brazil's land was deemed unsuitable for soybean cultivation. Only through profound changes on soybean cropping practices and the plants themselves, the crop became suitable for the regions where the majority of soybeans is planted today sand the highest yields are achieved.

The first reported attempt to cultivate soybeans in Brazil date back to 1882 in the state of Bahia (latitude ~12°S) without success. The soybean (*Glycine Max* cv. Merril) is a short-day plant, flowering earlier when days are shorter. This characteristic effectively hindered cultivation of the earlier varieties on low latitudes (Destro et al. 2001). Flowering occurred too soon on latitudes below 15°S, where the maximum photoperiod is less than 12.9 hours, and the short vegetative period led to short plants and low yields (Carpentieri-Pípolo et al. 2002).

As this was not a problem on higher latitudes, later attempts were more successful at 22°S in the state of São Paulo by the beginning of the 20^{th} century and later in the extratropical states in southern Brazil. The long summer days and the climate similar to that of southern U.S., where the soybean varieties of that time came from, made the state of Rio Grande do Sul specially suitable. With several government incentives and infrastructure improvements, such as a soil correction program and an industrial soybean processing complex, the crop was well established in all of southern Brazil by the end of the 1960s. Then, several factors pushed for an expansion towards central Brazil, including rising world soybean prices, low land prices and government incentives on infrastructure (EMBRAPA 2005, Gavioli 2013).

Despite some attractive conditions, such as more regular rains and a vast extension of flat, mechanizable soil, the environment in central Brazil posed several limitations for the soybean production systems of the time. In addition to the photoperiod limitations, high temperature and humidity led to poor quality of the grains to be used as seeds. Moreover, cropping systems and varieties of the time did not perform well on the poor fertility/high acidity soils of central Brazil, as specific soil correction techniques were still being developed and the varieties were sensitive to aluminum toxicity. Finally, the varieties were not resistant to the aggressive and resilient tropical pests and diseases, an ongoing issue for farmers and breeders (Spehar 1994, Almeida et al. 1999, Schnepf et al. 2001).

First significant research developments on soybean breeding started in the late 1960s at some universities and public research institutions, where several photoperiod tolerant but low yielding varieties were developed. On the 1970s, the Brazilian government invested heavily on agricultural research. EMBRAPA (Empresa Brasileira de Pesquisa Agropecuária), currently the largest government agricultural R&D (Research and Development) agency, was created in 1973, and a branch with the specific goal of developing tropical soybeans started operating in 1975 (Pessoa and Bonelli, 1997). EMBRAPA and several other research institutions, specially universities, worked in cooperation 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 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 more adapted varieties (Viana et al. 2013). Later work made them even less sensitive to photoperiod and improved yields under different environmental conditions (Spehar 1994, Gavioli 2013). This development also had the effect of flexibilizing planting dates, eventually leading to irrigated winter soybeans on some northern states (Carpentieri-Pípolo et al. 2002). In addition, breeding work 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, allowing farmers to plant multiple crops in a single season (Correa and Schmidt 2014).

As a result, by 1990 the crop was already firmly established on most regions of central Brazil. During the last two decades, the new major challenges for environmental adaptation of soybeans were the development of technologies for (i) the double cropping systems (mostly soy-maize and soy-cotton), which were made possible by the flexibilization of planting dates and (ii) the new agricultural frontier on the drier states of northeastern Brazil (Viana et al. 2013).

Soybean varieties of today can achieve appropriate vegetative periods and high yields under the high temperatures and the ~12h maximum photoperiod of the states of Maranhão and Pará, close to the equator (Bezerra et al. 2015). Average soybean yields more than doubled and harvested area increased threefold between 1974 and 2012 (FAO 2016). The vast majority of the new areas are located (and some of the record yields are achieved) in central, northern and northeastern Brazil, regions previously considered unsuitable for soybean production.

The past trajectory of technological changes, consequent expansion and the climate change associated is similar to a possible trajectory that countries may follow to adapt to future climate change. Current literature on adaptation to climate change generally focus on incremental and transformative adaptation (Moser and Ekstrom 2010, Vermeulen et al 2013). While incremental adaptation considers the options and technologies already available and used by farmers (e.g. Stehfest et al 2007, Challinor et al. 2014), transformative adaptation happens after viability thresholds are crossed (e.g. Rickards and Howden 2012, Rippke et al. 2016).

In this context, the development of new technologies is expected to be able to introduce changes in production systems that can alleviate negative impacts of climate change. They have the potential of better exploiting increased carbon dioxide concentrations (Ainsworth et al. 2002), solving issues of incremental adaptation (Taub et al. 2008) and counteracting overall impacts to the point of turning them positive (Challinor et al. 2014, Porter et al. 2014). Such systemic changes are hypothesized to be capable of even displacing viability thresholds (Rippke et al. 2016).

The technological changes that happened during the Brazilian soybean expansion are a classical example of large-scale efforts in that sense (Porter et al. 2014). Understanding the magnitude and timing of these changes is important to provide comparability with expectations for future conditions. A large scale quantitative assessment of these changes and their background is still lacking, and is made difficult by the limited spatial and temporal information available on soybean area, yields and especially planting dates, that are necessary to assess the actual climatic conditions the plants are subject to.

In this context, the objective of this work is to quantitatively assess the relationships between the soybean crop, climate and photoperiod in Brazil over the last four decades and compare them with expectations for future climate change. Specific objectives are: (i) characterize the past evolution of the photoperiodic dependence; (ii) develop a spatially and temporally explicit dataset of possible planting dates; (iii) analyze the relationships between geographic expansion, yields and climate and (iv) compare these relationships with expectations for future climate.

2. Methods

2.1. Area of study and period of analysis

This study focuses on areas in Brazil cultivated with soybeans during the last decades. Because of data availability constraints, the period starts on the harvest year of 1974 (with planting on 1973), and ends on the harvest year of 2012 (with planting on 2011). Brazil is a relatively large country, and as the soybean crop expanded to new areas it experienced different climate conditions. The soybean crop expansion started from southern Brazil, a region characterized by subtropical temperatures and rains well distributed through the year. As it expanded northward towards lower latitudes, it moved to the seasonal climate of *Cerrado* in central Brazil, with a well-defined rainy season and warmer temperatures, and then towards the wetter Amazonia and the somewhat drier northeastern *Cerrado*, both generally warmer than the typical *Cerrado*.

Expectations of future climate change are evaluated on the same areas harvested with soybeans in 2012 for the period between the expected harvests of 2013 and 2050.

2.2. Gridded soybean area and yields dataset

A Brazil-wide spatially explicit dataset on soybean planted area (km^2) and yields (t ha^{-1}) was developed using a similar methodology from the one used by Dias et al. (2016), which used the "Global Forest Cover" (GFC) dataset on tree cover (Hansen et al. 2013) to perform a spatial disaggregation of Brazilian census data on land use from 1940 to 2012, including harvested area and yields of soybeans. The version described here has minor modifications with respect to data periods and filtering to ensure pixel by pixel consistency across years on locations where census tracts changed, and covers the study period beginning on the 1974 harvest and ending on the 2012 harvest. Before 1974 the census data is not available every year.

Soybean yield and planted area data were obtained from the Brazilian Institute of Geography and Statistics (IBGE) and the Institute for Applied Economic Research (IPEA). The data for 1973-1990 were obtained from IPEA at the municipality level. As many municipalities have changed boundaries in the period, data was aggregated using the Minimum Comparable Areas (MCA) from Leite et al. (2011, 2012), which consists in the smallest set of municipalities with stable boundaries on the period 1973-1995. For the 1990-2012 period, data was obtained from IBGE for each microregion, whose boundaries are stable from 1990 forward and are generally smaller than the MCA's considered earlier.

The disaggregation using the GFC dataset was then performed to obtain an estimate of the planted area distribution at a scale smaller than the administrative unit. For efficiency in processing, the original 30 x 30 m data was resampled to an 1 x 1 km grid, and the inverse of tree cover data was calculated to obtain non-forest fraction maps. Assuming that soybean planted area is equally distributed inside the administrative unit's non-forest area and that yields were constant inside each unit, planted area and production (V, units km^2 and t respectively) for each gridcell i,j were obtained as follows:

$$V_{t,i,j} = NF_{t,i,j} \frac{V_{t,k}}{\sum NF_{t,i,j \in k}} \quad (1)$$

where NF is the non-forest fraction and k is an index representative of each administrative unit. For years before 2000, first year of the GFC dataset, the deforestation map for 2000 was used, assuming that distribution of non-forest fractions inside each administrative unit was constant. These assumptions lead to the allocation of planted area to every pixel with some nonforested fraction, only excluding fully forested ones. This limitation is partially overcome by using thresholds to exclude very low area values on specific analyses that can be sensitive to them (see Sections 2.3 and 3.3). However, as both assumptions affect only the distribution inside the administrative regions' boundaries, violations do not affect yield or total area values of each region.

2.3. Planting and harvesting limitations

The development cycle of the soybean plant can be roughly divided in 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 on some varieties) allocated to the reproductive organs. While actual grain filling happens in the reproductive period, the vegetative period must be long enough for the plant to have well developed canopy and roots when the reproductive period begins (Gavioli 2013).

The duration of the vegetative period depends on complex interactions between the variety's genotype and environmental factors, mainly temperature and photoperiod (Alliprandini 2009). Higher temperatures speed up the development process, while longer days delay it. The sensitivity to photoperiod is nonlinear, with very short days (<14h) having a weaker delaying effect and thus potentially leading to very short vegetative cycles (Cober et al. 2014). Most of Brazil's area is located at latitudes smaller than 30º, where the days are never longer than 14 h. So, the first soybean varieties that came from the U.S. and Asia had to be heavily modified to be less sensitive to short photoperiods (Destro et al. 2001, Spehar 1994).

Continuously developing new varieties with commercial yields under the small photoperiods of lower latitudes was an essential condition for the expansion, but also had the effect of flexibilizing planting dates (Carpentieri-Pípolo 2002). Cultivars suitable for planting in narrow, long-day time windows on the lowest latitudes of the time could be planted in wider time windows on higher latitudes. Eventually, the beginning of the rainy season may have become a more limiting factor for planting than daytime length, and today it is the most limiting factor for the soybean calendar in Brazil (Arvor et al. 2014).

Cycle length until full maturity is around 110-140 days. The soy plant fills grains until late on the reproductive period, at about 100-130 days after planting (Alliprandini et al. 2009, Bezerra et al. 2016). Keeping the plant from water stress until then is important to maximize yields, but also creates a planting window limitation at the end of the rainy season, as planting too late in the rainy season may lead to water stress at the end of the cycle. This limitation is specially important for the now common double-cropping systems, where planting must occur as soon as possible to accommodate two cycles. Here a methodology to estimate the evolution of these planting windows is presented.

Here it is assumed that farmers in a latitude band would plant the soybean crop only after having access to varieties well adapted to their longest photoperiod period (i.e. around the austral summer solstice, about December 21). Using the yearly 1 x 1 km soybean planted area maps, the northernmost pixel that had at least 1% of its area planted with soybeans was considered for calculating the minimum photoperiod needed for commercial varieties at each specific year. The 1% threshold was chosen because the disaggregation methodology (Section 2.2) assigns planted area to all pixels inside an administrative unit, including very small values to pixels that have a high forested fraction in the GFC dataset. Such small fractions do not represent well-established soybean farming and thus were removed from the analysis. The results are qualitatively very similar if a threshold of 0.5% is used instead.

According to Gavioli (2013), the minimal vegetative period for optimal yields is 45 days. To get the longest possible days in this period, the planting date should be half this time (~ 22 days) before the austral summer solstice, at around December 1st, putting the solstice (when the longest day happens) in the middle of the 45-day period and thus maximizing the average photoperiod of the vegetative period. For a given year, this is the single planting date possible for the latitude closest to 0° where a variety could be planted.

In every latitude south of that reference, there are two dates where the photoperiod is the same as the summer solstice photoperiod of the reference latitude, one after and one before. The photoperiod-limited planting window was then delimited as a function of N, the photoperiod of the summer solstice of the lowest latitude with soybeans of each year. In each latitude, the planting window is the period between:

(i) 23 days before the day with photoperiod N, before the summer solstice and;

(ii) 23 days before the day with photoperiod N, after the summer solstice.

The astronomical equations used here can be found in many textbooks, such as Vianello and Alves (2012). The austral summer solstice photoperiod (N, hours) of the lowest latitude (ϕ) of each year was determined using Equation 2, setting the Sun declination angle (δ) to the austral summer solstice value (-23.45°). All angles are represented here in degrees.

$$N = \frac{2}{15^\circ} \arccos(-\tan\phi \tan\delta) \quad (2)$$

To find the two days in the year that this same N value happens in all other latitudes, first Equation 2 is solved for the declination angle (δ):

$$\delta = \arctan\left(-\frac{\cos(15^\circ \frac{N}{2})}{\tan\phi}\right) \quad (3)$$

and then use the solution to find the two corresponding days of the year (n_j, one before and one after the solstice) by solving Cooper's equation for n_j:

$$n_j = \frac{365}{360^\circ} arcsen\left(\frac{\delta}{23.45^\circ}\right) - 284 \quad (4)$$

The middle of the 45-day vegetative period, the photoperiod-limited planting window, is then obtained by subtracting 23 days from each n_j.

The planting window also depends on the rainy season, so an analysis of its onset, end and duration was also made. The data used was gridded (1.0° x 1.0°) daily precipitation from the Princeton University Terrestrial Hydrology Research Group (PTHRG, Sheffield et. al. 2006), which is a merge of the Tropical Rainfall Monitoring Mission (TRMM), Global Precipitation Climatology Project (GPCP) and the National Centers for Environmental Prediction - National Center for Atmospheric Research (NCEP–NCAR) reanalysis, covering the 1974-2012 period. To determine the onset and end of the agricultural rainy season, I used a modified version of the Anomalous Accumulation method (AA, Liebmann et al. 2007), which was successfully used by Arvor et al. (2014) for the same purpose on the Brazilian State of Mato Grosso using gridded data from the TRMM 3B42 product. The Anomalous Accumulation (AA, mm day^{-1}) of day t is calculated by:

$$AA(t)=\sum_{n=1}^{t}\left(R(n)-R_{ref}\right) \tag{5}$$

where R(n) is rainfall at day n and R_{ref} is a reference rainfall value, both in mm day^{-1}. The onset (end) date of the rainy season is defined as the day of minimum (maximum) AA. The value of R_{ref} used was 2.5 mm/day, representative of a soybean seedling's needs.

Based on these analysis, three planting calendars for soybeans at each year were developed. First, a photoperiod and meteorological rain calendar (PMR), based on the actual yearly rainy season and photoperiodic limitations, is used to represent the climate actually experienced by farmers at each year on further analyses. Second, a photoperiod and climatological rain calendar (PCR), based also on the evolution of yearly photoperiodic limitations but climatological rainy season, is used to characterize the temporal evolution of possible planting windows caused by the relaxation of the photoperiodic limitations at each latitude. It also represents a risk based view of the rainy season, as it considers the 20% shortest rainy season years. Third, a meteorological rain-only calendar (MRO) was also developed. It is used to evaluate the effects of local long-term trends in climate by fixing the photoperiodic limitations as the more recent ones, thus providing hypothetical planting windows if the most recent long-juvenile soybeans were used in the past.

For the photoperiod and meteorological rain calendar (PMR), the following criteria are applied:

- The earliest possible planting date is defined as either the earliest day of the photoperiod-limited planting window calculated using the latitude closest to the equator of each year or the rainy season onset of each year, whichever happened later.
- The latest possible planting date is defined as the earliest date between: i) the latest photoperiod-limited planting date and ii) 90 days before the rainy season end for single cropping soybeans or 200 days (110 for soy plus 90 for a second crop) before the rainy season end for double cropping systems. This is a conservative approach, as it considers a relatively short 110-day soybean cycle and a second crop with the same length, while the generally used corn and cotton have longer cycles. The usage of 90 days before the rainy season end also assumes a 110-day cycle, but considers 20 days of use of soil moisture at the end of the cycle.

- The latest possible harvest date is defined as 30 days after the rainy season end. This assumes soil moisture usage for 20 days and 10 days for drying up the grains before harvest.

The criteria for the photoperiod and climatological rain calendar (PCR) are the same as in the meteorological rain calendar, except that the rainy season onset used for all years was the 20% latest on the 1974-2012 period, representing an one fifth risk of seedling failure and the need to replant. The climatological rainy season end was the 20% latest onset plus the median rainy season duration for the same period.

For the meteorological rain-only calendar (MRO), the criteria were also the same as in the photoperiod and meteorological rain calendar, but the photoperiodic limitations considered at every year were calculated using the lowest latitude of 2012.

2.4. Local and expansion-driven climate change

The soybean crop expanded toward regions with climatic conditions very diverse from the original, in southern Brazil. This resulted in an expansion-driven climate change, that occurred alongside the local climate trends. Here these effects are calculated on daily average temperature ($\overline{T}$, °C) and excess precipitation ($\overline{P\text{-}ETC}$, mm day^{-1}) during the soybean cycle. The trends on the average conditions experienced by soybeans at each year will be analyzed to assess the climatic changes due to the expansion and the local climate trends during the period.

The definition of excess precipitation used here considers the potential crop evapotranspiration (ETC), which is defined as the evapotranspiration of a disease-free, well fertilized crop under optimum soil water conditions. As a potential measure, the use of ETC neglects the negative effect of low soil water availability during dry spells on the actual evapotranspiration, as well as potentially negative effects of disease and nutrient stresses (Allen et al. 2006). Thus, the estimates of $\overline{P\text{-}ETC}$ here may be considered conservative underestimations for climate change purposes.

To quantify these effects, two gridded climate datasets at 1.0° x 1.0° resolution were analyzed along with the soybean area and yields dataset. Daily precipitation, specific humidity, solar radiation, minimum maximum and average temperature were taken from both the PTHRG dataset and the Climate Research Unit TS3.1 (CRU, Harris, 2013) dataset.

