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# MODIS Time Series to Detect Anthropogenic Interventions and Degradation Processes in Tropical Pasture

**Daniel Alves Aguiar [1,2,*], Marcio Pupin Mello [3], Sandra Furlan Nogueira [4], Fabio Guimarães Gonçalves [5], Marcos Adami [6] and Bernardo Friedrich Theodor Rudorff [1]**

1 Agrosatélite Geotecnologia Aplicada, Florianópolis 88032, Brazil; bernardo@agrosatelite.com.br
2 Divisão de Sensoriamento Remoto, Instituto Nacional de Pesquisas Espaciais, São José dos Campos 12227, Brazil
3 The Boeing Company, Boeing Research & Technology—Brazil, São José dos Campos 12227, Brazil; marcio.p.mello@boeing.com
4 Brazilian Agricultural Research Corporation (EMBRAPA), Monitoramento por Satélite, Campinas 70770, Brazil; sandra.nogueira@embrapa.br
5 Canopy Remote Sensing Solutions, Florianópolis 88032, Brazil; fabio@canopyrss.tech
6 Centro Regional da Amazônia, Instituto Nacional de Pesquisas Espaciais, Bélem 66077-830, Brazil; marcos.adami@inpe.br
* Correspondence: daniel@agrosatelite.com.br; Tel.: +55-48-988-331-172

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**Abstract:** The unavoidable diet change in emerging countries, projected for the coming years, will significantly increase the global consumption of animal protein. It is expected that Brazilian livestock production, responsible for close to 15% of global production, be prepared to answer to the increasing demand of beef. Consequently, the evaluation of pasture quality at regional scale is important to inform public policies towards a rational land use strategy directed to improve livestock productivity in the country. Our hypothesis is that MODIS images can be used to evaluate the processes of degradation, restoration and renovation of tropical pastures. To test this hypothesis, two field campaigns were performed covering a route of approximately 40,000 km through nine Brazilian states. To characterize the sampled pastures, biophysical parameters were measured and observations about the pastures, the adopted management and the landscape were collected. Each sampled pasture was evaluated using a time series of MODIS EVI2 images from 2000–2012, according to a new protocol based on seven phenological metrics, 14 Boolean criteria and two numerical criteria. The theoretical basis of this protocol was derived from interviews with producers and livestock experts during a third field campaign. The analysis of the MODIS EVI2 time series provided valuable historical information on the type of intervention and on the biological degradation process of the sampled pastures. Of the 782 pastures sampled, 26.6% experienced some type of intervention, 19.1% were under biological degradation, and 54.3% presented neither intervention nor trend of biomass decrease during the period analyzed.

**Keywords:** EVI2 time series; biophysical parameters; phenological metrics; biological degradation; pasture reformation; pasture renewal; pasture recovery

## 1. Introduction

The increasing demand for food as a result of population growth and the global urbanization process [1], the growing demand for renewable energy sources [2] and the improved management of natural resources have been calling the attention of governments, the scientific community and society on issues such as agriculture and livestock, aiming at a better use of the territory [3,4].

Beef suppliers will be required to react to fulfill a predicted increase of 44% in the global demand for beef in 2030 as a consequence of income increase in developing countries [5]. Brazil plays an important role as the second largest beef producer and the number one beef exporter in the world. Nevertheless, the increase of beef supply must be associated exclusively to the improvement in livestock productivity, given the goals set by governments of developing countries to reduce rates of deforestation and greenhouse gas emissions [6,7], and land competition for production of grain and biofuels [8–11].

The most important premise for the increase in livestock productivity is the improvement of pastures in terms of quality, and the degradation process is the main cause of quality loss in tropical countries, where most of the herd is on pasture year round. This is a chronic problem, being a limiting factor to the increase in livestock productivity. Dias-Filho [12], focusing on tropical pasture, classified the process of pasture degradation into two types, i.e., biological and agricultural. The biological degradation is the loss of the pasture ability in sustaining its productivity due to soil conditions, while the agricultural degradation represents the inability of the pasture to be economically feasible due to competition with invasive plants.

Remote sensing (RS) images acquired by Earth observation satellites make it possible to evaluate the changes in land-use/land-cover over the past four decades, on scales never explored before (e.g., [13–16]). The synoptic and repetitive coverage provided by these images, along with ecological indicators and vegetation biophysical parameters, allows the application of integrated data analysis and the development of predictive models useful for decision makers [17,18].

However, there are no studies that distinguish, on a regional scale and based on RS images, the consequences of the adopted management practices in tropical pastures (including grazing), from those arising from variations intrinsic to the ecosystem [19].

In this sense, time series of two-band Enhanced Vegetation Index (EVI2; [20]) derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument may be used to understand phenological patterns and support the assessment of anthropogenic interventions and degradation process on tropical pastures. Starting from this premise, the objective of this study was to propose and test a new protocol for identifying anthropogenic interference (i.e., pasture management) and pasture degradation processes using phenological metrics extracted from time series of MODIS/EVI2.

*Theoretical Basis for Tropical Pastures Assessment Using EVI2 Time Series*

Climatic and edaphic factors, anthropogenic interventions, cattle grazing and the occurrence of fires define the spectral dynamics of pasture lands in time. Thus, models that are based on the assumption that the vegetation behavior is linear and gradual are not valid to describe the behavior of tropical pasture under grazing [17,21,22].

The pasture response to the complex interaction of these factors can be gradual, linear, non-linear or abrupt [17], with indicators that can be observed by satellite sensors, allowing the assessment of pasture behavior in relation to changes in their composition. Metrics from time series of vegetation indices, associated with the empirical knowledge of the aforementioned factors, allow the monitoring of vegetation in search for indicators of change [13,23–25]. Unlike agricultural crops—with its well defined planting and harvesting schedules—and forests—where the seasonal variability in biomass is, in general, not relevant—there is not a well defined schedule for pasture and the annual variability in biomass can be high, depending on the grass type, soil and climate conditions [17,26–28].

A tropical pasture under biological degradation [12], combined with the lack of a proper management, cover and soil nutrient loss, causes the emergence of patches of exposed soil [27,29,30]. Time series of vegetation indices extracted from satellite images are sensitive to changes of this kind [22]. On the other hand, pastures under agricultural degradation—where there are changes in the biological composition due to secondary succession—or experiencing undergrazing, show an increase in biomass [12], a process which is also detected in time series of vegetation indices [31].

In fact, the typical pasture behavior over time is due to the seasonal variation in biomass related to water availability [27,32]. This variation is expressed in time series of vegetation indices as a seasonal behavior that characterizes, in each crop year, dry (with low values for the index) and wet (with high values) periods [24,27]. On the other hand, significant changes in pasture and grazing management (e.g., increased stocking rate, change from continuous to rotational grazing, or anthropogenic interventions for pasture improvement) are characterized by meaningful changes in the typical temporal behavior of the vegetation index [17].

For Macedo et al. [30], the recovery of a degraded pasture is characterized by the reestablishment of the pasture production, with the planting of the same species or cultivar. Alternatively, the renewal of a degraded pasture is characterized by the introduction of a new pasture species [30]. The reformation is related to corrections and/or repairs made after the establishment of the pasture. Both the recovery and the renewal can be performed directly and indirectly, i.e., with or without the use of summer crops or annual pasture.

In this study, the recovery and renewal processes were grouped together due to the difficulty of distinguishing them because of the scale of the analysis. Both processes are characterized by soil tilling, which significantly changes the minimum values of EVI2 in the beginning of these processes, allowing their identification in EVI2 time series.

Thus, the hypotheses for the establishment of the assessment protocol based on EVI2 time series of tropical pasture are: (i) anthropogenic interventions typically associated with pasture reformation cause an increase in the pasture biomass and are not preceded by soil exposure [30,33]; (ii) anthropogenic interventions typically associated with renewal/recovery processes cause an increase in the pasture biomass and are preceded by tillage [30,33]; (iii) biological degradation of pastures result in the decrease of biomass over time [12]; and (iv) vegetation indices extracted from time series of satellite images are sensitive to the changes described above.

A pasture that has gone through some sort of intervention in a given period could also be subject to degradation after the intervention, resulting in loss of biomass. Factors such as inadequate management, problems during planting, insufficient fertilization, and adoption of stocking rates above the pasture carrying capacity can accelerate the degradation process. However, it was assumed, for the purpose of this study, that only pastures that have not gone through any sort of human intervention, and showed a tendency of decrease in biomass during the analyzed period, could be classified as degraded pasture.

