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When do Farmers Burn Pasture in Brazil: A Model-Based Approach to Determine Burning Date

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ABSTRACT

Fire is widely used by farmers in Brazil during the winter, or the dry season, to remove accumulated dead pasture biomass. These practices have substantial impacts on vegetation, soil nutrients and carbon emissions. However, they are rarely represented within process-based fire models embedded within Dynamic Global Vegetation Models (DGVM). We developed an algorithm named Chalumeau to estimate the expected burning dates from daily precipitation or temperature depending on the seasonality type. By coupling with a fire module from a DGVM, Chalumeau enables the ignition of fire as an essential part of modelling fire practices. The burning dates are evaluated by comparing against observed fire dates on pasture. From these estimated dates, we extract the timing strategies of ranchers, which vary regionally within Brazil. This study confirms that climatic conditions are the main trigger for farmers decisions to set fire and shows the different burning strategies across Brazil.

Introduction

Fire has been used as a management tool by farmers on grass-dominated lands for centuries in Brazil (Cochrane, 2009; Mistry et al., 2005; Pivello, 2011). At the same time, fire is subject to much debate in science and society (Durigan and Ratter, 2016; Mistry et al., 2019) with regard to the increase of wildfire risk, preservation of natural grassland ecosystems and the sustainability of pasture management. Fire practices are usually carried out during the winter or dry season and are based on land managers' observations of vegetation conditions (Mistry, 1998; Sorrensen, 2000; van der Werf et al., 2008). Burning is mostly employed to remove excess dead biomass and stimulate resprouting (Csiszar et al., 2012; Mistry, 1998; Pillar and de Quadros, 1997). Indeed, large parts of the aboveground biomass die off during low temperature or low precipitation periods, here referred to as the dormant season. The accumulated material is burned to stimulate regrowth of grasses with high nutritional value for grazing animals (Mistry, 1998; van der Werf et al., 2008). Burning also removes or at least reduces biomass from unpalatable plant species. Lastly, the ashes generated by fire provide readily available nutrients for freshly sprouting plants (López-Mársico et al., 2019; Pivello, 2011).

Burning aims to improve the productivity of farms (Laterra et al., 2003). From a social and economic point of view, it is the cheapest and easiest way for farmers to prepare their pasture for the new vegetation period (Mistry, 1998). Additionally, setting prescribed burns prevents wildfires, especially in the Cerrado region (Pivello, 2011; Welch et al., 2013).

Timing, spatial extent and frequency of burning vary considerably among regions in Brazil. The setting of fire is motivated and constrained by the condition of the vegetation (van der Werf et al., 2008) which is determined directly by the climate and its seasonality. The choice of an earlier or later date for burning within the dormant season influences the impact on the fire extent, the soil, the vegetation and consequently on livestock production (Williams et al., 1998). For instance, the vegetation die-off during the dormant season and the subsequent accumulation of dead biomass

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can lead to higher fire intensity as it increases the amount of dry fuel and consequently the energy content of the fire.

Fire regimes depend on the type of pastures, and these differ greatly across Brazil. Natural grasslands are covered by native species but these are being replaced in many regions by highly productive forage species which raise the capacity of pastures to feed livestock (Baggio et al., 2021; Dias-Filho, 2014). Tropical C4 forage grasses are intensively cultivated in large parts of the country, though some of them are invasive (Pivello, 2011). In the southern part of the country, C3 species of mostly European origin are cultivated as well (Nabinger et al., 2000).

Brazil's phytogeographic domains ('biomes' according to IBGE (2019)) vary in terms of area of natural and planted pastures (Baggio et al., 2021). The Amazon domain is one of the areas with the highest proportion of planted pastures (Baggio et al., 2021; Dias-Filho, 2014). In regions like the Atlantic Forest, the Cerrado, the Pantanal or the Pampa, extensive areas consist of natural grasslands and savannah formations (Andrade et al., 2019; Dias-Filho, 2014; Overbeck et al., 2015; 2005; Pillar and de Quadros, 1997; Sattler et al., 2018) which are utilised by farmers for livestock production (Souza et al., 2020).

Rabin et al. (2015) concludes by a statistical method that fire practices on pasture may be the cause of more than 40% of the annual burned area in South America. Moreover, the influence of these practices on wildfires in the Amazon rainforest has been proven (Brando et al., 2020; Cano-Crespo et al., 2015). Uncontrolled human-caused and management fires can spread into the neighbouring vegetation, specifically into remaining forest fragments which have the driest edges and are prone to burn (Achard et al., 2002; Bonaudo et al., 2014; Nepstad et al., 2008). Such spreading fires are intensified by deforestation and fragmentation which lead to an expansion of the interface length between natural and agricultural lands (Cochrane and Laurance, 2002; Cochrane, 2009).

The collection of precise information about the method of burning is highly limited since data sets describing human behaviour require much expenditure. Moreover, policy regulations and the illegal nature of burning add another layer of complexity, increasing the sensitivity of this issue. Due to this additional obstacle, the availability of literature and data on this topic is rather scarce (Mistry, 1998; Mistry et al., 2019). Although the use of fire in Brazil is prohibited, exceptions can be made for agricultural activities and management in protected areas or research (Congresso Nacional, 2012).

Most DGVMs that include fire activities have difficulties in capturing human ignitions in the natural vegetation and do not consider human-made fires on managed land. The main reason is that the ignition of fire on pasture depends on the status of the vegetation and climatic conditions as well as the ranchers own decision. Usually, farmers make use of an ideal burning window depending on their perception and objectives, i.e. they consider climatic conditions but also social and economic factors (Mistry, 1998; van der Werf et al., 2008).

The aim of this study is to investigate the timing of burning on pastures and its link to climatic conditions across the different phytogeographic domains in Brazil. We develop a rule-based algorithm named Chalumeau, which 1) calculates the dormant season from daily climate data, either winter or dry season, in areas under temperature or precipitation seasonality type and 2) extracts burning dates representing the burning timing. These calculated burning dates can be used to start the fire ignition routine in a DGVM that accounts for burning practices. By comparison against observational data and by conducting a sensitivity analysis, we 1) obtain a pattern of the timing when farmers are burning pastures in the different regions in Brazil and 2) test the assumption that fire practices are triggered by climatic conditions and evaluate how burning strategies are linked to it.

Methods

We develop a new algorithm, called 'Chalumeau' (French for blowtorch), to estimate a burning date depending on climatic conditions (Fig. 1). First from daily climate data, the respective seasonality type is determined either as temperature or precipitation dominated (Sec. *Seaonality module*). After determining the dormant season *DS*, either for the winter or dry season, the burning dates are extracted from *DS* and the chosen burning strategy (Sec. *Chalumeau module*). The evaluation process of Chalumeau uses fire and land-use data which have to be processed and is explained in section *Evaluation module*.

Description and processing of input and validation data

Climate input data

The computation of the seasonality type and the burning date is based on daily temperature and precipitation data from the years 1948 to 2019 from the NASA Global Land Data Assimilation System (GLDAS, NASA, 2015b; Rodell et al., 2004). Both data sets are provided at a spatial resolution of $0.25^\circ \times 0.25^\circ$ longitude and latitude and a temporal resolution of 3 hours. We aggregate the data to a daily resolution of $0.5^\circ \times 0.5^\circ$ for our purposes using the Climate Data Operator software (CDO, Schulzweida, 2019).

Validation data

Vegetation net primary productivity

To evaluate the *DS*, we use the net primary productivity (*NPP*) results provided by the Dynamic Global Vegetation Model with managed Land, LPJmL4.0 (Schaphoff et al., 2018a) covering the years 1948 to 2019. LPJmL4.0 simulates the growth and productivity of natural and agricultural vegetation driven by soil characteristics and climatic conditions on a spatial resolution of $0.5^\circ \times 0.5^\circ$ longitude and latitude (Schaphoff et al., 2018b).

The requirement to quantify *DS* at a daily resolution constrains our choice for a suitable evaluation data set. *NPP* is calculated using daily reanalysis climate data (GLDAS, NASA, 2015b; Rodell et al., 2004). Therefore, *NPP*, *DS*s and burning dates are calculated by consistent climate input at the same spatiotemporal resolution, but employ different modelling approaches, ensuring their independence from each other.

Fire detection products

From the available fire products, the choice for evaluation data is challenging because of two requirements: a) daily resolution to evaluate simulated burning dates and b) high spatial resolution of fire and land-use data to identify burning practices on pasture (Sec. *Preocessing of fire products*).

The FireCCIS1SA10 product from the European Spatial Space Agency Fire, Climate Change Initiative (ESA CCI, Belenguer-Plomer and Pettinari, 2019) combines spectral information from the Sentinel-1 satellite and thermal information from the MODIS Active Fire Product. This fire product, called here ESA, is available only for the year 2017 on a resolution of 40 m $\times$ 40 m. The data set covers the Amazon basin, the northern part of the Cerrado (north of 15°S) and the south-western area of the Caatinga (west of 40°W). Due to the high spatial resolution of ESA product, it is unlikely that two fires occur within the same year in the same grid cell, because of the subsequent lack of fuel. Therefore, for each grid cell, only the first burning day of the year is reported.

