Comparison of Post-fire Patterns in Brazilian Savanna and Tropical Forest from Remote Sensing Time Series

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Abstract: Monitoring of fire-related changes is essential to understand vegetation dynamics in the medium and long term. Remote sensing time series allows estimating biophysical variables of terrestrial vegetation and interference by extreme fires. This research evaluated fire recurrence in the Amazon and Cerrado regions, using Moderate Resolution Imaging Spectroradiometer (MODIS) albedo time series, enhanced vegetation index (EVI), gross primary productivity (GPP), and surface temperature. The annual aggregated time series (AAT) method recognized each pixel’s slope trend in the 2001–2016 period and its statistical significance. A comparison of time trends of EVI, GPP, and surface temperature with total fire recurrence indicates that time trends in vegetation are highly affected by high fire recurrence scenarios ($R^2$ between 0.52 and 0.90). The fire recurrence and the albedo’s persistent changes do not have a consistent relationship. Areas with the biggest evaluated changes may increase up to 0.25 Kelvin/Year at surface temperature and decrease up to −0.012 EVI/year in vegetation index. Although savannas are resistant to low severity fires, fire regime and forest structure changes tend to make vegetation more vulnerable to wildfires, reducing their regeneration capacity. In the Amazon area, protection of forests in conservation units and indigenous lands helped in the low occurrence of fires in these sensitive areas, resulting in positive vegetation index trends.

Keywords: fire recurrence; Amazon; Cerrado; vegetation biophysics; MODIS; Landsat

1. Introduction

Fire is a natural agent present in most terrestrial biomes, contributing to the dispersion, evolution, and diversity of species, especially in biomes with intermediate primary productivity such as savannas [1,2]. The regions with high primary productivity, such as tropical forests, present a low natural fire occurrence because of their high humidity. However, agricultural use has altered tropical forests, where the fire is one of the main types of land management [3]. Although the localized fire use in pastures and agriculture spreads over large areas during years of severe drought [4]. Moreover, fire in savanna areas generally does not obey the natural fire regime, occurring mainly at the end of dry periods, when there is a higher probability of high-severity fires [5].

Fires cause changes in surface albedo, nutrient cycling, energy exchanges between the surface and the atmosphere, ecological processes, and climate [6–9]. The albedo change from the burning is due to the ash’s vegetation cover, which directly influences the surface energy balance. Although albedo changes are short-lived, changes in plant cover can also cause albedo changes in the medium term, both in the increase of surface albedo in forest areas or the decrease in savannas, given the floristic differences [10,11]. Fire intensifies the air and soil heat fluxes, increasing the surface temperature
immediately after the fire. The temperature directly correlates with the fire severity, biomass converted to ash and exposed soil area [12].

Another critical parameter of vegetation dynamic is gross primary productivity (GPP), one of the main components in the carbon biogeochemical cycle. It represents carbon exchanges between terrestrial ecosystems and the atmosphere [13]. The fire effects on GPP are related to the loss of vegetation biomass, and each biome’s restoration rate [14]. Large-scale changes in GPP by burning impact carbon flux and, consequently, on the global climate [13,15,16]. Finally, the fires modify the structure, composition, distribution, and diversity of terrestrial biomes [17,18], influencing the regeneration rates and phenological patterns.

Studies of fire effects on environmental parameters mainly follow two approaches: (a) analysis of net productivity and radiation balance from ground measurements immediately after the occurrence of fire [6] or by flux towers that provide a nearly continuous dataset over a long-term experiment [10,11]; and (b) quantification of biophysical changes from remote sensing time series [12,19,20]. Site-specific studies, with field or flux towers measurements, provide the primary data for analysis of vegetative processes. However, the point extrapolation for regional analysis is difficult, given its spatial and temporal restriction [13]. On the other hand, remote sensing data accuracy is related to its various resolutions, as temporal and spatial, critical to the continuous monitoring of the same area for several analyzes of post-fire dynamics [21–24]. Despite the diversity of studies, few sought to compare the mid-term fire influence between forest-savanna, such as in the Amazon and Cerrado (Brazilian Savanna), and remote sensing products as alternatives to areas where no flux towers are available.