## 2. Materials and Methods

### 2.1. Study Area and Field Campaigns

Two field campaigns were conducted for data collection and characterization of pasture cover conditions, both in the context of "Rally da Pecuária" [34]. The routes of the campaigns were defined based on the distribution of cattle production, according to the number of heads per census tract (Figure 1; [35]), taking into account road conditions and logistical constraints. The access restrictions observed during the first campaign, and the changes observed in the field relative to the census data, were taken into account when defining the route of the second campaign. The first campaign was held between 25 September and 12 November 2011, while the second campaign was held between 22 August and 1 October 2012, both campaigns including the South, Southeast, Midwest and North regions of Brazil (Figure 1). The total distance covered in these campaigns was 40,000 km and the number of samples collected in each was 369 and 413, respectively.

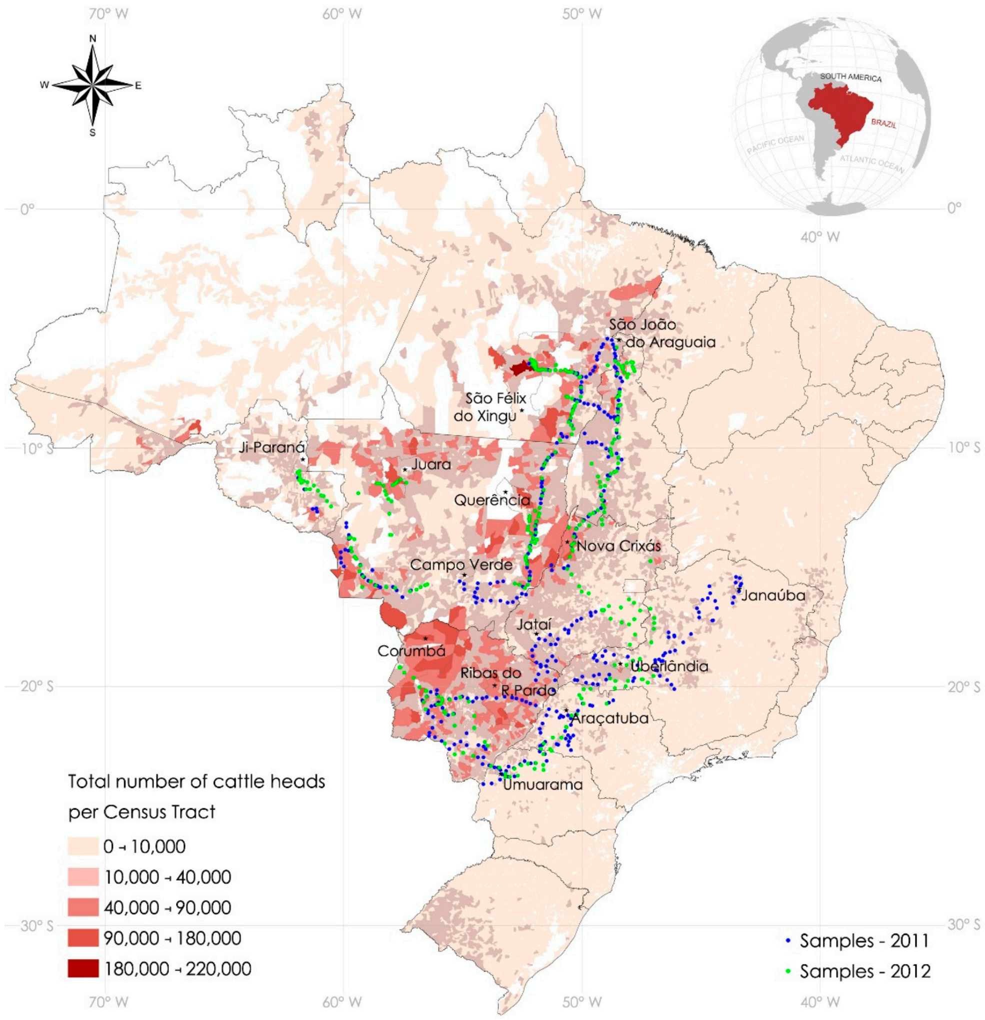


**Figure 1.** Location of the pastures sampled during the 2011 and the 2012 campaigns, and total number of cattle heads per census tract [35].

### 2.2. In Situ Pasture Data Collection

The characterization of the pasture cover (sampling) was performed every 20 or 40 km, depending on the path length. For each pasture sample, we measured biophysical parameters of the vegetation to determine the pasture stand, took panoramic and vertical photographs, collected geographical coordinates, and observed characteristics of the pasture and the landscape, including pasture species, topography, soil texture, and others. All data were recorded on numbered field sheets, which were associated to the photographs taken and the EVI2 time series.

Biophysical parameters considered for determination of the pasture stand were: (i) number of invasive plants, stools, and termite mounds (i.e., degradation and management indicators) found within three circles with a radius of 3 m randomly placed within each sampled pasture; (ii) number of plants and dry weight of the pasture harvested from a 1 $m^2$ quadrat placed within the first circle, following the methodology of [36]; and (iii) height, measured at three locations within each sampled pasture (see Appendix A—Figure A1 for illustration).

This set of parameters was considered for the determination of the pasture stand by a specialist, who evaluated the status of all pastures visited, classifying them as *degraded*, *intermediate*, or *appropriate*. The results of this evaluation were compared to the results obtained remotely.

The following rules were adopted for selection of sampling points within the pastures: (i) the samples were located at least 150 m away from the edges of the pastures to compensate for GPS positioning errors and edge effects that could potentially influence the biophysical parameters; and (ii) the sites chosen were representative of the conditions of the pastures sampled, i.e., the heterogeneity of the pasture was taken into account after a visual inspection in the field.

### *2.3. Remotely Sensed Data*

MODIS 16-day composite EVI2 time series [20] and monthly 25 km Tropical Rainfall Measuring Mission (TRMM) rainfall estimates from 2000 to 2012 were obtained for all points sampled in the field campaigns [37]. To reduce noise in the MODIS EVI2 time series, we first removed dates where the reflectance was greater than 10% in the blue band and where the view zenith angle was greater than 32.5°, following methods of [38]. The time series were filtered using the wavelet transform, following [39].

Pixels representing the visited pasture were chosen with the aid of high spatial resolution images available at the virtual globe of *Google Maps*, and images of medium spatial resolution sensors (TM and ETM+) from 2000 to 2012, acquired in the dry (April to October) and wet periods (May to September). This information was integrated into a web-based tool adapted from [40]. Pastures smaller than the pixel size (250 m × 250 m), or not represented by any "pure" pixel (i.e., a pixel totally contained within the pasture), were excluded from the analysis.

#### 2.3.1. Protocol for Pasture Assessment Using Vegetation Index Time Series

For the development of this protocol, seven farms were visited in the states of São Paulo, Mato Grosso do Sul, and Pará in October 2012, in the context of the Geodegrade project coordinated by EMBRAPA Satellite Monitoring [41]. During these visits, experts were consulted to establish the criteria that relate the EVI2 time series to the interventions (renovation/recovery, reform, and degradation process) that occurred from 2000 to 2012. From these relationships, phenological metrics were established, as described in the following section.

#### 2.3.2. Phenological Metrics

Except for the vegetative vigor, all phenological metrics extracted from the time series were based on the identification of maximum (*max*) and minimum (*min*) values of EVI2 during a given crop year (Figure 2). For the identification of these values, it was established a time window in which an R language [42] algorithm identified the minimum EVI2 value and the date on which it occurred (*dmin*). For the first crop year, the algorithm searched the lowest observed value in the eight months that succeeded the date of the first observation of the series, whereas for all the following crop years, the algorithm had as its starting point the *dmin* identified in the previous crop year plus 12 months. Based on that date, it searched for the *min* (and the *dmin*) within a time window of eight months, considering four months before and four months after the date.

