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Precipitation Drivers of Cropping Frequency in the Brazilian Cerrado: Evidence and Implications for Decision-Making

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ABSTRACT

The Amazon basin has been subjected to unprecedented rates of land-use change over the past several decades, primarily as a result of the expansion of agriculture. Enhanced rain forest conservation efforts toward the end of the twentieth century slowed deforestation of the Amazon but, in turn, increased demand for land repurposing in the adjacent Cerrado (savanna) region, where conservation regulations are less strict. To maintain or increase yields while minimizing the need for additional land, agricultural producers adopted a form of intensification in which two rain-fed crops are planted within a single growing season (double cropping). Using 10 years (August 2002 to July 2012) of MODIS and TRMM data, it is demonstrated that there exists a threshold growing season rainfall amount (1759 mm) for double cropping. But more nuanced is the relationship between observable precipitation information available to farmers at the time of planting decision and the choice to "double crop" in a given year. An evaluation of decision-available precipitation characteristics provides strong evidence for the importance of high rainfall frequency during a critical period prior to, and including, the rainy season onset.

1. Introduction

Brazil has experienced unprecedented rates of land-use and land-cover change (LUCC) over the past several decades (Nepstad et al. 2009), driven in part by the clearing of tropical rain forest and adjacent savanna for increasing agricultural production (Morton et al. 2006). Indeed, Brazilian gross domestic agricultural product (GDAP, as measured by constant 2010 U.S. dollars) has risen steadily by nearly a factor of 5 since 1965, exceeding $104 billion (U.S. dollars) in 2015 (World Bank 2016). Concurrently, cumulative deforestation in the Brazilian Amazon exceeded 60 000 000 ha by 2000, more than 80% of which occurred after 1970 (Fearnside 2005).

Pressures from international and domestic environmental advocates, however, have challenged the sector to maintain GDAP growth while minimizing forest degradation. This gave rise to the soy moratorium in 2006, an agreement whereby soy traders pledged not to purchase soybeans grown on land deforested in the Amazon after 2006 (Gibbs et al. 2015). Macedo et al. (2012) observe that while all of the increased soy production in the state of Mato Grosso for the 5 years preceding this policy was attributable to expansion onto pastures or newly cleared forests, nearly one-quarter of the increased production in the remainder of the decade was from increased yields from existing agricultural lands. Concomitant with this transition was the rapid expansion of "double cropping," a form of yield intensification in which two crops are planted successively within a single growing season. This increasingly widespread practice has arguably served to reconcile, at least partially, the competing interests of conservation and agricultural development, although such a "land sparing" effect from intensification more generally is debatable in Brazil and elsewhere (e.g., Macedo et al. 2012; Strassburg et al. 2014; Ewers et al. 2009; Gollnow and Lakes 2014).

Although it has been documented that double cropping confers numerous socioeconomic benefits in Mato Grosso (VanWey et al. 2013), its relative novelty in Brazil more broadly invites questions about its sustainability, particularly within the context of climate change: it is not yet known whether uncertainties presented by changing precipitation regimes (Chou et al. 2012) will affect the suitability for double cropping in this region, where nearly all of the cropland is currently rain fed.

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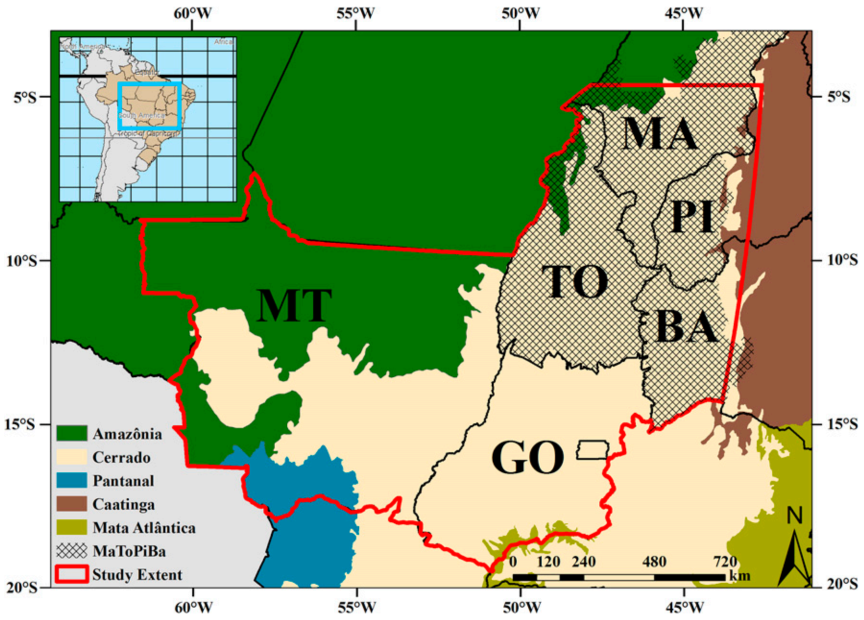

FIG. 1. The study region covers the majority of the agricultural frontier in the Brazilian Cerrado (beige), including all of MT to the west, GO to the southeast, and most of the newly designated MaToPiBa frontier (indicated by cross-hatching) to the northeast. Agricultural data extent for this study is indicated in the bold red outline. Some of the agricultural data in MT includes cropping in the Amazon biome (green).

And while significant policy and research attention has been given to the Amazon biome, relatively less importance is placed on the adjacent Cerrado, a vast expanse of savanna ecosystems that has become a focal point of the Brazilian agricultural frontier since 1960 (Barretto et al. 2013). Despite the characterization of this region as a biodiversity hot spot with substantial ecological endemism, only 20% of lands are required to be held in protective legal reserve, compared to 80% in the Amazon biome (Klink and Machado 2005). Consequently, substantial portions of the natural vegetation have been cleared: Beuchle et al. (2015) estimated that over 260 000 km^2 of natural vegetation in the Cerrado were cleared between 1990 and 2010, leaving just under half of the total natural vegetation intact, and Sano et al. (2010) estimated that only 1.4% of the Cerrado was permanently protected as national park areas as of 2002.

Our study region focuses on this agricultural frontier in the central-west region of Brazil, including much of the Cerrado biome and a small portion of the Amazon rain forest. Specifically, our study region includes the highly agriculturally productive state of Mato Grosso (MT), as well as the state of Goiás (GO), and the majority of the newly designated region of MaToPiBa, which is a portmanteau designation that includes portions of the states of Maranhão (MA), Tocatins (TO), southern Piauí (PI), and western Bahia (BA) in the northeastern Cerrado (Fig. 1). Although the Cerrado biome is not entirely captured in this extent, the study area is broadly representative of the variability of both farming practices and climates throughout the Cerrado. Agriculture in this region has both expanded (i.e., increased land clearing for crops) and intensified (i.e., increased cropping frequency, or double cropping) rapidly over the past two decades (Gibbs et al. 2015): total agricultural area has increased by about one-third from 7 to 9.4 million hectares, while intensified cropping areas have increased threefold from 1.7 to 5.4 million hectares during the study period between 2003 and 2012 (Fig. 2).