As the original CRU dataset only has information on monthly means and daily data is required for the analysis, the version used here was disaggregated using the PTHRG daily data. First the monthly means of the PTHRG dataset were calculated. For the temperature variables, the difference between CRU and PTHRG monthly means were then summed to the PTHRG daily dataset, thus obtaining a version of the PTHRG daily data with the same monthly means as the CRU dataset. A similar procedure was applied for precipitation, wind speed and specific humidity, but using ratios instead of differences as they cannot assume negative values.

ETC was calculated using the FAO reference evapotranspiration method (Allen et al. 2006). In this method, the potential evapotranspiration of a reference grass is first calculated and then multiplied by a coefficient specific to a certain crop development stage (Eq. 6). Reference evapotranspiration (ETo) was calculated for both datasets using the FAO-Pennman-Monteith equation:

$$ETC = ETo\,Kc \tag{6}$$

$$ETo = \frac{0.408\,\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34\,u_2)} \tag{7}$$

where ETo is the reference evapotranspiration (mm day^{-1}), R_n is the net radiation at the reference grass' surface (MJ m^2 day^{-1}), G is the soil heat flux (MJ m^2 day^{-1}, here assumed to be negligible compared to Rn for a whole day), T is the mean daily temperature (ºC), u_2 is the wind speed (m s^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), Δ is the slope of the vapour pressure curve (kPa ºC^{-1}) and γ is the psychrometric constant (kPa ºC^{-1}). The parameters R_n, γ, Δ, e_s and e_a were calculated according the methods specified in Allen et al. (2006) using the available daily data on solar radiation, wind speed, specific humidity, maximum, minimum and mean temperatures

Crop potential evapotranspiration (ETC mm day^{-1}) was then calculated at each gridcell using crop coefficients (Allen et al. 2006). Crop coefficients are multiplicative factors applied to the reference evapotranspiration (ETo) that represent the specificity of each crop and development stage. This method requires an explicit definition of the crop cycle to estimate the crop coefficient (Kc) for each day. To obtain representative values at each gridcell of the growing season's ETC, an average of all possible 110-day cycles with planting starting from the earliest possible planting date to 90 days later was calculated. The first 90 days were chosen because a comparison of the PCR with the literature on recommended planting dates (review by Silva et al. 2015) has shown that those are generally within this period (see Section 3.2). The average ETC ($\overline{ETC}$, mm day^{-1}) for each gridcell (i,j) is then:

$$\overline{ETC}_{i,j} = \frac{\sum_{k=1}^{90} \sum_{t=1}^{110} ETo_{i,j}(t+k)\, Kc(t)}{90 \times 110} \quad (8)$$

where t is the number of days past planting and k the number of days after the earliest planting date defined on each of the calendars. The values of Kc used for each possible cycle are illustrated in Figure 1. Stage duration values are proportional to those found in Allen et al. (2006) under “Soybeans: Tropics” on Table 11, but rescaled to a 110-day cycle from the original 85-day cycle. Kc values were obtained from Table 12 of the same publication.

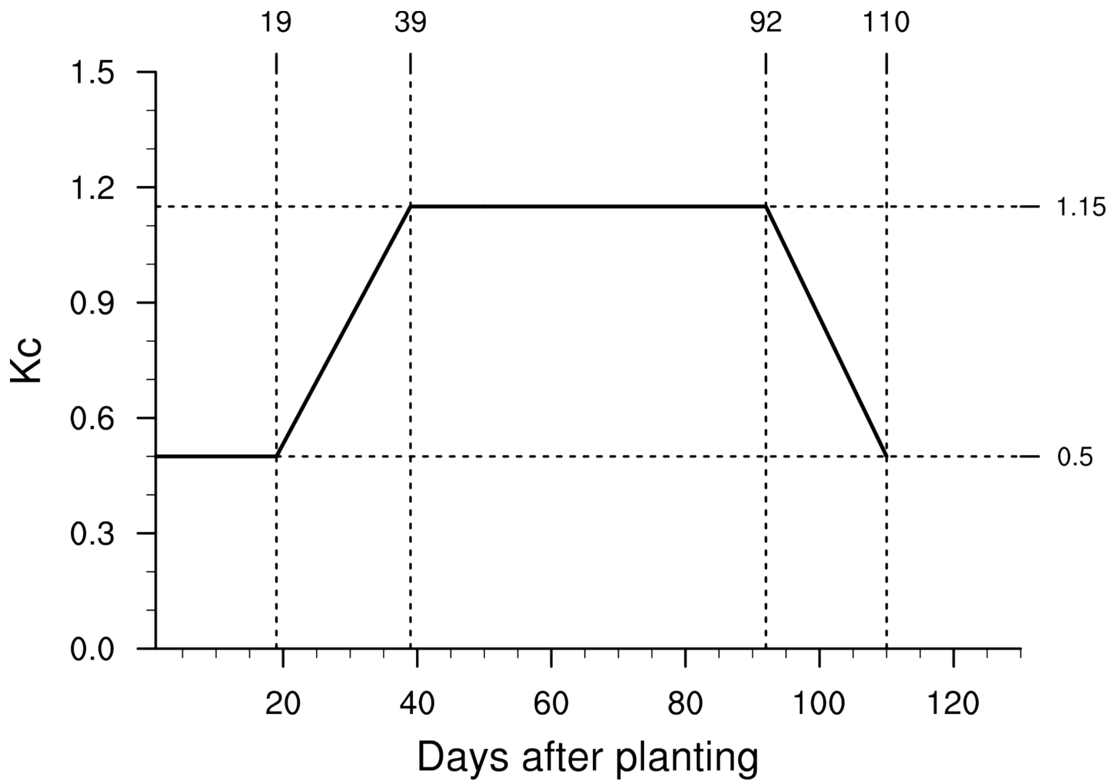

Figure 1: Crop coefficients used for calculating evapotranspiration. Stage duration values are proportional to those found in Allen et al. (2006) under "Soybeans: Tropics" on Table 11, but rescaled to a 110-day cycle from the original 85-day cycle. Kc values were obtained from Table 12 of the the same publication.

Temperature and precipitation averages ($\overline{\mathrm{T}}$ and $\overline{\mathrm{P}}$, respectively in °C and mm day^{-1}) were calculated using a similar process, e.g.:

$$\overline{T}_{i,j}=\frac{\sum_{k=1}^{90}\sum_{t=1}^{110}T_{i,j}(t+k)}{90\times 110} \quad (9)$$

The distinction of local and expansion-driven climate trends was made at the national level by using different calendars and approaches to re-aggregate the data. Local climate trends are quantified by using the rain-only calendar and gridcell soy production of a fixed year (2012) as weights, an approach similar to those of global assessments such as Lobell et al. (2011). On the other hand, total climate change experienced by soybeans during the expansion was calculated using the meteorological calendar and by weighting each gridcell by its soy production of the corresponding year.

2.5. Comparison with expectations for future climate

In order to compare the climate change experienced by soybeans in the past with expectations of future climate change, the same procedure used on the PTHRG and CRU datasets was applied on simulations of future climate of models on the Coupled Model Intercomparison Project phase 5 (CMIP5, Taylor et al. 2012). The Representative Concentration Pathway 8.5 W m^{-2} is chosen for being the most pessimistic scenario on the CMIP5, and so the most conservative in terms of risk analysis.

As the methodology described here for the estimation of planting windows is dependent on the rainy season, and some CMIP5 models may not adequately represent precipitation in Brazil, only output from four models was used (Table 1). Those models were found by Pires et al. (2016) to reasonably describe precipitation and the rainy season onset and end over soybean areas in Brazil. Daily data of the same variables described on Section 2.4 from each model was averaged to create an ensemble mean dataset. Using the precipitation data, the rainy season was estimated for each model and for the ensemble mean. Separate calendars were then estimated using the 2012 soybean area in a procedure analogous to that of the MRO calendar. With those calendars, growing season averages of T and P-ETC were calculated for each model and the ensemble mean for the period between the harvests of 2013 and 2050.

Table 1: CMIP5 models used in this study, based on Pires et al. (2016).

Model name	Acronym	Institute
Model for Interdisciplinary Research on Climate, version 5	MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine- Earth Science and Technology
Meteorological Research Institute Coupled Atmosphere–Ocean General Circulation Model, version 3	MRI-CGCM3	Meteorological Research Institute (MRI), Japan
Norwegian Earth System Model, version 1 (medium resolution)	NorESM1-M	Norwegian Climate Centre (NCC)
The Hadley Centre Global Environmental Model, version 2	HadGEM2-ES	Hadley Centre, United Kingdom

3. Results and discussion

3.1. Gridded soybean area and yields dataset

Figure 2 shows the evolution of areas harvested in each 1 km x 1 km pixel with soybeans from 1974 to 2012. Total soybean harvested area grew from 5.1 Mha to 24.9 Mha in the 39-year period. The geographical extent of this expansion was wide, as the number of states with expressive soybean presence (1% of the 1 km^2 pixel) doubled in the period (from 7 in 1974 to 14 in 2012). The expansion started from southern Brazil. In 1974, 83% of the soybean area was located south of the Tropic of Capricorn. Despite the growth in area (to 8.2 Mha in 1979), the expansion was constrained to southern Brazil and some regions on SP (São Paulo), MG (Minas Gerais), MS (Mato Grosso do Sul) and southern GO (Goiás) until the 1980s, when soybeans started to spread to MT (Mato Grosso) and northern GO, eventually reaching western BA (Bahia). Most of these new regions are in the *Cerrado* biome, while some of northern MT are in the *Amazonia* biome.

By 1989, more than half (6.2 Mha out of 12.2 Mha) of the soybean area was in the intertropical region. During the 1990s, the expansion was relatively slow, as harvested area rose by only 0.85 Mha from 1989 (12.2 Mha) to 1999 (13.0 Mha), fact that may have been due to a convergence of economic factors (Melo 1999, see discussion on yields of the 1990`s). However, the soybean crop consolidated its presence in the *Cerrado* biome, that had 4.4 Mha of soy harvested in 1989 and 6.0 Mha in 1999. During the 2000s, the expansion again gained strength as the harvested area nearly doubled from 1999 (13.0 Mha) to 2012 (24.9 Mha). About half (6.3 Mha) of this increase happened in *Cerrado*, that represented half of total soybean area by 2012 (12.3 Mha). Soy presence on the states of MA (Maranhão), TO (Tocantins), PI (Piauí) and BA (Bahia), on the northeastern *Cerrado*, had a strong geographical expansion in the 2000s. Total soybean harvested area tripled from 1999 (0.8 Mha) to 2012 (2.5 Mha) in the MATOPIBA region, the world's newest agricultural frontier. In 2012, 65% (16.3 Mha) of soy area and 74% of soy production (48.9 Mton) were to the north of the Tropic of Capricorn.

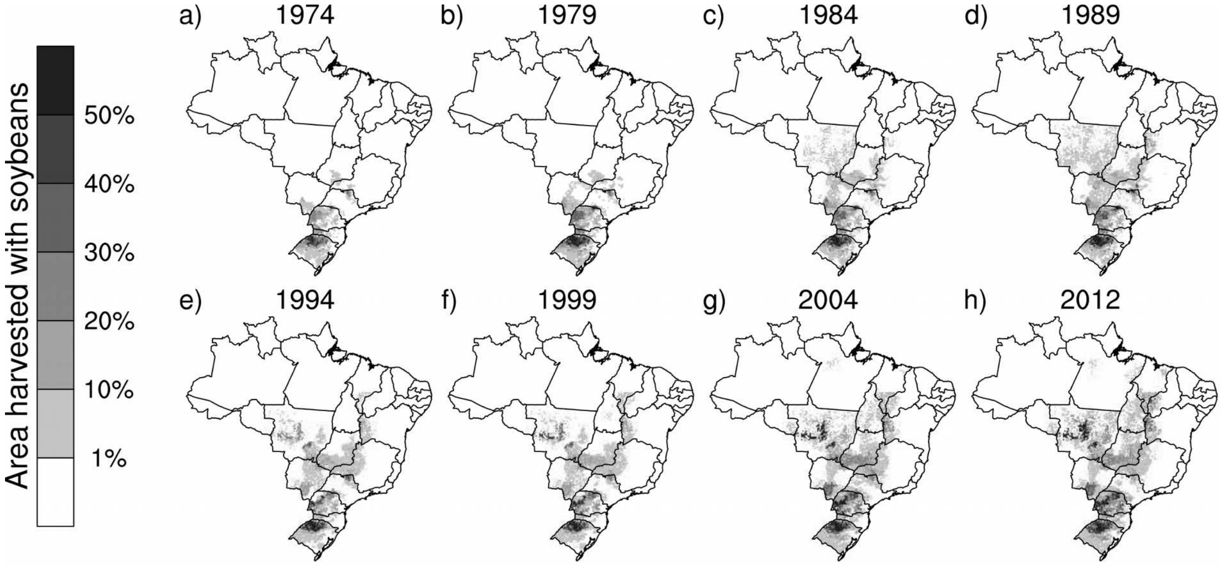

Figure 2: Evolution of soybean planted area by harvest year

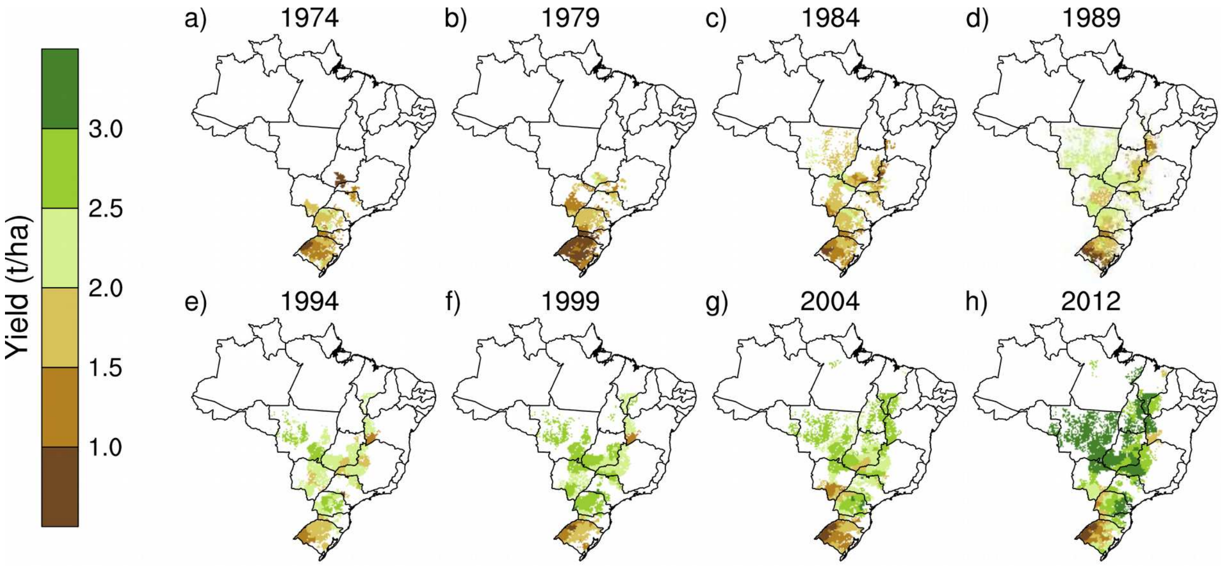

Figure 3: Evolution of soybean yields by harvest year

The spatial distribution of soy yields for selected harvest years is shown in Figure 3, while Figure 4 shows the temporal evolution of average yields for some regions. Yields were relatively low in 1974 (1.53 t ha^{-1} in Brazil), being slightly lower in central Brazil (states of MS, MT and GO, 1.42 t ha^{-1}) compared to southern Brazil (1.54 t ha^{-1}).

The regions with the highest yields at the time were in PR (Paraná, 1.75 t ha^{-1}) and the non-*Cerrado* part of MS (1.93 t ha^{-1}), both at 20-30°S. Yields didn't improve much and had a similar pattern of large interannual variability across regions until the late 1970s when yields in central Brazil started to rise steadily (Figure 4).

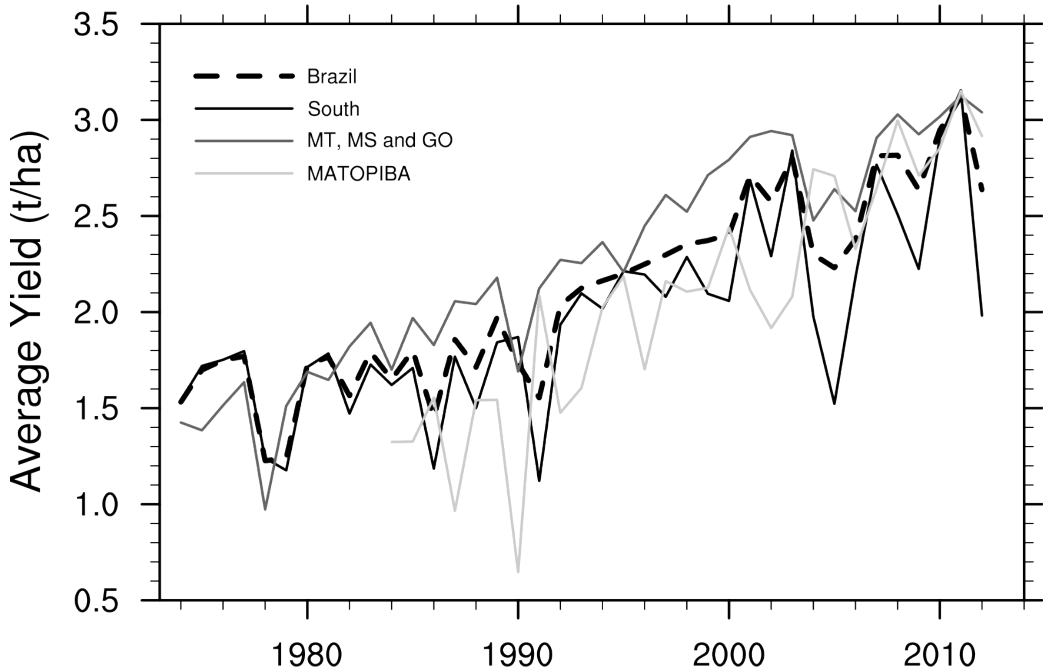

Figure 4: Evolution of average yields of the whole country (dashed line), southern Brazil (black solid line), the states of MT, MS and GO (dark gray line) and the agricultural region of MATOPIBA (light gray line)

It's worth restating that several Brazilian universities were already working on adapting soybeans to tropical conditions in the 1960s, and overall investment in agricultural research improved substantially during the 1970s (Pessoa and Bonelli, 1997). EMBRAPA, the largest government agricultural R&D agency, was created in 1973. A branch with the specific goal of developing tropical soybeans (EMBRAPA Soja) started operating in 1975, combining efforts with the other research institutions working on the same goal. The steady rise of yields on central Brazil in the late 1970s suggest that agricultural R&D efforts to adapt soybeans to tropical conditions may had started to pay off by then. This is supported by the report of Pardey et al. (2006), which states that Brazilian soybean farmers generally use varieties that were released between 3 and 7 years before. Pardey et al. (2006) attribute most of the economic soybean research benefits on the 1981-2003 period to Brazilian public and private research institutions (59-77%, excluding EMBRAPA), followed by EMBRAPA (40-23%) and R&D spillovers from other countries, specially the U.S. (4-21%).