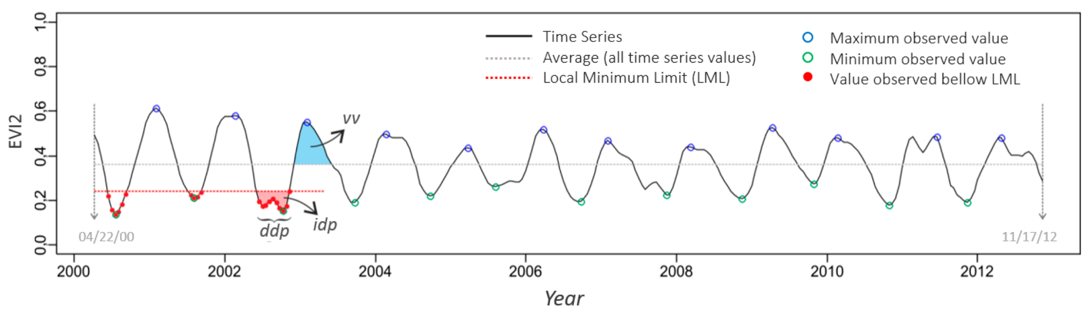


**Figure 2.** Average EVI2 time series of a visited pasture, highlighting the Local Minimum Limit and the duration of the dry period (*ddp*), the intensity of the dry period (*idp*), and the vegetative vigor (*vv*) for the 2002/2003 crop year.

After finding the dates corresponding to the minimum (*min*) vegetation indices for all crop years, the identification of the maximum values (*max*), and their dates of occurrence (*dmax*), was performed by searching the periods comprised between the dates associated with two consecutive minima. The *min* and *max* values for each crop year of the time series and their respective dates were used to calculate other phenological metrics described in Table 1.

**Table 1.** Description of the seven phenological metrics.

| Metric | Description |
|---|---|
| *max* | Maximum observed value of EVI2 (its corresponding date is *dmax*—Julian Day) |
| *min* | Minimum observed value of EVI2 (its corresponding date is *dmin*—Julian Day) |
| *amp* | Amplitude: *max*–*min* |
| *gur* | Green-up rate (($max - min$)/($dmax - dmin$)) |
| *ddp* | Duration of the dry period (number of 16-day EVI2 composites) |
| *idp* | Intensity of the dry period |
| *vv* | Vegetative vigor |

For the calculation of the *duration* and the *intensity* of the *dry period* (*ddp* and *idp*), we calculated a Local Minimum Limit (*LML*) based on the observations of the analyzed crop year and the observations of the two previous crop years, which defined the so-called "dry period". The *LML* was calculated as:

$$LML = min_{year} + \frac{a - b}{4} \quad (1)$$

where $min_{\text{year}}$ is the *min* observed for the crop year under analysis; *a* is the smallest *max* value observed for the last three crop years ($max_{\text{year}}$, $max_{\text{year-1}}$ and $max_{\text{year-2}}$); and *b* is the smallest *min* value observed for the last three crop years ($min_{\text{year}}$, $min_{\text{year-1}}$ and $min_{\text{year-2}}$).

The *LML* is represented by a horizontal line in the graph of the time series (Figure 2). All EVI2 values that were lower than the *LML* were considered to represent a dry period. The number of compositions of a crop year in which the EVI2 values were lower than the *LML* defines the *ddp*. The area between the time series curve and the *LML* defines the *idp* (Figure 2).

The vegetative vigor (*vv*) metric was calculated as the area, in each crop year, between the time series curve and the mean EVI2 calculated considering all the values of the time series (Figure 2). The amplitude (*amp*) was calculated as the difference between *max* and *min*, and the green-up rate (*gur*) was calculated as:

$$\frac{max - min}{dmax - dmin} \quad (2)$$

Boolean Criteria and Numeric Comparisons

The use of phenological metrics allows comparison of two or more crop years. To understand the processes that occur over time (such as pasture degradation), or even processes that are characterized by detectable changes in a specific time period (for example, human intervention in pasture), it is common to compare phenological metrics of a given crop year with those from crop years that precede and/or succeed it [26,43]. This study was based on comparisons between the crop year and the two previous years using 14 Boolean criteria (i.e., true or false). Additionally, 14 numerical comparisons were performed (Table 2).

**Table 2.** Description of the 14 Boolean (bc) and numerical (nc) criteria used for comparisons between the phenological metrics of a crop year (year) with those from the two previous years (year-1 and year-2).

| bc | Boolean Criterion (bc) | nc | Numeric Criterion (nc) |
|---|---|---|---|
| *bc1* | is $max_{\text{year}}$ greater than $max_{\text{year-1}}$? | *nc1* | $(max_{\text{year}} - max_{\text{year-1}})/max_{\text{year-1}}$ |
| *bc2* | is $max_{\text{year}}$ greater than $max_{\text{year-2}}$? | *nc2* | $(max_{\text{year}} - max_{\text{year-2}})/max_{\text{year-2}}$ |
| *bc3* | is $min_{\text{year}}$ lesser than $min_{\text{year-1}}$? | *nc3* | $(min_{\text{year}} - min_{\text{year-1}})/min_{\text{year-1}}$ |
| *bc4* | is $min_{\text{year}}$ lesser than $min_{\text{year-2}}$? | *nc4* | $(min_{\text{year}} - min_{\text{year-2}})/min_{\text{year-2}}$ |
| *bc5* | is $amp_{\text{year}}$ greater than $amp_{\text{year-1}}$? | *nc5* | $(amp_{\text{year}} - amp_{\text{year-1}})/amp_{\text{year-1}}$ |
| *bc6* | is $amp_{\text{year}}$ greater than $amp_{\text{year-2}}$? | *nc6* | $(amp_{\text{year}} - amp_{\text{year-2}})/amp_{\text{year-2}}$ |
| *bc7* | is $gur_{\text{year}}$ greater than $gur_{\text{year-1}}$? | *nc7* | $(bgi_{\text{year}} - bgi_{\text{year-1}})/ive_{\text{year-1}}$ |
| *bc8* | is $gur_{\text{year}}$ greater than $gur_{\text{year-2}}$? | *nc8* | $(ive_{\text{year}} - ive_{\text{year-2}})/ive_{\text{year-2}}$ |
| *bc9* | is $ddp_{\text{year}}$ greater than $ddp_{\text{year-1}}$? | *nc9* | $dds_{\text{year}} - dps_{\text{year-1}}$ |
| *bc10* | is $ddp_{\text{year}}$ greater than $dpp_{\text{year-2}}$? | *nc10* | $dds_{\text{year}} - dps_{\text{year-2}}$ |
| *bc11* | is $idp_{\text{year}}$ greater than $idp_{\text{year-1}}$? | *nc11* | $idp_{\text{year}} - ips_{\text{year-1}}$ |
| *bc12* | is $idp_{\text{year}}$ greater than $idp_{\text{year-2}}$? | *nc12* | $idp_{\text{year}} - ips_{\text{year-2}}$ |
| *bc13* | is $vv_{\text{year}}$ greater than $vv_{\text{year-1}}$? | *nc13* | $(ivv_{\text{year}} - ivv_{\text{year-1}})/ivv_{\text{year-1}}$ |
| *bc14* | is $vv_{\text{year}}$ greater than $vv_{\text{year-2}}$? | *nc14* | $(ivv_{\text{year}} - ivv_{\text{year-2}})/ivv_{\text{year-2}}$ |

#### 2.3.3. Identification of Anthropogenic Intervention in the Pasture

It is possible to define, with the help of a livestock specialist, procedures for identifying intervention processes. Pasture reformation, for instance, is characterized by a fast and steep increase in vegetative vigor, which is reflected as an increase in the vegetation index, especially in the maximum observed values of EVI2 (*max*) and in the green-up rate (*gur*). The *gur* reflects abrupt changes in the vegetation [44] and, in the case of pasture, is associated with fertilization, control of invasive plants and pests, among other factors.

In this study, pasture reformation was characterized by pixels where the Boolean criteria *bc1, bc2, bc5, bc6, bc7,* and *bc8* were *true*, whereas the criteria *bc11* and *bc12* were *false* (see Table 2). In addition, the pixels should have a *max* value in the current crop year at least 15% higher than in the previous crop year; i.e., $nc1 \geq 0.15$ (Table 2). This threshold was established based on examples of reformed pasture observed in the monitored farms (Section 2.3.1). We expect that the proposed protocol will detect only successful reformations, where an increase of the pasture biomass is observed as a result. However, we note that not all reformations will result in increased biomass due to factors that range from the choice of the reformation strategy to the availability of financial resources [30,33]. In such cases, no significant changes are expected for the EVI2 values.

The renewal/restoration processes were characterized by pixels where all Boolean criteria were true, except for *bc7* and *bc8*, which could be either true or false. This was because a fast increase of the vegetative vigor is a more striking feature in the reformation process than in the renewal and restoration processes, for which one must consider the time of formation of the new pasture. Moreover, the renewal/restoration were characterized by pixels showing a vegetative vigor (see Figure 2) in the current crop year at least three times greater than that of the previous year; i.e., $nc13 \geq 2$ (see Table 2).