This study aims to examine the post-fire impact in Amazon and Cerrado environments from remote sensing time series considering the following attributes: albedo, enhanced vegetation index (EVI), GPP, and surface temperature; and how these parameters behave over 15 years. The trend analysis of the time series of Moderate Resolution Imaging Spectroradiometer (MODIS) products (moderate resolution imaging spectroradiometer) considered the period 2001–2016 in the Amazon (Ji-Paraná river basin) and Cerrado (Cantão State Park and Araguaia National Park). Therefore, this research evaluates consistent changes in vegetation in the medium term and the response of phytosociomacies at different fire frequencies. The survey results can help Brazil’s new burning policy, identifying sensitive areas with a high frequency of fires, and describing their behavior over time. Furthermore, the remote sensing time series analysis minimizes the costs of field activities and facilitates continuous monitoring.

2. Materials and Methods

2.1. Study Area

As areas of study, we consider the effect of fire on the Brazilian Cerrado and Amazon biomes (Figures 1 and 2), which contain different ecological characteristics. These regions are subject to high fire incidence, despite the climatic and vegetation differences [25]. The land-cover/land-use data came from the Project for the Conservation and Sustainable Use of Brazilian Biological Diversity (PROBIO) [26], which mapped Brazilian vegetation cover and its phytosociomacies based on LANDSAT images for the year 2002 (http://mapas.mma.gov.br/). To update the PROBIO mapping for the base year 2016, we used data from the Project for the Satellite-Based Monitoring of Brazilian Biome Deforestation (PMDBBIS) [27], which also uses Landsat images to update annual deforestation in each Brazilian biome (https://siscom.ibama.gov.br/). The two areas have a typical pattern with overlapping of fully protected conservation units (severe land-use restrictions) and indigenous lands, generating a multi-managed environment. In this research, we divided the natural vegetation into preserved vegetation and altered vegetation in high fragmentation or selective cutting.
The study area in the Amazonian biome is the Ji-Paraná River Basin (JPRB) in the State of Rondônia, covering 12,200 km² (Figure 1). The annual average rainfall varies between 1400 and 2600 mm, with up to three months of drought, and the average temperature varies between 24 and 26 °C [28]. The fire pattern of the JPRB is the same as that observed in most of the Brazilian Amazon, with anthropic fires in the driest months, from August to October. The fire in this region occurs mainly in deforested areas, high vegetation fragmentation areas, and the area used for pasture maintenance [25].

According to official data from PROBIO, the JPRB presents the following land-use/land cover classes: (a) savanna/forest transition; (b) altered savanna/forest transition; (c) Ombrophilous forest.
(mainly in conservation units and indigenous lands); (d) altered Ombrophilous forest; (e) anthropic use (pasture/livestock); (f) woody savanna; and (g) altered woody savanna (Figure 1b).

The study area of the Cerrado biome includes the Araguaia National Park (ANP) (5555 km$^2$) and the Cantão State Park (CSP) (1004 km$^2$), belonging to the State of Tocantins (Figure 2). The annual average rainfall is 1700 mm and an average temperature of 26 °C. Precipitation is not evenly distributed during the year, presenting a period of up to 5 months of drought, usually from May to September [29].

The ANP-CSP corresponds to the Cerrado biome’s largest seasonally humid area, with a complex flooded plain system and high phytophysiognomic variability. The greatest accumulation of biomass occurs at the end of the wet period, between March and April, while the lowest biomass period occurs at the end of the dry period, in September [30]. Most anthropic fires concentrate at the end of the dry season, mainly reaching grassland areas to accelerate regrowth and serve as input for livestock that is the main activity in the region [31]. The ANP-CSP area shows the following classes: (a) seasonal forest; (b) pasture/livestock; (c) forested savanna; (d) altered forested savanna; (e) grassy-woody savanna; and (f) savanna parkland (Figure 1b).

2.2. MODIS Dataset

The MODIS sensor onboard the Terra and Aqua satellites, developed by the National Aeronautics and Space Administration (NASA), aims to continuously monitor the Earth’s surface, having 36 spectral bands ranging from 0.4 µm to 14.4 µm in three different spatial resolutions (250, 500 and 1000 m) [32]. We used the following products derived from the MODIS sensor: (a) MOD13Q1, which provides the enhanced vegetation index (EVI) at 250-m spatial resolution and 16-day composite; (b) MOD09Q1, surface reflectance (bands 1 and 2) at 250-m spatial resolution and in the 8-day composite; (c) MOD09A1, surface reflectance (bands 1 to 7) at 500-m spatial resolution and 8-day composite; (d) MOD11A2, surface temperature at 1-km spatial resolution and 8-day composite; and (e) MOD17A2, GPP at 500-m spatial resolution and 8-day composite. Data acquisition used the NASA website (https://search.earthdata.nasa.gov/). The definition of the surface albedo ($\alpha_s$) used the MOD09Q1 and MOD09A1 products according to the equation [33]:

$$\alpha_s = 0.160p_1 + 0.291p_2 + 0.243p_3 + 0.116p_4 + 0.112p_5 + 0.081p_7 - 0.0015$$

where $p_i$ is the surface reflectance of the MODIS bands (1–7), except band 6.