Although the spatial resolution of ESA satisfies our criteria, this fire product covers only one year and not the entire area of Brazil. We use another data set to fully evaluate Chalumeau results. We include the MODIS Aqua and Terra Thermal Anomalies and Fire lo-

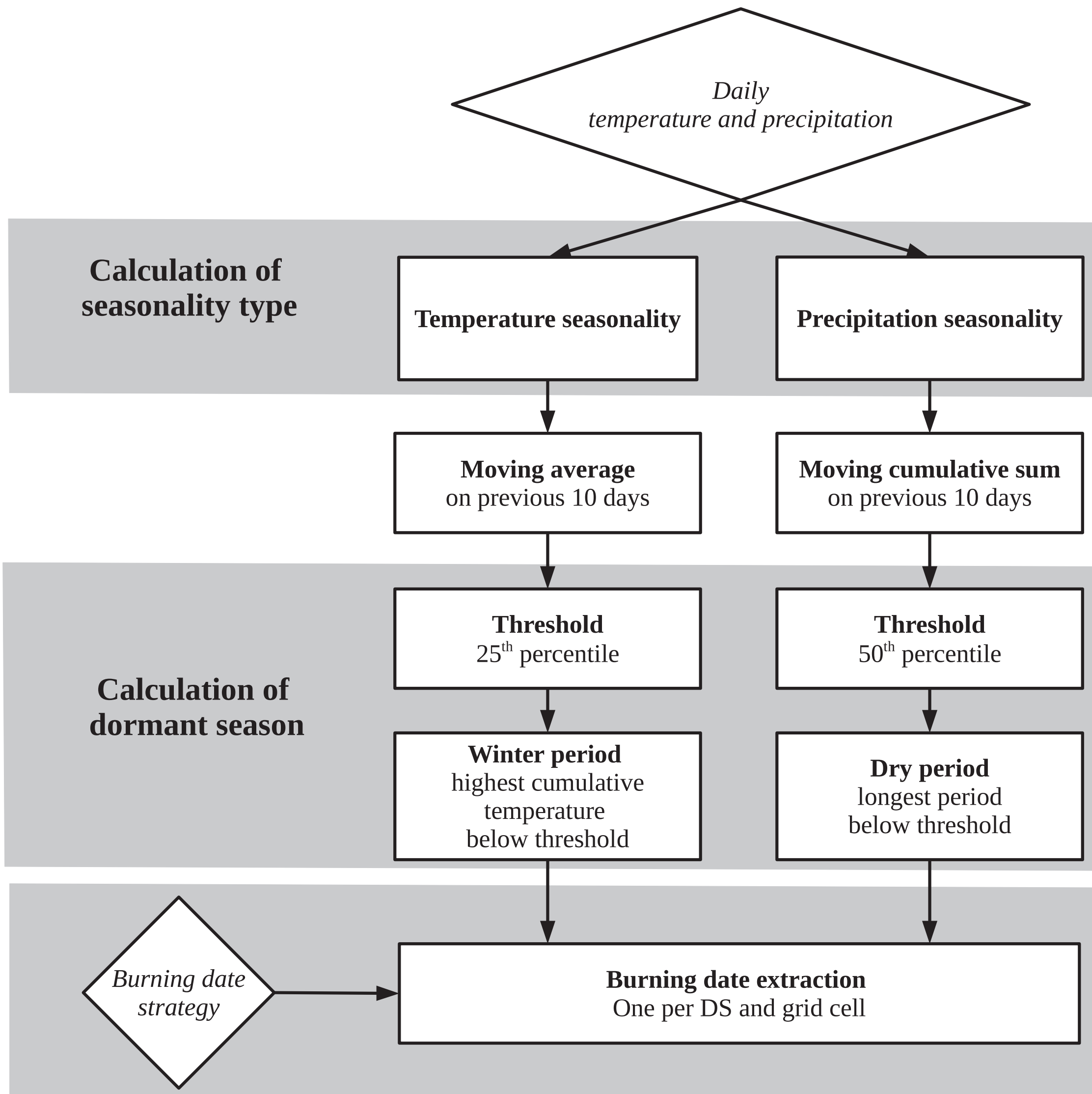

Fig. 1. Process to calculate the dormant season, *DS*, depending on the daily climate data and extract the burning date based on *DS*'s duration and burning strategy. The seasonality type is evaluated using the seasonality module from Waha et al. (2012). Input data and parameters are indicated by rhombus boxes. The resulting burning dates are extracted per grid cell and *DS*.

cations collection 6 generated by the Moderate Resolution Imaging Spectroradiometer (MODIS, Giglio et al., 2016; NASA, 2015a). The data, called MODIS here, are available globally from November 2000 for Terra and July 2002 for Aqua EOS satellites to December 2019. Active fire detections are represented with a resolution of 1 km × 1 km by the MODIS MOD14/MYD14 Fire and Thermal Anomalies algorithm (Giglio et al., 2003).

Land-Use information

We employ the MapBiomas collection 4.0 (MapBiomas, 2018) with a resolution of 30 m × 30 m. These land cover and land-use maps are the result of a large collaboration between Brazilian research groups and offer a classification of 33 land categories. We use the categories 'pasture' and 'grassland formation' that include all grassland areas, natural or planted, and are almost entirely under grazing for livestock production (Souza et al., 2020). As fire is used as a management measure in parts of the natural grasslands and planted pasture, we included both categories. For the analysis, we consider each Brazilian region separately with the exception of the Pantanal, which is included into the Cerrado due to its low number of grid cells.

Processing of fire products

The land-use product MapBiomas (MapBiomas, 2018) is first rasterised to a binary file for the two categories 'pasture' and 'grassland'. Then, it is regridded into the resolutions of the two fire products, 40 m × 40 m for ESA and 1 km × 1 km for MODIS, with the Geospatial Data Abstraction software Library (GDAL, GDAL/OGR contributors, 2020). We extract from the intersection of MODIS and MapBiomas a percentage of the amount of either pasture or grassland cells belonging to one MODIS cell. Fire detections are considered when this percentage is above 20%.

Allocation of fire detections

For the ESA fire detection product, all regional detections for the year 2017 are merged into one tile using the GDAL algorithm. It is then intersected with the regridded land-use data set and fire detections are allocated to both grass-dominated land-use types.

For the MODIS product, we select 5 different years representing interannual variability, including years with positive and negative phases of the El Niño-Southern Oscillation (Fig. 2). The merging is done per domain and per year between fire detections and both land-use types.

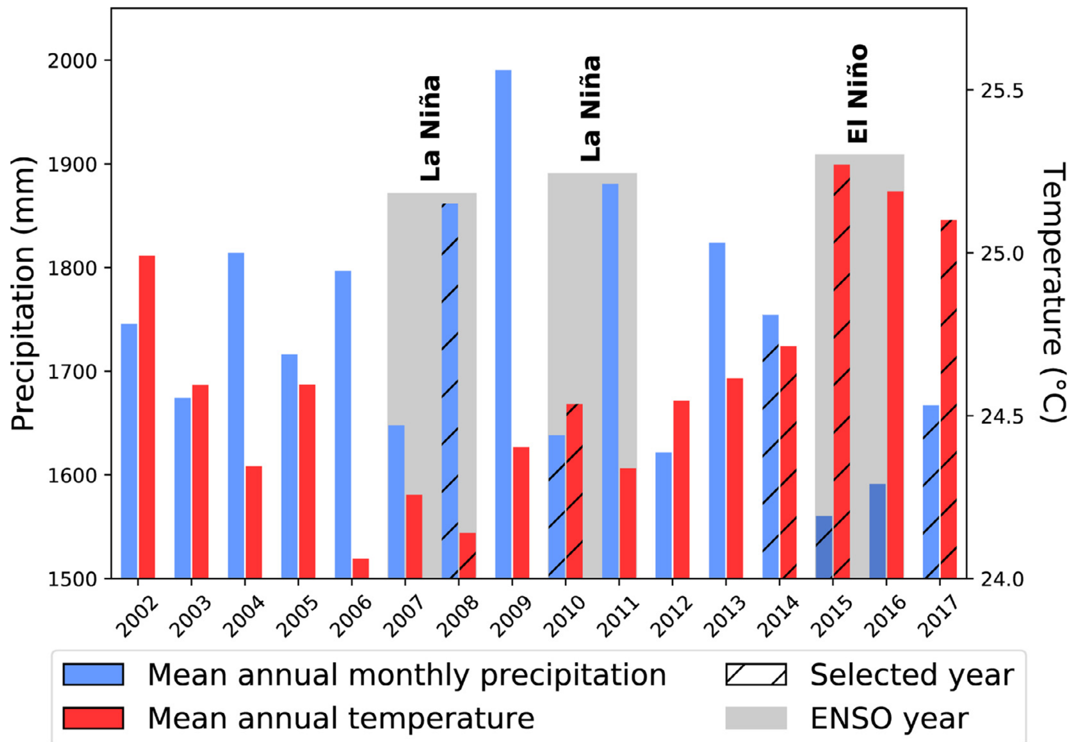

Fig. 2. Annual climatic conditions in Brazil from 2002 to 2017. Selected years are denoted by hatches and ENSO occurrences highlighted in grey.

The new allocated fire data sets from MODIS and ESA are regridded to a resolution of $0.5^\circ \times 0.5^\circ$ to be consistent with the chosen resolution of Chalumeau results. Each fire is attributed to a grid cell depending on its latitude and longitude. The final data consists of the detection day and the location of the grid cell.

Concerning the ESA product, we didn't merge fire detections from the same date and adjacent 40m x 40m cells which are presumably from the same fire event. Thereby potential large fires are represented by several fire detections and have a higher weight in the calculation of burning dates than isolated fires.

Analysis of fire observations

In order to compare the timing of the observed fires on pasture and grassland to the calculated burning dates from Chalumeau, we extract the fire season and the average burning date from the observations.

To identify the main fire season, a ratio is used that reflects whether fires occur regularly or rather rarely. The ratio r is calculated by dividing the duration of the interval between the first and last day with a fire detection by the total number of days with fire detections within a year in one grid cell. Thus, high values of r indicate rarely occurring fires within a long period and low values regular fires without long breaks. This allows to isolate potential burning seasons, BS_p, as subsequent days with fire detections without breaks longer than $\max(r, 20)$ days. For each BS_p, the cumulative numbers of fires, C_{fire}, is determined as the sum of the number of fires within the BS_p. Finally, the main fire season BS is defined as the BS_p with the highest C_{fire}.

The annual burning date BD is extracted from the main burning season (Eq. 1) as the average day within the burning season weighted by the number of fire detections per day i, f_i.

$$BD = \frac{\sum_{i=L}^{M} i \times f_i}{\sum_{i=L}^{M} f_i} \tag{1}$$

where $\begin{cases} L, M = \text{first and last day in the main burning season} \\ BD = \text{burning date} \end{cases}$

Seasonality module

Climatic zones in Brazil reach from subtropical to tropical and their seasonality is specified by temperature or precipitation. To determine the driving climate variable for the seasonality, we follow the approach described in Waha et al. (2012). Coefficients of variation for precipitation (CV_P) and temperature (CV_T) are used to distinguish seasonality types based on past daily climate data. They are calculated as the ratio of the standard deviation to the mean of the daily temperature or precipitation values. With this method, three seasonality types are calculated in Brazil: precipitation seasonality characterised by $CV_P > 0.4$ and $CV_T \leq 0.01$, temperature seasonality by $CV_P \leq 0.4$ and $CV_T > 0.01$ and no seasonality by $CV_P \leq 0.4$ and $CV_T \leq 0.01$ (Fig. 3) (Waha et al., 2012). However, daily temperatures in some areas without seasonality show similar patterns as in areas with temperature seasonality but with a lower coefficient of variation (Fig. S1; available online). To better represent human winter perception, we decide to reduce the CV_T limit to 0.008. Thereby, temperature seasonality is newly defined by $CV_P \leq 0.4$ and $CV_T > 0.008$ and no seasonality by $CV_P \leq 0.4$ and $CV_T \leq 0.008$ (Fig. 3).