Rainfall in the study region tends to be highest over the Amazon and in the Cerrado region just east of the rain forest, and decreases on a gradient from the northwest to the southeast (Fig. 3). The total amount of precipitation received over this area varies substantially in space, from about 0.5 $\mathrm{m\,yr^{-1}}$ in the Cerrado to over 2.5 $\mathrm{m\,yr^{-1}}$ along the rain forest boundary. The temporal pattern of rainfall is strongly seasonal in accordance with the South American monsoon (Gan et al. 2004, Zhou and Lau 1998), with the majority of annual total rainfall occurring in the single rainy season from October to April. When considered in tandem with the role of evapotranspiration from the Amazon, the spatial distribution of precipitation in the Cerrado becomes apparent. Dense, perennial vegetation in the rain forest stores and recycles water, releasing significant latent heat

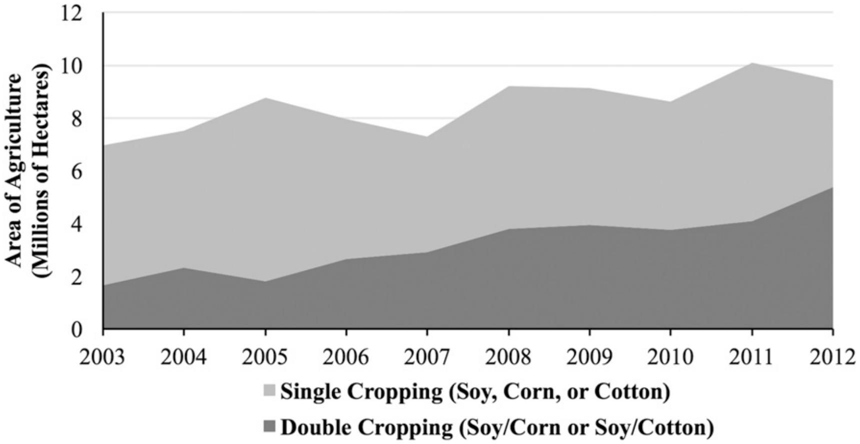

FIG. 2. Both the total area of agriculture and the proportion of agriculture in DC rotations in the Brazilian Cerrado have increased since 2003. DC as a method of agricultural intensification carries many socioecological benefits, but its geophysical drivers and socioecological consequences remain uncertain.

that, in turn, drives atmospheric convection (Gedney and Valdes 2000; Spracklen et al. 2012). Some of this moisture is transported by northwesterly winds from the Amazon into the adjacent Cerrado, where it converges in south-central Brazil. What results is a corridor of precipitation along a northwest–southeast gradient and relatively drier conditions to the northeast and southwest of this path.

This precipitation is highly temporally variable on yearly and decadal time scales, due to a variety of factors. Perhaps most important is the role of sea surface temperatures (SST) from the Atlantic Ocean. While Pacific SST anomalies associated with El Niño tend to have a drying effect on the north-northwestern and central equatorial regions of the Amazon basin (Liebmann and Marengo 2001), they do not appear to have a significant effect on the rainy season

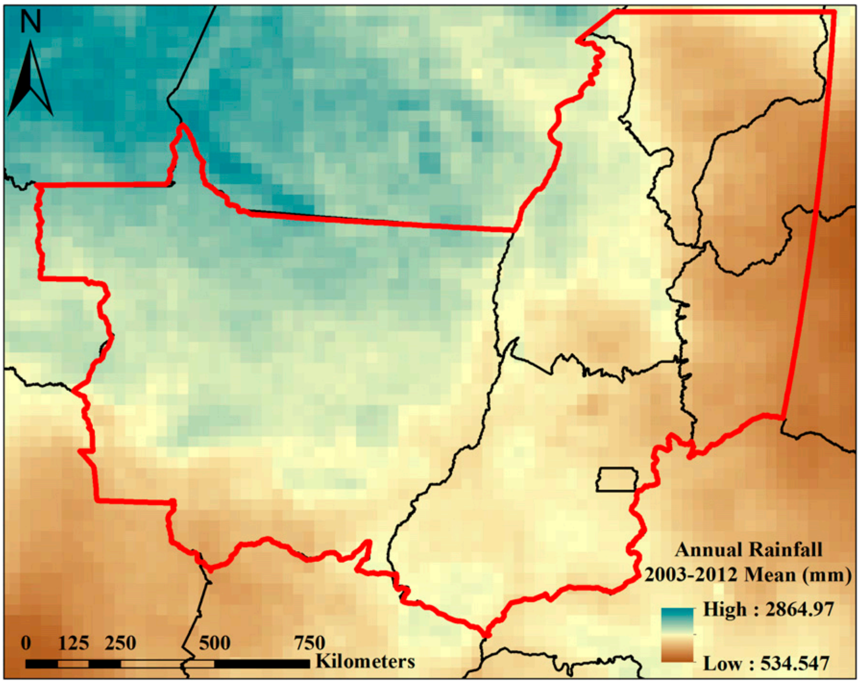

FIG. 3. Annual cumulative rainfall across the region of interest follows a northwest–southeast gradient, with the wettest regions being in the Amazon rain forest to the northwest and the driest in the easternmost Cerrado.

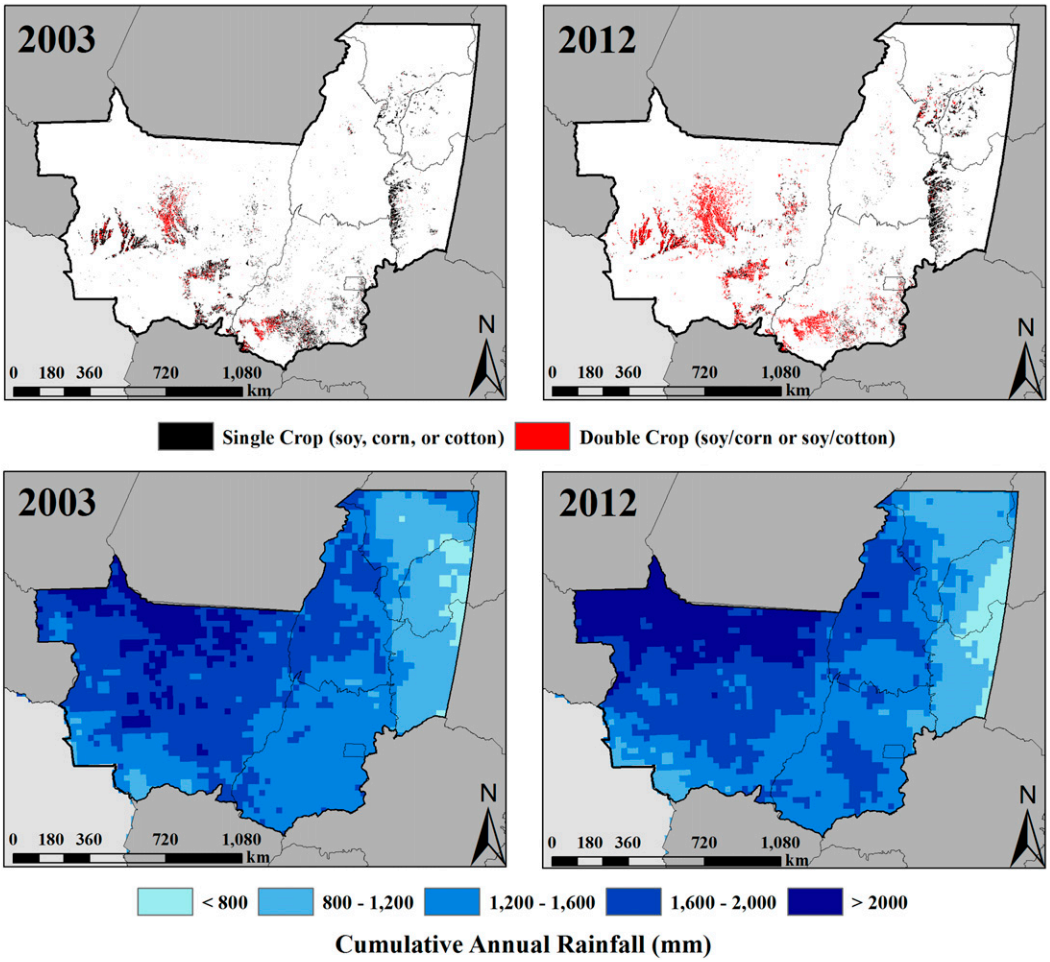

FIG. 4. Two snapshot years of agriculture and cumulative annual rainfall are shown here: (left) 2003 and (right) 2012. Both the total area of all agriculture (black and red pixels) and the proportion of DC agriculture (red pixels) have expanded across the study region. Increases in DC are particularly pronounced in MT (to the west) and in GO (to the southeast), but adoption of this practice is also seen in the MaToPiBa region (to the northeast). Rainfall in these snapshot years is consistent with the climatology for the region.

onset in the southern Amazon basin (Marengo et al. 2001). However, enhanced meridional SST gradients in the tropical Atlantic are associated with a northward shift of the intertropical convergence zone (Wagner 1996), which leaves the southern Amazon basin drier than usual.