MODIS data were from the period 2001–2016, eliminating low-quality pixels from the available quality parameters. We resampled the products with 500- and 1000-m spatial resolution to 250-m by the nearest neighbor interpolation method and the 8-day composite to 16-days from the mean value. The Savitzky–Golay filter [34] was applied to reduce noise in the time series. This filter has been widely used in remote sensing time series, using local polynomial regression to remove noise and retain the waveform from the natural characteristics of vegetation [35–37].

2.3. Ground Measurements

To support the remote sensing analysis in this study, we compared the MODIS data with the Large-Scale Biosphere-Atmosphere (LBA) dataset. We used eddy covariance flux tower data for the land-surface temperature (LST) and GPP variables (https://daac.ornl.gov/LBA/guides/CD32_Brazil_Flux_Network.html), and ground-based reflectance measurements for EVI/Albedo data, in the JPRB area in the year 2002 (https://daac.ornl.gov/LBA/guides/ND01_Pasture_Spectra.html), and in the CSP-ANP in the same year (https://daac.ornl.gov/LBA/guides/LC19_Field_2002.html) (Table 1).
Table 1. Summary of Large-Scale Biosphere-Atmosphere (LBA) data for the study areas: Araguaia National Park and Cantão State Park (ANP-CSP) and Ji-Paraná River Basin (JPRB). The variables used were Land-Surface Temperature (LST), Gross Primary Productivity (GPP), and reflectance.

| Site Name                        | Study Area | Lat  | Long  | Variable | Period       |
|----------------------------------|------------|------|-------|----------|--------------|
| Tocantins-Javaes Flux Tower      | ANP-CSP    | −9.824 | −50.159 | LST/GPP  | 10/2003 to 12/2004 |
| Reserva Jaru Flux Tower          | JPRB       | −10.0780 | −61.93310 | LST/GPP  | 04/2000 to 06/2002 |
| Cangusu 8-year Pasture           | ANP-CSP    | −10.04658 | −49.8998 | Reflectance | 06/2002 |
| Cangusu Cerrado woodland         | ANP-CSP    | −10.06633 | −49.90696 | Reflectance | 06/2002 |
| Cangusu 3-year pasture           | ANP-CSP    | −10.06339 | −49.91322 | Reflectance | 06/2002 |
| Cangusu 1-year pasture           | ANP-CSP    | −10.06155 | −49.90547 | Reflectance | 06/2002 |
| Santana do Araguaia 20-year pasture | ANP-CSP  | −9.71817 | −50.40072 | Reflectance | 07/2003 |
| Santana do Araguaia Capoeira      | JPRB       | −9.7454 | −61.9888 | Reflectance | 07/2003 |
| Ji-Paraná LC 1                   | JPRB       | −10.896 | −62.081 | Reflectance | 07/2003 |
| Ji-Paraná LC 2                   | JPRB       | −10.714 | −61.9888 | Reflectance | 07/2003 |
| Presidente Medici PR             | JPRB       | −11.242 | −61.7967 | Reflectance | 07/2003 |

The analysis of the variables considered averages of 8 and 16 days from daily data. We apply a simple linear regression between each MODIS variable and the field data, discarding no-data values. Given the low availability of field measurements, we use the entire period available. However, the GPP variable had few days available, while the reflectance variable had several points distributed in the same period. Details of the flux tower dataset and JPRB/ANP-CSP ground measurements can be found respectively in [38–40].

2.4. Burned Area

The burned areas delimitation used semi-automatic methodology, applying threshold values in normalized near-infrared time series (band 2) from z-score and mean methods [37,41]. The near-infrared band presents a higher ability to distinguish burned and unburned areas [41,42]. The best-threshold definition considered five Landsat scenes (TM, ETM+, and OLI) for both regions (Table 2). Validation data used visual image inspection for each year (2001–2016).