Chalumeau module

Calculation of dormant season for temperature seasonality

The calculation is based on daily temperatures averaged over the 10 previous days (T_{ma}) (Sec. *Climate input data*). Annual thresholds for separating dormant seasons are taken as the 25^{th} percentile of T_{ma} of the respective year. These dormant seasons, in the following denoted as DS_{bt}, are defined by intervals with T_{ma} below the threshold and without warm spells longer than 10 days. Indeed, we assume that such a spell shorter than 10 days is not perceived as a potential end of the winter but just as a warm event. For each DS_{bt}, the cumulative temperature below the thresh-

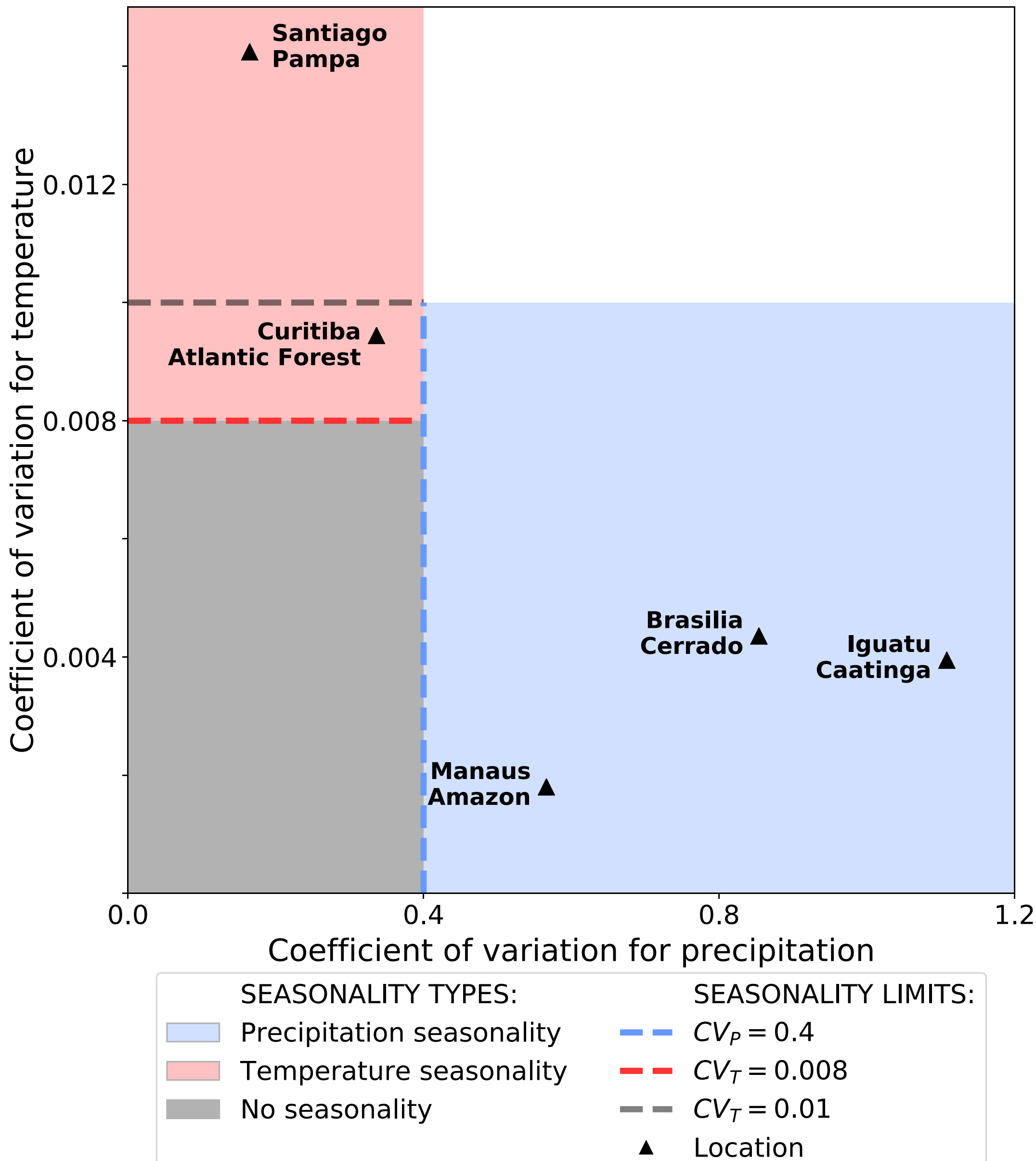

Fig. 3. Classification of seasonality types by coefficients of variation for temperature and precipitation represented by coloured areas and thresholds represented by lines. The exemplary locations in Brazil (black triangles with indication of Brazilian biomes according to IBGE (2019)) are placed within the seasonality classification.

old (C_{bt}) is calculated as follows :

$$\forall \quad DS_{bt}, \quad C_{bt} = \sum_{i=m}^{n} \begin{cases} td_i & \text{if } td_i \le 0 \\ 0 & \text{if } td_i > 0 \end{cases} \tag{2}$$

$$\text{where} \quad \begin{cases} td_i & = T_{ma,i} - T \\ T & = \text{annual temperature threshold} \\ m,n & = \text{first and last day in one } DS_{bt} \end{cases}$$

Finally, the annual resulting dormant season (DS) corresponds to the DS_{bt} with the highest C_{bt}.

Calculation of the dormant season for precipitation seasonality

The calculation is based on moving cumulative sums of the daily precipitation over the previous 10 days (P_{cs}) (Sec. *Climate input data*). Days belonging to the possible dormant season are those with P_{cs} below the 50^{th} percentile threshold of the respective year. Within Chalumeau, the periods below the threshold are marked and the one with the longest duration is selected as DS. Criteria for the identification of shorter wet spells are integrals over the daily precipitation in periods above the threshold. If the integral is below 2% of the annual precipitation, we assume the wet spell to be part of the dry season, and otherwise as the end of the potential dry season.

Since the calculation is intended for Brazil in the southern hemisphere, DS can overlap with the end of the calendar year. In case of an unfinished DS, i.e. P_{cs} is below the threshold at the end of the year, Chalumeau considers the P_{cs} of the next year without changing the threshold and follows the same procedure. The days belonging to this DS are not considered in the calculation for the next year.

Finally, for each grid cell and both seasonality types, the annual date of the beginning, DS_B, and the end of DS, DS_E, are calculated. The duration of DS, DS_D, is the difference between these two dates:

$$DS_D = DS_E - DS_B \tag{3}$$

Extraction of the burning date

We assume that most of the burning practices on pastures and grasslands are taking place at the end of DS, i.e. either winter or dry season. To emulate personal preferences and strategies of farmers, we include different choices for the burning date in relation to DS. According to the average duration of DS depending on the seasonality type, a fraction of DS_D is chosen to define the burning strategy:

$$DS_F = \begin{cases} DS_D/8 & \text{for precipitation seasonality} \\ DS_D/4 & \text{for temperature seasonality} \end{cases} \tag{4}$$

The two factors for the fraction differ for the seasonality type because of their average duration.

We implement four strategies in Chalumeau corresponding to certain choices of setting fire before or after the end of the DS. Burning before the end of the period as ‘short season’ or ‘early season’ refer to two and one DS_F before the end of the season. A third choice would be the ‘end season’ which corresponds to the last day of DS. And finally, the ‘early spring’ strategy is burning one DS_F later than the last day.

Evaluation of the algorithm Chalumeau

We evaluate the DSs computed by Chalumeau against NPP simulated by LPJmL4.0 for natural vegetation (Schaphoff et al., 2018a) (Sec. *Validation data*). We calculate the NPP percentage over DS, NPP_{DS}, which corresponds to the relative share of NPP from the beginning to the end of the DS. This gives an insight on the vegetation development during this period and we expect it to be low.

With the aim to appraise burning dates from Chalumeau, we first translate the position of burning dates within the burning seasons obtained by the analysis of the observed fire data sets. We specified as 0 the beginning and 1 the end of the observed burning seasons and the relative positions of burning dates are derived by proportionality. We can then evaluate whether calculated burning dates are inside (relative position between 0 and 1) or outside the observed burning season.

To determine which burning strategy reproduces fire detections best, we define two values. Firstly, we evaluate burning dates by the ratio of the burning dates from Chalumeau divided by the observed burning dates, both averaged per year and domain. Secondly, we calculate the percentage of burning dates within the observed burning season per year and domain. These ratios and percentages are computed for all four strategies. The ratio gives an indication of the precision of burning dates while the percentage provides a general appreciation on modelled burning dates compared to observed burning seasons.

Finally, to determine which of the four strategies reproduces the observed fires per domain and year best, we take the strategy for which the ratio and percentage are the closest to the target point, which is ratio = 1 and percentage = 100%.

Results

Distribution of seasonality types over Brazil

Over most areas of Brazil, seasonality is driven by precipitation (Fig. 4). The southern and eastern part of the Amazon rainforest, the Cerrado, the Pantanal wetland region and the semiarid Caatinga exhibit this seasonality type as well as the central and northern area of the Atlantic Forest. Temperature seasonality is occurring in the Pampa, which is dominated by grasslands, and in the southern region of the Atlantic Forest. In the transition zones between the seasonality types, the seasonality can alternate depending on the annual climate (hatched areas in Fig. 4).

Dormant periods

Dormant periods are calculated from climate data depending on the seasonality types either from moving cumulative sums of daily precipitation, P_{cs} or from daily temperature averages over the 10 past days, T_{ma} (Fig. S2; available online).