This interannual variability is critical when seeking to understand the influence of weather and climate on agricultural decision-making in the Cerrado. While there is evidence that double cropping in Mato Grosso State is adopted in places with generally earlier, wetter, and longer rainy seasons (Arvor et al. 2014; Spera et al. 2014), it is not known whether this relationship is consistent or systematic between years. Further, it is unlikely that this correlation per se forms part of the decision-making process by individual producers each year, since the characteristics of a given rainy season cannot be known with certainty a priori. Complicating this is the rapid expansion of both single-cropped (SC) and double-cropped (DC) agriculture across a range of precipitation regimes throughout the region: during the study period, double cropping expanded dramatically not only in the states of Mato Grosso and Goiás, where rainfall is relatively high, but also expanded nominally in the somewhat drier MaToPiBa region (Fig. 4), which as a nascent agricultural frontier saw greater adoption of single-cropped agriculture, consistent with observations of double cropping tending to supplant single cropping after a period of only a few years (Galford et al. 2008). And while Cohn et al. (2016) suggests that interannual climatic variability, as measured by monthly means, can concurrently influence cropping area, frequency, and yield in Mato Grosso, there is lingering uncertainty about the specific role played by temporally higher-resolution rainfall metrics in the agricultural decision-making process. The question thus posed is whether known and observable precipitation characteristics play a part in double cropping as both a deliberative and elastic practice.

Of course, in complex social–ecological systems, interactions make it difficult to determine causation (Ostrom 2009). This is particularly true for farming systems, in which adaptive decision-making is made in an uncertain and dynamic landscape of biophysical, economic, social, and cognitive conditions (Jain et al. 2015). Nonetheless, there is compelling evidence that precipitation plays a role in year-to-year decisions of which crops to plant, and at what time, in other rain-fed systems, such as in Uganda (Orlove et al. 2010), India (Jain et al. 2015; Gadgil et al. 2002), Zimbabwe (Grothmann and Patt 2005), Senegal (Mertz et al. 2009), and Burkina Faso (Maatman et al. 2002). In the case of agriculture in the Cerrado, there are many factors that have the potential to influence decisions to double crop in any given year, ranging from economic market conditions (e.g., differential demands for soybean as a function of the value of the Brazilian real; Richards et al. 2012) to individual risk tolerance. It will not be posited here that rainfall characteristics are the primary driver of decision-making; rather, this analysis will provide evidence in a multiyear analysis that specific and directly observable rainfall characteristics are robustly associated with double cropping. Hence, the rainfall characteristics identified in this study are appropriate targets for future assessments of vulnerability of the Cerrado to future climate change.

Presented here is a 2003–12 analysis of agricultural land-use and precipitation patterns in the Brazilian Cerrado. In section 2, a comparable methodology to test further the hypothesis by Arvor et al. (2014) that the rainy season onset is earlier and greater in areas employing double cropping will be described, and the statistical significance will subsequently be demonstrated using a longer temporal dataset (10 years of land-use data) over a larger spatial extent (including Mato Grosso and much of the greater Cerrado region). In section 3, novel evidence of a threshold growing season rainfall amount for double cropping will be presented, and additional data will be shown to suggest how the decision to double crop in this region could be made at least partially on the basis of incomplete information about observable early-season precipitation. Finally, a discussion about the role played by rainy season characteristics in determining the long-term sustainability of this agricultural practice in the context of climate change will be explored in section 4.

2. Datasets and methods

To assess the associations between precipitation and agricultural patterns, spatially and temporally high-resolution land-use and weather data were employed over the Brazilian Cerrado for the growing years from 2003 to 2012. Here, the growing year is defined as 1 August of the previous year through 31 July [e.g., growing year 2003 (GY03) goes from 1 August 2002 to 31 July 2003].

a. Land-use imagery

Phenology-based landscape definitions were derived from the MODIS (MOD13Q1) enhanced vegetation index product (Didan 2015; Huete et al. 2002; Zhang et al. 2003). For each growing year, 250 m × 250 m pixels were assigned one of seven agricultural categories, based on their spectral properties: single-cropped corn, soy, or cotton; double-cropped soy–corn or soy–cotton; sugarcane; or irrigated agriculture, following the approach of Spera et al. (2014). For the purpose of this study, which seeks to assess differences specific to single versus double cropping, "total agriculture" will refer only to areas with soy, corn, cotton, soy–corn, or soy–cotton (which comprise the majority of farmland in the Cerrado). The area of interest (Fig. 1) contains at least 80% of the total agriculture of the Cerrado.

Data were aggregated across years and also organized in two ways for different comparison purposes: 1) rounded and binned to the nearest 10% proportion of double cropping; and 2) binned by qualitative degree of intensification: "double cropped" (more than 75% of agriculture double cropped), "mixed single–double cropped" (25%–75% double cropped), and "single cropped" (less than 25% double cropped).

b. Precipitation data

Precipitation data were obtained from the Tropical Rainfall Measuring Mission (TRMM) 3B42, version 7, product, which provides daily precipitation totals at a resolution of 0.25° × 0.25° (Huffman et al. 2007). To compare the land-use and precipitation data, the higher-resolution LUCC maps were aggregated to match the resolution of the TRMM data. Therefore, the maps were discretized with an overlaid 0.25° × 0.25° grid and the proportion of each agricultural type within each TRMM pixel was calculated. Those pixels in which less than 5% of the total area consisted of single or double cropping were excluded. TRMM pixels that were not at least 99% within the area of interest were also excluded.

The proportion of agriculture devoted to double cropping within each of the pixels was calculated for each of the 10 growing years. Annual cumulative precipitation, onset of the rainy season, offset of the rainy season, length of the rainy season, frequency of rainy days, rainfall intensity (defined as the mean rainfall amount per rainy day), and proportion of early-season

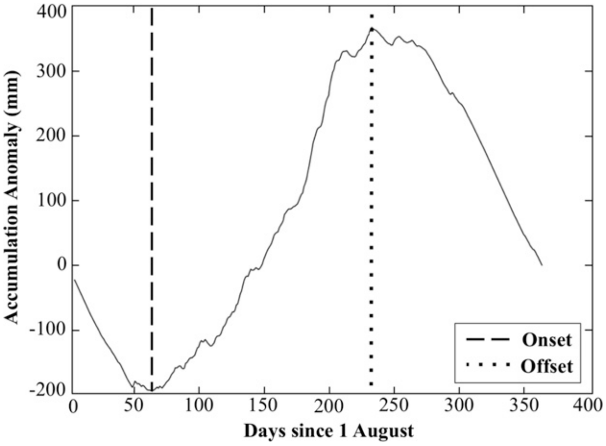

FIG. 5. An example of an AA curve for a single TRMM pixel, calculated using Eq. (1). The absolute minimum value corresponds to the rainy season onset date, while the absolute maximum value corresponds to the offset date.