This threshold was also established based on data of recovered and renewed pastures in the monitored farms and expert consultation. Due to the high cost of the operations associated with renewal/recovery processes [30,33], it was assumed that these interventions occured only in pastures that had undergone severe degradation. These pastures show a low amplitude between the maximum and minimum values in the EVI2 time series. The low EVI2 amplitude, the period of exposed soil between the removal of the degraded pasture and the planting of the new pasture (reflected as a decline in the EVI2 values), and the maximum values of EVI2 associated with the new pasture in the wet period, all influenced the choice of the *nc13* threshold.

For each sample, the algorithm identified the occurrence of reformation or renewal/recovery processes. For samples in which no intervention was detected in the analyzed crop years, the algorithm searched for degradation processes. Assuming that the typical degradation process observed in the visited farms in São Paulo and Mato Grosso do Sul is characterized by reduction of vegetative vigor (i.e., biomass) and, consequently, a reduction in the pasture carrying capacity, degradation was defined based on the *vv* phenological metric, as described below.

#### 2.3.4. Identification of Degradation Process in Pasture

The identification of degradation process was performed using linear regression analysis [45,46]. For every pixel in which no intervention was identified, the 12 calculated values of *vv* (2000–2012) were taken as observations of a dependent variable, while time (years) was defined as the independent variable. Both variables were normalized between zero and one before fitting the regression line (e.g., Figure 3). Once the assumptions for regression analysis were met [47], a slope test using Student's *t* was conducted in order to verify if the regression slope was significant at the 10% level, indicating the occurrence of biological degradation. Figure 3 shows the scatterplot of the normalized values of *vv* versus time for the 12 analyzed crop years for one of the pixels monitored in the Geodegrade project, with the estimated regression line.

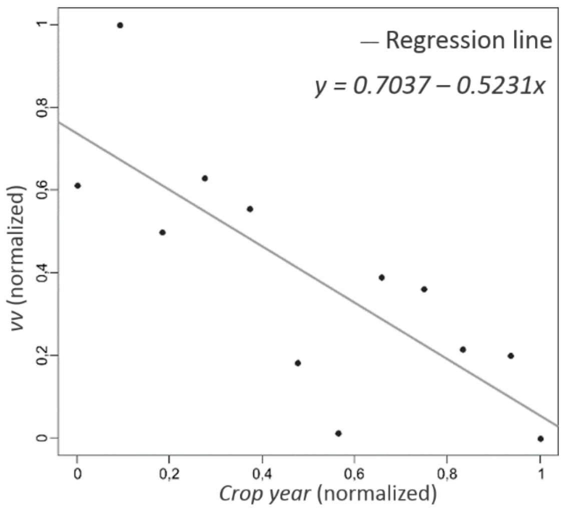


**Figure 3.** Scatterplot of the normalized values of *vv* versus time for the 12 crop years of a sample pixel, with the estimated regression line.

## 3. Results

### *3.1. Regional Analysis*

Figure 4 presents the average EVI2 time series for the 267, 389, and 106 samples collected in the Amazon, Cerrado, and Atlantic Forest biomes, respectively. On average, the pastures sampled in the Amazon presented maximum values of EVI2 higher than those sampled in other biomes. It is possible that the difference in maximum values of EVI2 among the three biomes is related not only to soil and climate characteristics, but also to differences in stocking rates, which are generally higher in the Atlantic Forest and the Cerrado [48], directly impacting the availability of forage.

In addition to differences in precipitation regimes, the differences in the minimum values of the EVI2 curves among biomes in Figure 4 can be partially explained by the predominant type of degradation process in each biome. Invasive plants tend to remain green during the dry season due to their greater ability to absorb water from the soil in dry conditions. As a result, pastures infested with invasive plants tend to maintain EVI2 values higher than pastures without invasive plants [12]. In the Amazon, the main cause of pasture degradation is the change in the biological composition due to secondary forest succession [21,49]. Pastures that have management problems during the establishment stage, or those attacked by insect pests, are more susceptible to this type of degradation.

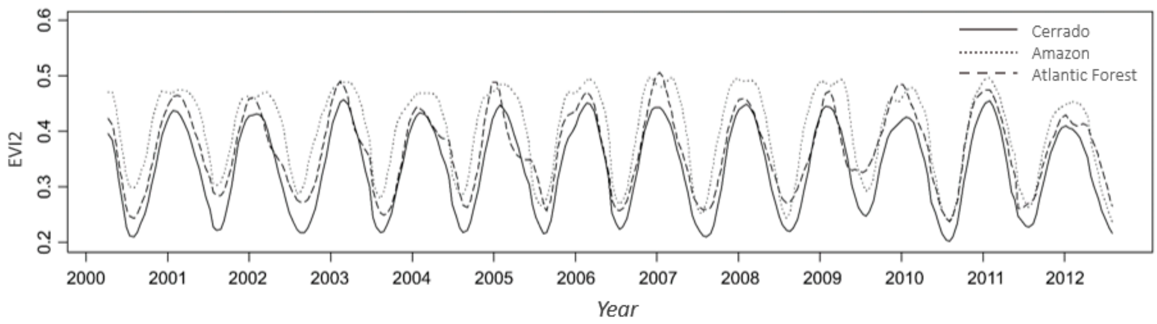


**Figure 4.** Mean values of EVI2 (2000–2012) for the pastures sampled in field campaigns in the Amazon, Cerrado and Atlantic Forest biomes (267, 389 and 106 samples, respectively).

Figure 4 can also be used to assess changes in the precipitation regime during the analyzed period and the impacts of these changes on the pasture. However, the influence of rainfall on vegetation indices derived from satellite images varies according to the type of vegetation and soil properties [50]. In the case of pasture, there is yet another important variable that must be taken into account: grazing. The distinction of the impact of each of these variables on the pasture can only be performed in controlled environments, where the history of grazing and precipitation is known [51,52].

### *3.2. Degradation and Intensification Trends in the Sampled Pasture Lands*

The results of the application of the protocol to the pastures sampled in the field campaigns are presented in Table 3. Only 14.1% of the pastures were reformed between 2003 and 2011, which is less than the required for rehabilitating degraded pastureland in Brazil by 2020 (15 Mha), as established by the *Sectorial Plan for Mitigation and Adaptation to Climate Change for the Consolidation of a Low-Carbon Economy in Agriculture* (ABC programme; [53]). Of the sampled pastures, 19.0% presented a significant decline in biomass as measured by the regression analysis described in Section 2.3.4.

**Table 3.** Results of the application of the protocol for pasture assessment using vegetation index time series.

| Pasture Status | 2011 | | 2012 | | Total | |
|---|---|---|---|---|---|---|
| | **Samples** | **%** | **Samples** | **%** | **Samples** | **%** |
| Reformation | 52 | 14.1 | 52 | 12.6 | 104 | 13.3 |
| Renewal/Recovery | 50 | 13.6 | 49 | 11.9 | 99 | 12.7 |
| Reformation and Renewal/Recovery | 3 | 0.8 | 2 | 0.5 | 5 | 0.6 |
| In Degradation | 58 | 15.7 | 91 | 22.0 | 149 | 19.1 |
| Without Intervention | 206 | 55.8 | 219 | 53.0 | 425 | 54.3 |
| Total | 369 | | 413 | | 782 | |

The results of the intersection between the assessment of the pastures in the field and the classification obtained with the EVI2 time series are presented in Table 4. We found that, of the 778 samples evaluated by both the protocol and the field assessment, 34 (4.4%) displayed a significant reduction in biomass as shown in the EVI2 time series, and were classified as *degraded* when the field survey was performed. The pastures classified as *intermediate* or *degraded* in the field require some kind of intervention, without tilling of the soil and/or changing the forage. We found 30 samples (3.8%) in this category, and 80 (10.3%) samples with suitable stand, but with a decreasing trend in biomass.