Table 2. Landsat database used to define the best threshold for mapping of burned areas, considering the sensors: Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI).

| Amazon Forest | Cerrado |
|---------------|---------|
| **Scenes**    | **Sensor** | **Scenes** | **Sensor** |
| **(Path-Row)** | **Image Date** | **(Path-Row)** | **Image Date** |
| 01/10/2002    | ETM+     | 20/09/2001 | ETM+     |
| 01/10/2005    | TM       | 18/09/2003 | TM       |
| 223–67        | 223–68   | 13/09/2007 | 21/09/2010 | TM |
| 223–68        | 10/10/2014 | OLI      | 16/09/2014 | OLI |
| 27/09/2015    | OLI      |           |          |      |

2.5. Temporal Trend

The change detection in 2001–2016 trends for the different parameters used the aggregated annual time series (AAT) method [36]. The AAT is available in the Land Surface Phenology and Trend Analysis package in the R software (http://greenbrown.r-forge.r-project.org/). The AAT method estimates each pixel’s trend and the predictable significance of each temporal segment using the Mann–Kendall test [37,38]. The annual average is the basis for detecting structural changes or significant breakpoints in a regression analysis, requiring data with at least four years [39]. The result indicates the annual magnitude of increase or decrease per pixel, and if that value is significant. Simple linear regression analysis demonstrated the relationship between AAT trends with fire recurrence, from an average of 100 random points within each fire recurrence class. In addition, we estimated the relationship
between biophysical variables trends, land use/land cover, and recurrence fire, using an average of 50 random points in each possible combination of fire recurrence and type of land use/land cover.

To illustrate the changes caused by the fire in the temporal profile of biophysical variables, we have also selected some of the variables with greater representativeness. In this case, we selected random pixels from the same 50 pixels used for the regression analysis for time profile analysis.

3. Results

3.1. Validation of MODIS Biophysical Data

The accuracy assessment of MODIS biophysical data compared ground measurements with LST, GPP, and reflectance data (Figure 3). Our results indicate that the MODIS estimates of biophysical variables were consistently accurate compared to the flux towers (LST and GPP) and ground-based reflectance (albedo and EVI). The reflectance data reached the highest correlation in both areas: JPRB ($R^2 = 0.97$) and ANP-CSP ($R^2 = 0.91$). The $R^2$ for LST ($R^2 > 0.76$) and GPP ($R^2 > 0.82$) was significant for both study areas.

![Figure 3. Validation using Large-Scale Biosphere-Atmosphere data for: (a) Land-Surface Temperature (LST) from the Moderate Resolution Imaging Spectroradiometer (MODIS) data, (b) Gross Primary Productivity (GPP) from the MODIS data, (c) MODIS reflectance in the Araguaia National Park and Cantão State Park (ANP-CSP), and (d) Ji-Paraná River Basin (JPRB).](image)

Figures 4 and 5 show the time series used for validation. In both study areas, we had more than one year data available for LST analysis (Figure 4a,b) and less than one year for the GPP (Figure 4c,d). In general, the estimated MODIS values for the two variables (LST and GPP) were slightly higher than the values measured in the field. Figure 5 compares the average reflectance between LBA field measurements and the MODIS data, considering six collections in the ANP-CSP area and three collections in the JPRB area. Unlike the LST and GPP variables, the MODIS reflectance values were lower than those measured in the field but maintained the same pattern.
3.2. Fire Recurrence

In 2001–2016, the area burned at least once in the JPRB region was about 1400 km² (12%) (Figure 6a; Table 3). Most of the fires occurred in forest–pasture conversion areas, while forest areas showed fewer fire events. The ANP-CSP region burned about 4400 km² (68%) between 2001 and 2016 (Figure 6b, with a higher concentration of fires in grasses compared to forest areas. The total unburned area varies significantly in the two regions. About 88% of the JPRB region did not present any fire event in the 15 years analyzed. While at ANP-CSP, this scenario occurs in only 32% of the area.
The spatial patterns of fire were distinct in the two biomes. The JPRB region has high vegetation fragmentation; consequently, the burn scars are small and with low connectivity. Furthermore, JPRB has a little fire recurrence, where most of the burned areas (11% of the total area) presented a fire recurrence of 1 to 3 years over 15 years. The ANP-CSP region, with high connectivity of native vegetation, presented areas with more significant fire recurrence than the Amazon region, where about 25% of the total ANP-CSP burned between 7 and 9 times in the period, concentrated mainly in grassy vegetation (Table 3).

3.3. Vegetation Dynamics

The vegetation trend analysis indicated different spatiotemporal patterns in the variables of albedo, EVI, GPP, and surface temperature (Figures 7 and 8). The JPRB and ANP-CSP areas presented little change in the albedo and GPP variables, with an average of less than 1% of significant changes. On the other hand, the EVI and surface temperature variables showed greater representativeness of substantial changes in both areas.