annual rainfall during the critical preplanting period (15 September through 15 October) were calculated for each TRMM pixel for each growing season. The onset of the rainy season is defined here as the day on which the accumulation anomaly begins to increase consistently; this corresponds to the point at which daily rainfall becomes reliably greater than the mean daily rainfall for the entire year (Liebmann et al. 2007). This methodology calculates the accumulation anomaly (AA) as a time series summation [Eq. (1); Fig. 5] of the difference between daily precipitation p at each time step t and the mean daily rainfall for that year $\overline{p}$. Leap days are accounted for by combining the total precipitation on 28 and 29 February and assigning this value to the former day, but in fact the contribution of leap day precipitation to the annual cumulative precipitation is negligible. The offset of the rainy season occurs when the accumulation anomaly reaches a maximum and inflects downward to increasingly dry conditions,

$$\mathrm{AA}(t) = \sum_{t=0}^{364} p(t) - \overline{p}. \tag{1}$$

Two-tailed Welch's t tests were used to test the null hypotheses that there is no significant difference in mean values of precipitation characteristics (e.g., annual cumulative rainfall, onset of the rainy season, and offset of the rainy season) between predominantly double-cropped and single-cropped areas. These data appear reasonably to follow normal distributions based on visual inspections of histograms and quantile–quantile (Q–Q) plots (data not shown); moreover, others have demonstrated the efficacy of t tests to violations of the assumption of normality if the sample size is sufficiently large, a condition met by our data [see also Lumley et al. (2002) for a literature review on the assumption of normality in the t test]. Welch's t test was used in place of the traditional Student's t test in order to account for the differing sample sizes and variances between the samples; the number of observations for single-cropped pixels is higher than double cropping, and the standard deviation of these values tends to be higher than that of the double-cropped areas.

3. Analysis and results

Statistically significant differences exist between areas that are predominantly double cropped (>75% DC) and areas that are predominantly single cropped (<25% DC) for nearly all of the precipitation covariates analyzed (Table 1). On average, for the growing years 2003–12, areas with over 75% of agriculture using double-cropped regimes received 1763.2 mm yr^{-1} of precipitation, while areas with less than 25% of land under double cropping received only 1505.7 mm yr^{-1} (Fig. 6). This difference of approximately 258 mm yr^{-1} is significant at the 1% level. In addition, total precipitation in the single-cropped areas has a standard deviation that is approximately 44% greater than that of double-cropped areas, consistent with the observation of Spera et al. (2014) that double cropping has more "selective" climatic characteristics than traditional single-cropped agriculture.

But perhaps more important than annual precipitation is rainy season timing, since this most directly affects when the first crop can be planted. In Brazil, soy cannot be planted during the "sanitary period," which ends no sooner than 15 September, in order to prevent the development of soy rust; while there is an economic incentive to planting very shortly after the cessation of this period, this comes with higher climatic risks, as the rainy season typically does not begin for several weeks after (Pires et al. 2016). The rainy season onset date [i.e., start of season (SOS)], on average, occurs about 10 days earlier where double cropping is preferred ($p < 0.001$), and the total length of the season is about 12 days longer ($p < 0.001$). While the offset date is slightly later in double-cropped areas, the difference is not significant at the 1% level, indicating that the difference in total length is best explained by the earlier onset date.

While producers may have information about previous years' precipitation, they cannot know with certainty at the time of planting—or indeed for some time after—that the rainy season has formally begun, whether this date presages a rainier-than-average season, or how much total rainfall will occur during the growing year. To understand how precipitation may be related to decision-making, we assessed differences between double cropping and single cropping based on information that producers readily

TABLE 1. Student's *t*-test statistics of rainfall characteristics in DC and SC areas of the Cerrado from 2003 to 2012. Means and standard deviations for several rainfall characteristics during the rainy season and early-season critical period are presented here. The difference between areas primarily DC (>75% DC) and SC (<25% DC) are given in the final column. All variables are statistically significant at the 5% level of alpha, as indicated by the 95% confidence intervals (CI); all variables except for rainy season offset date are statistically significant at the more stringent 1% level.

Variable	μ_{DC} [95% CI]	σ_{DC}	μ_{SC} [95% CI]	σ_{SC}	$\mu_{DC} - \mu_{SC}$ [95% CI]
Annual rainfall (mm yr^{-1})	1763.2 [1745.3, 1781.1]	197.9	1505.7 [1494.42, 1516.9]	284.9	257.5[a] [236.4, 278.7]
Rainy season					
Onset (days since 1 Aug)	77.2 [75.5, 79.0]	19.6	87.4 [86.6, 88.3]	21.3	−10.2[a] [−12.1, −8.2]
Offset (days since 1 Aug)	251.1 [249.5, 252.7]	17.6	249.1 [248.4, 249.8]	17.4	2.0 [0.3, 3.8]
Length (days)	173.9 [171.8, 175.9]	22.4	161.6 [160.8, 162.5]	21.6	12.2[a] [10.0, 14.4]
Critical period (15 Sep–15 Oct)					
Rainy days	14.8 [14.4,15.1]	3.9	10.7 [10.5,10.9]	4.8	4.1[a] [3.7,4.5]
Cumulative rainfall (mm)	103.7 [100.3,107.2]	38.4	66.1 [64.3,67.9]	46.3	37.6[a] [33.7,41.6]
Rainfall intensity [mm (rain day)$^{-1}$]	7.3 [7.0,7.5]	2.8	6.3 [6.2,6.5]	3.8	1.0[a] [0.7,1.3]
Annual rainfall (%)	5.9 [5.7,6.1]	2.2	4.3 [4.2,4.4]	2.8	1.6[a] [1.4,1.8]
N	471		2471		

[a] Denotes statistical significance at the 1% level.

have at the time of planting: namely, the characteristics of the precipitation that they have observed since the beginning of the growing year (1 August) through the approximate start of season (15 October). In particular, we looked at what emerged as a critical period between the earliest possible legal planting date (15 September) and a more generalized optimal planting date (15 October) to coincide approximately with the rainy season onset.

On average, double-cropped areas receive greater total rain accumulations, more rainy days, and increased rainfall intensity during the critical period. This does not necessarily directly translate to a rainier-than-average growing season, as these same areas tend to have a greater proportion of total rainfall concentrated during the critical period. On average, single-cropped areas receive 4.3% of annual rainfall during the critical period, while double-cropped areas receive 5.9%—a difference of 1.6 percentage points that is significant at the 1% level (Table 1).

When the pixels are binned by the nearest 10% of agriculture in a double-cropped rotation, strong correlations with the *number* of rainy days are particularly apparent (coefficient of determination $r^2 = 0.89$; Fig. 7).This is true also for cumulative precipitation ($r^2 = 0.84$) and rainfall intensity ($r^2 = 0.81$) during the critical period (data not shown). Interestingly, these relationships are weaker when expanding the temporal range to the beginning of the growing year (1 August through 15 October) and weaker still when considering only through the earliest planting date (1 August through 15 September; see

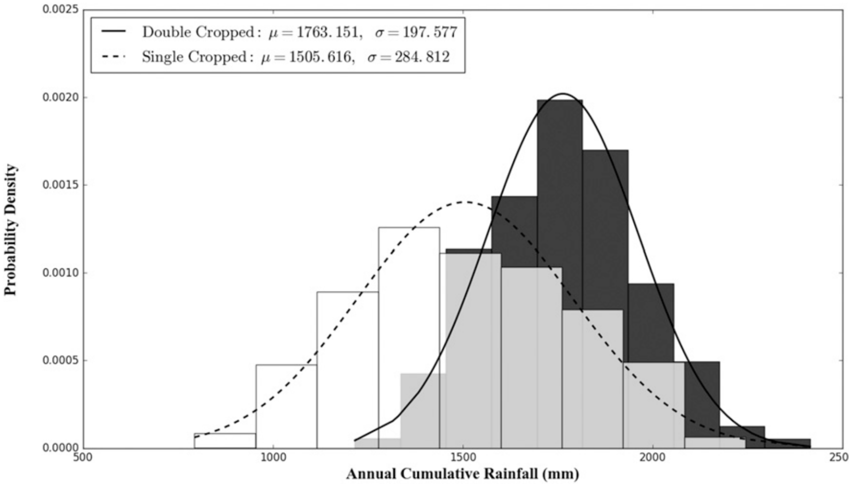

FIG. 6. Annual cumulative precipitation is significantly greater in areas predominantly DC (>75% DC) than in those primarily SC (<25% DC). The range and standard deviation are lower among DC pixels, as indicated by the lower spread of the histogram.