**Table 4.** Results of the intersection between the field assessment and the pasture classification obtained with the EVI2 time series.

| Intervention/Degradation (EVI2 Time Series) | Stand (Field Assessment) | | | | | |
|---|---|---|---|---|---|---|
| | Appropriate | | Intermediate | | Degraded | |
| | Samples | % | Samples | % | Samples | % |
| Reformation | 63 | 14.4 | 20 | 11.8 | 20 | 11.8 |
| Renewal/Recovery | 54 | 12.3 | 27 | 15.9 | 18 | 10.7 |
| Reformation and Renewal/Recovery | 4 | 0.9 | 1 | 0.6 | 0 | 0.0 |
| In Degradation | 80 | 18.2 | 30 | 17.6 | 34 | 20.1 |
| Without Intervention | 238 | 54.2 | 92 | 54.1 | 97 | 57.4 |
| Total | 439 | | 170 | | 169 | |

Among the 207 pasture samples found to have gone thought some kind of intervention, only 38 were classified as *degraded* in 2011 or 2012. However, if we consider the interventions carried out in 2009, 2010, and 2011, only one sample was classified as *degraded* in the field, and this sample was classified by the protocol as pasture reformed in 2011, after the field visit. From the pastures showing no degradation trend (427), which have not gone through interventions in the analyzed period, 330 (42.4%) were classified as *appropriate* or *intermediate* (Table 4).

The results of the application of the protocol are presented in Table 5 and Figure 5 by biome. The samples collected in the Pantanal biome had the greatest percentage of pasture under degradation (40%). However, the number of sampled pastures in this biome was relatively small (20 samples) when compared to other biomes. Among the biomes with the greatest number of samples, the Amazon had the highest percentage of pasture samples in degradation process, followed by the Cerrado, and the Atlantic Forest. Pasture reformation was a more common practice in samples of Atlantic Forest, while renewals/recoveries were more common in the Amazon pastures, when the Pantanal is not considered (Table 5). These differences can be explained, in part, by the level of technology adopted in each biome [48]. However, factors such as cattle price, market conditions, and distance to the main consumer markets may influence the producer's decision on whether to intervene [54].

**Table 5.** Pasture status for the samples collected in this study. Percentages are expressed as a fraction of the total number of samples per biome.

| Pasture Status | Amazon | | Cerrado | | Atlantic Forest | | Pantanal | |
|---|---|---|---|---|---|---|---|---|
| | Samples | % | Samples | % | Samples | % | Samples | % |
| Reformation | 31 | 11.6 | 53 | 13.6 | 18 | 17.0 | 2 | 10.0 |
| Renewal/Recovery | 38 | 14.2 | 46 | 11.8 | 12 | 11.3 | 3 | 15.0 |
| Reformation and Renewal/Recovery | 1 | 0.4 | 2 | 0.5 | 2 | 1.9 | 0 | 0.0 |
| In Degradation | 60 | 22.5 | 69 | 17.7 | 7 | 6.6 | 8 | 40.0 |
| Without Intervention | 137 | 51.3 | 219 | 56.3 | 67 | 63.2 | 7 | 35.0 |
| Total | 267 | | 389 | | 106 | | 20 | |

In Midwest Brazil, where the Cerrado biome is predominant, the most direct cause of pasture degradation is the systematic use of stock numbers that exceed the pasture carrying capacity, causing defoliation and loss of soil nutrients, aggravated by the lack of a proper management for pasture recovery [29,54,55]. Overgrazing reduces the vegetation cover and increases the decomposition rates of organic matter and erosion, which are features of biological degradation [12]. For this kind of degradation, the most adopted strategy is the recovery of the soil fertility by manuring, usually performed during the process of reformation.

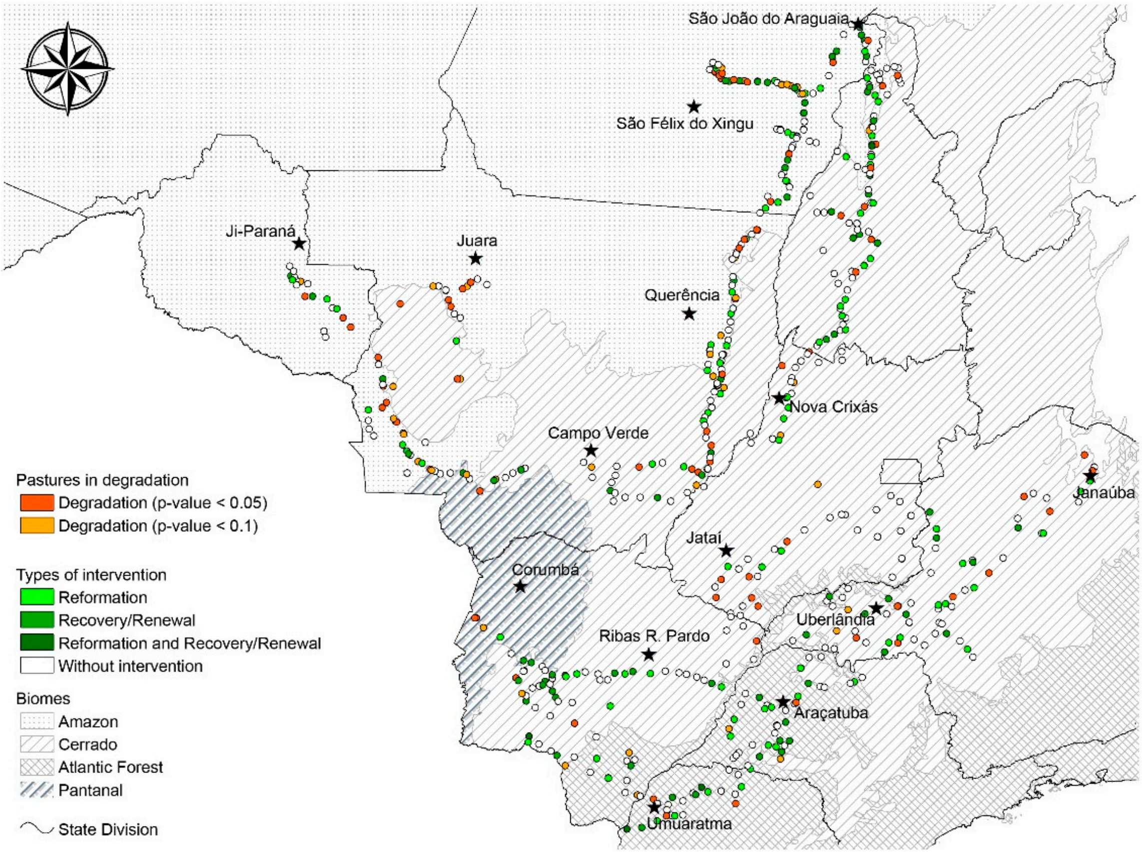


**Figure 5.** Pasture lands sampled in the field campaigns and intervention/degradation status of the samples as assessed with our protocol using MODIS EVI2 time series.

## 4. Discussion

### *4.1. Anthropogenic Interventions*

The seven phenological metrics adopted for the evaluation of the EVI2 time series were calculated for all pastures sampled in each year of the analyzed period and were used to evaluate the Boolean and numeric criteria proposed in the protocol. Figure 6 illustrates an example of pasture where intervention was detected and classified as indirect renewal/recovery. There was a change in *max* between the 2000–2004 and 2008–2012 periods, with the *max* values of the second period 10.5% higher on average than those of the first period. In September 2004, there was an abrupt decrease in EVI2. In the two following crop years, the maximum values of EVI2 and the duration of the cycles indicated the presence of a summer crop followed by a winter crop—in 2004/2005 and 2005/2006 [56]—and a longer cycle crop in 2006/2007 followed by pasture planting. This fact is corroborated by [30,33], who state that indirect renewal can be peformed using summer and winter crops.

A typical characteristic observed in EVI2 time series of pasture is the presence of small fluctuations, which are better observed in the unfiltered curve (blue line in Figure 6). These noise-like fluctuations are believed to represent the effect of grazing (i.e., introduction and removal of livestock from the area or significant changes in stocking rate) and are not visible in the period when agricultural crops were present (2005–2007). However, the absence of these fluctuations in the EVI2 time series may indicate continuous grazing, or even be related to a pasture without cattle present, a management practice that is commonly adopted in the rainy season aiming at the accumulation of forage to be consumed in the dry season [57].