In the JPRB, the albedo change varied between $-0.0019$ and $+0.0019$ per year (<0.5% of the area with significant changes). Meanwhile, the Cerrado values ranged between $-0.0049$ and $+0.0057$ (<1.2% of the area with significant changes). The ANP-CSP area was more susceptible to albedo changes, both positive and negative.
Figure 7. Spatial distribution of the trend per pixel in the period 2001–2016 for: (a) albedo in the Ji-Paraná River Basin (JPRB), (b) Enhanced Vegetation Index (EVI) in the JPRB, (c) albedo in the Araguaia National Park and Cantão State Park (ANP-CSP), and (d) EVI in the ANP-CSV.

Figure 8. Spatial distribution of the trend per pixel in the period 2001–2016 for: (a) Gross Primary Productivity (GPP) in the Ji-Paraná River Basin (JPRB), (b) surface temperature in the JPRB (c) GPP in the Araguaia National Park and Cantão State Park (ANP-CSP), and (d) surface temperature in the ANP-CSP.
The EVI trend indicates that approximately 22% of the ANP-CSP and 10% of JPRB showed statistically significant vegetation changes (Figure 7b,d,e). In the JPRB, significant negative EVI trends (up to $-0.012$ EVI per year) occurred in the region with higher deforestation and vegetation fragmentation, revealing pasture and forest degradation signs. In contrast, positive trends (up to $+0.007$ EVI per year) occurred mainly in conservation units and indigenous lands with little altered vegetation. In the ANP-CSP area, there were significant negative trends in the EVI (up to $-0.011$ EVI per year) in degraded vegetation and mobile riverbanks. In contrast, the positive EVI trends occurred mainly in forest areas that are also least affected by fire, earning up to $0.008$ EVI per year, indicating biomass accumulation.

In both study areas, GPP values had less than 2% of areas with significant changes (Figure 8a,c). In the JPRB, we observed GPP changes between $-0.001$ and $0.0005$ kg C m$^{-2}$ per Year, restricted to small areas of altered vegetation in cases of a negative trend. While in ANP-CSP, the GPP values had greater amplitude and varied between $-0.163$ and $+0.0007$ kg C m$^{-2}$ per Year, and just as in the JPRB, the negative values occurred mainly in fragments of altered vegetation.

The surface temperature was the variable with the highest number of pixels with a statistically significant change in the JPRB area (>30% of the area with significant positive changes), with an increase of up to 0.192 Kelvin per year. In contrast, the ANP-CSP area had 10% of the total area with significant positive changes in surface temperature. However, the maximum values were higher, with an increase of up to 0.252 Kelvin per year (Figure 8b,d). The surface temperature variable did not present significant negative changes in any of the areas.

### 3.4. Biophysical Changes and Recurrence of Fire

Figure 9a,d illustrate the relationship between the MODIS biophysical parameters and fire recurrence from the linear regression analysis. The significant temporal changes of EVI and GPP showed a strong relationship with the increase in fire recurrence ($R^2 > 0.74$) (Figure 9b,c). We did not observe a significant relationship between albedo changes and fire recurrence ($R^2 < 0.29$) (Figure 9a). The relationship between LST and fire recurrence was greater in the JPRB area ($R^2 = 0.62$) compared to the ANP-CSP area ($R^2 = 0.52$) (Figure 9d). However, the fire recurrence did not fully explain the variations in surface temperature.

![Figure 9](image)

**Figure 9.** Fire recurrence relationship in the Ji-Paraná River Basin (JPRB) and Araguaia National Park/Cantão State Park (ANP-CSP) areas with (a) Albedo, (b) Enhanced Vegetation Index (EVI), (c) Gross Primary Productivity (GPP), and (d) Land-Surface Temperature (LST).

Table 4 shows the result of $R^2$ for all analyzed combinations of land use/vegetation and fire recurrence. The relationship between fire recurrence and albedo was irregular in the different classes.
of land use/vegetation. Some areas showed no association with the increase of fire recurrences ($R^2 = 0$), such as seasonal forest and altered Ombrophilous forest. In contrast, others showed a medium relationship ($R^2 < 0.57$), such as grassy-woody savanna and woody savanna.