These technological improvements may have boosted the expansion on the states of central Brazil during the 1980s, as most of them had yields among the highest in 1989 (Figure 3d). On that year, average yield in Brazil was 1.97 t ha^{-1} and 2.18 t ha^{-1} in the central states. Yields in southern Brazil improved slowly during this decade, with high interannual variability (Figure 4). This pattern of variability can be associated with the high climate variability during the summer in the region, with an average good climate but also with long dry spells and low precipitation during La Niña years, that cause frequent crop failures in soybeans (Berlato e Fontana 2001, Melo et al. 2004). This climate variability could be one of the causes of the lack of investments in soil correction in RS reported on the early 1990s (Conto and Montoya 1994) that could in turn explain the persistence of low yields in the state relative to the rest of the country (Figure 3). The decade of 1980 was also when the soybean crop first had an expressive presence in the MATOPIBA region, with low initial yields in 1984 (1.32 t ha^{-1}) relative to the country average (1.65 t ha^{-1}).

During the 1990's, yields rose rapidly nationally despite the slow growth of soybean planted area, going from an average of 1.97 in 1989 to 2.37 t ha^{-1} in 1999. Yields in southern Brazil and MATOPIBA, that were relatively stagnated until the early 1990s, also begun to rise rapidly but with a high interannual variability (Figure 4). Melo (1999) observes a rise in overall agricultural land productivity at the time, and suggests it was a consequence of a combination of economic factors. The economic instability of the late 1980s/early 1990s may have caused farmers to search for new technologies to improve resource allocation. Agricultural input prices (mainly fertilizers and agrochemicals) also were falling, while both global soybean prices (in local currency) and local land value were rising, encouraging the adoption of technology to increase production for exports.

Albuquerque and Silva (2008) compare results from different papers on soybean breeding and state that genetic improvements increased yields at a rate of 60 kg ha^{-1} $year^{-1}$ on the period 1964-1984, but at a much slower pace (26 kg ha^{-1} $year^{-1}$) on the 1980-1990 decade. This difference supports the hypothesis that the fast rising yields of the 1990s may have been more an effect of technology adoption than actual development of soybean technologies. Still, the same authors calculate that about half of the yield gains in the 1986-2005 period were caused by genetic gains.

This pattern of rising yields continued during the 2000-2012 period, with yields increasing faster in MATOPIBA than in the other regions (Figure 4). The overall spatial pattern is that newly explored regions in central Brazil tended to have high yields compared to the rest of the country, while in MATOPIBA they generally had low yields and eventually reached high levels by rising fast (Figure 3), likely due to the development of the region's infrastructure at the time. By 2012, with the notable exception of the aforementioned RS state, most states had regions with yields higher than 3.0 t ha^{-1}, with a national average of 2.63 t ha^{-1}. Average yield was 2.99 t ha^{-1} north of the tropic against 1.96 t ha^{-1} south of it.

3.2. Planting limitations

Figure 5a is a combination of some of the maps in Figure 2, showing the areas with at least 1% of the 1 km^2 pixels harvested with soybeans on several years. Figure 5b shows the latitude of the 1 km^2 pixel with at least 1% harvested soybean area that were closest to the equator at each year.

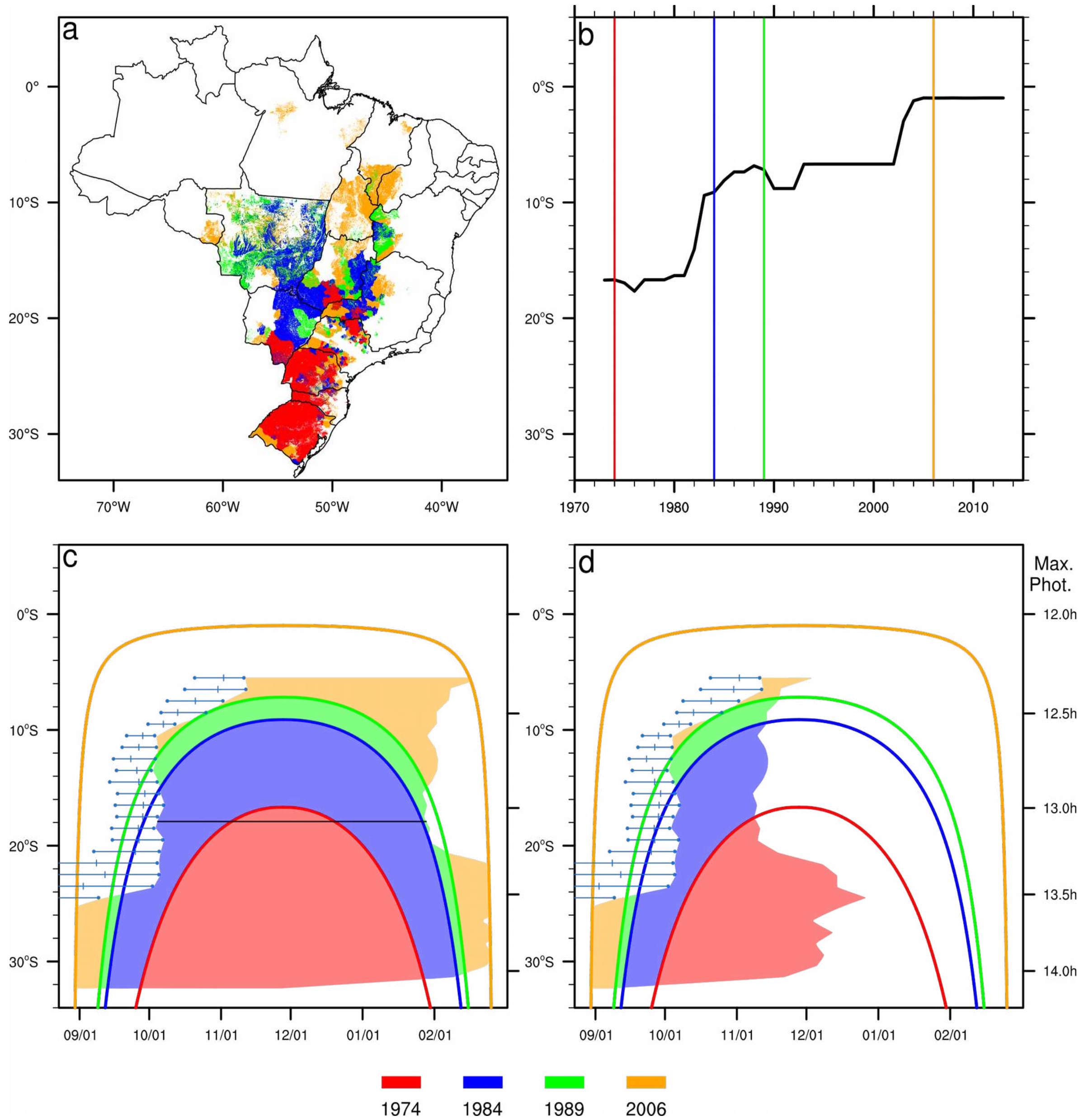

Figure 5: (a) Location of soybean areas for various harvest years; (b) Lowest latitude with harvested soybeans at each year, selecting harvest years when the lowest latitude plateaued; (c) Estimation of the planting window for each latitude and selected harvest years. Solid thick lines represent the planting dates window, considering the photoperiod limitations of the cultivars available at the selected harvest years. Light-blue horizontal bars represent the earliest rainy season onset date on 80% (left dot), 50% (vertical bar) and 20% (right dot) of the years considered, weighted by the soybean planted area at each 1° band of latitude. The shaded areas represent the possible planting window for a single crop of soybeans, assuming a 110 days cycle, considering the limitations of photoperiod, onset and end of rainy season; (d) Same as (c), but shaded areas represent the planting window for soybeans on a double cropping system with a combined cycle of 220 days (110 soybeans + 110 corn). The left vertical axis shows the maximum photoperiod at each latitude. The black horizontal line refers to the 18°S example in Section 3.2

Figure 5c illustrates the planting window considering the photoperiod and climatological rain (PCR) calendar. Light-blue horizontal bars represent the zonal average of earliest rainy season onset date on 80% (left dot), 50% (vertical bar) and 20% (right dot) of the years in the 1974-2012 period. Rainy season data is not shown north of 3°S as soybean areas are very discontinuous, misrepresenting the zonal average. The rainy season limited planting window is the region limited on the left by the 20% onset date quantile and on the right by the median rainy season duration after this date minus 90 days (not shown), representing the time for grain filling on a very short cycle soybean. The photoperiod limited planting window at each highlighted year is represented by the arc-senoid thick colored lines, calculated using Equation 4. Shaded areas represent the estimated planting window after combining both limitations.

For example, farmers in latitude 18°S (southern GO, black horizontal line in Figure 5c) had access to varieties in 1974 that could be planted in a 46-day period between November 3 (left side of red line) and December 19 (right side of red line), as those days have a photoperiod of 13 h. Outside that period, the photoperiod was too short and would likely cause early flowering and yield losses to the varieties of the time, as there were no significant areas with soybeans above 16.6°S, where the maximum photoperiod is 13 h. By 1984 soybeans were planted as north as 9.11°S, providing evidence that the varieties of the time could achieve good yields on photoperiods as low as 12.5 h. That means that farmers on latitude 18°S could plant later, until January 25 (right side of blue line), and in theory as early as September 27 (left side of blue line). However, in 20% of years the rainy season started only after October 3 (right light blue circle). So, in 20% of the years, planting could only happen after the latter date and thus would be limited by the rainy season. Therefore by 1989, despite advancements on photoperiod limitations, farmers couldn't plant earlier than October 3, even though there were soybeans at 7°S, where the maximum photoperiod of 12.4 h would theoretically allow planting as early as September 20 (left side of green line). Planting later than 1984's January 25 limitation was possible but, in 20% of the years, planting after January 27 (right edge of shaded green area) would lead to the rainy season ending less than 90 days later (April 27), before the completion of grain filling in a 110-day cycle variety.

Figure 5c provides insight on the north-south patterns of climatological planting limitations. The photoperiod was the limiting factor for the soybean planting window at all latitudes until the beginning of the 1980s (~1984), when the rainy season onset became the limiting factor for latitudes between 24°S and 16°S. As of 1990 all latitude bands north of 25°S, where the rainy season is well defined, were already limited by the rainy season or the photoperiodic limitation was very close to the defined rainy season limitation (one fifth climate risk). This is consistent with reports that the "first cycle" of soybean breeding in Brazil, which had the main objective of obtaining late flowering varieties suitable for the tropical regions lasted until the late 1980s (Spehar 1994). However, despite the photoperiod not being a limiting factor for planting anymore it still has a strong influence on yields, being one of the determinants of optimal yielding planting dates (Alliprandini et al. 2009, Silva et al. 2015).

The progressive overcoming of the photoperiod limitations also had the effect of flexibilizing possible planting dates. As mentioned in the above example, the 18°S latitude band had a climatological 46-day planting window by 1974, and by 1989 farmers on that latitude could explore their full rainy season, leading to a climatological low-risk 116-day planting window. This effect is progressive and more proeminent in recent regions, due to the "flat-top" shape of the arcsenoid that describes the photoperiod limitations. It is also fundamental to the northward expansion of double-cropping systems.

Figure 5d is the same as Figure 5c, but the shaded areas are limited to the right by the median rainy season duration after the 20% onset quantile minus 200 days, representing the planting window for a double cropping system with both varieties with a relatively short duration. Double cropping systems started being used in the state of Mato Grosso only in the 1990s, first as a way to reduce economic and environmental vulnerability to pests by planting a cheaper second crop and then evolved to modern soy-corn and soy-cotton systems where the second crop can be as economically important as the first one (Arvor et al 2012). Results indicate a strong flexibilization of planting dates for double cropping systems. Latitudes of northern Mato Grosso for example (10-14°S) had the possibility of planting double cropping systems by 1984, but only in a very narrow window. After 1990, however, planting was possible right after the rainy season started on the late onset years. These results indicate that not only the expansion of soybeans to MT, but also the feasibility of planting two crops were a result of the development of photoperiod-insensitive varieties in the first cycle of soybean breeding in Brazil. Further analyses will reinforce this notion.

Although this is to my knowledge the first work to quantify the large-scale effects of the overcoming of the photoperiod barriers, the flexibilization of planting dates is known to have been a desired effect of breeders (Spehar 1994). The use of the northernmost latitude with harvested soybeans is a methodology that delays the detection of new technologies, as they will only be detected when adopted at threshold conditions. However, during the rapid expansion of the 1970-80s, technology adoption by pioneers was known to be very fast. Varieties suitable for planting above 15°S are reported to have been developed in 1980 and made available to the large public about two years later (Spehar 1994, Destro et al 2001), year when our methods first detected harvest above 15°S (Figure 5b). Moreover, the fact that experimental optimal-yielding planting dates are generally close to the beginning of the rainy season (Silva et al 2015, discussed in Table 2 later) and that double cropping systems depend on planting as early as possible are a strongly indication that, in addition to allow the northern expansion of tropical soybeans, the radical changes in photoperiodic dependence during 1974-1990 had a strong influence on the efficiency and profitability of soybean farms through the flexibilization of planting dates.

The regional photoperiod and climatological rain (PCR) calendar was developed using the same rationale described in Figure 5c-d. Based on the climatological rain, it describes the temporal patterns based on the evolution of photoperiod dependence and an estimate of climate risk by using the 20% latest rainy season onset quantile. Figure 6 shows the earliest possible planting dates based on the PCR calendar, while Figure 7 shows the latest possible planting dates for single cropping soybeans on the same calendar, both along their limiting factors.

In the 1970s, the beginning of planting was mostly limited by photoperiod. As explained earlier, planting in most regions became limited by the rainy season during the 1980s (Figure 6a,b,i,j). The most notable exception is southern Brazil, where rain is well distributed through the year. The northernmost portions of MT and MATOPIBA were also limited by the photoperiod until the late 1990s.

Table 2 presents a comparison of the possible planting window of the photoperiod and climatological rain (PCR) calendar for the 2012 harvest year with a recent assessment of recommended planting dates for several regions in Brazil (Silva et al. 2015). This assessment is a review of multiple experimental results and expert recommendations on the planting dates that maximize yields with suitable plant heights. All recommended planting dates fall inside the possible planting window defined. With the exception of southern Brazil, where the low latitudes and poorly defined rainy season make the planting window very wide, the recommended planting dates fall within the first 90 days after the earliest possible planting date. The planting window described here considers all the dates when the plants are not subject to continuous drought or severe cycle shortenings due to photoperiod. The definition of optimal yielding planting dates, however, also take into account factors such as amount of radiation and temperature dependencies that are more dependent on the specific variety used. The fact that all recommended dates are inside the possible planting window defined by the PCR calendar, and with the particular pattern of being on the first months, indicates that the methods presented here are robust and consistent with field experience.