In precipitation seasonality regions, the DSs’ duration is mostly rather long between 125 and 225 days (Fig. 5). Short durations are predominately located in temperature seasonality areas between 25 and 125 days and in precipitation seasonality zones close to alternating regions with durations between 50 and 100 days. A short duration can be explained by highly variable daily precipitation values and a less clearly defined dry season signal in comparison to location 2 in the Cerrado domain.

DSs’ durations in precipitation seasonality regions are nearly normally distributed between 25 and 225 days with slight differences between years (Fig. 6a). In the year 2014, areas with shorter DSs are more widespread. On the contrary, duration of DSs in temperature seasonality zones for the same year is predominantly longer: between 100 and 125 days (Fig. 6b). However, the distribution in temperature seasonality regions is more characterised by narrow peaks. There are years with short durations between 30 and 40 days, such as 2008 and 2010, whereas in average years the durations of DSs are between 50 and 110 days. The occurrence of ENSO years does not play a significant role for the duration of DSs in precipitation seasonality areas (Fig. 6a). In temperature seasonality regions, winters tend to be shorter for the El Niño and La Niña years (2008, 2010, 2015) (Fig. 6b).

In order to evaluate the DSs calculated from Chalumeau, we compare the share of the net primary productivity (NPP_{DS}, Sec. *Evaluation of the algorithm Chalumeau*) within and outside the DSs (Fig. 6c,d). The distribution of NPP_{DS} in precipitation seasonality regions consists of two parts (Fig. 6c). The first one with NPP_{DS} between 0 and 10% represents the Caatinga (see Appendix, Fig. A.1). The second part is larger and displays different patterns depending on the climatic conditions in particular years. The El Niño extreme years 2010 and 2015 show lowest modes for the distribution. This means that a lower proportion of the annual NPP is produced during DS. During these extreme years, the calculated DSs represent well the dormant phase of the vegetation. On the other hand, for the extreme La Niña year 2008 a higher mode of the distribution is determined at 35% with maximum values at 60%. This shows that in some areas the vegetation is less impacted by the dry season and is even more productive than within the growing period of the vegetation (Appendix, Fig. A.1a).

In temperature seasonality regions (Fig. 6d), extreme years, either El Niño or La Niña, tend to have the lowest mode of the distribution between 5 and 10%. Average years such as 2014 and 2017 and partly 2015 have moderately higher NPP_{DS} between 10 and 20% (Appendix, Fig. A.1).

For the majority of DSs calculated by Chalumeau, the corresponding NPP_{DS} values are below 40%. Thus, the resulting DSs represent the season with the lowest productivity of the vegetation.

Calculation and evaluation of burning dates

Burning dates calculated from Chalumeau

In Chalumeau, four burning timing strategies are implemented (Sec. *Extraction of the burning*). Burning dates derived from DSs for the strategy ’end season’ display a difference between temperature and precipitation seasonality regions (Fig. 7). Indeed, regions under temperature seasonality show earlier burning dates around July and August. This is due to earlier DSs during the year in comparison to the more northern areas, like the Cerrado, which are under precipitation seasonality and have burning dates during September and October. In 2014 (Fig. 7a), the southern part of the Atlantic

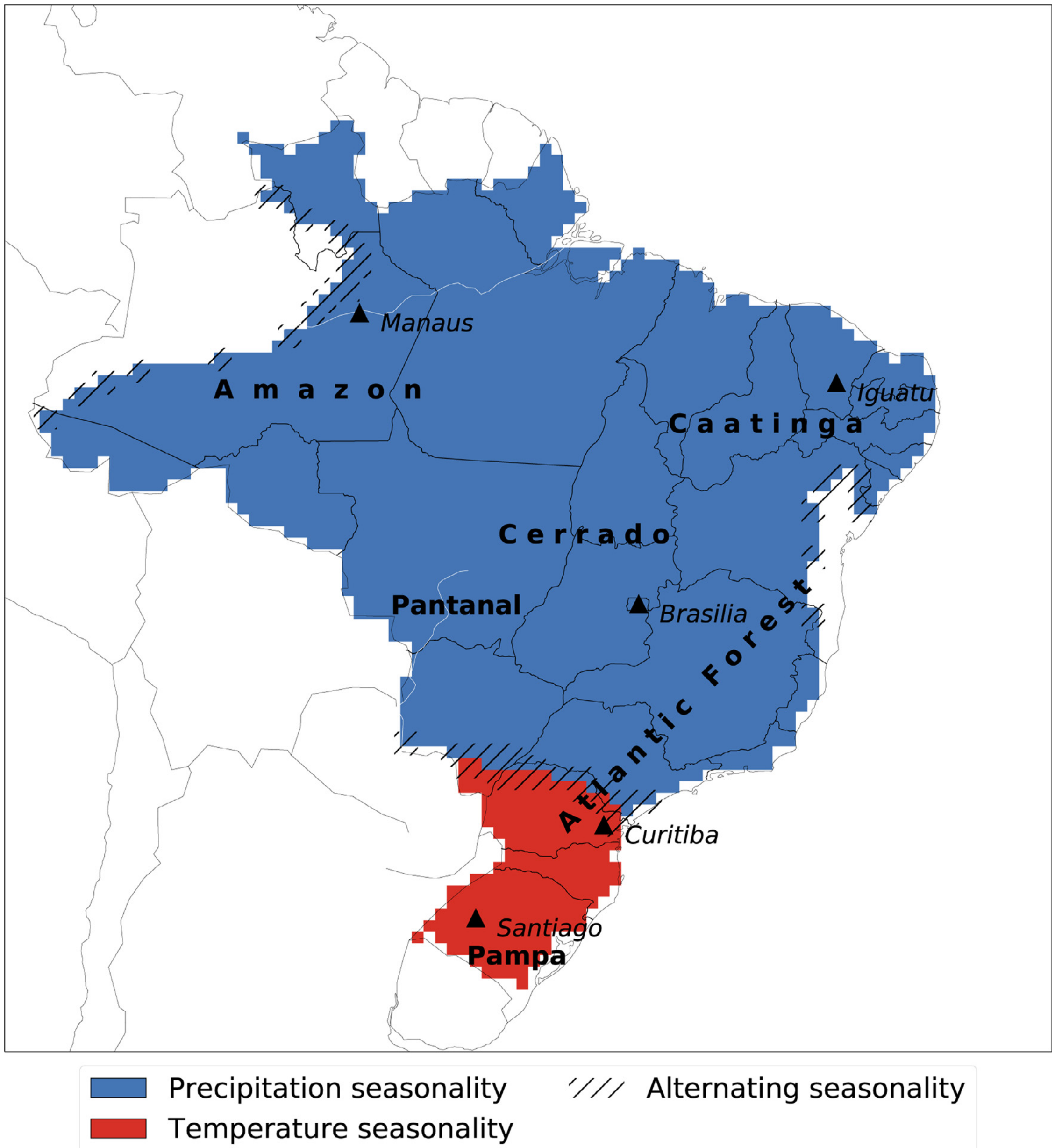

Fig. 4. Distribution of precipitation and temperature seasonality over Brazil between 1948 and 2017 calculated by the LPJmL seasonality module. Areas with alternating seasonality types are denoted by hatching.

Forest displays early burning dates in June and July due to an exceptional early dry season. Finally, northern Brazil has the latest burning dates which occur between November and January of the following year.

Burning season according to ESA CCI data set

The allocation of fires captured by ESA on pasture and grassland and the calculation of fire seasons and burning dates (Sec. *Processing of fire products*) are represented as season duration and burning months (Fig. 8). The original data set covers only the Amazon basin and the northern part of the Cerrado. According to the ESA data set, the Cerrado region exhibits long fire seasons between 250 and 350 days for both land-use types (Fig. 8a and b). Indeed, a high number of fires is detected in this area over the whole year. In the Amazon region, burning seasons are shorter with values around 50 to 100 days.

Burning dates occur mainly from September to December (Fig. 8c and d). The Cerrado which has longer fire season tends to have earlier burning dates in August. The northern coastal region has later burning dates around November and December. For pastures in the northern part of the Amazon rainforest, early burning dates during April and May are observed.

Burning season according to MODIS data set

Fire detections on pasture in the MODIS data set cover all Brazil except the southern region and western part of the Amazon rainforest (Fig. 9a) where this land-use type does not occur. The duration of the fire seasons is between 150 and 200 days in the Amazon domain, and shorter, between 50 to 100 days, in other regions like the Cerrado and the south of Brazil. Burning dates extracted from these fire seasons are around the month of September in the Cerrado, the Atlantic Forest and the south of the Amazon (Fig. 9c). In Pampa, where natural grasslands dominate, the burning dates

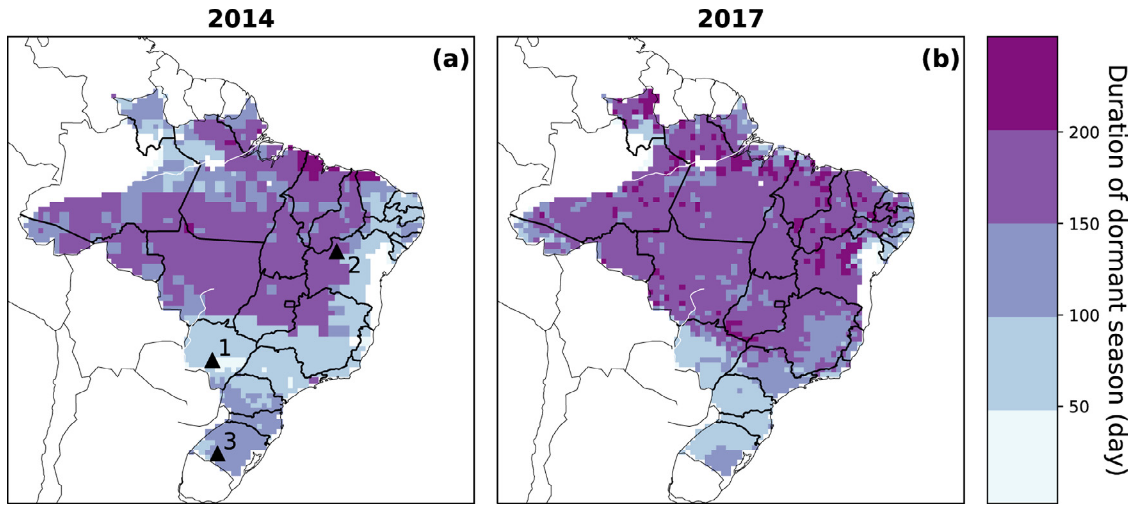

Fig. 5. Duration of the dormant seasons in Brazil for the years 2014 and 2017 and location of study sites under precipitation (locations 1 and 2) and temperature seasonality (location 3).