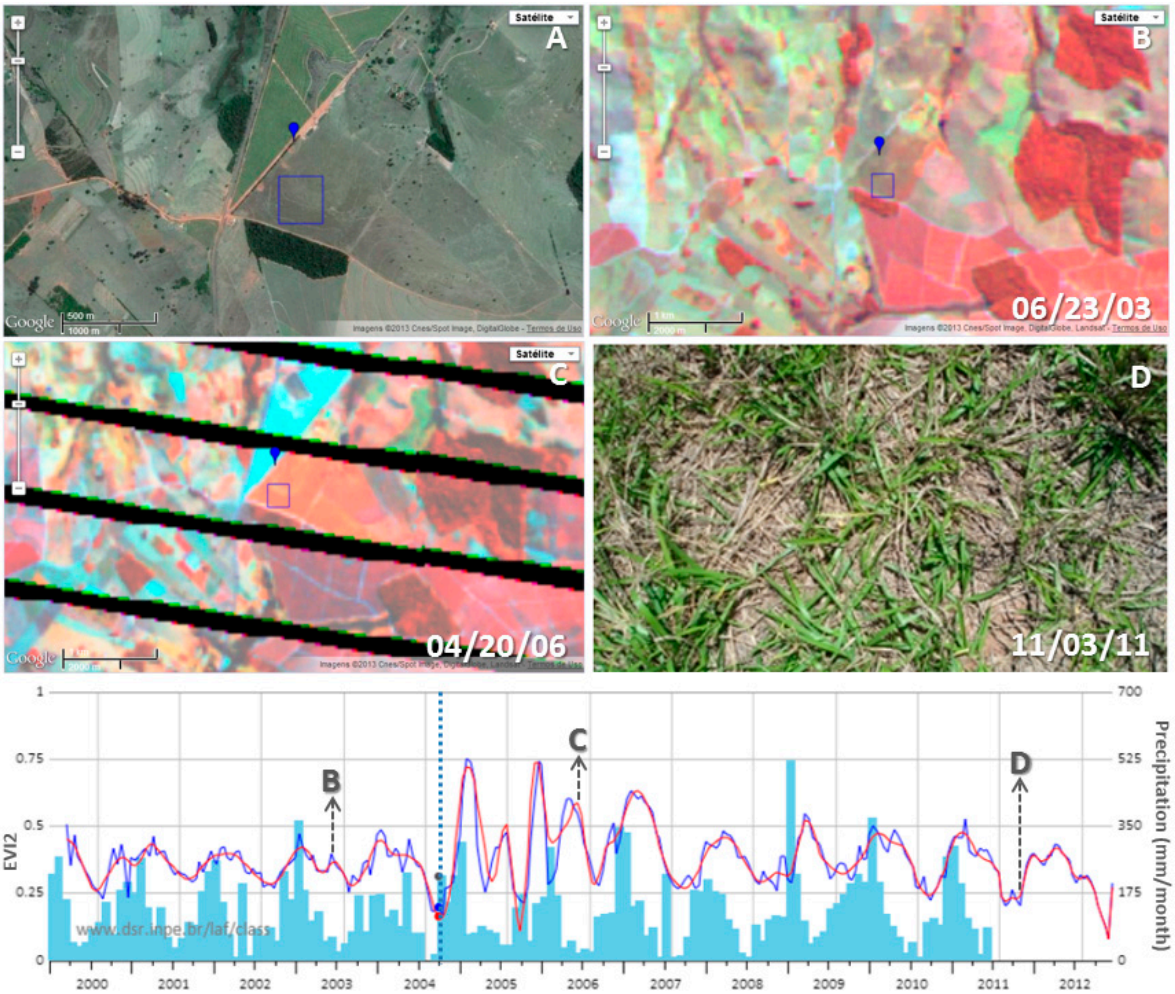


**Figure 6.** EVI2 time series for a pasture (*Brachiaria brizantha*) sampled in the Atlantic Forest biome in the State of São Paulo (18.916°S, 47.855°W); the stand was classified as "appropriate" in the field: (**A**) A high-resolution Google Earth image; (**B**) A TM/Landsat image (B3G5R4); (**C**) An ETM+/Landsat image (B3G5R4); and (**D**) The photograph acquired in the field, respectively. The blue line is the first filtered EVI2 time series. The red line is the wavelet transform series. The blue bars are TRMM precipitation time series. The blue dotted line indicates the intervention detected by the protocol. The year label indicates July for each crop-year.

Figure 7 presents an EVI2 time series of a pasture sampled in Mato Grosso in September 2012. A gradual reduction of EVI2 values is notorious between 2003 and 2007, when there was a direct renewal/recovery of the pasture, according to the protocol. During this period, there was a 27% reduction in the maximum values of EVI2. In the 2007/2008 crop year, there was an increase of 54% in the maximum EVI2 and 443% in the vegetative vigor (*vv*), whereas the *min* in the preplanting period was 24.3% lower than the *min* observed in the dry season of the previous crop year.

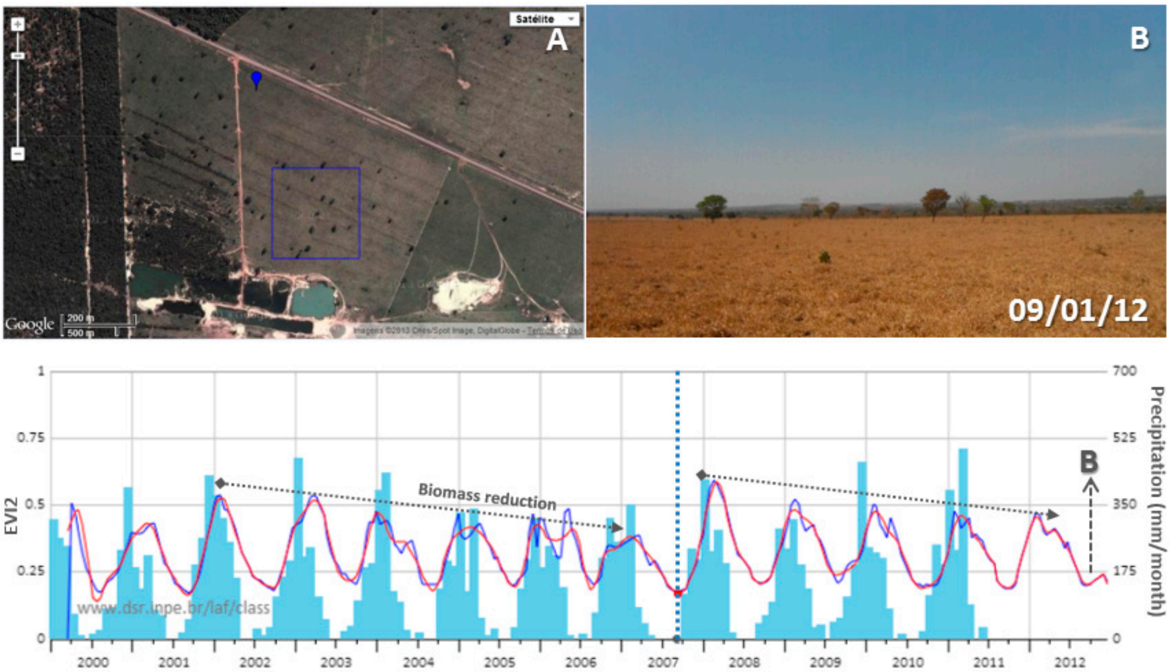


**Figure 7.** EVI2 time series for a pasture (*Brachiaria brizantha*) sampled in the Cerrado biome in the State of Mato Grosso (15.87°S, 52.392°W); the stand was classified as "appropriate" in the field: (**A**) The high-resolution Google Earth Image and (**B**) The photograph acquired in the field, respectively. The blue line is the first filtered EVI2 time series. The red line is the wavelet transform series. The blue bars are TRMM precipitation time series. The blue dotted line indicates the intervention detected by the protocol. The year label indicates July for each crop-year.

In this pasture, the reduction in the *max* that occurred between 2003 and 2007 was also influenced by a decrease in precipitation, which further influenced the biomass availability of the pasture. Nevertheless, in the second period of biomass reduction (2008 to 2012), there were some years in which the annual precipitation was higher than the mean precipitation of the analyzed period (e.g., 2009/2010 and 2010/2011). Considering that rainfall and grazing are the main factors affecting the structure and function of the pasture [58], a possible explanation for the difference in the EVI2 response to the variation in precipitation between periods may be a change in stocking rate.

Figure 8 shows the EVI2 time series of a pasture sampled in September 2012 in Jauru, Mato Grosso (Amazon biome), where an intervention was identified as reformation. Unlike the previous examples, the time series presented in Figure 8 shows no values of EVI2 indicating exposed soil or activities related to pasture renewal or recovery. The phenological metric *gur* (green up rate) for the 2004/2005 crop year was greater than that for the 2002/2003 and the 2003/2004 crop years. This metric is related to abrupt changes in vegetation [44] and, in the case of pasture, these changes are usually associated with manuring and fertilization.