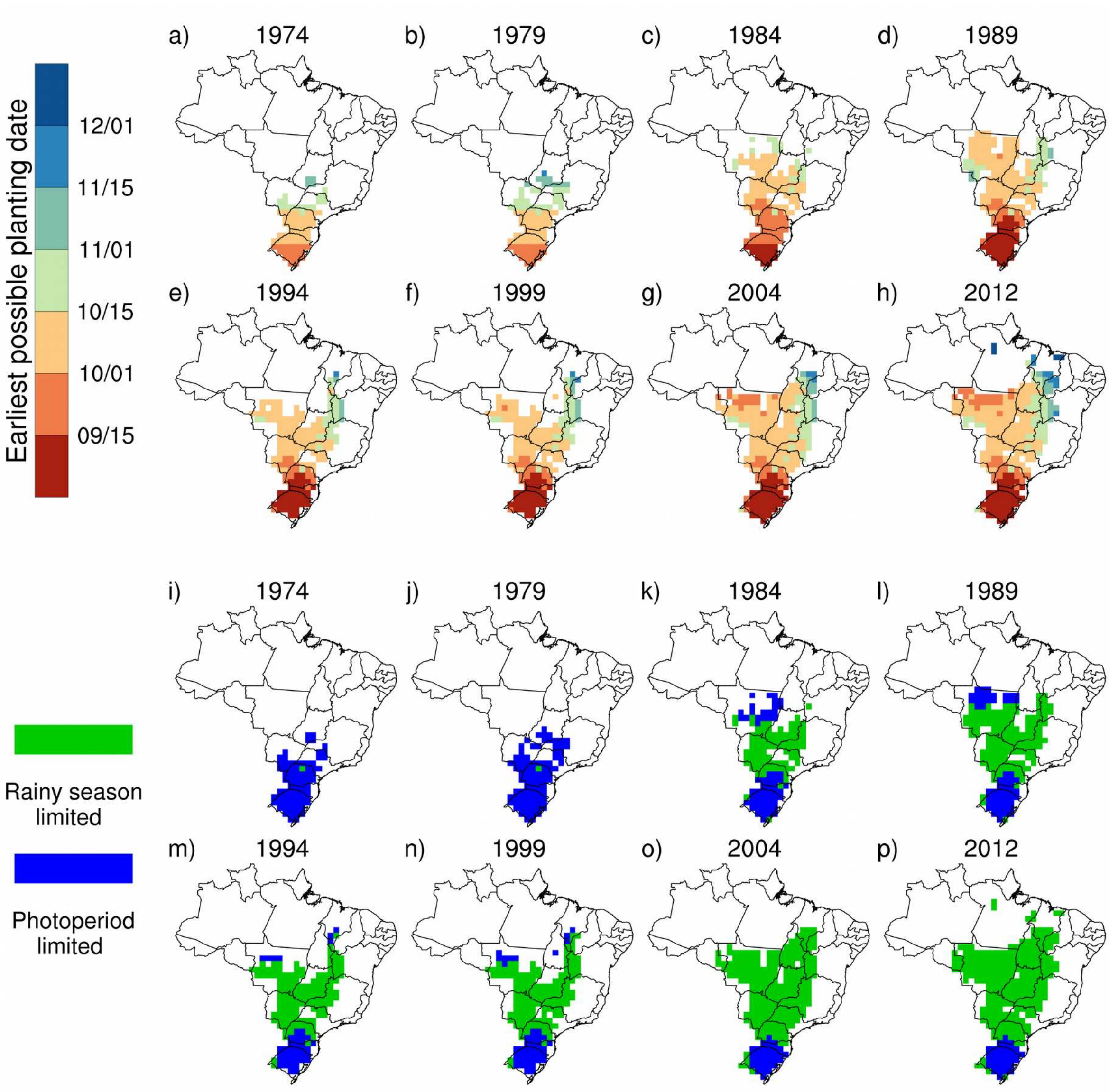

Figure 6: Estimated earliest planting dates for selected years on the photoperiod and climatological rain calendar (PCR, a-h) and their corresponding limiting factors (i-p)

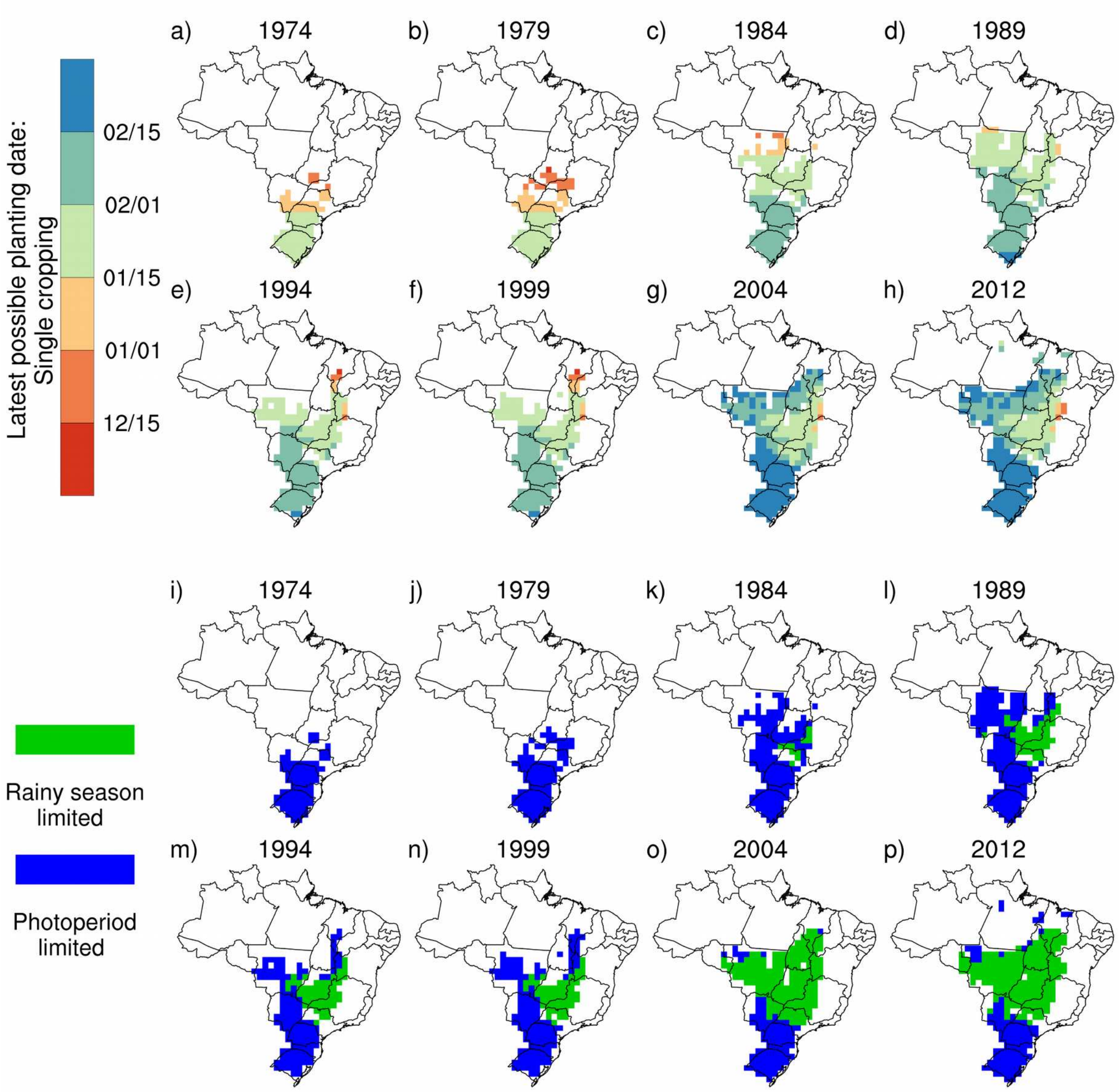

Figure 7: Estimated latest planting dates of single cropping soybeans for selected years on the photoperiod and climatological rain calendar (PCR, a-h) and their corresponding limiting factors (i-p)

Table 2: Comparison of the possible planting window of the photoperiod and climatological rain (PCR) calendar with the recommended planting dates found on Silva et al. (2015). Each column represents a 2-week period.

Region	Source	Sep		Oct		Nov		Dec		Jan		Feb	
South	PCR 2012	x	x	x	x	x	x	x	x	x	x	x	x
	Silva et al. (2015)				x	x	x	x					
MG	PCR 2012			x	x	x	x	x	x	x	x	x	
	Silva et al. (2015)				x	x	x						
MT,MS and GO	PCR 2012		x	x	x	x	x	x	x	x	x	x	x
	Silva et al. (2015)			x	x	x	x	x					
MATOPIBA, except northern MA	PCR 2012			x	x	x	x	x	x	x	x	x	x
	Silva et al. (2015)					x	x	x					
Northern MA and northeastern PA	PCR 2012							x	x	x	x	x	
	Silva et al. (2015)								x	x	x		

The latest possible planting dates of the first crop in a double cropping system in the PCR calendar are presented in Figure 8. Pixels are labeled “not possible” if the earliest possible planting date is after the latest possible date. This occurs when the rainy season in 20% of the years is too short or if the photoperiod limitations make the usable part of the rainy season too short for exclusively rainfed double-cropping. The practice may then be possible on “not possible” pixels with the use of irrigation. The limiting factor for the latest planting date was found to be the duration of the rainy season for all regions where double cropping was considered possible in the entire period, as suggested by Figure 5d. The rainy season limitation is constant over time on PCR. Therefore, all pixels where double cropping was labeled “not possible” in earlier years but eventually became rainy-season limited (and thus possible) were limited before by the photoperiod. That said, double cropping in the areas of GO that were planted with soybeans in 1979 (Figure 8j) was made possible only in 1984 (Figure 8k) with the flexibilization of planting dates caused by the overcoming of photoperiodic limitations. The yearly evolution of these limitations (Figures 9) shows that double cropping in southern MT was progressively made possible by the gradual overcoming of photoperiodic limitations between 1980-1984.

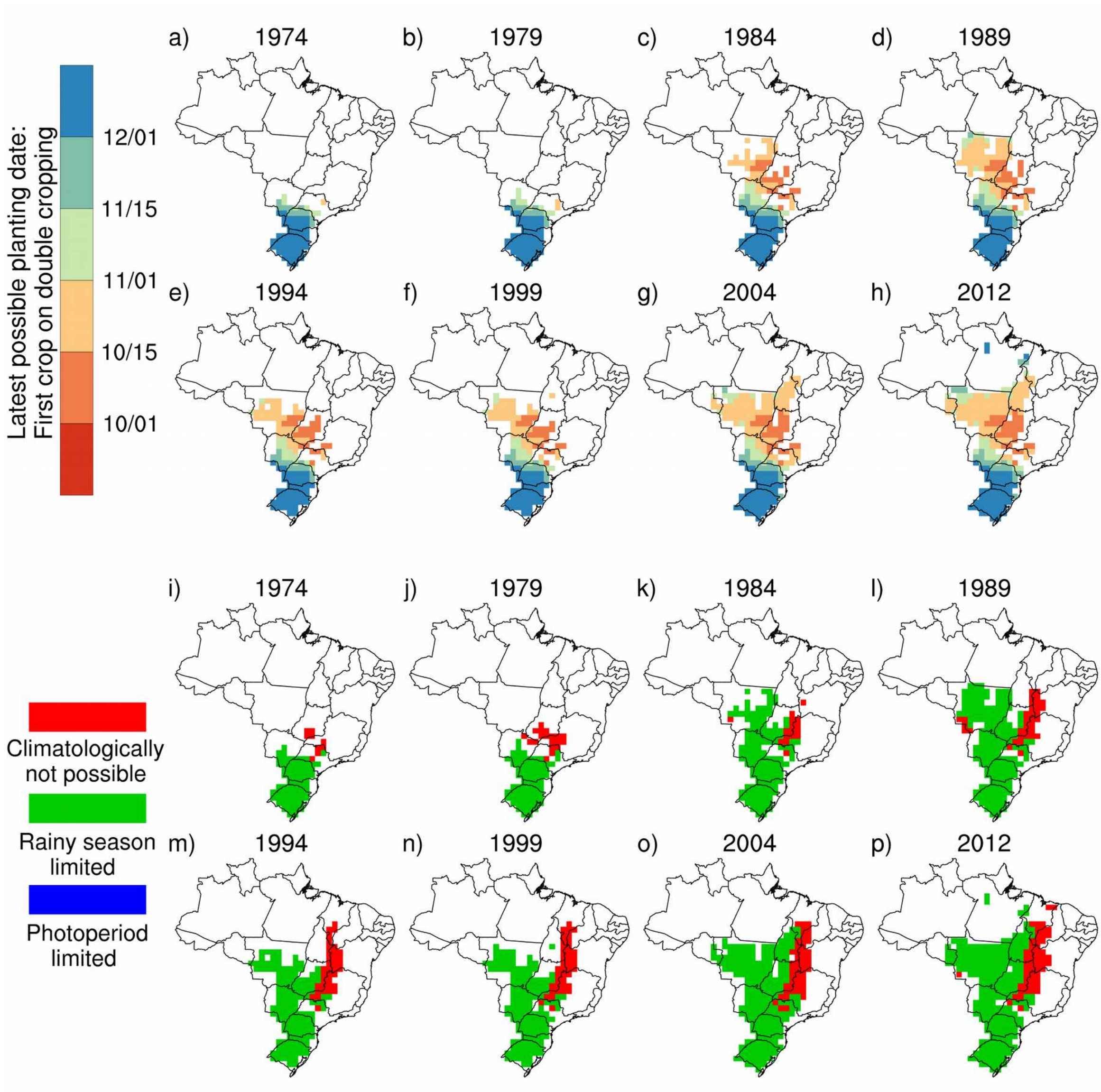

Figure 8: Estimated latest planting dates of the first crop in a double cropping system for selected years on the photoperiod and climatological rain calendar (PCR, a-h) and their corresponding limiting factors (i-p)

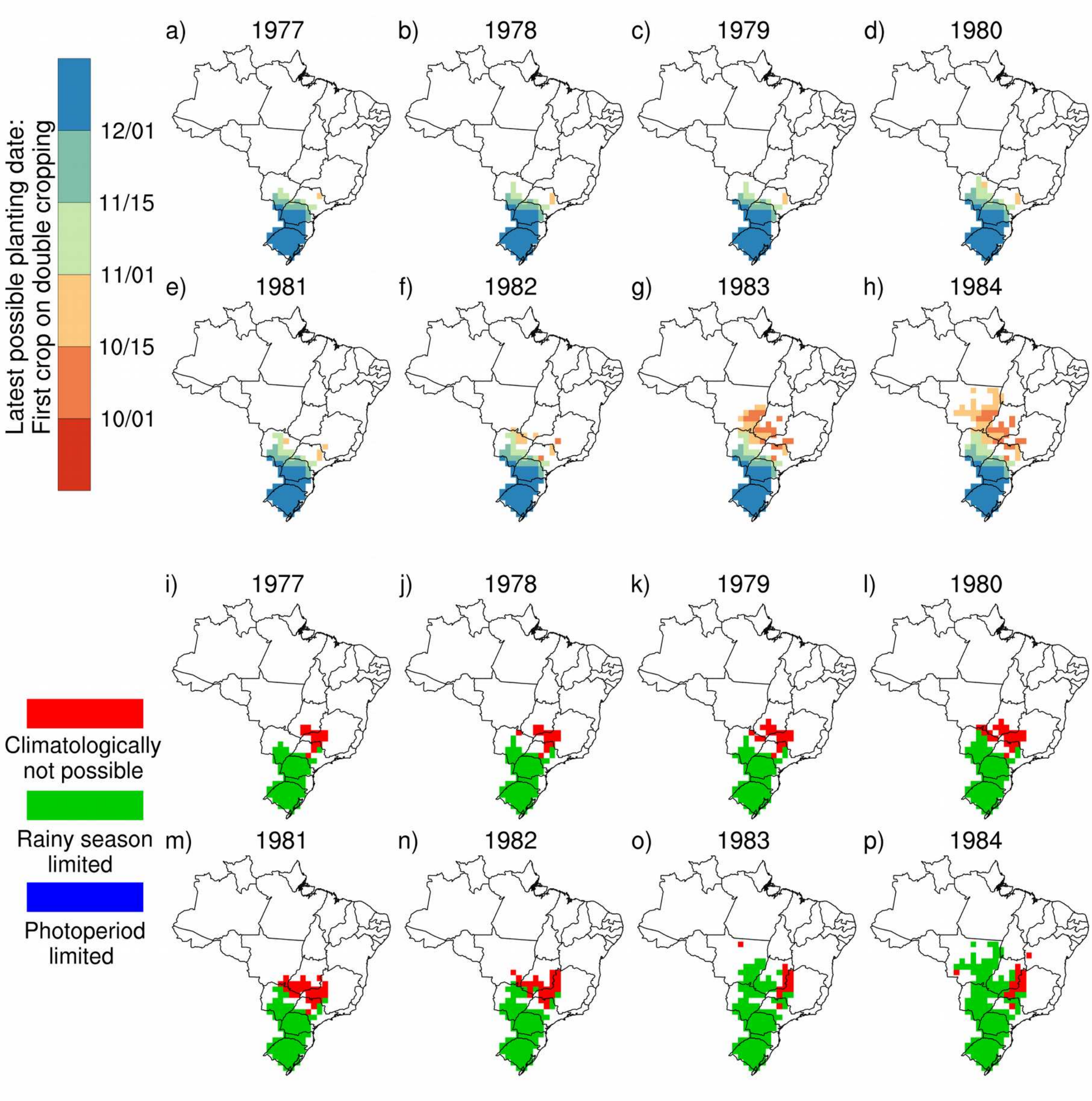

Figure 9: Same as Figure 8, but for the years between 1977 and 1984

Latest possible harvest dates do not change with time in the photoperiod and climatological rain calendar (Figure 10) as they are based only on climatological rainy season parameters. On four fifths of the years, harvest can happen until May in practically all regions harvested with soybeans in 2012, and later than June 1st on most of them. However, a 2007 federal law determined that every state must set a sanitary break period of at least 60 days to break the life cycle of some diseases, in particular the Asian rust (Seixas and Godoy 2007). During this period it is illegal to have any soybean plants in the field, so harvest (planting) must happen before (after) it. The exact dates of the sanitary break vary between and within states, but are generally in the end of the dry season, between mid June to late September on the Midwest, South and Southeast and between early July and late October for most of MATOPIBA, generally outside the earliest planting – latest harvest window defined on the photoperiod and climatological rainy season calendar.