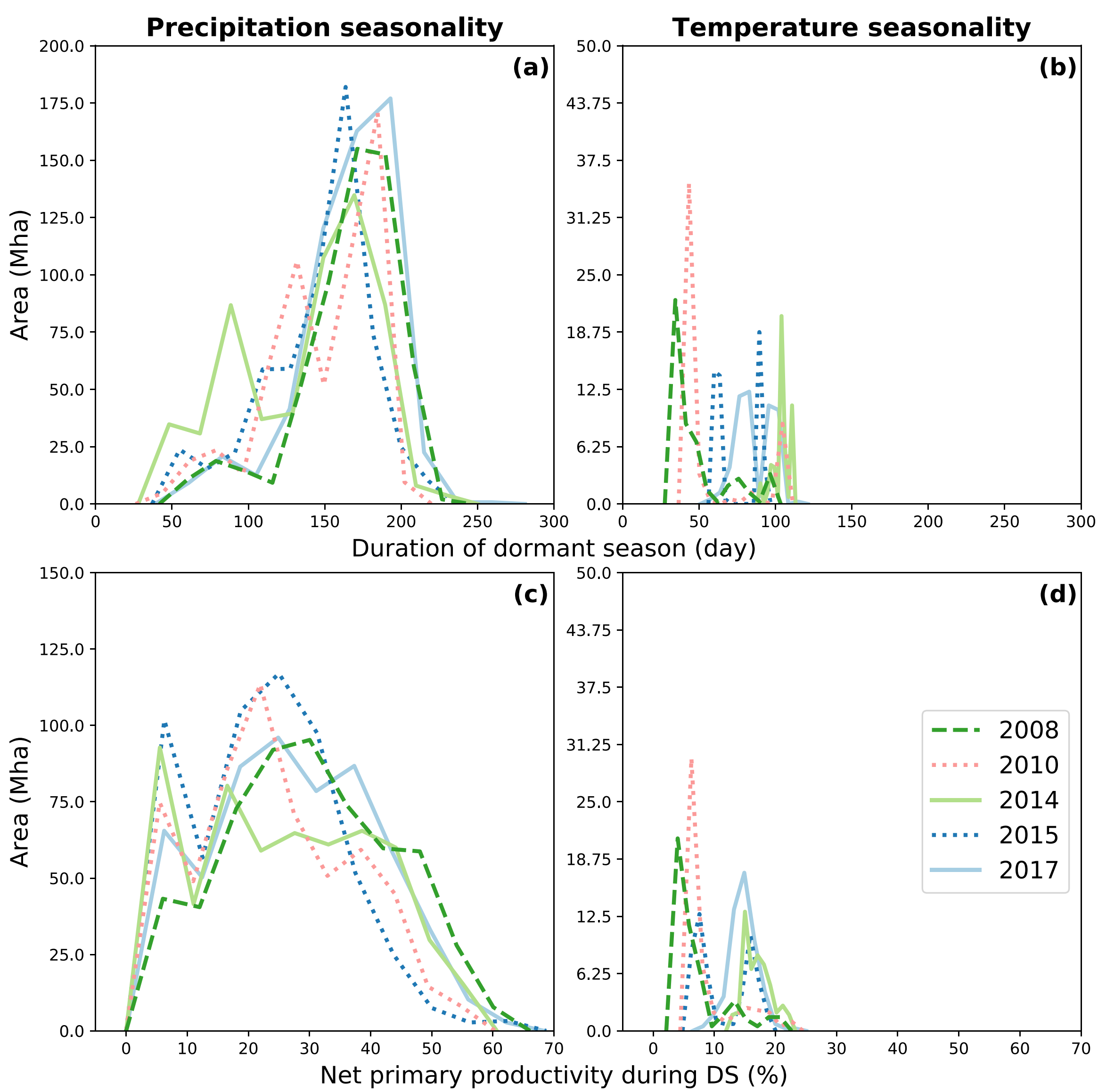

Fig. 6. Distribution of the duration of the *DS*s over precipitation and temperature seasonality regions for different years. The distribution is given in area (Mha). Dotted and dashed lines display extreme events, respectively El Niño and La Niña years. Distributions of the percentage of net primary productivity during the dormant season, NPP_{DS}, over precipitation and temperature seasonality regions and for different years. Dotted and dashed lines represent extreme events, respectively El Niño and La Niña years.

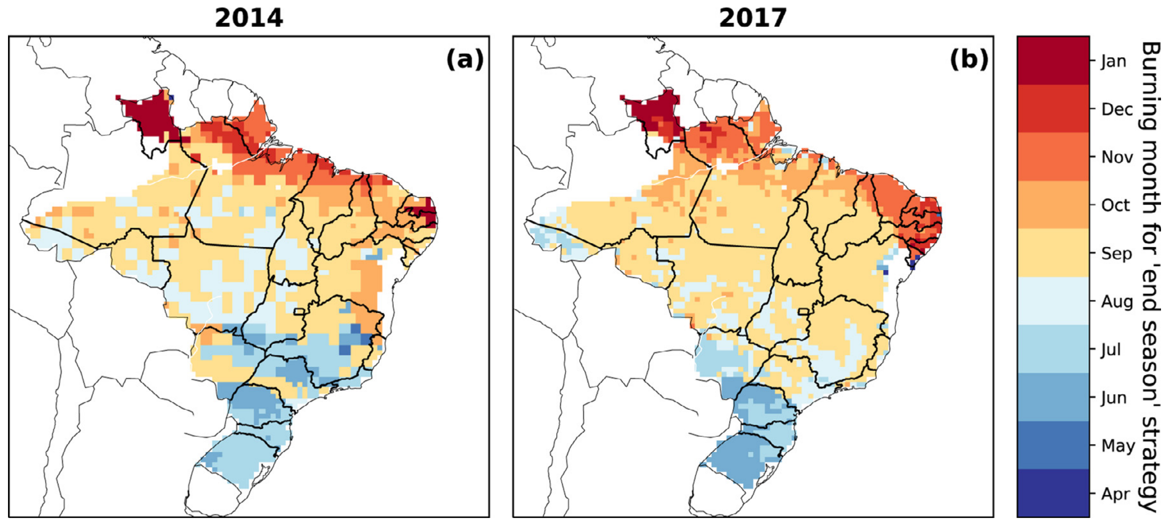

Fig. 7. Burning months derived from the dormant season and the strategy 'end season' calculated from Chalumeau for the years 2014 and 2017. Burning dates in January occur for *DSs* which are spanning over two calendar years like in the north of Brazil.

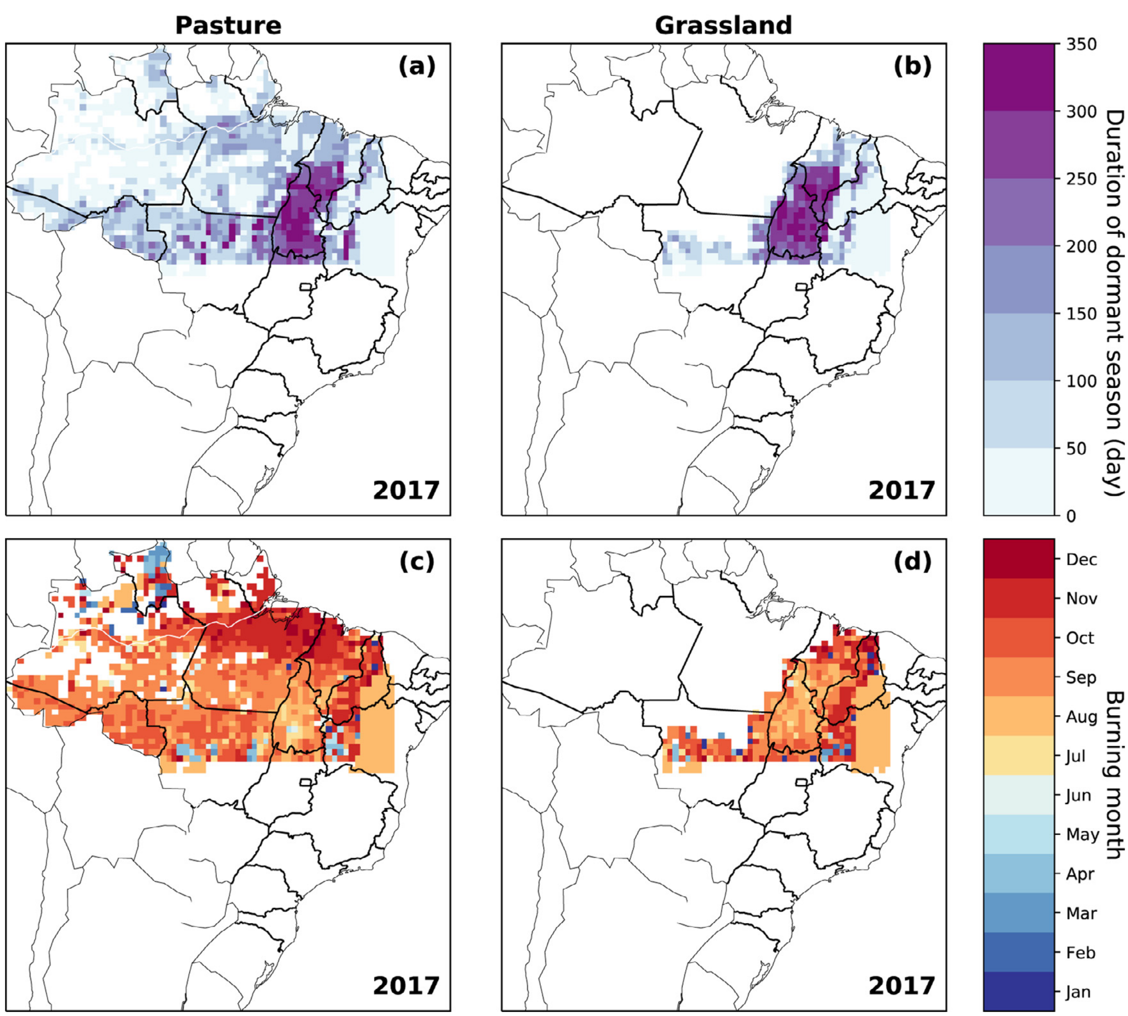

Fig. 8. Duration of the burning season (a and b) calculated from ESA fire detections data set (Belenguer-Plomer and Pettinari, 2019) and extracted burning months (c and d) on pasture (a and c) and grassland (b and d) for the year 2017. Burning seasons and burning months are given in a resolution of $0.5^{\circ} \times 0.5^{\circ}$.