Compared to the *max* of the 2003/2004 crop year, there was an increase of 30% in the 2004/2005 crop year, even with a reduction of 2.9% in the amount of accumulated precipitation. We note that there was no clear trend of biomass reduction from 2006 to 2012, which could be explained by the maintenance of good management practices, a strategy strongly recommended [30].

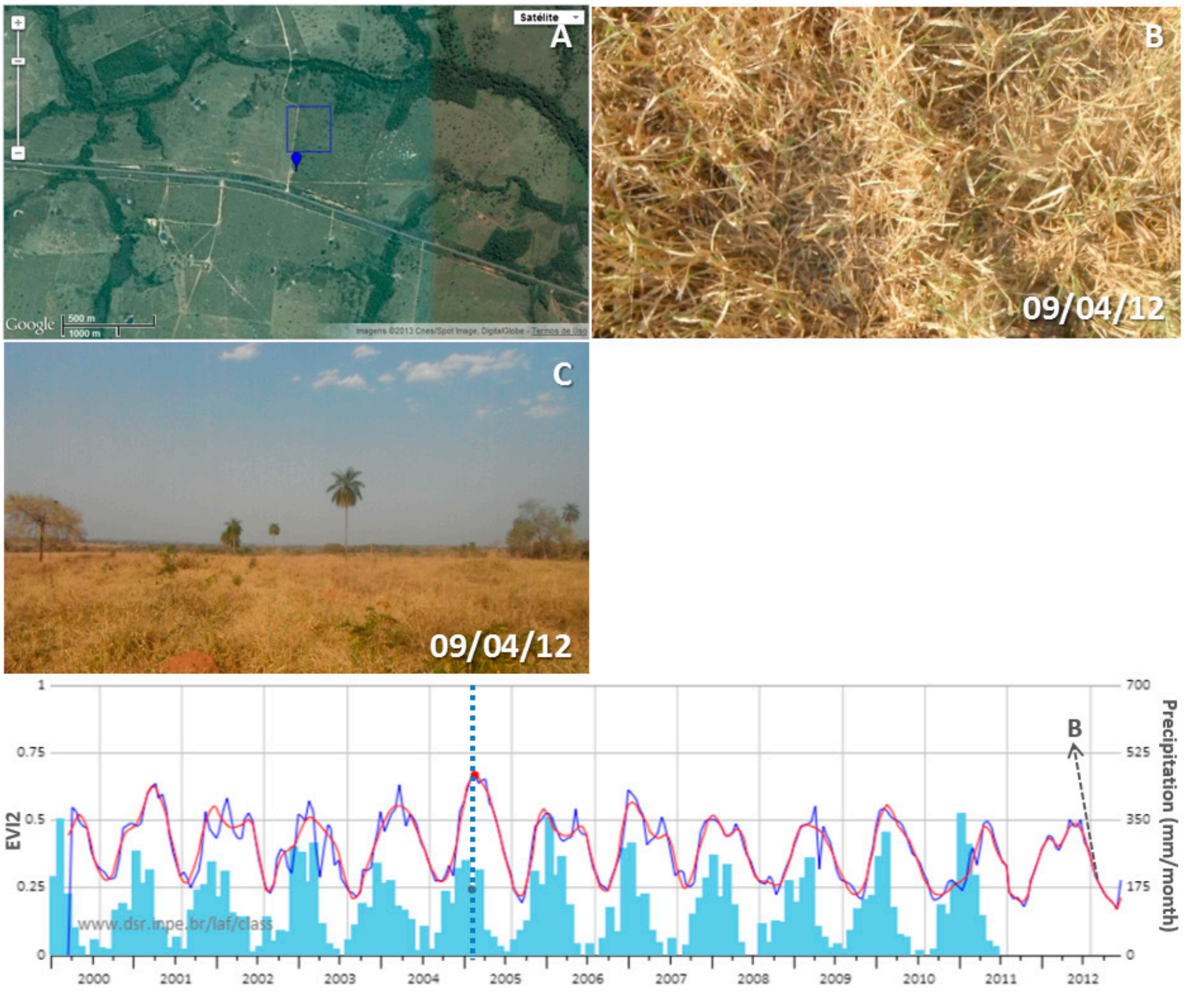


**Figure 8.** EVI2 time series for a pasture (*Brachiaria brizantha*) sampled in the Amazon biome in the State of Mato Grosso (15.597°S, 58.863°W); the stand was classified as "appropriate": (**A**) the high resolution Google Earth Image and (**B**,**C**) the photographs acquired in the field. The blue line is the first filtered EVI2 time series. The red line is the wavelet transform series. The blue bars are TRMM precipitation time series. The blue dotted line indicates the intervention detected by the protocol. The year label indicates July for each crop-year.

## *4.2. Degradation Process*

Figure 9 illustrates a pasture sampled in Porto Nacional, Tocantins, where the slope coefficient in the linear regression (−0.679) was statistically less than zero ($R^2$ = 0.61; *p*-value = 0.001). Until the 2004/2005 crop year, the *vv* values indicated that the biomass level was above the average observed for the previous pasture sampled in the Cerrado biome. From the 2006/2007 crop year on, there was a clear decrease in *vv*, and in the 2011/2012 crop year, the accumulated value of EVI2 was 36.6% less than in the 2001/2002 crop year.

Despite the increase in the EVI2 values in 2007/2008, the Boolean criteria did not show any kind of intervention in this pasture. *Bc11* and *bc12* (*idp*) were true indicating no reformation, and *bc3* and *bc4* (*min*) were false indicating no recovery/renewal. The EVI2 values for the rainy season in the 2006/2007 crop year were atypical in comparison to the other crop years and did not show the expected pattern for a pasture with the *Andropogon* grass (Figure 9). This may be an indication that there was some prejudicial intervention or change in the grazing regime, decreasing the biomass availability. If this crop year is excluded from the analysis, the pasture degradation becomes even more evident, corroborating the classification based on the protocol.