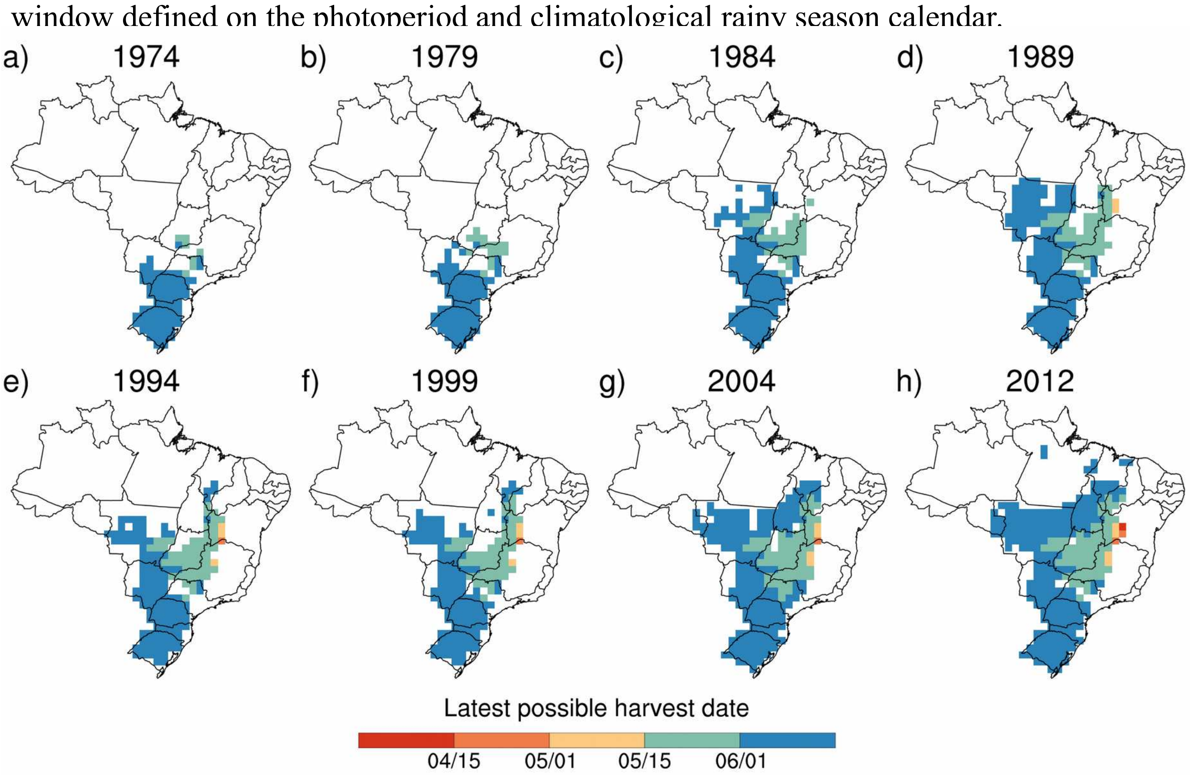

Figure 10: Estimated latest possible harvest dates for selected years on the photoperiod and climatological rain calendar (PCR)

The photoperiod and meteorological rain calendar (PMR) was developed based on the same principles as PCR but using the actual rainy season onset and end of each year (Figures 11, 12, 13 and 14). It presents the same general patterns of the PCR calendar, but adds the variability between the years as a consequence of considering the interannual variability in rain. By combining the evolution of photoperiodic limitations validated with the PMR calendar with year by year information about the rainy season, the PMR calendar provides unprecedented precise spatial and temporal information on the actual soybean growing season in Brazil. The planting date information used on previous works that analyze relationships between climate and agriculture worldwide or even on specific countries have spatial descriptions limited to broad regions (e.g. Sacks et al. 2010, Ray et al. 2015) or whole countries (e.g. Schlenker and Roberts. 2009, Burke and Emerick 2015), and no temporal informational at all, although they generally recognize its importance. On short timescales, such spatial and temporal detail leads to a better representation of the interannual climatic variations the plants are subject to. For example, calculating precipitation averages over a period after a fixed planting date can lead to sampling days outside the rainy season in years where its onset is unusually late, and thus underestimate the growing season average. On long time scales, such detail is essential to capture the climatic variations when cropping areas change, as was previously noted by Lobell and Field (2007) and will become clear in the Brazilian case in Section 3.3.

Similar to Figure 8, pixels are labeled “not possible” in Figures 11 and 12 if the earliest planting date falls after the latest planting date estimated for single cropping systems, meaning that the portion of the rainy season with suitable photoperiods is shorter than the 90 days discussed above. Therefore, in some years (1974, 1979, 1989 and 2012 shown in Figures 11 and 12) regions on southern RS and central PI experienced short rainy season conditions that likely had a negative impact on yields due to water stress. Lower yields on these regions can be verified on Figure 3 for all the aforementioned years except for the PI regions on 2012. It should be noted, however, that irrigated soybeans are increasingly common on the area (EMBRAPA 2016), and the relatively coarse resolution of the precipitation data can mask diverse subgrid conditions. Figure 13 displays the limitations for double cropping, where “not possible” pixels also mean short usable rainy season conditions that may had a negative impact on double cropping systems at each particular year, specially on the second crop.

The meteorological rain-only calendar (MRO) does not represent the spatial reality for the years before 2012, and is identical to the PMR calendar on 2012 (Figure 15h). It represents the theoretical planting limitations if the photoperiod-insensitive varieties of 2012 were available in 1974, and will be used in the next section to quantify the effects of local trends in climate.

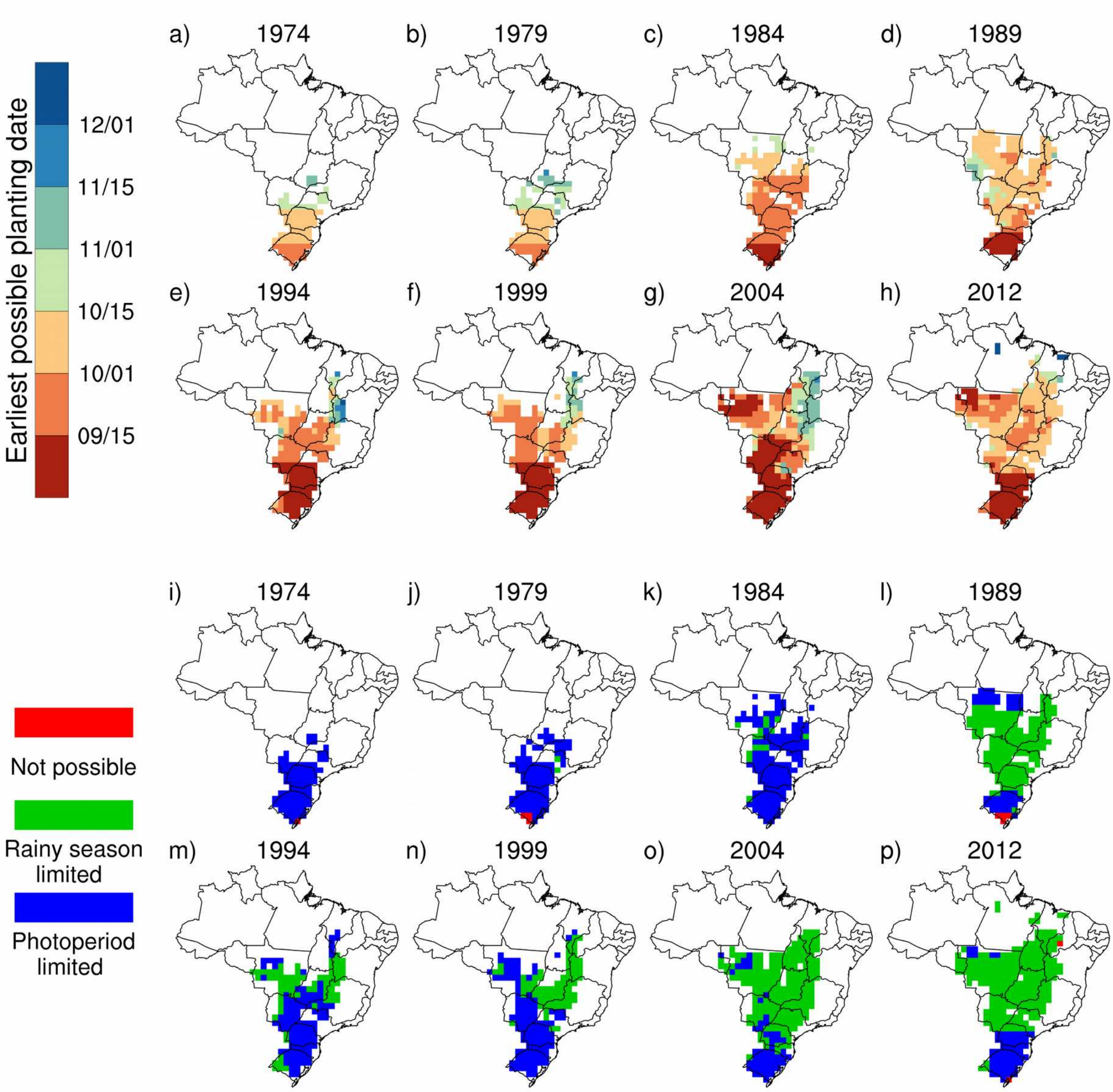

Figure 11: Estimated earliest planting dates for selected years on the photoperiod and meteorological rain calendar (PMR, a-h) and their corresponding limiting factors (i-p)

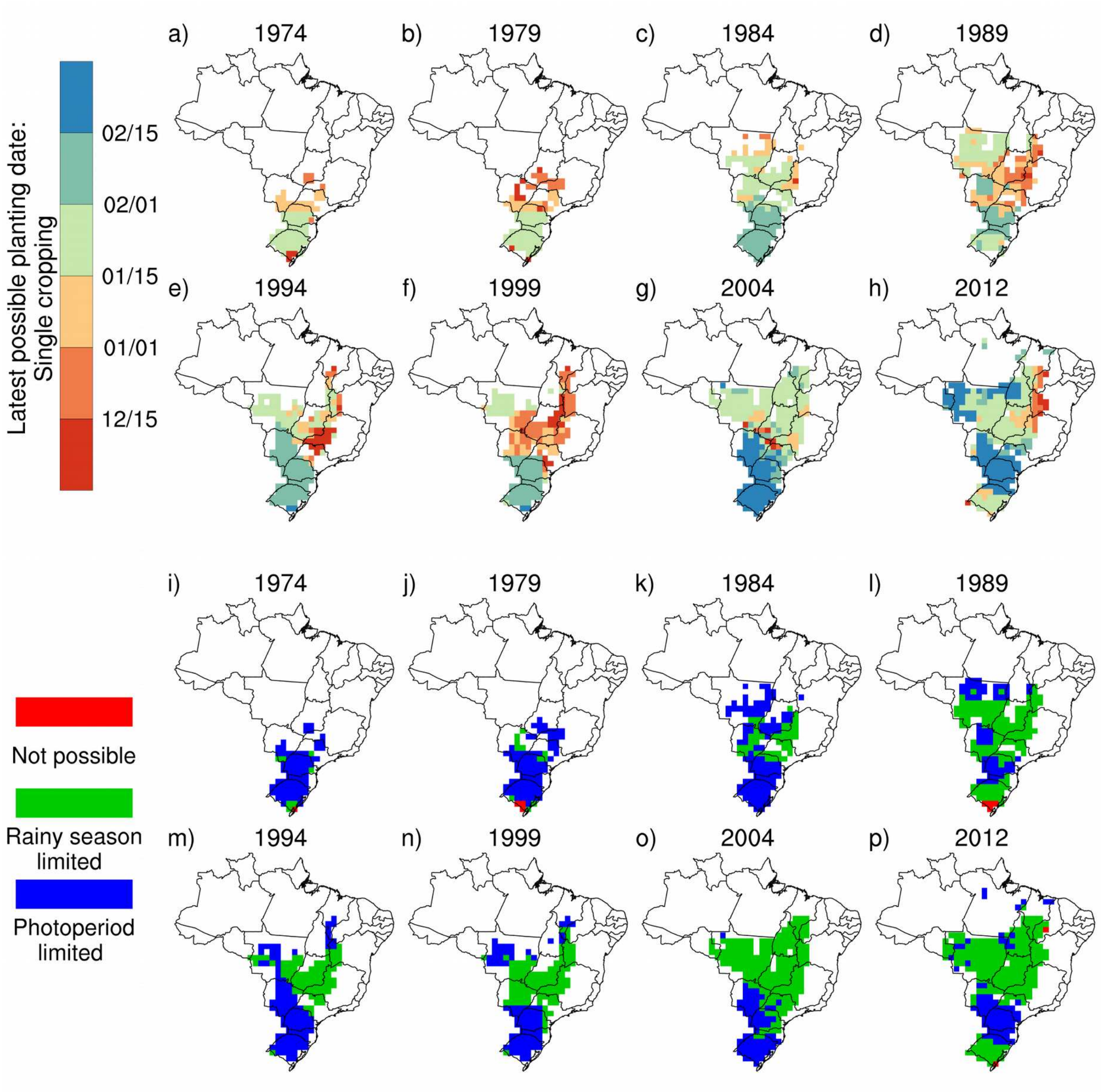

Figure 12: Estimated latest planting dates of single cropping soybeans for selected years on the photoperiod and meteorological rain calendar (PMR, a-h) and their corresponding limiting factors (i-p)

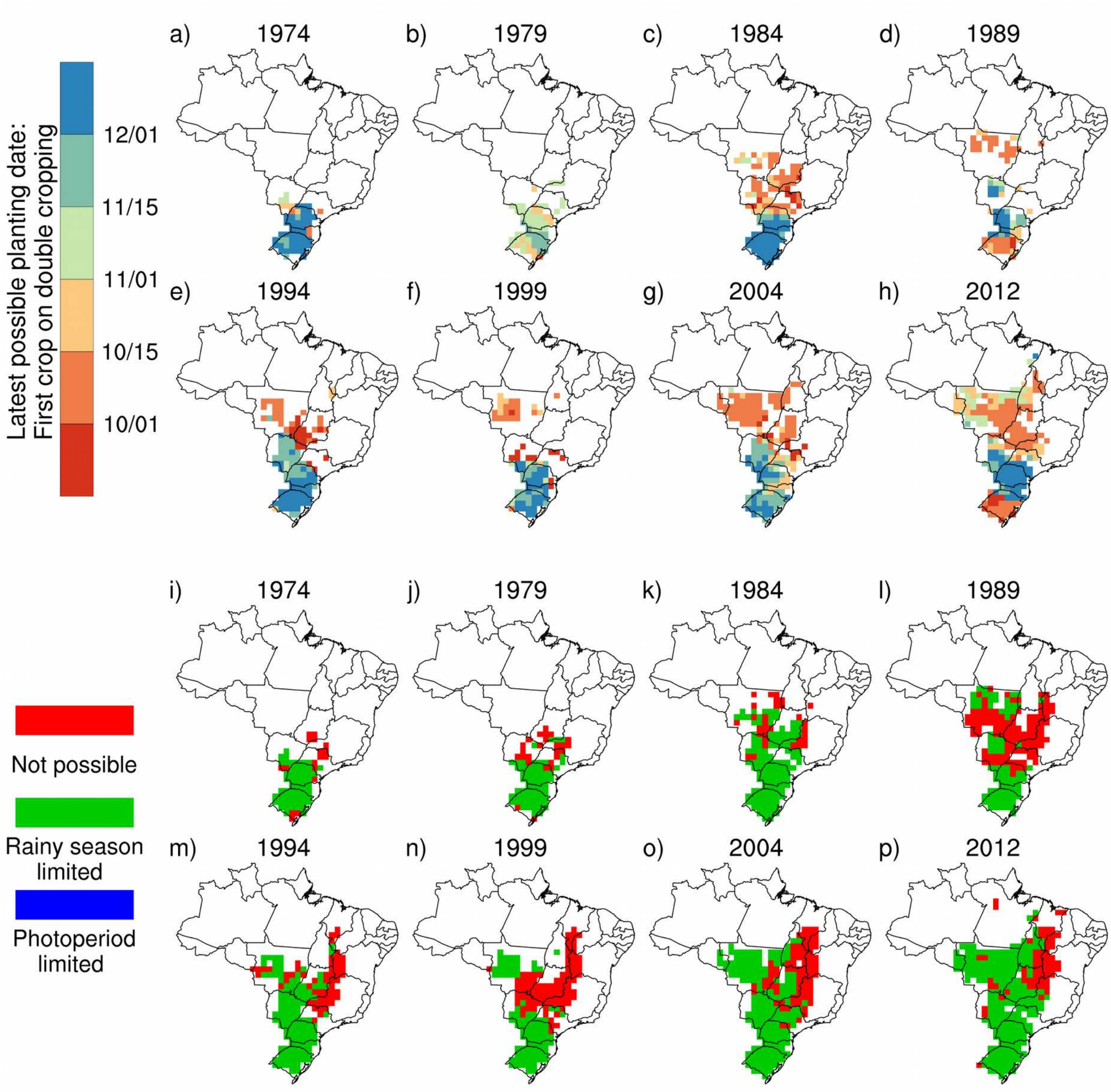

Figure 13: Estimated latest planting dates of the first crop in a double cropping system for selected years on the photoperiod and meteorological rain calendar (PMR, a-h) and their corresponding limiting factors (i-p)

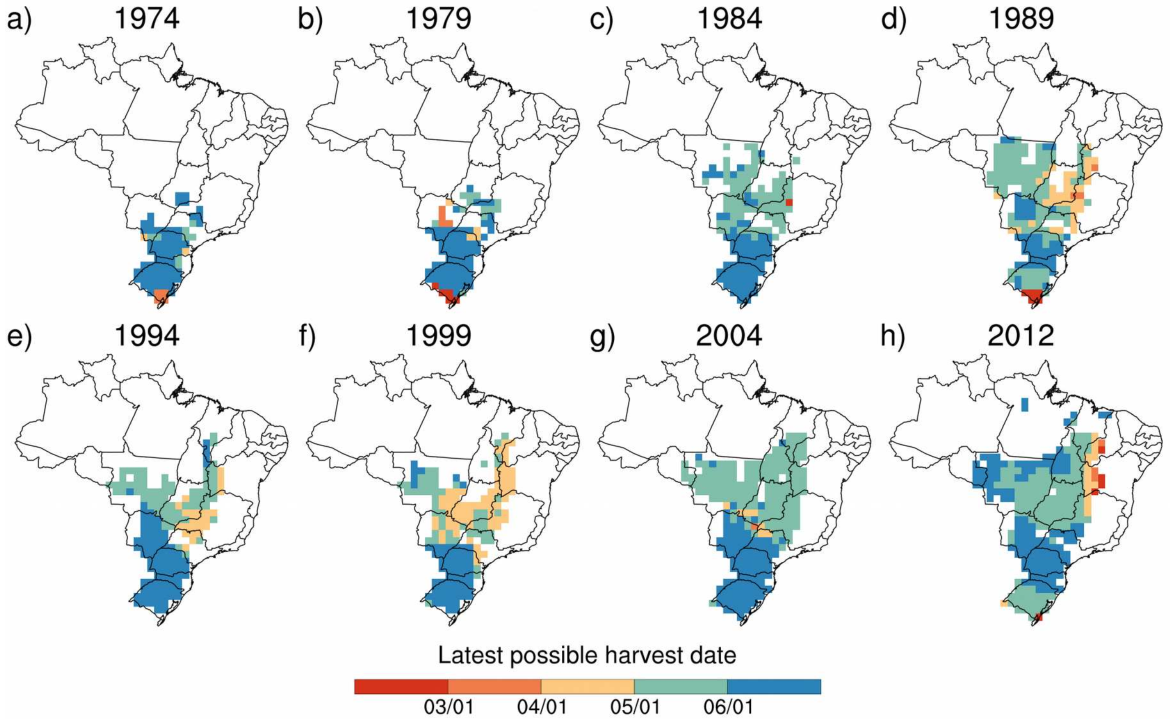

Figure 14: Estimated latest possible harvest dates for selected years on the photoperiod and meteorological rain calendar (PMR)