**Table 4.** $R^2$ values by land use/vegetation types for the relationships between MODIS biophysical variables and fire recurrence. The classes in the JPRB area were: Altered Ombrophilous Forest (AOF), Altered Savanna/Forest Transition (ASFT), Altered Woody Savanna (AWS), Ombrophilous Forest (OF), Pasture/Livestock (PA), Savanna/Forest Transition (SFT), and Woody Savanna (WS). In the ANP-CSP, the classes were: Altered Forested Savanna (AFS), Forested Savanna (FS), Grassy-woody Savanna (GWS), Pasture/Livestock (PA), Seasonal Forest (SF) and Savanna Parkland (SP).

| Study Area | Land Use/Vegetation | Albedo-Fire | EVI-Fire | GPP-Fire | LST-Fire |
|------------|---------------------|-------------|----------|----------|----------|
| ANP-CSP    | AFS                 | 0.321       | 0.883    | 0.618    | 0.480    |
|            | FS                  | 0.310       | 0.796    | 0.921    | 0.559    |
|            | GWS                 | 0.521       | 0.864    | 0.745    | 0.540    |
|            | PA                  | -           | 0.867    | -        | 0.458    |
|            | SF                  | 0.000       | 0.796    | 0.864    | 0.696    |
|            | SP                  | 0.504       | 0.906    | 0.790    | 0.913    |
|            | AOF                 | 0.000       | 0.814    | 0.864    | 0.644    |
|            | ASFT                | 0.440       | 0.909    | 0.805    | 0.723    |
|            | AWS                 | 0.001       | 0.890    | 0.920    | 0.460    |
|            | OF                  | 0.419       | 0.507    | 0.703    | 0.727    |
|            | PA                  | 0.073       | 0.617    | 0.915    | 0.351    |
|            | SFT                 | 0.013       | 0.754    | 0.885    | 0.717    |
|            | WS                  | 0.570       | 0.802    | 0.930    | 0.230    |

In most phytophysiognomies analyzed, pixels with significant EVI changes showed medium to a high relationship with increased fire recurrence ($R^2 = 0.50$ to 0.90). In the JPRB area, the greatest relations between EVI and fire recurrence were altered vegetation areas, compared to preserved vegetation areas (Table 4). The ANP-CSP area showed the same pattern, except the savanna parkland, which had the highest $R^2$ in the period.

The GPP $R^2$ values do not follow the same direction as the EVI values. Despite the GPP changes had low spatial representativeness, showed the most significant relationship with the recurrence of fire in forested savannas and woody savannas (including the altered woody-savannas) ($R^2 > 0.92$). However, there are phytophysiognomies with less relation as altered forested savannas and Ombrophilous forests ($R^2 < 0.70$). The relationship between trends in surface temperature and fire recurrence differs in the analyzed physiognomies. The largest association occurred in the savanna parkland in the ANP-CSP area ($R^2 = 0.91$).

The vegetation classes with anthropic alterations did not have a constant pattern in the GPP and LST parameters. In some cases, the altered vegetation has a greater relationship with the fire recurrence than the native vegetation, such as Ombrophilous forest (GPP) and savanna/forest transition (LST). In contrast, the forested savanna (native vegetation) had a most significant association with the fire recurrence.

We selected some of the variables with the most significant inclinations to exemplify their temporal pattern. In this case, we selected the classes of pasture and altered Ombrophilous forest in the JPRB area; and altered forested savanna and grassy-woody savanna in the CSP-ANP area; to exemplify the variables of EVI and surface temperature in different burning scenarios (Figures 10–13). Pastures in the JPRB area (Figure 10a) have distinct EVI patterns since the beginning of the time series due to the different management. Furthermore, there is a gradual increase in pasture with many fires, where both showed decreasing EVI pattern. The altered Ombrophilous forests (Figure 10b) also show drastic differences in the EVI pattern, whether selective cutting, difference in biomass or quantity of tree species.
Even without fires, such as the periods 2001–2007 and 2012–2015, there was an intense disturbance of the EVI temporal pattern.

Figure 10. Time series of Enhanced Vegetation Index (EVI) in the Ji-Paraná River Basin, considering: (a) pastures, with four (dotted line) and eight (gray line) years of fire; and (b) Altered Ombrophilous Forest, with two (dotted line) and four (gray line) years of fire. Arrows indicate the exact dates of fires in these pixels, black arrow for dotted line, and gray arrows for the gray line.

Figure 11. Time series of Enhanced Vegetation Index (EVI) in the Araguaia National Park and Cantão State Park, considering: (a) Altered Forested Savanna, with five (dotted line) and seven (gray line) years of fire; and (b) Grassy-woody Savanna, with six (dotted line) and seven (gray line) years of fire. Arrows indicate the exact dates of fires in these pixels, black arrow for dotted line and gray arrows for the gray line.
Figure 11. Time series of Enhanced Vegetation Index (EVI) in the Araguaia National Park and Cantão State Park, considering: (a) Altered Forested Savanna, with five (dotted line) and seven (gray line) years of fire; and (b) Grassy-woody Savanna, with six (dotted line) and seven (gray line) years of fire. Arrows indicate the exact dates of fires in these pixels, black arrow for dotted line and gray arrows for the gray line.