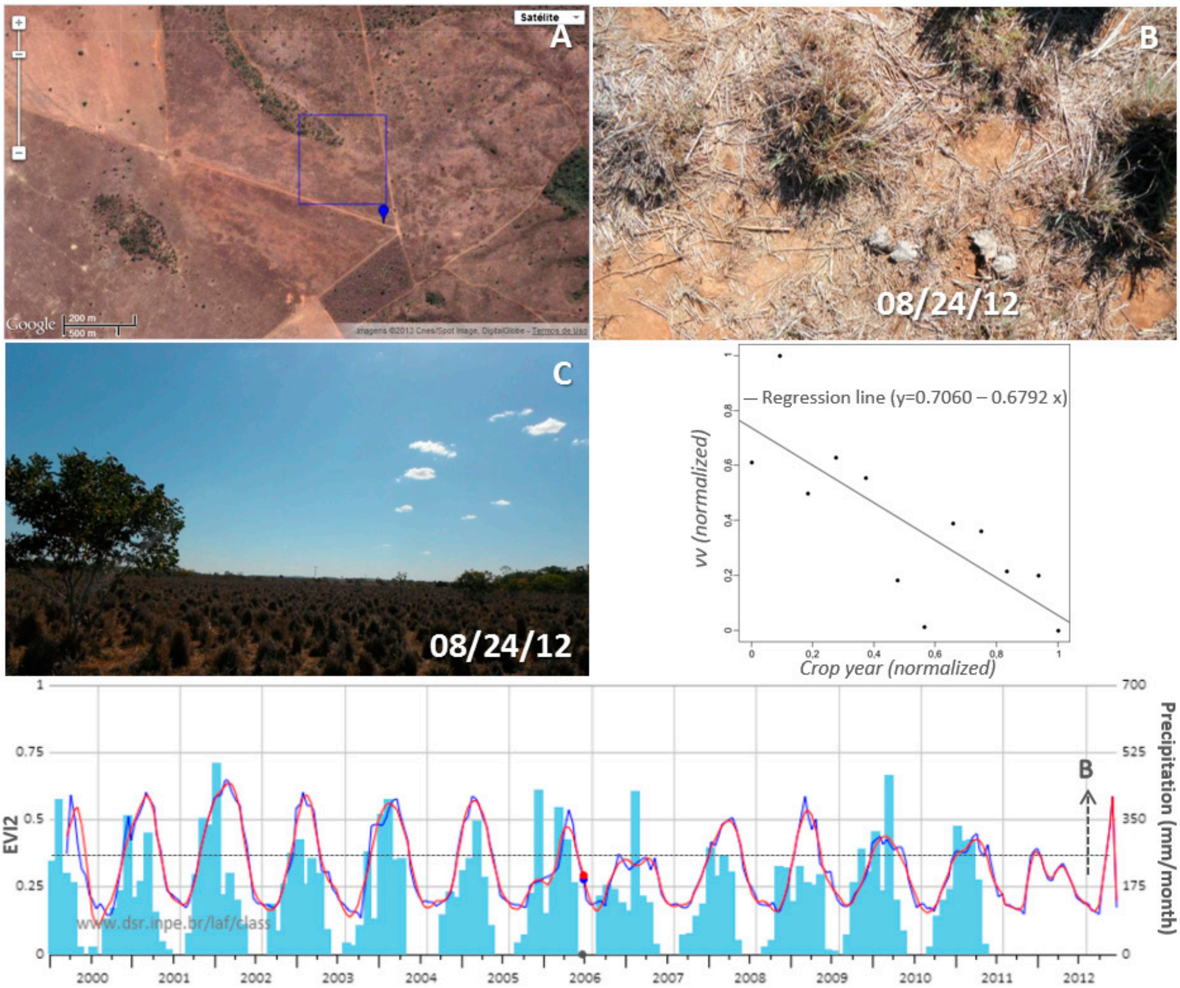


**Figure 9.** EVI2 time series for a pasture (*Andropogon*) sampled in the Cerrado biome in the Tocantins State (10.406°S, 48.476°W); the stand was classified as "intermediate": (**A**) the high-resolution Google Earth Image and (**B**,**C**) the photographs acquired in the field. The blue line is the first filtered EVI2 time series. The red line is the wavelet transform series. The blue bars are TRMM precipitation time series. The year label indicates July for each crop-year.

## 4.3. Caveats

The protocol discussed here was proposed to assess tropical pastures using a moving time window, which considered the typical seasonality. Therefore, areas converted after 2000 or those that had other usages during the analyzed period (e.g., temporary crops, forests or sugar cane) may not meet the adopted premises.

For these cases, the definition of phenological metrics should consider other criteria such as those established by [59] for mapping forest and rubber trees; by [60] for mapping vegetation types; by [61] for estimating gross primary production of subtropical pasture; or by [25] in the elaboration of an interpretation key to evaluate changes in land use and land cover as a result of sugar cane expansion.

The extensive use of fire as a management practice for pasture and the high incidence of wildfires, particularly in the dry season in the Cerrado and in the Amazon [54], may also introduce error in the protocol. Pasture burning drastically reduces the pasture biomass. However, the supply of potassium derived from the ashes increases the pasture productivity after burning [12]. The effect of this process in the EVI2 time series can resemble that of renewal/recovery antropic processes.

Well-managed pastures can also be erroneously classified by the criteria used in the protocol. For instance, irrigated pastures do not have the expected typical behavior because they do not depend on seasonal water availability. In these cases, the identification of maximum and minimum EVI2 values makes no sense.

As previously discussed, unsuccessful interventions may not be identified by the protocol. Nevertheless, they usually do not represent a biomass gain and an improvement of pasture carrying capacity and, therefore, do not contribute to the intensification of livestock [30]. Abrupt and significant changes in pasture stocking rate may contribute to the increase in the amount of biomass, resulting in EVI2 values similar to those observed for pasture reformation. According to [56], drastic reductions in pasture stocking rate are not common and are usually associated with economic factors such as cattle price.

Assuming that agricultural degradation is characterized by EVI2 time series as an increasing trend of $vv$, one can identify this process by adopting the same methodology proposed in this study, considering the pasture as degraded when the slope coefficient of the linear regression is positive and significant. However, according to [15], distinguishing pasture with good productivity from those under agricultural degradation using satellite imagery is a complicated task, since several factors may contribute to the biomass increase of a pasture land. This includes subgrazing, the adequacy of the pasture stocking rate, and the use of appropriate grazing practices (e.g., maintenance manuring).

Finally, we note that because our pasture samples were not selected randomly from the entire population in each biome, extending the results obtained for these samples to the biome scale would be speculative.

## 5. Conclusions

Time series of MODIS EVI2 data have the potential to be used for detecting degradation processes in tropical pastures, as well as anthropogenic interventions (i.e., renewal/recovery and reformation).

From the pastures sampled in this study, 19.1% presented a trend of biomass reduction, 26.6% went through some kind of intervention for pasture improvement, and 54.3% showed no intervention or biomass reduction in the analyzed period. Among the biomes with most samples, the Amazon presented the highest percentage of samples of degraded pastures (22.5%), followed by the Cerrado (17.7%) and the Atlantic Forest (6.6%).

These results are based on a protocol defined with empirical knowledge acquired in the literature and three extensive field campaigns. We found some difficulties in obtaining historical data about pasture and grazing management (i.e., pasture condition, including biomass measurements over time, stocking rate, introduction/removal of cattle, and management techniques used for renewal/recovery and reformation procedures), which could be used to improve the protocol presented here.

There are still few studies that have explored the use of remote sensing tools for assessing tropical pastures. This study represents a novel attempt to assess tropical pasture using indicators of intensification and pasture degradation. The protocol developed here may be used to support funding mechanisms for pasture improvement, and serve as a basis for the elaboration of public policies focused on livestock and the environment.

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**Author Contributions:** D.A.A. conceived, designed, and performed the study; collected and analyzed the data; and wrote the paper. M.P.M. assisted with the protocol design, protocol transcription for R language, and writing of the paper. S.F.N. assisted with data collection and writing of the paper. F.G.G. contributed to parts of the analysis and the review of the paper. M.A. contributed to parts of the analysis and writing of the paper. B.F.T.R. assisted with study design and writing of the paper.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

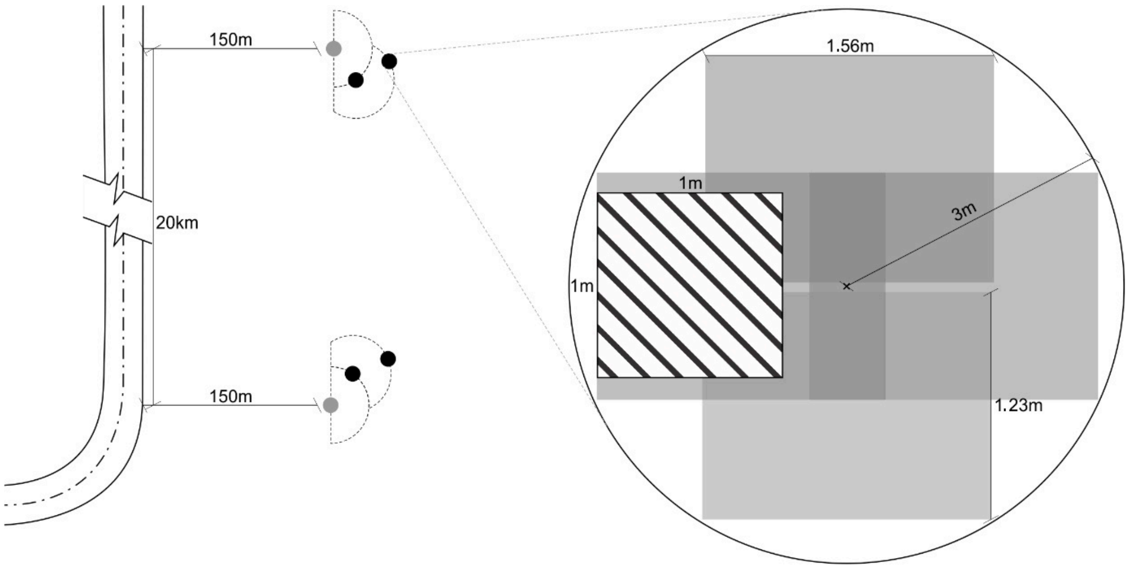


**Figure A1.** Schematic representation of the adopted sampling strategy, emphasizing the location of sample points within the pasture (solid circles); the average distance between samples (20 steps; dashed lines); the field of view of the vertical photographs (≈192 $cm^2$; gray rectangles); and the footprint of the area used for counting the number of invasive species, stools, and termite mounds (open circle).

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