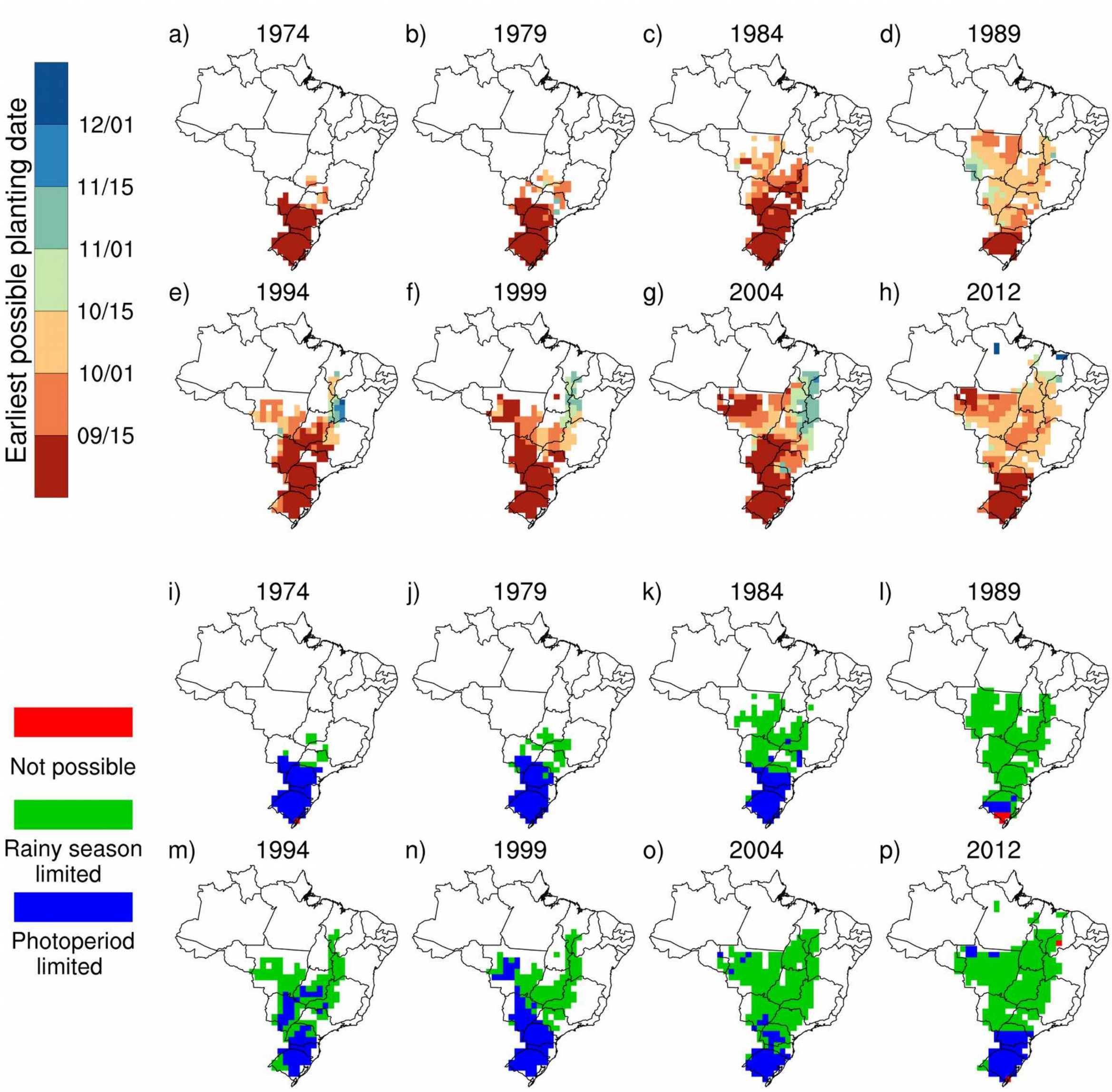

Figure 15: Estimated earliest planting dates for selected years on the meteorological rain only calendar (MRO, a-h) and their corresponding limiting factors (i-p)

3.3. Local and expansion-driven climate change

After defining the planting window with the PMR and MRO calendars, growing season averages were calculated for average daily temperature ($\overline{T}$) and excess precipitation ($\overline{P\text{-}ETC}$) using both datasets and Equations 7,8 and 9. The choice of using only the first 90 days of the planting window as planting dates was based on the comparison of the calendars with literature on recommended planting dates (see the discussion on Table 2).

Figure 16 summarizes the results for $\overline{T}$ of the average of both datasets, using the growing season defined using the earliest planting date of the PMR calendar (with one exception, mentioned later). Figures 16a-c are maps of yields (raster color) with growing season isotherms overlaid as contour lines, both averaged over 5-year periods. Each colored dot in Figure 16d represents the yield of a 1° x 1° pixel with a fraction of soybean harvested area higher than 0.5% at each year on the Y axis, with their color representing their average growing season temperature with the same temperature classes as Figures 16a-c. Values are spread on the X axis inside each year based on their temperature values. Horizontal color bars are the area-weighted yearly average growing season temperature, while thick color lines are trend lines of these averages for each temperature class. The 0.5% threshold was used here for the same reasons as the 1% in Section 2.3, and is higher in order to be more inclusive on the scale of the coarser grid.

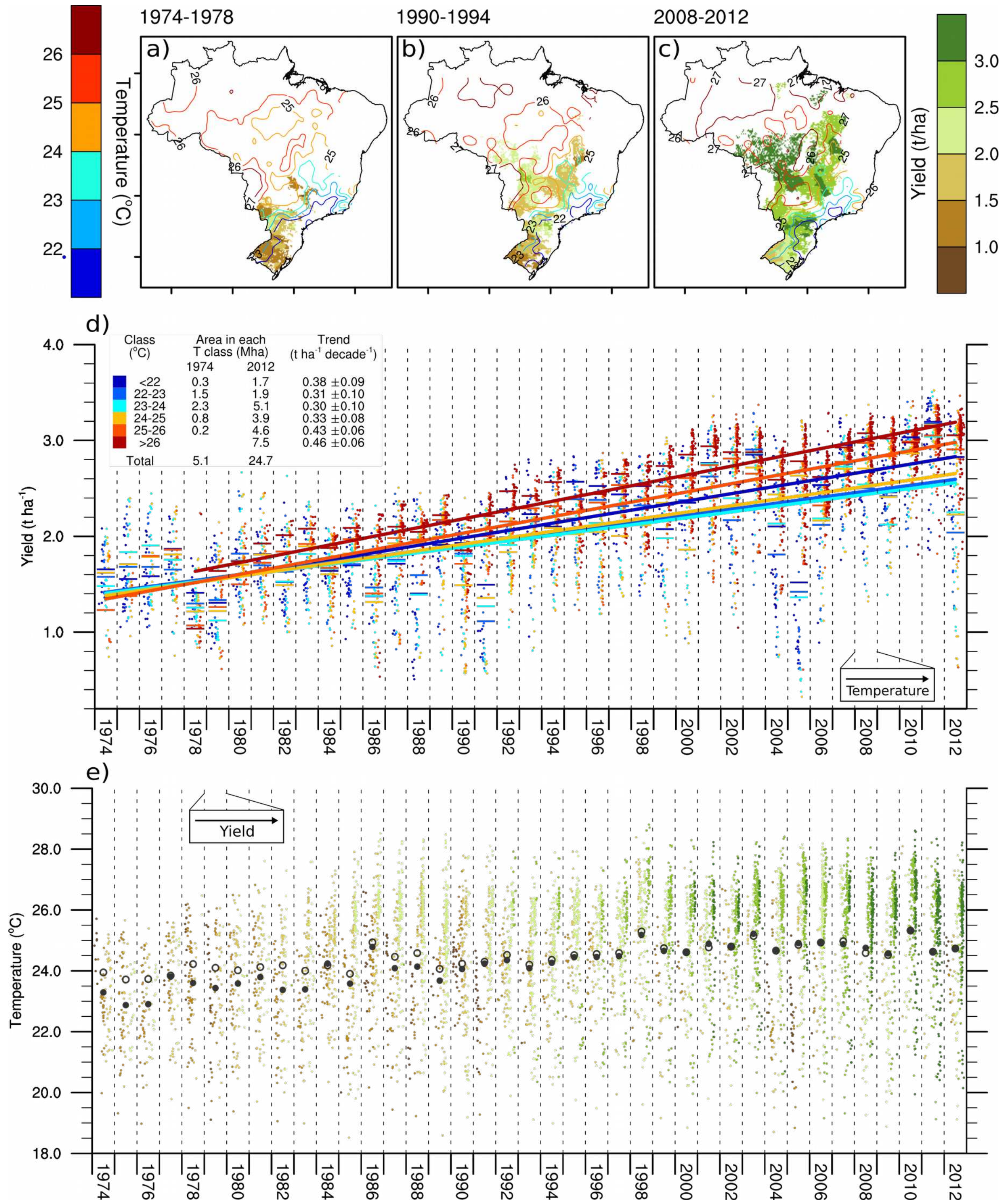

Figure 16: (a-c) Average soybean yields, with average growing season isotherms overlaid, calculated with the MRO calendar; (d) Yield values by temperature classes. Each point represents a 1° x 1° pixel with harvested soy area >0.5%, with colors representing growing season temperature calculated using the PMR calendar. Horizontal colored bars are the area-weighted gravity centers for each temperature class in each year, and colored thick lines are the trends in these values; (e) Same as (d), but temperature values by yield classes. Black filled circles indicate the average temperature on the PMR calendar, weighted by the area of each year, representing the total climate variation during the expansion. Black hollow circles are the same but using the MRO calendar and weighting all years by the production of 2012, representing only the local variations in climate.

Figure 16e is similar to Figure 16d, but each dot represents the average growing season temperature on the Y axis, while their color represent the yield in the same classes as Figures 16a-c. Black filled circles are the area-weighted average temperature at each year. These circles represent the expansion-driven climate change, accounting for local climate trends, changes in area distribution and the flexibilization of planting dates caused by the photoperiod changes. To isolate the local climate trends' effect, the climate variables were also averaged using the MRO calendar, that considers the photoperiod limited planting window of 2012, and weighting all years by the harvested area of 2012. The results of this procedure for $\overline{T}$ are the hollow circles in Figure 16e. Using the area weights of a single, recent year was the procedure adopted for the global studies of Lobell et al (2011) and Lobell and Field (2007) and is a reasonable approximation for most extratropical agricultural regions, where cropping areas haven't shifted significantly. As discussed before this is not the case in Brazil (Figure 2), and the marked differences between it and the year-by-year weights on Figure 16e illustrate the differences that can arise from this simplified approach.

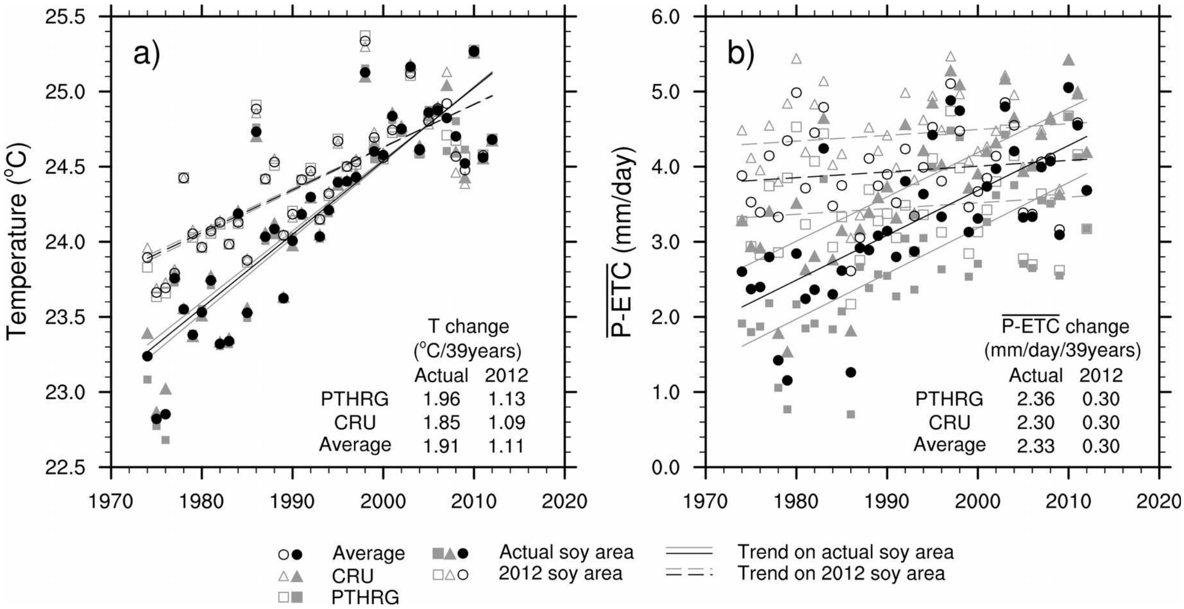

Figure 17: Trend analysis of area-weighted growing season averages of (a) temperature and (b) precipitation minus crop potential evapotranspiration ($\overline{\text{P-ETC}}$) for both climate datasets and their average. Gray symbols represent data for each separate dataset (PTHRG and CRU) and gray lines the trend on each. Black symbols and lines are the same but for the average of the datasets.

Soybeans moved mostly toward warmer regions, but the regions with soybeans in 2008-2012 were also generally warmer then the same regions on 1974-1978 (Figures 16a-c). Total local warming was of 1.11°C on the 39-year period on average, with similar results using only the PTHRG (1.13°C) or CRU (1.09°C) datasets (Figure 17a). When the expansion-driven climate trends are accounted for the total effect is of 1.91°C, a 65% increase in relation to the local trends only. This means that about 40% (0.78°C) of the total warming suffered by soybeans in Brazil as a whole were due to changes in location of the crop i.e., the planting areas expanding into warmer regions.

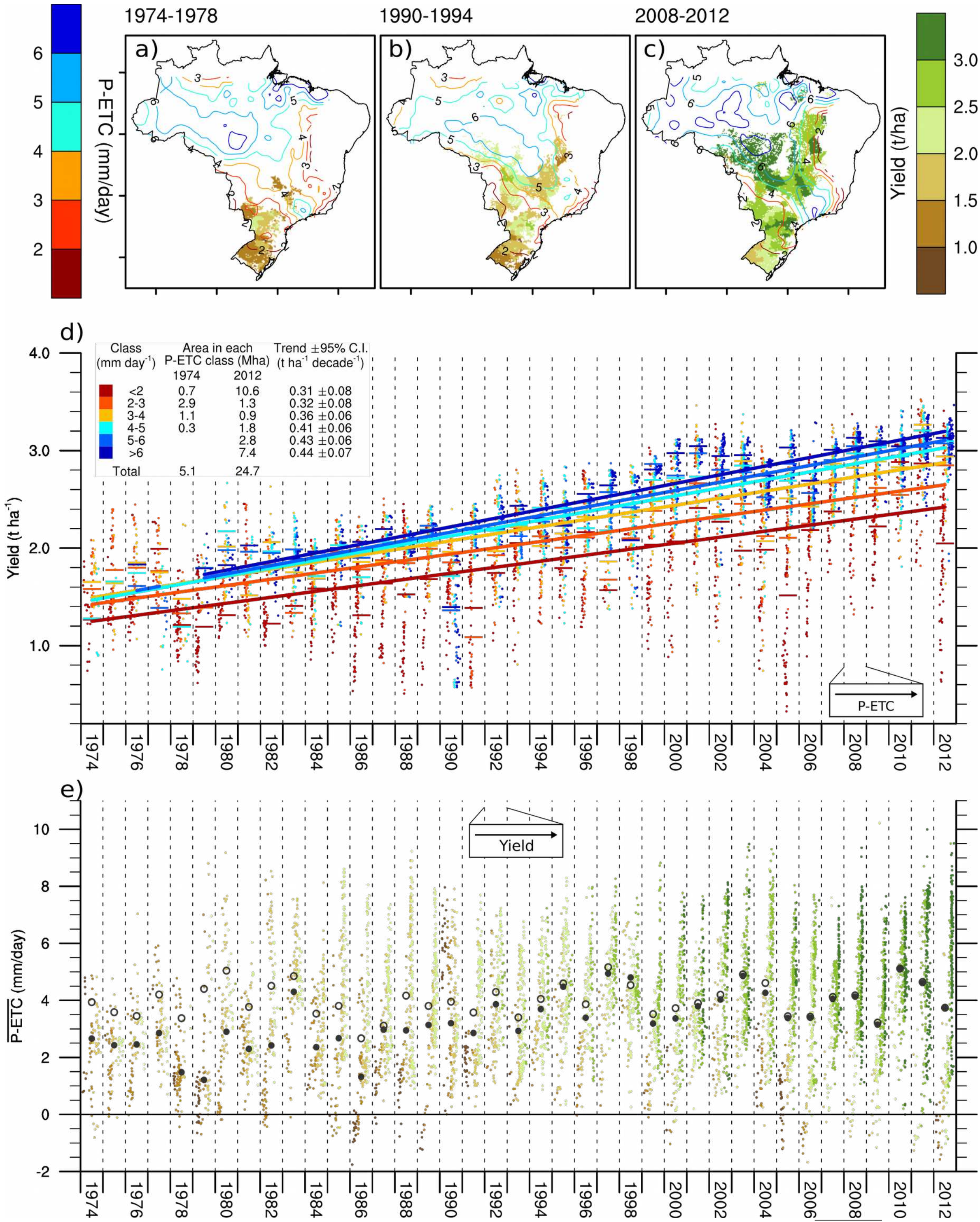

Figure 18: (a-c) Average soybean yields, with average growing season isolines of $\overline{\text{P-ETC}}$ overlaid, calculated with the MRO calendar; (d) Yield values by $\overline{\text{P-ETC}}$ classes. Each point represents a 1° x 1° pixel with harvested soy area >0.5%, with colors representing growing season $\overline{\text{P-ETC}}$ calculated using the PMR calendar. Horizontal colored bars are the area-weighted gravity centers for each $\overline{\text{P-ETC}}$ class in each year, and colored thick lines are the trends in these values; (e) Same as (d), but $\overline{\text{P-ETC}}$ values by yield classes. Black filled circles indicate the average $\overline{\text{P-ETC}}$ on the PMR calendar, weighted by area year by year, representing the total climate variation during the expansion. Black hollow circles are the same but using the MRO calendar and weighting all years by the production of 2012, representing only the local variations in climate.