Figure 12. Time series of Land Surface Temperature in the Ji-Paraná River Basin, considering: (a) pastures, with four (dotted line) and eight (gray line) years of fire; and (b) Altered Ombrophilous Forest, with two (dotted line) and four (gray line) years of fire (b). Arrows indicate the exact dates of fires in these pixels, black arrow for dotted line and gray arrows for the gray line.

Figure 13. Time series of Land Surface Temperature in the Araguaia National Park and Cantão State Park, considering: (a) Altered Forested Savanna, with five (dotted line) and seven (gray line) years of fire; and (b) Grassy-woody Savanna, with three (dotted line) and five (gray line) years of fire. Arrows indicate the exact dates of fires in these pixels, black arrow for dotted line and gray arrows for the gray line.
In the Cerrado area, fire events significantly influence the reduction of EVI in the medium term. As in the altered Ombrophilous forest’s temporal patterns, there are divergences in the altered savannah (Figure 11a). Despite this, it is possible to observe a pattern in both time series: the sharp fall in the post-fire EVI; and the accumulation of biomass after each fire, represented by the increase in EVI. At the end of the time series, the EVI value no longer reaches the maximum marks in 2003, 2006, 2008, and 2009.

The surface temperature in all classes in the Amazon and Cerrado was highly sensitive to fire events (Figures 12 and 13). The different scenarios of fire recurrence altered areas with similar initial temperature patterns. All classes showed a positive trend with great peaks in the years of fires. In addition, the annual amplitude of the surface temperature increases in the final years of the temporal series. However, the initial minimum values have not been reached.

4. Discussion

Spatial analysis of fire recurrence showed a distinct effect considering land use/land cover and biophysical variables. The Amazon (not adapted to fire) and Cerrado (adapted to fire events of low recurrence) areas showed negative EVI and GPP trends and positive LST trends with the increase in fire recurrence, despite their different natural adaptations [43]. Most phytophysiognomies showed a negative EVI trend with the fire recurrence increase, highlighting a possible environmental fragility. The EVI and GPP variables demonstrated a high association between altered vegetation and fire recurrence, achieving the highest R² values. ANP-CSP showed high rates of degradation even though it contained a mosaic of protected areas of full protection. In the rest of the biome, the low rates of protected areas resulted in natural vegetation indiscriminate use [44]. In the Amazonian biome, the protected areas in the JPRB were essential for the maintenance of biophysical parameters. The indigenous lands, which present a low incidence of fires, allow more remarkable vegetation preservation [45].

Land cover governs changes in the post-fire albedo. Fire can increase albedo rates in forest areas, while grass and savanna areas may decrease due to different vegetation regeneration rates [10]. However, post-fire albedo changes do not remain long-term on the surface because of ash removal and vegetation recovery [10,46]. We could not see a pattern in the relationship between albedo temporal trends and fire recurrence in this analysis. Other studies have found a similar pattern of albedo changes [10,12]. Right after the fire, albedo values may drop from 0.01 to 0.15, attenuating over the years. As the albedo change is ephemeral, we found less significant values in the last 15 years (between −0.001 and −0.004), similar to that described by Planque et al. [47] with losses of up to −0.008. The vegetation albedo behavior was consistent with other studies [10,48]; areas with a higher density of trees show less loss of albedo compared to grassland. In our case, the savanna formations from the ANP-CSP area showed a more significant decrease in albedo than the forest areas of the JPRB area.

Several studies analyze the fire action through time series of vegetation indexes [12,19,49]. The vegetation indices can estimate the removal of vegetation by fire and the elimination of fragile species. In this research, the EVI index allowed us to quantify vegetation changes and correlate with fire recurrence. Studies confirm that fires negatively affect EVI annual slopes, with changes that can reach −0.07 to 0.07 EVI per year, but with the highest concentration range between −0.01 and 0.01 [50,51], the same as observed in the ANP-CSP and JPRB areas. In both study areas, EVI had an increase in protected forest areas and a decrease in altered vegetation. The protected area had an accumulation of biomass and growth in woody species. On the other hand, altered vegetation areas have less regeneration capacity due to the loss of fire-resistant species and exotic species [19]. The recurrence of fire by anthropic action was the leading cause of the decrease of EVI during the 15 years, proving that even the savanna (fire-adapted vegetation) has a fragility to the anthropic perturbation [1].