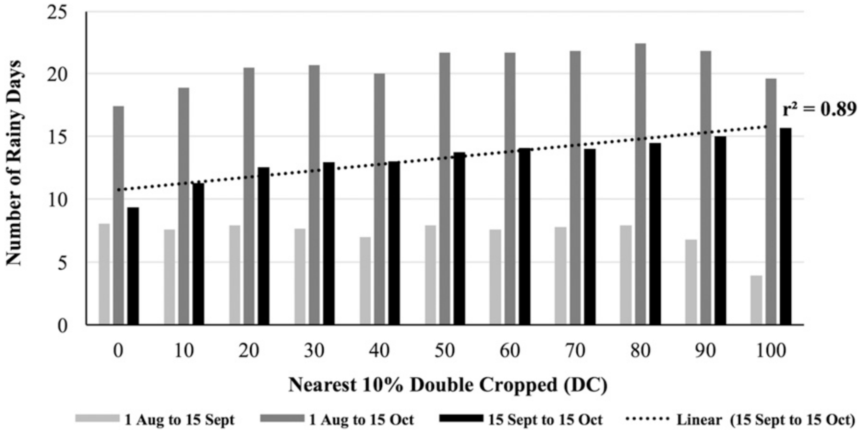

FIG. 7. When pixels are binned to the nearest 10% proportion of agriculture DC, a very strong linear correlation emerges with the number of rainy days during the critical period. When the time frame is expanded to include 1 Aug through 15 Oct, the relationship is still positive but much less strong. When considering precipitation only between the growing year start date (1 Aug) and earliest planting date (15 Sep), the relationship with double cropping is very weak and negative.

again Fig. 7); that is, precipitation characteristics specifically during the critical period are strongly related to subsequent implementation of double cropping that season. When disaggregated (i.e., not binned by the nearest 10%), these relationships hold, though the coefficients of determination are intuitively lower.

For the rainy season onset date, a strong trend ($r^2 = 0.85$) is seen among the mean SOS dates within each of the 10% double-cropping bins (Fig. 8); however, this relationship is virtually absent in the disaggregate ($r^2 = 0.04$; data not shown). It should also be noted that while the nearest 10% of DC is almost perfectly correlated with the rainy season onset for 0%–40% ($r^2 = 0.99$), the goodness of linear fit is about halved for values at or above 50% ($r^2 = 0.51$), suggesting that the variation in majority-double-cropped areas is not as well explained by the SOS as it is in majority-single-cropped areas.

Annual rainfall data demonstrate characteristics of nonlinearity when plotted against the proportion of double-cropped agriculture, in both aggregate and disaggregated forms (Fig. 9). In particular, the distributions appear to have diminishing returns, such that greater proportions of double cropping are associated with increased annual rainfall up to a threshold, at which point additional rainfall is not related to increased areas of double cropping. A piecewise regression centered around 1759 mm yr^{-1} of precipitation supports this: 23% of the variation in double cropping can be explained by annual

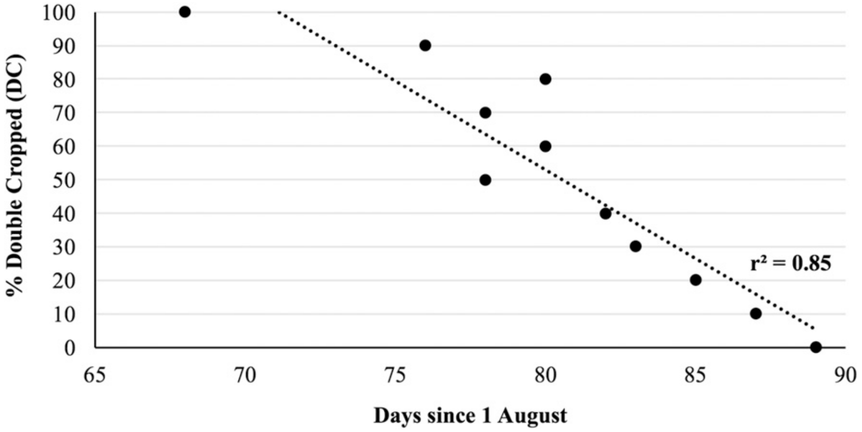

FIG. 8. The proportion of agriculture in DC rotations is strongly correlated with the rainy season onset date (SOS), such that double cropping increases with earlier SOS when aggregated to the nearest 10% bins. In the disaggregated form, however, the relationship is virtually absent, with an r^2 value of only 4%.

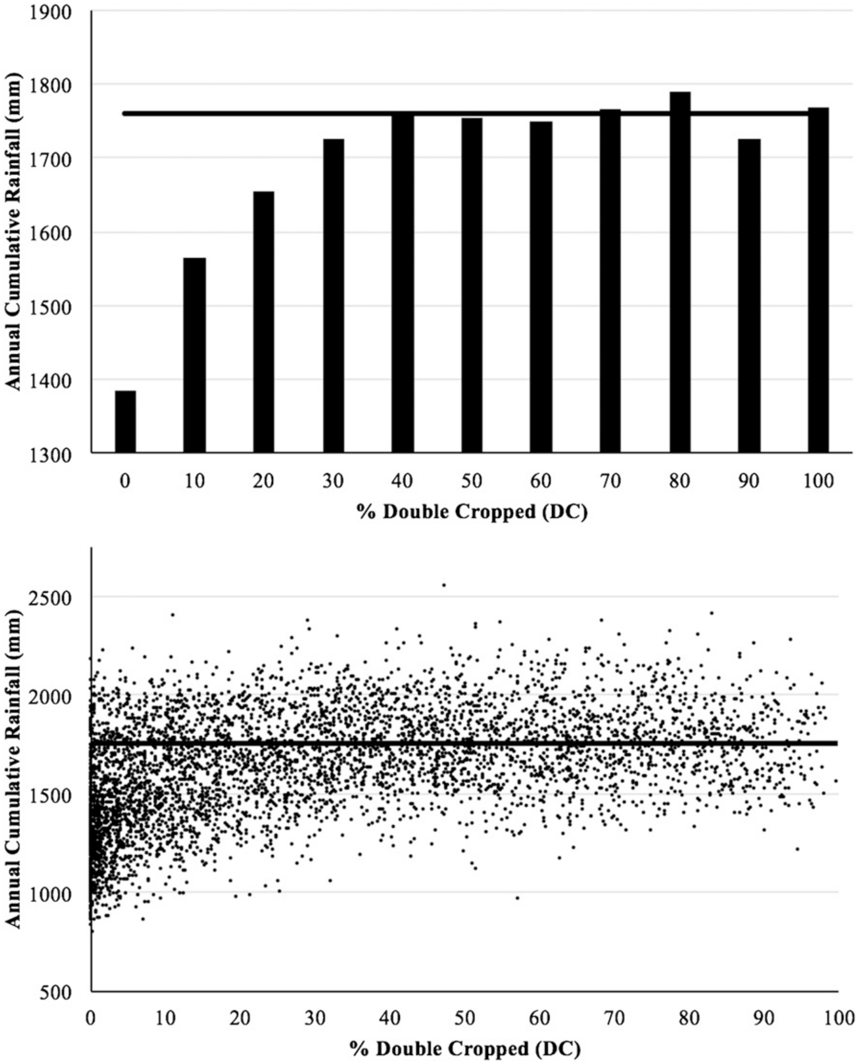

FIG. 9. The proportion of DC agriculture is positively correlated with annual cumulative precipitation; however, the relationship exhibits diminished returns beyond approximately 40% in both the (top) aggregate and (bottom) disaggregate. This suggests that cumulative annual rainfall does not vary significantly among the majority of DC areas. The solid line indicates an annual precipitation amount of 1759 mm yr^{-1}.