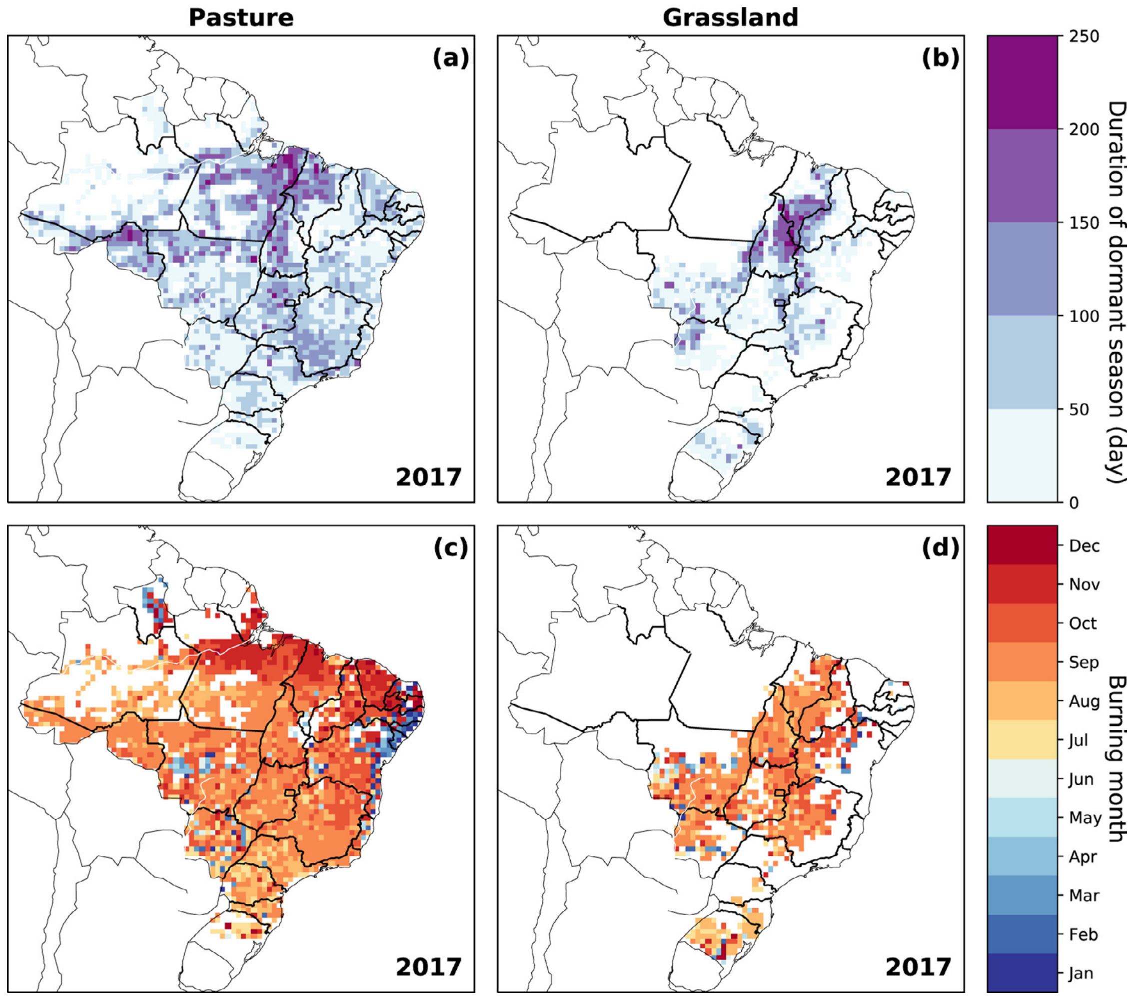

Fig. 9. The duration of fire seasons (a and b) calculated from MODIS fire detection data set (Giglio et al., 2016) and the extracted burning months (c and d) for the year 2017 for the land-use types pasture (a and c) and grassland (b and d). Burning seasons and burning months are given in a resolution of $0.5^\circ \times 0.5^\circ$.

are earlier in July. Later burning dates occur in the northern Atlantic coast during the months of November and December.

Fire detections on grassland cover the Cerrado, Pampa and southern Atlantic Forest (Fig. 9b) and follow the distribution of grassland as land-use type in Brazil. The duration of fire seasons in the Cerrado ranges between 100 and 250 days and burning dates occur between the months of September and October. The Pampa area observes short burning seasons of less than 50 days and earlier burning dates, mostly in July.

Evaluation of the burning strategies

When assembling all calculated burning dates based on *DS*s for each strategy (early, late, end season and early spring, resp.), we obtain seasonal distributions of burning dates per domain (Fig. 10). The goal is to identify the strategy that falls into the time window of the observed fire seasons.

The late season strategy corresponds to the observed fire seasons in most domains and land-use types when looking at the mode of distribution. The results for pasture and grassland are similar in the Cerrado for both data sets (compare Fig. 10b,c with e,g). Calculated burning dates are concentrated in the second half of the observed fire seasons extracted from ESA (Fig. 10b and c). This can be explained by the duration of the burning seasons derived from ESA (Fig. 8a and b) which is longer than *DS*s (Fig. 5b). For the Pampa region, we do not see a clear seasonality pattern for either strategy due to the low number of fire detections in this region (Fig. 10j).

For the evaluation of burning strategies calculated by Chalumeau, two criteria were used. The first one is the ratio of burning dates from Chalumeau to the observed one, both averaged over the year and the domain. The second criterion is the percentage of burning dates of one year and one region within the observed fire season (Sec. *Evaluation of the algorithm Chalumeau*). For each domain and each year, the closest strategy to the target point (ratio = 1 and percentage = 100%) was considered as the strategy best representing farmers' decisions (Fig. 11).

In the Amazon and the Cerrado, burning strategies fluctuate between early and late season over years with high burning date ratios and percentages (Fig. 11a, b and c). Divergences between years are more pronounced in the Caatinga and the Atlantic Forest where the evaluation percentages are between 40 and 80% (Fig. 11d and e). Although fire detections from satellites in the Pampa are low, figure 11f shows the end season as the burning strategy which best represents the burning practice with percentages between 50 and 60%. Finally, there is no significant difference in results between the two land-use types, except for the year 2008 where the grasslands seem to burn earlier than the pastures following the MapBiomas classification (Fig. 11b and c). Divergences between years are notable in some regions but there is no direct and evident link between ENSO years or particular climatic conditions.

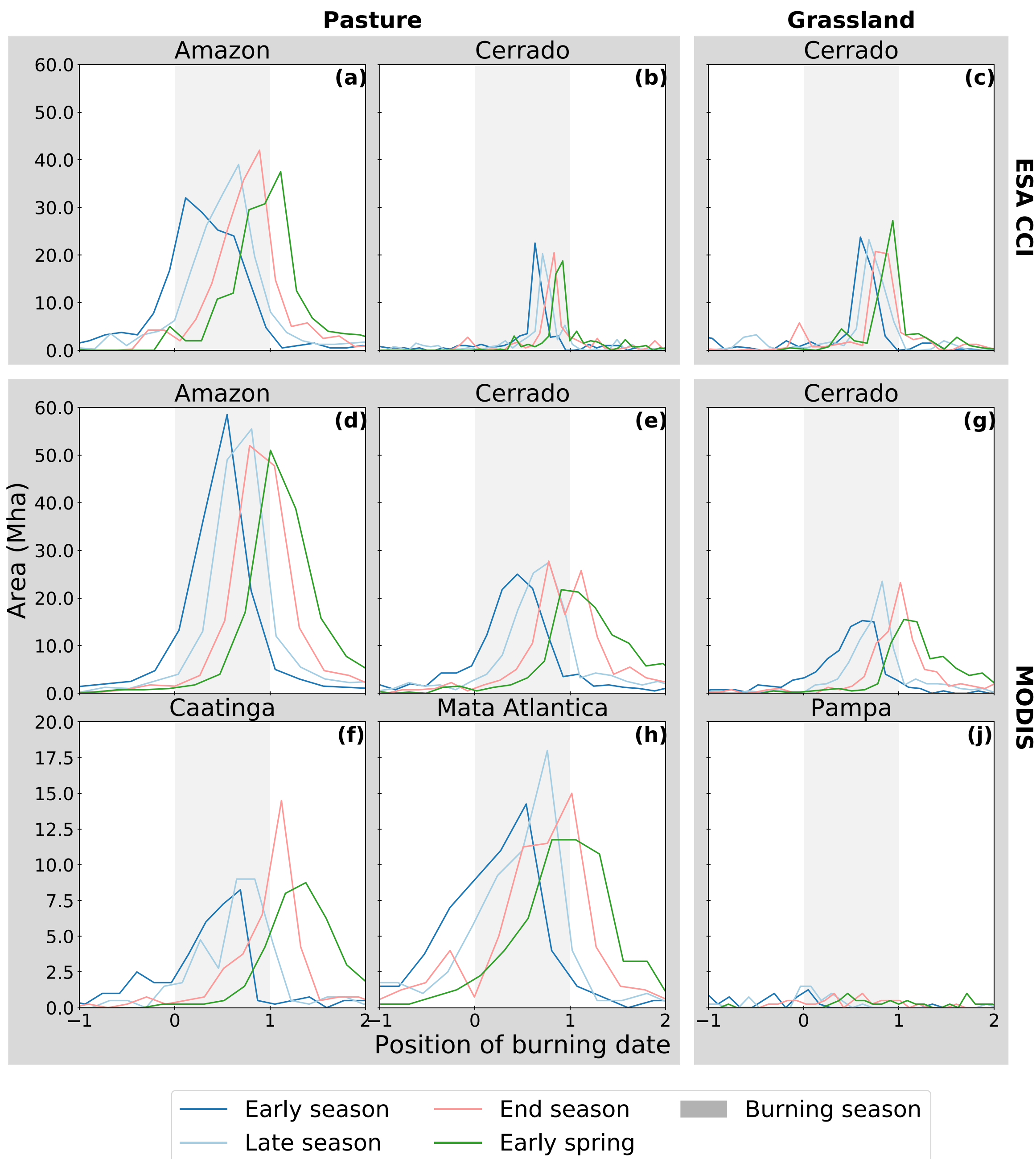

Fig. 10. Seasonal distributions of burning dates per phytogeographic domain for the year 2017 calculated by Chalumeau. The burning dates are displayed over the four strategies depending on the duration of the dormant season. Fire seasons are extracted from ESA (Belenguer-Plomer and Pettinari, 2019) and MODIS fire detection data sets (Giglio et al., 2016). Values 0 and 1 represent respectively the beginning and the end of the observed burning season. The distribution is expressed in Mha which refers to the area of the grid cell.