Figure 16d indicates that yields in warmer regions generally rose faster than in colder regions, although no trend is statistically significantly different from the others (all p-values > 0.3). An exception is the regions with temperature below 22°C. This can be partially explained by the warming of the generally low yielding west of RS, that commonly had temperatures on that range in the beginning of the period (Figure 16a) but gradually warmed and started belonging to higher temperature classes with time (Figures 16b-c). On the 1970s, when the soy crop still wasn't consolidated in the warmer central Brazil, colder regions generally yielded better (Figure 16d). After the consolidation of MT and northeastern GO as high yield regions in the 1980s (Figure 3c), the highest average yields started being normally achieved on regions with temperatures above 25°C (Figure 16d).

As discussed before, the yields in southern Brazil that were relatively stagnated started to rise rapidly in the 1990s creating a convergence of yields throughout the country (Figure 4). Consequently, average yields on cooler regions (<24°C) were occasionally higher than in the warmer ones (>25°C) after the mid-1990s. However, this was not frequent, likely because of the aforementioned problem of heavy interannual variability of southern Brazil's climate.

The general pattern observed on all panels of Figure 16 is that the highest yields are normally achieved in warmer regions, and that yields also grew more rapidly in such regions. This result apparently conflicts with the general notion that warming on tropical regions is harmful to soybean yields, supported by both empirical and process-based modeling studies (Lobell et al. 2011, Rozenzweig et al. 2014). This negative effect is generally associated with decreases in photossynthetical efficiency, increases in evapotranspiration and the acceleration of the crop's cycle, that shortens the time for plant development and carbon assimilation (Avila et al. 2013, Gavioli 2013, Puteh et al. 2013, Silva et al. 2015).

The effect of temperature on plant development is important to yield response, as higher temperatures accelerate the plant's cycle, specially the vegetative period. This leaves less time for the plant to accumulate the dry matter necessary to support optimal grain filling during the reproductive period (Gavioli 2013, Viana et al. 2013). Hastening of the reproductive period due to higher temperatures is also detrimental as there is less time to fill grains (Assad et al. 2013). However, after decades of breeding to the very diverse environments in Brazil, farmers can select from a wide range of varieties in terms of cycle length. The current varieties available vary considerably in terms of development dependence on temperature, and may have cycles as long as 137 days and as short as 108 days in both the cool south and the warm central Brazil (Alliprandini et al. 2009). In fact, farmers in central Brazil prefer shorter-cycle varieties due to the possibility of double cropping. Therefore, even if future temperature conditions exceeds farmer's previous experience in terms of cycle shortening, the varieties that have longer cycles under the current lower temperatures may be suitable to their needs.

More careful investigation is needed on the effects of higher temperatures on photosynthetical efficiency and development rates in Brazil and will be left to further studies. However, the positive effects of higher rainfall of central Brazil may have offset the theoretically negative effects of higher temperatures, specially on evapotranspiration. This higher precipitation effect may be important but it will be shown later that, with the careful determination of planting windows, most of soybeans in Brazil were and still are planted under excess rainfall on most years. Therefore, the negative effects of increased evapotranspiration may be small.

It is likely, however, that as part of the development of systems and varieties of soybeans for the warmer regions during the expansion, those effects were minimized at great extent. EMBRAPA (2011) states that the optimal temperature for soybeans plants in Brazil is around 30°C. This is 4°C above the 26°C observed in the U.S. by Schlenker and Roberts (2009), although these values may not be comparable due to methodological differences (see Section 3.4). It's worth mentioning that a considerable part of the genetic material of Brazilian soybeans was originated from the U.S. The profound changes in sensitivity to both temperature and photoperiod described here are widely considered as the result of large and efficient efforts in soybean research and development that effectively reinvented the crop (Albuquerque and Silva 2008, Gavioli 2013, Bezerra et al. 2015).

One also might argue that the higher yields on warmer regions are caused by other factors, such as better soil, infrastructure or pest conditions. As discussed, adapting the systems to the different soil and pest conditions of central Brazil was a major challenge to researchers of the 1970s. In either way, it still stands that soybeans are achieving the highest yields today on environments that the extensive literature cited regarded as unsuitable in the 1970s.

Figure 18 is the same as Figure 16, but for average excess precipitation ($\overline{\text{P-ETC}}$). As the calculation of crop potential evapotranspiration ($\overline{\text{ETC}}$) does not account for reductions in evapotranspiration caused by soil water deficits, our estimates of excess precipitation can be considered as lower bound conservative. The careful definition of the growing season used prevents the inclusion of dry periods before the onset of the rainy season on the analysis. A negative value of $\overline{\text{P-ETC}}$ means that total precipitation was less than the potential evapotranspiration, and therefore on average plants were subject to water deficit. But, as $\overline{\text{P-ETC}}$ is an average value, it can mask variations within the growing season, such as dry spells, that may have led to water stress in some days and consequently to negative impacts on yields. Such dry spells are known to be important on southern Brazil, where the rainy season is not well defined (Melo et al. 2004). Here it is considered, however, that the zero $\overline{\text{P-ETC}}$ value is a conservative limit to harmful drought because (i) as ETC is a potential measure of evapotranspiration, $\overline{\text{P-ETC}}$ is a lower bound estimate of excess precipitation; (ii) water stored in the soil can be enough for the soybean plant's needs during short dry spells, as its water uptake capacity is relatively robust to high soil water tensions (Allen et al. 2006). Also, higher average season excess precipitation ($\overline{\text{P-ETC}}$) generally lead to less chance of negative P-ETC on a given short time period.

As higher temperatures normally lead to higher evapotranspiration, one could expect that the patterns for $\overline{\text{P-ETC}}$ would be the opposite of temperature. However, the warmer regions of central Brazil to where the soybean expansion first went have substantially more precipitation during the growing season than southern Brazil, thus leading to higher $\overline{\text{P-ETC}}$ (Figure 18a-c). The local trend in $\overline{\text{P-ETC}}$ (i.e. the trend on areas with soybeans in 2012 using the MRO calendar) represents a total change of 0.30 mm day^{-1} on the entire period (Figure 17b). This trend is very robust to the choice of climate dataset, even though the actual values of $\overline{\text{P-ETC}}$ differ substantially across them. If the changes in location are considered, however, the average trend in $\overline{\text{P-ETC}}$ over the 39-year period is of 2.33 mm day^{-1}, with little changes when the PTHRG (2.36 mm day^{-1}) or CRU (2.30 mm day^{-1}) datasets are considered separately.

This shift to regions with more excess precipitation can be seen in more detail on Figure 18e. Soybean areas were close to the zero line in the beginning of the period, with dry years such as 1978 and 1979 having $\overline{\text{P-ETC}}$ values around 1 mm day^{-1}. There were regions with $\overline{\text{P-ETC}}$ below zero in some years, all located in the state of RS (not shown). In these regions, yields were among the lowest of their years. The growing season averages in the 2000s were all above 3 mm day^{-1}, with maximum values above 5 mm day^{-1}.

The significant increase of 2.33 mm day^{-1} in excess precipitation on the period means that typically Brazilian soybean production became more resilient to possible negative changes in average precipitation. However, when the most sensitive portion of the production is analyzed the same did not happen. Figure 19 is the same as Figure 18e, but with $\overline{\text{P-ETC}}$ values relative to total precipitation and weights calculated by production instead of area. Horizontal bars delimits the 5% production with lowest $\overline{\text{P-ETC}}$ relative to total precipitation. That means, for example, that 5% of total soybean production would be under average water stress if total precipitation was 11.02% lower in 2012, with negative impacts on yields.

The trend in the 5% lowest $\overline{\text{P-ETC}}$ relative to $\overline{\text{P}}$ values was not different than zero at a 95% confidence level (p-value = 0.10), despite the significant trend towards rainier conditions observed on the average (p-value < 0.001). This indicates that, although the average of the country's production is about 2.33 mm day^{-1} more resilient to negative precipitation changes in 2012 than in 1974, the 5% more vulnerable are not significantly more resilient. This is mostly because the reduction in relative contribution from the low excess precipitation southern Brazil was offset by an increase of contribution from the also dry MATOPIBA (Figure 18). All points below 5% were located in these two regions (not shown).

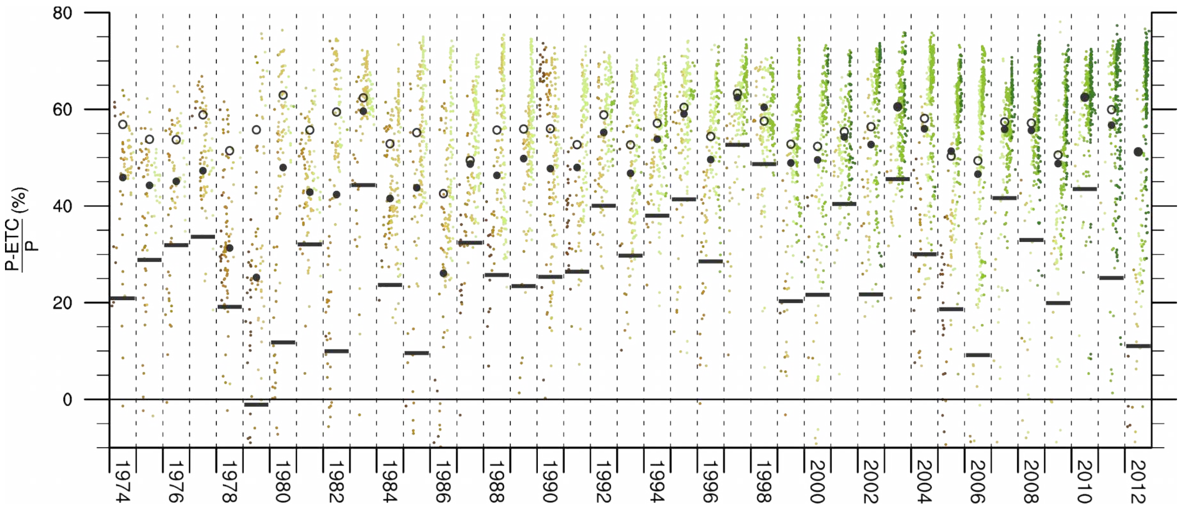

Figure 19: Same as Figure 18e, but with values of P-ETC relative to total P. Horizontal bars represent the 5% of total production with lowest P-ETC relative to total P.

The increase in atmospheric CO_2 concentration is also likely to have played a role in increasing yields. However, as this effect is strongly related with water stress, with little variation when P-ETC>0 (Sakurai et al. 2014), it is likely to be relatively uniform across the country. This apparently contradicts the findings of Sakurai et al. 2014, where most of Brazilian soybeans are generally subject to water stress. As discussed before, such differences can arise from a less detailed determination of planting dates.

3.4. Expectations for future climate

Figure 20 extends Figure 18e with the climate models' projections for $\overline{\text{P-ETC}}$. There is no significant trend on the ensemble mean $\overline{\text{P-ETC}}$ for the period 2013-2050. Also, the ranges on the ensemble mean remained similar to those of the late 2000's. Therefore no major changes on large scale drought in Brazilian soybeans are expected on the period analyzed. There are, however, large uncertainties on the range and spatial pattern of these changes. Some models predict an intensification of drought on the most sensitive regions (lower gray dashed line). Also, the pixels with minimum $\overline{\text{P-ETC}}$ on the ensemble mean (lower black dashed line) are consistently below zero, while minimum $\overline{\text{P-ETC}}$ pixels generally oscillate around zero for most of the historical period (lower black solid line). In the five years between 2045 and 2050, 2.84% of the soybean area (1.61% of production) are subject to $\overline{\text{P-ETC}}<0$ on the ensemble mean.

This effect is mostly due to more frequent severe droughts ($\overline{\text{P-ETC}}<0$) in southern Brazil in the ensemble mean for the future period (Figure 21). Also, the soybean area increased significantly during the 2000's on MATOPIBA, a region where negative $\overline{\text{P-ETC}}$ values occur in some years(Figure 21, see sections 3.1 and 3.3). Zero-crossing droughts in the region are predicted in the ensemble mean to be as infrequent as in the historical period (less than 10% of years), and to happen only in western BA where irrigation is common. However, this analysis does not account for the double-cropping systems that are increasingly common in MATOPIBA. Such systems are dependent on a long rainy season, and there is evidence that they might be threatened in the 2013-2050 period by changes in the seasonality of precipitation (Pires et al. 2016).

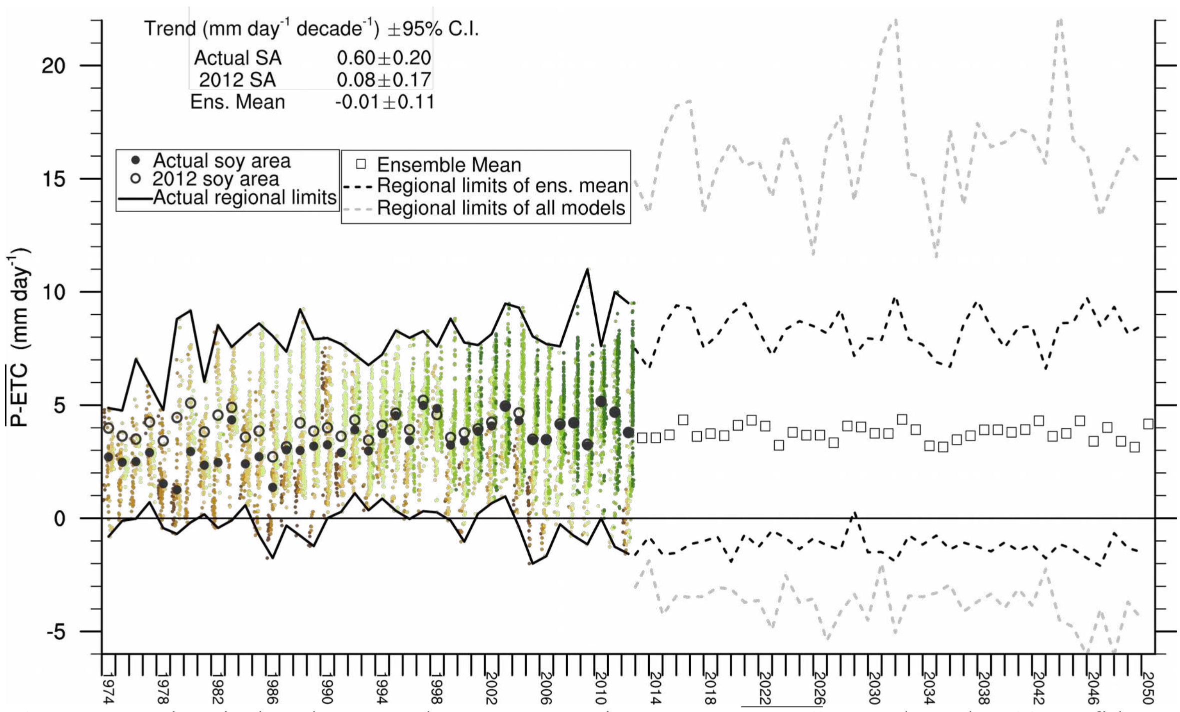

Figure 20: Historical and expected average growing season $\overline{\text{P-ETC}}$. Trends and 95% confidence intervals are calculated for area-weighted averages using actual yearly soy areas (filled circles), 2012 soy areas for historical data (hollow circles, 1974-2012) and 2012 soy area for the mean of the ensemble of CMIP5 RCP 8.5 models (hollow squares, 2013-2050). Solid black lines represent pixels with the maximum and minimum average $\overline{\text{P-ETC}}$ values of each year. Dashed black lines represent the pixels with maximum and minimum of each year on the ensemble mean, and gray black lines the minimum and maximum among all models and pixels. Small dots represent individual historical pixels and are the same as in Figure 18e, with greener dots representing higher yields.