precipitation where rainfall is less than 1759 mm yr^{-1}, while less than 1% is explained for instances with precipitation greater than 1759 mm yr^{-1} (Fig. 10). There is relatively strong concordance between this threshold and double cropping: most of the double cropping that occurred in 2012 took place in areas that had at least one year of rainfall exceeding the 1759-mm threshold over the preceding study period, including in MaToPiBa, where double cropping is less widely adopted (Fig. 11).

4. Discussion and conclusions

Our research provides new insights into the potential role of precipitation in agricultural decisions regarding cropping frequency in the Brazilian Cerrado, and it builds upon the conventional assumptions that this planting regime is simply associated with places with historically wetter, earlier, and longer rainy seasons. While we have determined that double cropping, on average, occurs where there is more and earlier precipitation up to a critical threshold, positing this relationship in isolation would imply having access to perfect, highly resolved information of seasonal rainfall projections. Our analysis has instead demonstrated the influence of *directly observable* early-season precipitation characteristics on double cropping frequency. This finding concurs with the broader literature on agricultural decision-making, invites additional questions about adaptive capacities of farmers

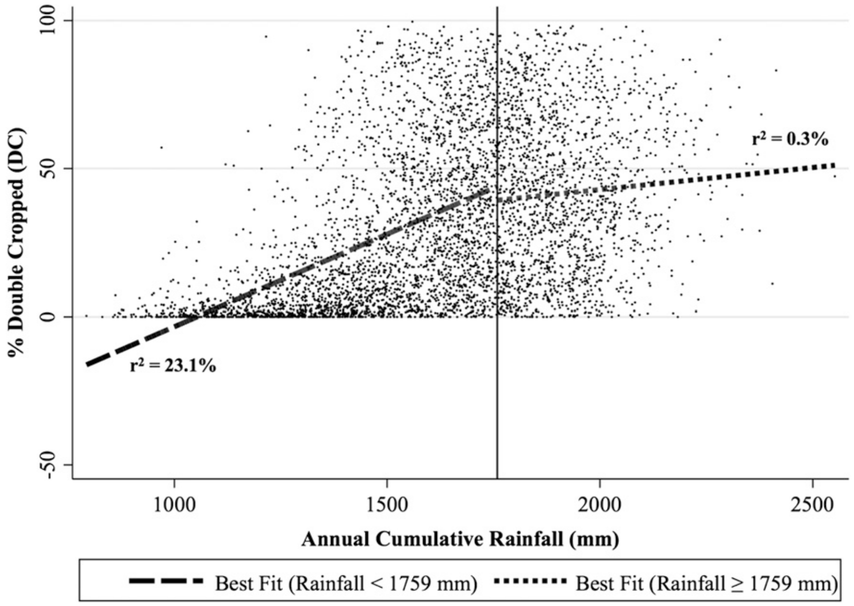

FIG. 10. A threshold is detected in the scatterplot of annual cumulative precipitation and the proportion of agriculture that is DC. At values less than approximately 1759 mm yr^{-1}, a linear regression shows that annual precipitation explains about 23% of the variation in the proportion of double cropping; values greater than 1759 mm yr^{-1}, however, have virtually no correlation with the proportion of double cropping.

to increased climatic variability, and contributes further evidence for the utility of robust seasonal forecasting for increasing resilience of farming systems to climate change.

To expand upon these findings, at the time of planting, agricultural operations managers have incomplete information about the precipitation characteristics of the coming growing season and imperfect information about present conditions. Although they can observe how much rain has fallen since the beginning of the growing season, they cannot know with certainty whether the rainy season has officially started, how long the rainy season will be, or how much total rainfall will occur over the growing season. Among experienced producers, observations of long-term variability in precipitation are likely to contribute to the perception of the relative likelihood of rain in a particular year

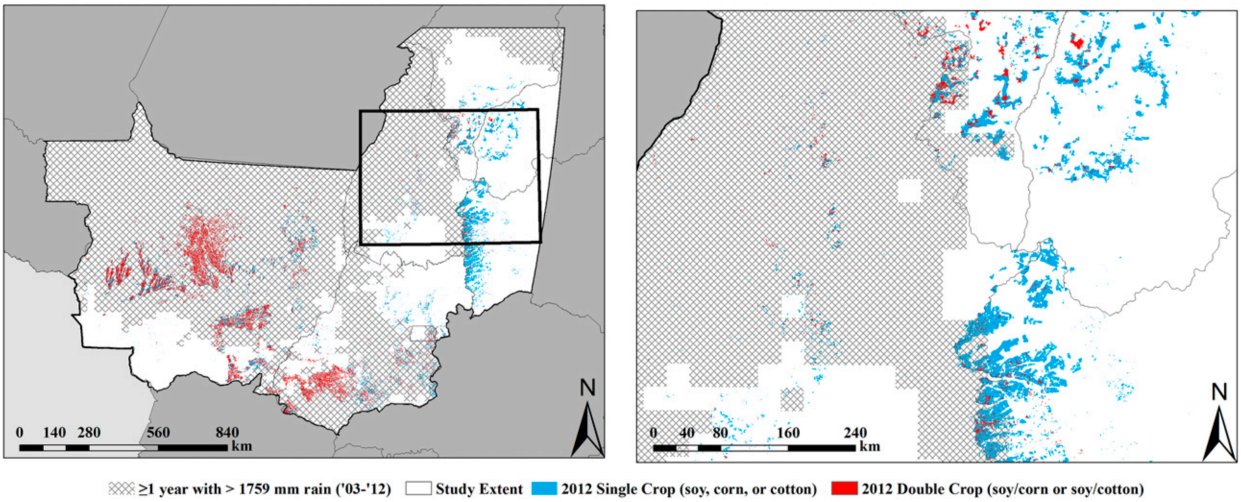

FIG. 11. (left) Nearly all of the double cropping that occurred in 2012 took place in areas that had at least one year of rainfall exceeding the 1759-mm threshold in 2003–12, (right) including MaToPiBa, where double cropping is less widely adopted.

(Orlove et al. 2010). However, the reliability of historical experience can be challenged by current observations, especially in the context of an awareness of climate change. Indeed, others have observed that sowing decisions are ultimately elastic, with farmers from various locales altering their choice of crop variety and timing to coincide with a wide range of location-specific observations, including wind patterns, migratory bird sightings, and temperature changes, as well as rainfall amounts (Zubair 2002; Orlove et al. 2010; Roncoli et al. 2002).