Discussion

The model-based approach Chalumeau estimates burning dates on grassland and pasture across Brazil. The principal hypothesis is that climatic conditions are the main decision factor for the timing of the setting of fire (Mistry, 1998; van der Werf et al., 2008). This assumption is confirmed by the rancher's objective of supporting grass regrowth and removing dead biomass (López-Mársico et al., 2019; Pivello, 2011) which is done during the winter or dry period, here called the dormant season *DS*. The burning dates are estimated from the duration of *DS*s calculated from climate data in Chalumeau.

The evaluation of the results from Chalumeau with the MODIS and ESA fire detections products confirms that burning practices on grass-dominated areas are occurring during the dormant season all over Brazil (Fig. 10). Therefore, we can state that climatic conditions are the principal decision factor in the burning process. Fire seasons and dry periods have already been connected by van der Werf et al. (2008), but without a specific categorisation of the land-use types where fires occur. Mistry (1998) have inter-

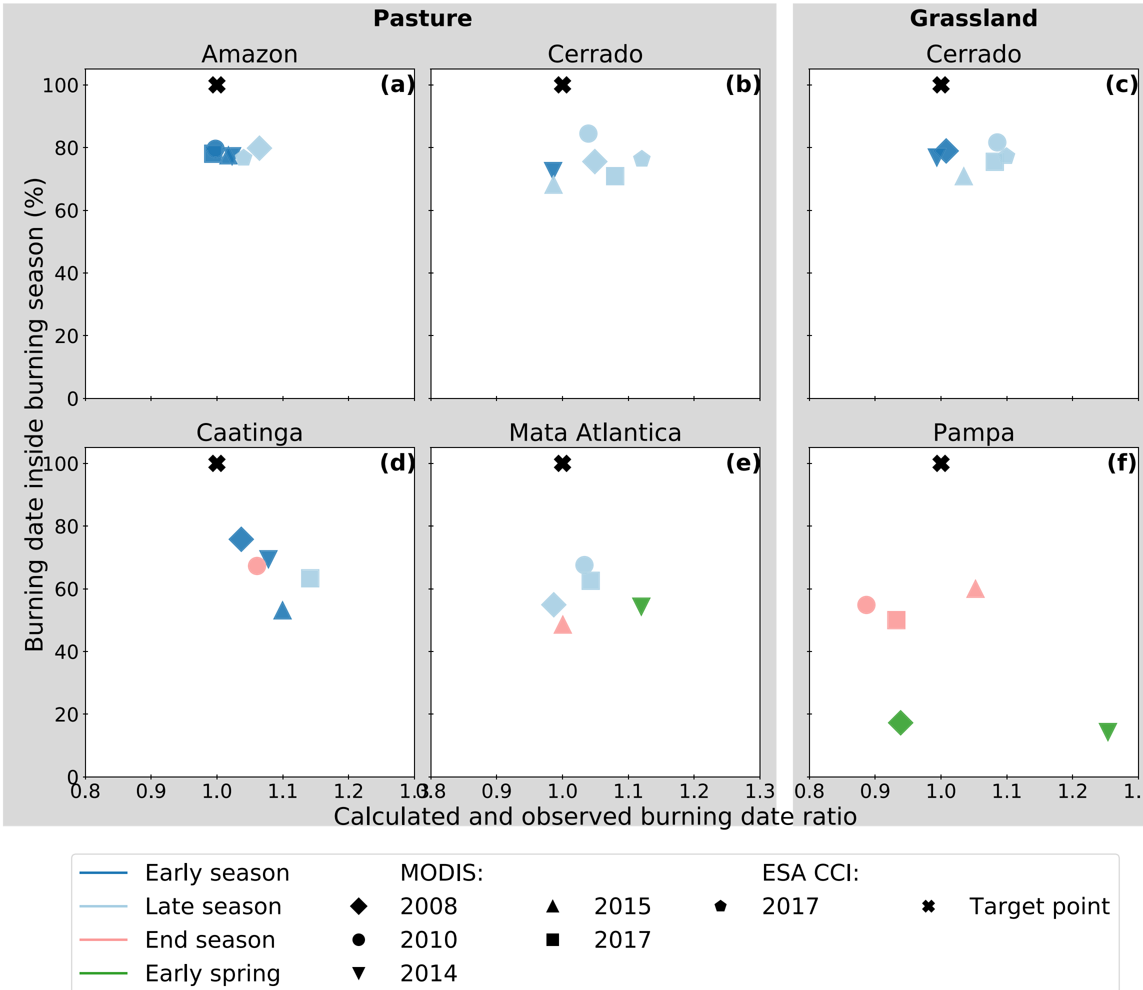

Fig. 11. Burning strategies for all years and all biogeographic regions which represent best the observed fire seasons from both fire detections data sets. Each strategy is represented by the ratio of averaged burning dates calculated from Chalumeau divided by averaged burning dates observed and by the percentage of calculated burning dates which are within the observed burning season.

viewed farmers in the Cerrado region and have characterised the main burning timing as 'mid-to late dry season'. Finally, previous investigations have defined a burning window between July and November (Mistry, 1998; Rabin et al., 2015; Sorrensen, 2000). Our model-based approach links the timing of setting fire to climatic conditions on a daily scale and enables us to estimate burning dates on a large spatial extent. Rabin et al. (2015) focuses on the statistical analysis of monthly burned areas from satellite data and gives information on the timing of burning at least at a monthly resolution. Although this is a valuable source of input for our validation, this approach is not suitable for the projection of burning dates as achieved by Chalumeau.

From the comparison of our results with observed fire data, the heterogeneity of burning strategies over the considered regions becomes apparent. For regions under precipitation seasonality, burning practices are identified during the early dry season. Temperature seasonality in southern Brazil leads to burning events at the end of the winter. Brazil covers a territory with different vegetation, climates and seasonality types so that this variability is to be expected. Nevertheless, studies are scarce on the description of burning practices considering entire Brazil.

Utilising climatic conditions as the main factor in determining burning dates results in reliable estimates of the peak of the fire season. Improving the precision of burning dates would require the consideration of other environmental factors. For instance, burning before a rain event might help nutrient infiltration into the soil and the choice of a day with low wind speed could prevent uncontrolled fire spread. The inclusion of further variables requires a better understanding of ranchers objectives, concerns and priority. We also assume that labour force availability, neighboring farmers' behaviour, and fire prohibition policies have an impact on the decision.

The allocation of daily fire detections on pasture and grassland requires data sets with high spatial and temporal resolution covering entire Brazil over several years. The selection of suitable fire detection data sets is limited by the availability of such products. We use the ESA data set (Belenguer-Plomer and Pettinari, 2019) with the resolution of 40 m $\times$ 40 m combined with the 30 m $\times$ 30 m resolution of the land-use MapBiomas data set (MapBiomas, 2018). ESA reports the first fire occurrence of the year per grid cell and fires which possibly happen later in the same cell are omitted. However, we assume due to the high spatial resolution of the ESA product that when a fire occurs either naturally or human-made, burning late in the season is rather unlikely due to the subsequent lack of fuel availability.

The ESA product is only available for the year 2017 and covers parts of the Amazon and the Cerrado. We include the fire detection MODIS data set (MODIS, Giglio et al., 2016; NASA, 2015a) which covers the entire area of Brazil in a resolution of 1 km $\times$ 1 km to consider more observed data for the evaluation of Chalumeau.

We apply a statistical approach with a confidence indication corresponding to the proportion of either pasture or grassland (Sec. *Processing of fire products*) to generate a reliable data set with a qualitative fire detection signal. Because of the high variation between ESA and MODIS resolutions and the different processing of the data sets, we do not compare directly the burning season and burning dates obtained by these two products. Nevertheless, the results show a high degree of similarity and are encouraging for their reliability. Further studies about fire practices of farmers would profit from data sets with high spatial resolution and better temporal and regional coverage.

Concerning the land-use data set MapBiomas, we consider the categories 'grassland' and 'pasture' as land with livestock farming and potential burning practices. As seen in section *Validation data*, this classification refers mostly to the type of vegetation (Souza et al., 2020). Therefore, the 'grassland' denomination describing dominant herbaceous vegetation includes zones with grazing activities. According to both fire products and the distribution of burning dates extracted, fire seasons and burning months observed are similar for the two land-use categories (Fig. 10). From the information we have, it is impossible to know if 100% of the fires detected on grassland are coming from farmers' management practices. Further investigations would need a more precise classification of 'grasslands and pastures'. Therefore, building high resolution fire detection data sets would help to improve model quality and reduce uncertainties of the obtained results.