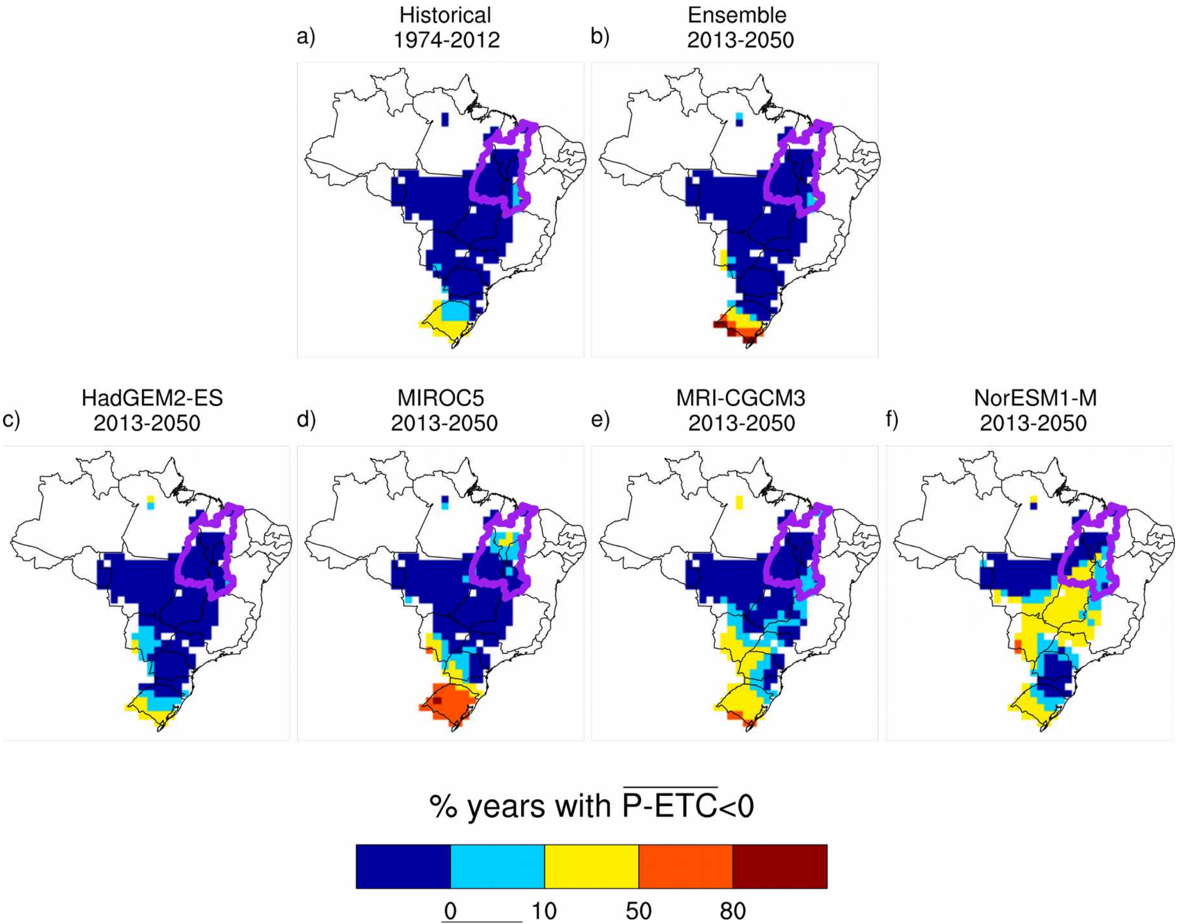

Figure 21: Fraction of years with $\overline{P-ETC}<0$ on the historical climate datasets' average (1974-2012 a), the climate models' ensemble average for the future period (2013-2050, b) and each separate model's prediction (c-f). The MATOPIBA region is delineated in purple.

Similarly, Figure 22 extends Figure 16e with the climate models' projections for temperature. The positive trend in $\overline{T}$ on the ensemble mean (2013-2050) is significantly different from zero (0.35 °C decade^{-1}, p-value < 0.05) and greater than the historical (1974-2012) trend on the same areas (0.29 °C decade^{-1}). However, it is smaller than the trend calculated using the actual soy area and thus accounting for the effect of the expansion (0.49 °C decade^{-1}). This indicates that, if soybean areas do not change, future warming on Brazilian soybeans is expected to be slower than the warming that was experienced in the past. Still, as stated before, yields more than doubled on that period and the highest yields are achieved in the warmer regions.

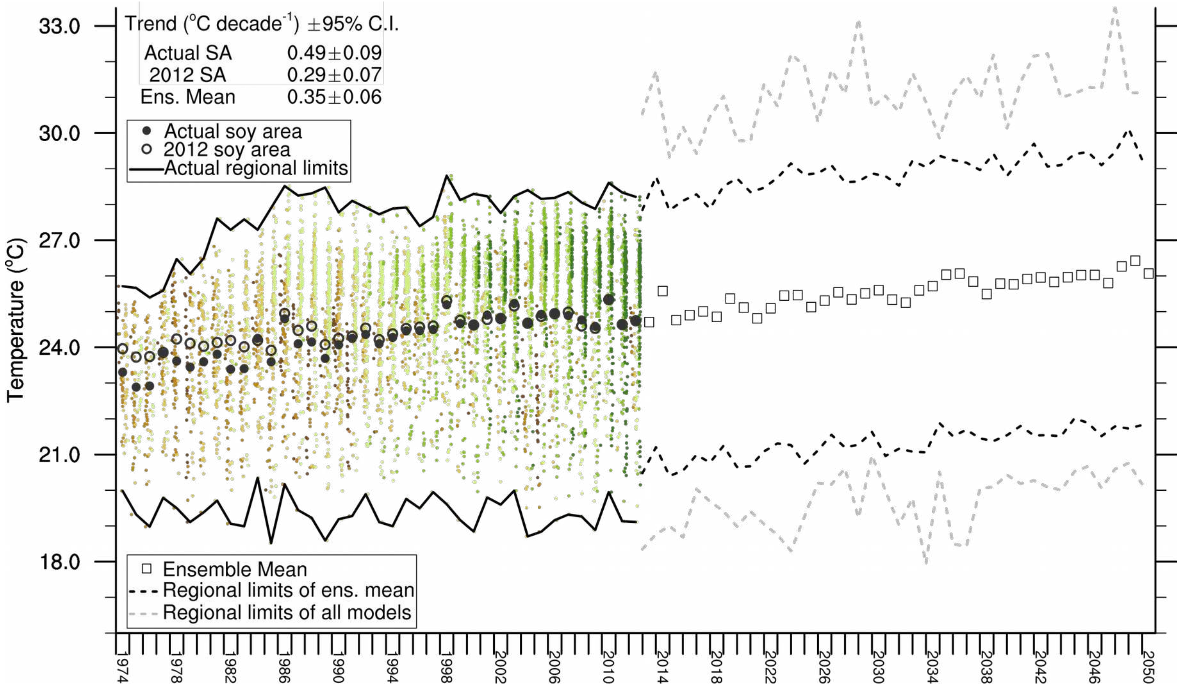

Figure 22: Historical and expected average growing season temperatures. Trends and 95% confidence intervals are calculated for area-weighted averages using actual yearly soy areas (filled circles), 2012 soy areas for historical data (hollow circles, 1974-2012) and 2012 soy area for the mean of the ensemble of CMIP5 RCP 8.5 models (hollow squares, 2013-2050). Solid black lines represent pixels with the maximum and minimum average temperature values of each year. Dashed black lines represent the pixels with maximum and minimum of each year on the ensemble mean, and gray black lines the minimum and maximum among all models and pixels. Small dots represent individual historical pixels and are the same as in Figure 16e, with greener dots representing higher yields.

This was achieved through the development of technologies to cultivate soybeans in warmer regions, among them the varieties with a wide range of sensibilities to temperature regarding cycle length (Alliprandini et al. 2009, see discussion on Section 3.3). Cycle shortening has been predicted to be one of the main issues for Brazilian soybean yields under future climate change (Assad et al 2013). The trend analysis then suggests that soybean R&D had overcome in the past greater warming rates than the upper bound expectations for the next decades in Brazil.

However, projections for the warmest regions show that it is likely that average temperatures will surpass experienced values (upper dashed gray and black lines), and therefore can cross to unexperienced biophysical thresholds. On the ensemble average, 0.36% of the current areas planted with soybean will be subject to temperatures higher than the historical maximum (29.1°C) in the period 2045-2050, although the exact fractions vary substantially across climate models (0.19-9.52%). As mentioned in Section 3.3, Schlenker and Roberts (2009) found that temperatures above 30°C have a strong negative effect on soybean yields in the U.S. using statistical models on large scale data. On the other hand, EMBRAPA (2011) states that strong negative effects on plant and flower development happen only after 40°C, based on experimental data and experts' opinions. The two studies use very different approaches and conclusions are not necessarily comparable, but show that strong nonlinear temperature effects and thresholds do exist in soybeans and must be accounted for when assessing climate vulnerability.

Although such biophysical limits exist and may pose a threat to soybeans in the future, especially on warmer regions, they may not be hard limits. According to the IPCC Fifth Assessment Report (AR5) definition (Klein et al., 2014), hard limits are thresholds after which no adaptive measures are possible to avoid intolerable risks to a system. In contrast, “soft” limits also cannot be overcome with current options, but may be in the future as a result of innovation or paradigm shifts. Biophysical limits to crops are generally considered as hard viability thresholds, after which the crop ceases to be cultivated on a specific region (Klein et al., 2014, Rippke et al., 2016).

The results and discussion on the photoperiod dependence of soybeans presented here show that tropical regions were considered unsuitable for soybean production on the 1960-70's due to their short days. After coordinated R&D efforts on overcoming the photoperiod limitations, those regions eventually became the most productive in Brazil. Soybean planting on almost all of tropical Brazil became limited by the rainy season instead of photoperiod only by the early 1990's, less than three decades after the first coordinated works towards that goal. But enough progress was already made by the early 1980's that allowed viable yields on the previously unsuitable central Brazil, overcoming the biophysical limit of short photoperiods. In addition, the maximum temperature where soybeans were planted also increased very rapidly in the past, about 2°C from the mid-1970's to the late 1980's (Figure 22). However, biophysical thresholds may not have been crossed at the temperature ranges of the time.

Although the results presented here show that Brazilian soybean R&D in the past overcame challenges of rapidly increasing temperatures and breaking a biophysical limit, they do not mean that the same will happen with challenges arising from future climate change. Besides the different nature of short photoperiod and extreme temperature constraints, there are several problems with inferring future resilience based on data from the expansion. The technological developments were proactive instead of reactive. Cultivating soybeans on the new regions was not technologically feasible before such developments, and the demand for them led to research efforts. It was possible to expand into the new regions only after such efforts have led to the new technologies. Thus, the climate change due to the expansion happened only because such advancements were made. Therefore the technological changes noted in this work are not necessarily probable under the same amount of climate change in the future, but serve as an indication of the magnitude such changes can possibly have.

Nonetheless, the Brazilian soybean case of "adapting to expand" have certain characteristics that may be important for successfully adapting an agricultural system to a different climate. Developers and farmers had explicit knowledge of the climate, photoperiod and soil conditions of the new regions to where soybeans were being adapted. This knowledge was an important factor to the success of soybean breeding programs (Spehar 1994). Under future climate change then, knowledge of the environmental conditions that will be faced by crops can be important to the success of systemic adaptation.

The role of uncertainty on this knowledge has yet to be assessed. Vermeulen et al (2013) show that, in some cases, incremental vs. transformative adaptation decisions can be relatively robust to the uncertainty of future climate predictions. Decisions regarding crop research and development for systemic adaptation, though, might be less robust. Technologies that improve yields under certain environments may not have the same effect under different conditions, especially under drought (Tester and Landridge, 2010, Ort and Long, 2014). With proper knowledge of the desired characteristics, however, breeders of today have access to increasingly large and well documented germplasm banks that can greatly facilitate and hasten the process of developing adapted varieties (Porter et al. 2014).

The Brazilian government also proactively fostered the development of technologies for central, northern and northeastern soybeans. The basic research needed to perform such large changes was funded by the government through its many universities and research entities in response to the large interest in taking soybeans to central Brazil (Pardey et al. 2006, Pessôa and Bonelli 1997). It included the development of the first late flowering varieties and soil correction techniques (Spehar 1994, Lopes and Guilherme 2007). With the high attractiveness of soybean prices and land availability on central Brazil, private companies also contributed to the development of tropical soybeans, but most of it was and still is done by public institutions. Even with the high costs and long time horizon involved, public agricultural R&D of soybeans is regarded as very cost effective to Brazil (Pardey et al. 2006, Correa and Schmidt 2014).

The results presented indicate that soybean agricultural R&D in Brazil may have a strong capacity of developing technologies for increasing yields on a different climate if well-coordinated, informed and funded. However, this capacity is poorly considered on Brazilian climate change adaptation plans. Although several institutions and researchers are individually tackling the problem, there are currently no integrated programmes focused on developing crop varieties and techniques for climate change. The government's agricultural R&D budget systematically fell in the 1990-2000's (Melo 1999, Alves 2005), and institutions have recently been suffering severe budget cuts. The capacity of agricultural R&D is explicitly mentioned on the National Plan for Adaptation to Climate Change (MMA, 2016), but no specific policies to foster it are outlined.

Most agricultural adaptation measures in the plan are of an incremental or transformative nature. Incremental adaptation, using the current available options to cope with future climate, has several limitations in the medium to long time frames (Vermeulen et al. 2013), some of which could be overcome with coordinated technological development. Current high yielding soybean varieties, for example, tend to reduce grain protein content under elevated carbon dioxide concentrations, but on some of them this effect is very reduced (Taub et al 2008). Proactively prioritizing the genetic material of such varieties on future crossings could prevent major declines on protein production under the much elevated CO_2 concentrations of the next decades (Fuss et al. 2014). On the other hand, migrations and mass crop switching associated with transformative changes when crop viability thresholds are crossed can have significant negative social and environmental impacts (Rickards and Howden 2012). New agricultural technologies can also have negative environmental impacts (Killebrew and Wolff 2010), and may lead to technology distribution issues (Freebairn 1995). Such issues, however, may be overcome with appropriate government policies (Pereira et al. 2012). Fostering systemic adaptation through coordinated agricultural R&D could be an effective way to counter climate change by building on current capacity without resorting to less sustainable options.

4. Conclusions and recommendations for future research

4.1. Conclusions

This work documented several major environmental and technological changes on Brazilian soybean production. Changes in area, yields, climate and photoperiod limitations were analyzed for the period 1974-2012, as well as climate estimates for 2013-2050. To that end, a spatially explicit dataset of soybean area and yields was developed, as well as maps that represent the spatial and temporal patterns of the soybean planting window.

The planting date estimates performed well when compared to current planting date recommendations and reports of photoperiod limitations. They provide unprecedented precise spatial and temporal information on the actual soybean growing season in Brazil through simple analysis of the most important factors that determine planting limitations (rainy season and photoperiod). Although those limitations and methods are specific to the region and crop of study, similar lines of thought may be useful to generate spatial and temporal growing season data for other crops and regions of the world.

The photoperiod limitations for soybean planting were gradually overcome through the development of new varieties. Soybean planting dates in Brazil were mostly limited by the photoperiod in 1974. With the overcoming of the photoperiod limitations, almost all regions with a well-defined rainy season were already limited by it in 1990.

The northward expansion of soybeans during the period of study (1974-2012) caused a significant shift of the production to regions with higher precipitation, thus increasing its resilience to future precipitation or evapotranspiration changes. However, the results indicate that the shift of production from low excess precipitation areas in the south to low excess precipitation areas in the northeast led to no net changes on the resilience of the most vulnerable portion of soybean production, and thus 5% of Brazilian production is still as vulnerable to an 11% reduction on average precipitation in 2012 as it was in 1974. However, only a small portion of the production is predicted to be subject to actual water stress ($\overline{P\text{-}ETC}<0$) by 2045-2050: 2.84% on the ensemble average (ranging from 1.12 to 15.63% across models).

Analysis of the temperature patterns of the expansion shows that the combined effect of local and expansion driven led to strong warming in the period 1974-2012 (0.49°C decade^{-1}). This warming was faster than what is expected for areas harvested with soybeans in 2012 for 2013-2050 (0.35 °C decade^{-1}). Highest soybean yields were generally achieved on warmer regions, and yields also grew more rapidly in such regions. This conflicts with the common notion that warming in tropical regions is detrimental to soybean yields and indicate major systemic changes on soybean varieties and cultivation practices. Although this is strongly supported by historical reports on agricultural R&D, other interpretations may be possible due to the relatively simple analysis conducted.

The analyses presented here show that major efforts on research and development turned an environment previously considered unsuitable to soybean production into one of the most productive in the world. With precise knowledge of the new conditions it was possible for the government, researchers and farmers to alter the relationship of soybeans with climate, photoperiod and soil. At least two examples indicate synergies between development for adaptation and overall yield gains: (i) the flexibilization of planting dates due to modifications of temperature and photoperiod effects, that led to the feasibility of double cropping systems and (ii) the outstanding growth in Brazilian yields, now among the world's highest, under relatively fast local and expansion-driven warming.

Although the analysis exemplifies how well functioning and funded agricultural R&D institutions are capable of developing new technologies to adapt systems to different environments, there are many significant differences between adapting to a different location and to a changing climate. There was no uncertainty on the prior knowledge on the environment to adapt to. In addition, all stakeholders, from pioneer farmers to research institutions and the government, were interested in working toward the same goal.

Under the gradual long-term changes expected for the future, however, objectives may not be naturally well aligned. Coordinating agricultural R&D towards specific goals of adapting systems to climate change, as well as better understanding these changes, is likely an efficient policy to counteract expected changes. Investments in this sense would certainly bring many beneficial side effects to agricultural production. Alternatives to such policies would lead to production losses or unsustainable agricultural practices. Therefore, coordinated action is urgently needed to repeat the successful use of the Brazilian R&D potential to sustainably increase agricultural production on a changing climate.

4.2. Recommendations for future research

Brazilian soybeans are a significant part of the world's agricultural production, and posed substantial challenges to agricultural R&D. However, there are likely other crops and locations where large scale efforts to alter cropping systems to different climate conditions also happened. A wider assessment of such efforts, be them successful or not, may provide basis for a more comprehensive framework on fostering systemic adaptation to future climate change. Meta-analyses and questionnaires applied on world experts could be useful tools to incorporate data on multiple experiences to reach more robust conclusions.

The assessment of the systemic changes presented here, although quantitative, was mostly descriptive, with interpretation of large scale environment-yield relationships based on historical literature. Future work could more accurately quantify these changes by estimating the evolution of crop characteristics such as optimal temperatures. Germplasm and seed banks could provide basis for such analyses, as well as more sophisticated statistical models applied to large scale data on yield and climate. Statistical modeling would face the challenge of dealing with changing relationships that are generally regarded as constant between yields and factors such as soil and climate. The common use of fixed effects to account for soil aptitude, for example, would not take into account the technological changes on varieties and management that turned the previously inapt soils of *Cerrado* into some of the most productive in the world, as well as the overcoming of the photoperiod limitations.

The driest soybean cultivating regions, namely southern RS and MATOPIBA, were identified as being possibly subject to more intense drought in the future. This could be critical for new investments on MATOPIBA, where soybeans are rapidly expanding. In future assessments, a thorough local analysis of future agricultural risk on these regions could be made with the use of climate model downscaling. Such analyses would also benefit from better understanding of the large scale atmospheric processes influencing precipitation on these regions under climate change, as well as of the possible impacts of deforestation on the rainy season.

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