Our data concur with these observations in the context of the Brazilian Cerrado. We observed emergent behavior in the social–ecological system reflected in the threshold of annual rainfall, whereby total cumulative precipitation was not significantly related to the proportion of agriculture in double-cropped rotations beyond 1759 mm yr^{-1}. We additionally found that the degree of double cropping appears to be influenced by observable characteristics of the early rainy season, specifically with respect to the number of rainy days during a critical 4-week period prior to the climatological rainy season onset. Indeed, while a farm manager in an area with historically early and wet rainy seasons may acquire the infrastructure necessary to double crop (Spera et al. 2014), this does not necessitate consistent utilization of this management practice between years, as others have seen that cropping frequency can vary interannually (Cohn et al. 2016). Since the decision to double crop is ultimately an economic cost–benefit analysis (as is generally the case in non-subsistence farming), it follows that farmers are likely to use their best judgments each year to decide whether the meteorological conditions are indicative of a growing season that is phenologically conducive to double cropping and, if so, to choose an allocation of land to be in such a rotation.

This finding contributes, then, to the knowledge base underpinning adaptive capacities to climate change in farming systems broadly and in the Brazilian context specifically. This is particularly salient in the context of recent modeling work done by Pires et al. (2016), which suggests that the long-term sustainability of double cropping in Brazil may be compromised by reductions in rainfall and other atmospheric changes. Although Rosenzweig and Tubiello (2007) acknowledge that farmers around the world have necessarily always adapted to a variety of environmental and economic changes, the rate and variability of meteorological conditions brought about by climate change may push them beyond their capacity. In the Cerrado, where farming systems range from subsistence to agro conglomerates, there is likely to exist a variety of knowledge systems that span a wide range of *awareness* regarding current and future climate change, *experience* regarding the interannual variability of rainy seasons, and *access* to specific advice concerning seasonal outlooks. Hence, a spectrum of capacities exists in this region to adapt to the changing context. Indeed, Rada (2013) observes that there is a substantial efficiency gap between the top agricultural producers and average-performing producers in the Cerrado, suggesting that future productivity gains are possible through technological and managerial innovations. However, if cropping decisions are being made at least in part on the basis of imperfect observations of early-season rainfall observations, then it follows that changes to both intra-annual and interannual variations in precipitation have the potential to convolute the decision-making process and, hence, may present difficulties in achieving such productivity gains in the context of future climate change.

What is therefore needed are robust seasonal forecasts for decision-makers that are place-based and congruent with the knowledge systems of stakeholders in the Cerrado. Others have provided evidence that farmers would alter planting decisions when presented with seasonal forecasts (Roudier et al. 2014) and that those who do tend to have greater yields than those who rely solely on historical climatology (Risbey et al. 2009). This is an open question with regard to farming systems in Brazil. Nonetheless, given the relationship between early rainy season characteristics and cropping frequency shown here, it is reasonable to posit that seasonal forecasts in the context of institutional support for producer awareness, experience, and access could be of utility to agricultural decision-makers in this region.

Depending on the direction and magnitude of change in precipitation patterns in the Cerrado, the feasibility and utility of agricultural intensification could be enhanced, diminished, or maintained only with infrastructural interventions, such as irrigation. Understanding the role that weather and climate play in informing agricultural decision-making under uncertainty is therefore of importance to long-term land-use planning and for building resilience to climatic changes.

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REFERENCES

Arvor, D., V. Dubreuil, J. Ronchail, M. Simoes, and B. M. Funatsu, 2014: Spatial patterns of rainfall regimes related to levels of double cropping agriculture systems in Mato Grosso (Brazil). *Int. J. Climatol.*, **34**, 2622–2633, doi:10.1002/joc.3863.

Barretto, A. G. O. P., G. Berndes, G. Sparovek, and S. Wirsenius, 2013: Agricultural intensification in Brazil and its effects on land-use patterns: An analysis of the 1975–2006 period. *Global Change Biol.*, **19**, 1804–1815, doi:10.1111/gcb.12174.

Beuchle, R., R. C. Grecchi, Y. E. Shimabukuro, R. Seliger, H. D. Eva, E. Sano, and F. Achard, 2015: Land cover changes in the Brazilian Cerrado and Caatinga biomes from 1990 to 2010 based on a systematic remote sensing sampling approach. *Appl. Geogr.*, **58**, 116–127, doi:10.1016/j.apgeog.2015.01.017.

Chou, S. C., and Coauthors, 2012: Downscaling of South America present climate driven by 4-member HadCM$_3$ runs. *Climate Dyn.*, **38**, 635–653, doi:10.1007/s00382-011-1002-8.

Cohn, A. S., L. K. VanWey, S. A. Spera, and J. F. Mustard, 2016: Cropping frequency and area response to climate variability can exceed yield response. *Nat. Climate Change*, **6**, 601–604, doi:10.1038/nclimate2934.

Didan, K., 2015: MOD13Q1: MODIS/Terra vegetation indices 16-day L3 global 250m grid SIN V006. NASA EOSDIS Land Processes DAAC, accessed 6 March 2014, doi:10.5067/MODIS/MOD13Q1.006.

Ewers, R. M., J. P. W. Scharlemann, A. Balmford, and R. Green, 2009: Do increases in agricultural yield spare land for nature? *Global Change Biol.*, **15**, 1716–1726, doi:10.1111/j.1365-2486.2009.01849.x.

Fearnside, P. M., 2005: Deforestation in Brazilian Amazonia: History, rates, and consequences. *Conserv. Biol.*, **19**, 680–688, doi:10.1111/j.1523-1739.2005.00697.x.

Gadgil, S., P. R. S. Rao, and K. N. Rao, 2002: Use of climate information for farm-level decision making: Rainfed groundnut in southern India. *Agric. Syst.*, **74**, 431–457, doi:10.1016/S0308-521X(02)00049-5.

Galford, G. L., J. F. Mustard, J. Melillo, A. Gendrin, C. C. Cerri, and C. E. P. Cerri, 2008: Wavelet analysis of MODIS time series to detect expansion and intensification of row-crop agriculture in Brazil. *Remote Sens. Environ.*, **112**, 576–587, doi:10.1016/j.rse.2007.05.017.

Gan, M. A., V. E. Kousky, and C. F. Ropelewski, 2004: The South America monsoon circulation and its relationship to rainfall over west-central Brazil. *J. Climate*, **17**, 47–66, doi:10.1175/1520-0442(2004)017<0047:TSAMCA>2.0.CO;2.

Gedney, N., and P. J. Valdes, 2000: The effect of Amazonian deforestation on the Northern Hemisphere circulation and climate. *Geophys. Res. Lett.*, **27**, 3053–3056, doi:10.1029/2000GL011794.

Gibbs, H. K., and Coauthors, 2015: Brazil's soy moratorium. *Science*, **347**, 377–378, doi:10.1126/science.aaa0181.

Gollnow, F., and T. Lakes, 2014: Policy change, land use, and agriculture: The case of soy production and cattle ranching in Brazil, 2001–2012. *Appl. Geogr.*, **55**, 203–211, doi:10.1016/j.apgeog.2014.09.003.

Grothmann, T., and A. Patt, 2005: Adaptive capacity and human cognition: The process of individual adaptation to climate change. *Global Environ. Change*, **15**, 199–213, doi:10.1016/j.gloenvcha.2005.01.002.

Huete, A., K. Didan, T. Miura, E. P. Rodriguez, X. Gao, and L. G. Ferreira, 2002: Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sens. Environ.*, **83**, 195–213, doi:10.1016/S0034-4257(02)00096-2.

Huffman, G. J., and Coauthors, 2007: The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *J. Hydrometeor.*, **8**, 38–55, doi:10.1175/JHM560.1.

Jain, M., S. Naeem, B. Orlove, V. Modi, and R. S. DeFries, 2015: Understanding the causes and consequences of differential decision-making in adaptation research: Adapting to a delayed monsoon onset in Gujarat, India. *Global Environ. Change*, **31**, 98–109, doi:10.1016/j.gloenvcha.2014.12.008.

Klink, C. A., and R. B. Machado, 2005: Conservation of the Brazilian Cerrado. *Conserv. Biol.*, **19**, 707–713, doi:10.1111/j.1523-1739.2005.00702.x.