The GPP is one of the main variables of the global carbon cycle, being correlated with climate change and fire activities [52]. The study areas had a negative GPP trend in the vegetation with high fire recurrence. Although GPP generally has a high correlation with EVI [20], the study areas
did not have this behavior due to the predominance of non-significant GPP trends, indicating the rapid recovery of photosynthetic processes after fire [13]. Sun et al. [53] show in a global study that most of the Brazilian territory increased the GPP trend from 1982 to 2015, except for the semi-arid region. However, the survey did not consider a significance test. Delgado et al. [54] did not observe significant GPP trends in the Atlantic forest of Brazil (Itatiaia National Park) from the non-parametric Mann–Kendall test.

The surface temperature was the variable with the largest number of pixels with significant changes in the study areas. Despite this, there is no observable pattern in phytophysiognomies, both those in which the increase in temperature was highly related to the fire recurrence as in those with medium-low proportion. The rise in surface temperature occurs immediately after the fire event, but these effects are attenuated over time [12]. However, the results demonstrate that surface temperature changes were consistent throughout the time series, even in areas not affected by the fire, suggesting other factors as determinants in the alteration of the surface temperature in the medium-long term. Moreover, most of the Brazilian surface temperature has a positive trend, especially in the Amazon-Cerrado transition with intense land-use change [55]. The annual temperature rise reached 0.25 K in the ANP-CSP area and 0.19 K in the JPRB area, higher than the values found in urban areas that may increase 0.14 K per year [56].

The research results indicate that even protected areas, such as the ANP-CSP, showed significant medium-term changes in biophysical parameters. In this case, the discussions for changes in the Brazilian fire policy must be based on the historical and current fire scenarios in each protected unit, and how they have impacted the vegetation pattern [57,58]. Remote sensing identification of critical locations optimizes the management of these areas with continuous vegetation monitoring. Thus, it is possible to carry out on-site activities, with prescribed burning practices to avoid the drastic changes observed in this research in the most sensitive areas.

The results demonstrate the AAT method’s effectiveness in evaluating vegetation changes from temporal series with moderate spatial resolution images such as MODIS. The MODIS time series allows identifying long-term changes in vegetation, besides having high reliability given its high relation with data observed in the field.

Despite the usefulness of MODIS data in this research, there are some limitations in its performance and possibilities to expand the analysis in future works. We mention the effect of low spatial resolution [21] and the spectral mixture among the limitations.

Future works may improve the analyzes carried out in this research. Despite the loss of spatial resolution to 500 m, studies may use the product Bidirectional Reflectance Distribution Function and Albedo (BRDF/Albedo-MCD43), attenuating the changes in radiation caused by scattering (anisotropy) [59], that result in changes unrelated to vegetation and incorrect data readings [60,61]. In this research, the inclusion of pre-processing steps with the Savitzky-Golay filter helped to attenuate these effects. In addition to the product MCD43, other biophysical parameters (not included in this analysis) can be highly affected by fire, such as the near-infrared reflectance of vegetation (NIRv) [62]. The NIRv index can bring advantages in the estimation of GPP data by satellite, and together with other methodologies such as Solar-induced chlorophyll fluorescence (SIF) [63], it can better detail the pre- and post-fire vegetation conditions.

5. Conclusions

This research presents the behavior of four biophysical variables for 15 years in different scenarios of fire recurrence in the Brazilian Amazon and Cerrado. This research shows a strict relationship between MODIS biophysical estimates and field data (R² values between 0.76 and 0.97). The increase in fire recurrence caused a significant trend change in the medium term, especially in the EVI (annual decrease of up to 0.011 in the ANP-CSP area and 0.012 in the JPRB area) and surface temperature (an annual increase of up to 0.25 K in the area ANP-CSP and 0.19 K in the JPRB area). The vegetation degradation (altered vegetation by selective cutting and fragmentation practices) generated significant
EVI trends. The biophysical variables most affected by the high fire recurrence per land-cover/land-use classes in the ANP-CSP area were: albedo changes in grassy-woody savanna ($R^2 = 0.521$), EVI in the savanna park ($R^2 = 0.906$), GPP in the savanna with forest ($R^2 = 0.921$), and LST in the savanna park ($R^2 = 0.913$). In the JPRB area, this influence was more significant in the following combination of classes: albedo in the woody savanna ($R^2 = 0.57$), EVI in the altered savanna/forest transition ($R^2 = 0.909$), GPP in the woody savanna ($R^2 = 0.930$) and LST in the Ombrophilous forest ($R^2 = 0.727$). The high fire recurrence influenced both study sites, reinforcing the need for an adequate national fire policy to maintain the vegetation structure.

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