Finally, we want to draw attention to the Pampa region in southern Brazil which is the smallest region in our assessment. The dominant vegetation is natural grassland used by ranchers for cattle raising which is an important economic activity. The signal of fire detection is very low and the duration of burning seasons extracted ranges between 0 to 20 days (Fig. 9). However, we have evidence from the literature (Andrade et al., 2016; 2019; Overbeck et al., 2018; Pillar and de Quadros, 1997) and our own observations that fire practices are occurring in this region. This discrepancy may also arise from the low fire intensity on Pampa grassland which is between 36 and 319 kW m^{-1} according to experiments from Fidelis et al. (2010). In comparison, Boone Kauffman et al. (1994) give intensity values between 2842 and 16 394 kW m^{-1} in the Cerrado. This lower value in the Pampa domain could be caused by the high-grazing intensity and the local climate, mild winter and occasional frost events, which altogether lead to low levels of dead biomass and thus accumulation of fuel. Fires with lower intensity could be less traceable for satellite detection because of their size, the local climatic conditions and the satellite resolution (Giglio et al., 2016). This leads to an underestimation of the number of fires detected especially in the Pampa so that more investigations in this region would be welcome.

Implications

With the model-based algorithm Chalumeau, we are now able to estimate the expected burning dates in Brazil from climatic data and regional strategies validated by observed daily fire detections covering large spatial scales. From this, we can state that burning practices indeed are closely linked to climatic conditions and that they are taking place mostly in the early-to-late dormant season. In the future, Chalumeau can be coupled to a process-based fire module embedded in a Dynamic Global Vegetation Model, where it would enable the simulation of fire practices on pasture.

Methods like Rabin et al. (2018) are based on the statistical analysis of fire observations, and as such they can extract monthly burned area but do not allow for future projections. With a model-based approach such as Chalumeau, the calculation of the burning timing on a daily basis is possible for any period for which climate data are available.

The implementation into a DGVM will allow for a better understanding of the effects of fire as a commonly used management practise on the vegetation, the soil carbon content (sink or source of carbon) and carbon emissions (Limb et al., 2016). Moreover, it enables the study of the evolution of such practices in the future and their impacts under climate change.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Comparison between NPP and dormant season

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rama.2021.08.003.

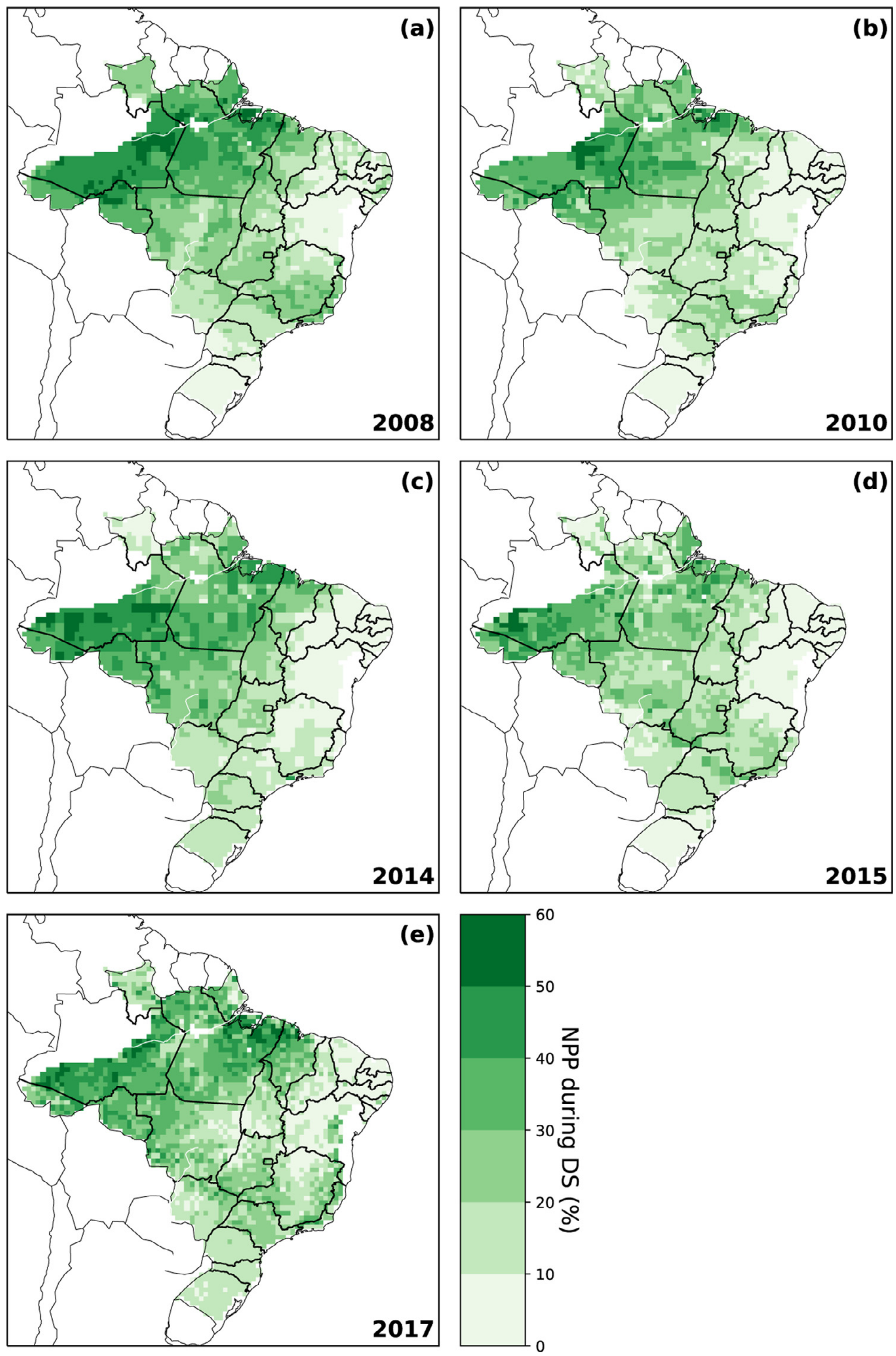

Fig. A.1. Percentage of net primary productivity during the dormant season NPP_{DS}. The Amazon and the Atlantic Forest display the highest NPP_{DS}. Even though these regions experiment dry period, the water supply of the vegetation is still sufficient. In this way, daily NPP stays relatively constant during the year without being impacted by climatic condition. At the opposite, the Caatinga region has the lowest value of NPP_{DS} with NPP value under 0. Due to the climate and desert vegetation, maintenance respiration is greater than gross primary productivity during the dry period.

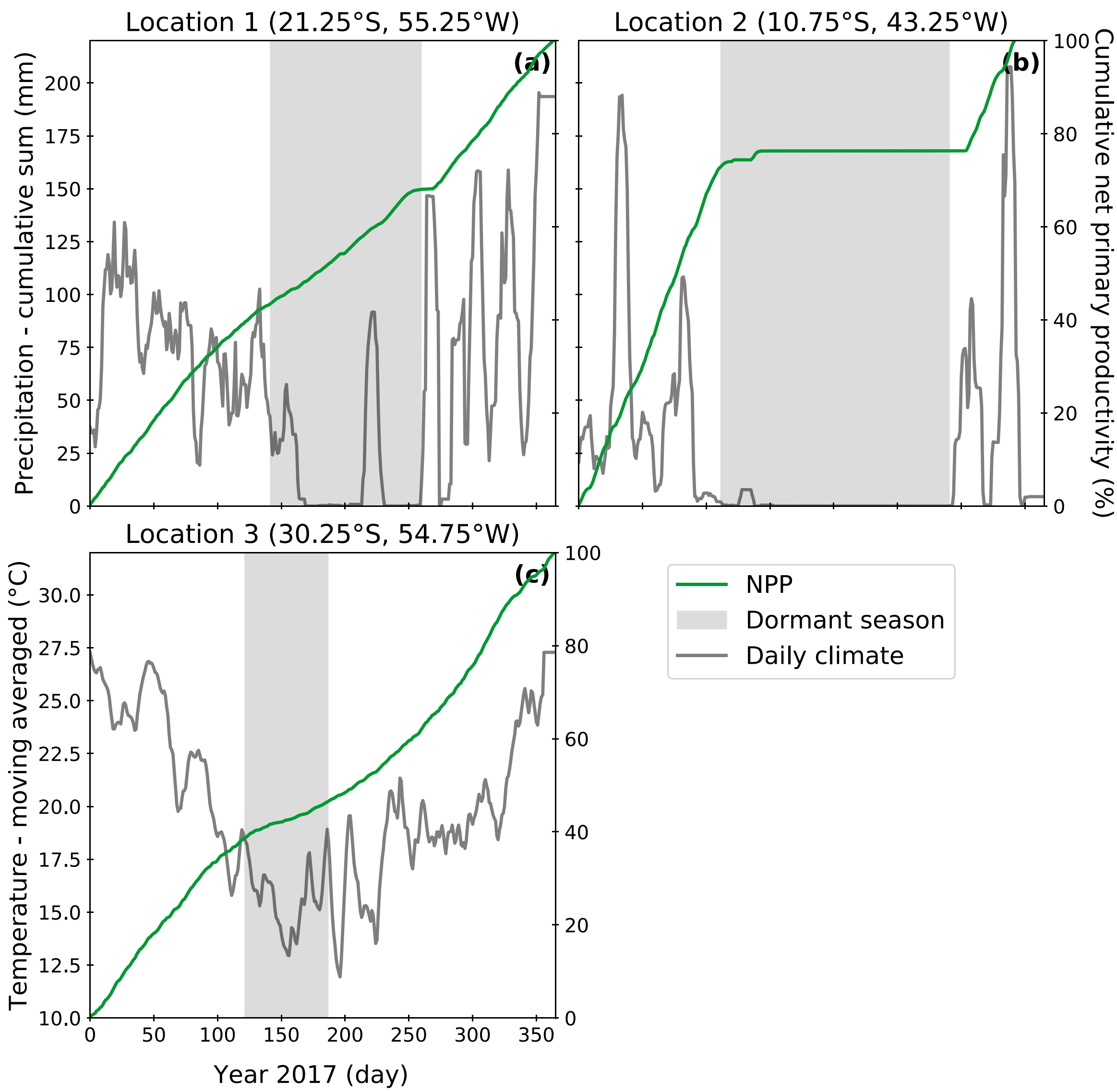

Fig. A.2. Cumulative net primary productivity in percentage NPP_{DS} over the year 2017 for three study cases locations. We can observe a slowing down of NPP during the dormant season calculated by Chalumeau.

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