Liebmann, B., and J. A. Marengo, 2001: Interannual variability of the rainy season and rainfall in the Brazilian Amazon basin. *J. Climate*, **14**, 4308–4318, doi:10.1175/1520-0442(2001)014<4308:IVOTRS>2.0.CO;2.

——, S. J. Camargo, A. Seth, J. A. Marengo, L. M. V. Carvalho, D. Allured, R. Fu, and C. S. Vera, 2007: Onset and end of the rainy season in South America in observations and the ECHAM 4.5 atmospheric general circulation model. *J. Climate*, **20**, 2037–2050, doi:10.1175/JCLI4122.1.

Lumley, T., P. Diehr, S. Emerson, and L. Chen, 2002: The importance of the normality assumption in large public health data sets. *Annu. Rev. Public Health*, **23**, 151–169, doi:10.1146/annurev.publhealth.23.100901.140546.

Maatman, A., C. Schweigman, A. Ruijs, and M. H. van der Vlerk, 2002: Modeling farmers' response to uncertain rainfall in Burkina Faso: A stochastic programming approach. *Oper. Res.*, **50**, 399–414, doi:10.1287/opre.50.3.399.7749.

Macedo, M. N., R. S. DeFries, D. C. Morton, C. M. Stickler, G. L. Galford, and Y. E. Shimabukuro, 2012: Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. *Proc. Natl. Acad. Sci. USA*, **109**, 1341–1346, doi:10.1073/pnas.1111374109.

Marengo, J. A., B. Liebmann, V. E. Kousky, N. P. Filizola, and I. C. Wainer, 2001: Onset and end of the rainy season in the Brazilian Amazon Basin. *J. Climate*, **14**, 833–852, doi:10.1175/1520-0442(2001)014<0833:OAEOTR>2.0.CO;2.

Mertz, O., C. Mbow, A. Reenberg, and A. Diouf, 2009: Farmers' perceptions of climate change and agricultural adaptation strategies in rural Sahel. *Environ. Manage.*, **43**, 804–816, doi:10.1007/s00267-008-9197-0.

Morton, D. C., R. S. DeFries, Y. E. Shimabukuro, L. O. Anderson, E. Arai, F. D. Espirito-Santo, R. Freitas, and J. Morisette, 2006: Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. *Proc. Natl. Acad. Sci. USA*, **103**, 14 637–14 641, doi:10.1073/pnas.0606377103.

Nepstad, D., and Coauthors, 2009: The end of deforestation in the Brazilian Amazon. *Science*, **326**, 1350–1351, doi:10.1126/science.1182108.

Orlove, B., C. Roncoli, M. Kabugo, and A. Majugu, 2010: Indigenous climate knowledge in southern Uganda: The multiple components of a dynamic regional system. *Climatic Change*, **100**, 243–265, doi:10.1007/s10584-009-9586-2.

Ostrom, E., 2009: A general framework for analyzing sustainability of social-ecological systems. *Science*, **325**, 419–422, doi:10.1126/science.1172133.

Pires, G. F., G. M. Abrahão, L. M. Brumatti, L. J. C. Oliveira, M. H. Costa, S. Liddicoat, E. Kato, and R. J. Ladle, 2016: Increased climate risk in Brazilian double cropping agriculture systems: Implications for land use in Northern Brazil. *Agric. For. Meteor.*, **228–229**, 286–298, doi:10.1016/j.agrformet.2016.07.005.

Rada, N., 2013: Assessing Brazil's Cerrado agricultural miracle. *Food Policy*, **38**, 146–155, doi:10.1016/j.foodpol.2012.11.002.

Richards, P. D., R. J. Myers, S. M. Swinton, and R. T. Walker, 2012: Exchange rates, soybean supply response, and deforestation in South America. *Global Environ. Change*, **22**, 454–462, doi:10.1016/j.gloenvcha.2012.01.004.

Risbey, J. S., M. J. Pook, P. C. McIntosh, M. C. Wheeler, and H. H. Hendon, 2009: On the remote drivers of rainfall variability in Australia. *Mon. Wea. Rev.*, **137**, 3233–3253, doi:10.1175/2009MWR2861.1.

Roncoli, C., K. Ingram, and P. Kirshen, 2002: Reading the rains: Local knowledge and rainfall forecasting in Burkina Faso. *Soc. Nat. Resour.*, **15**, 409–427, doi:10.1080/08941920252866774.

Rosenzweig, C., and F. N. Tubiello, 2007: Adaptation and mitigation strategies in agriculture: An analysis of potential synergies. *Mitigation Adapt. Strategies Global Change*, **12**, 855–873, doi:10.1007/s11027-007-9103-8.

Roudier, P., B. Muller, P. d'Aquino, C. Roncoli, M. A. Soumaré, L. Batté, and B. Sultan, 2014: The role of climate forecasts in smallholder agriculture: Lessons from participatory research in two communities in Senegal. *Climate Risk Manage.*, **2**, 42–55, doi:10.1016/j.crm.2014.02.001.

Sano, E. E., R. Rosa, J. L. S. Brito, and L. G. Ferreira, 2010: Land cover mapping of the tropical savanna region in Brazil. *Environ. Monit. Assess.*, **166**, 113–124, doi:10.1007/s10661-009-0988-4.

Spera, S. A., A. S. Cohn, L. K. VanWey, J. F. Mustard, B. F. Rudorff, J. Risso, and M. Adami, 2014: Recent cropping frequency, expansion, and abandonment in Mato Grosso, Brazil had selective land characteristics. *Environ. Res. Lett.*, **9**, 064010, doi:10.1088/1748-9326/9/6/064010.

Spracklen, D. V., S. R. Arnold, and C. M. Taylor, 2012: Observations of increased tropical rainfall preceded by air passage over forests. *Nature*, **489**, 282–285, doi:10.1038/nature11390.

Strassburg, B. B. N., A. E. Latawiec, L. G. Barioni, C. A. Nobre, V. P. da Silva, J. F. Valentim, M. Vianna, and E. D. Assad, 2014: When enough should be enough: Improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. *Global Environ. Change*, **28**, 84–97, doi:10.1016/j.gloenvcha.2014.06.001.

VanWey, L. K., S. Spera, R. de Sa, D. Mahr, and J. F. Mustard, 2013: Socioeconomic development and agricultural intensification in Mato Grosso. *Philos. Trans. Roy. Soc. London*, **368B**, 20120168, doi:10.1098/rstb.2012.0168.

Wagner, R. G., 1996: Decadal-scale trends in mechanisms controlling meridional sea surface temperature gradients in the tropical Atlantic. *J. Geophys. Res.*, **101**, 16 683–16 694, doi:10.1029/96JC01214.

World Bank, 2016: Agriculture, value added (constant 2010 US$). The World Bank, accessed 7 November 2016. [Available online at http://data.worldbank.org/indicator/NV.AGR.TOTL.KD?locations=BR.]

Zhang, X., M. A. Friedl, C. B. Schaaf, A. H. Strahler, J. C. F. Hodges, F. Gao, B. C. Reed, and A. Huete, 2003: Monitoring vegetation phenology using MODIS. *Remote Sens. Environ.*, **84**, 471–475, doi:10.1016/S0034-4257(02)00135-9.

Zhou, J., and K.-M. Lau, 1998: Does a monsoon climate exist over South America? *J. Climate*, **11**, 1020–1040, doi:10.1175/1520-0442(1998)011<1020:DAMCEO>2.0.CO;2.

Zubair, L., 2002: El Niño–Southern Oscillation influences on rice production in Sri Lanka. *Int. J. Climatol.*, **22**, 249–260, doi:10.1002/joc.714.