

Changes in vegetation cover and carbon stock in central South America: an analysis using field data and remote sensing

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Abstract

The central region of South America, where the Upper Paraguay River Basin (UPRB) is located, is considered to be one of the largest above ground carbon reservoirs on the planet. However, the surface occupied by these formations has been decreasing considerably which requires strategic actions to preserve these resources. In this context, the present study aimed to estimate the carbon stock in forest and savanna formations of UPRB, analyzing the variations that occurred in the years 2013 and 2018, using field data, remote sensing and geoprocessing. The proposed approach for the tri-national area of the basin is unprecedented and made it possible to quantify carbon in the UPRB vegetation, showing a reduction of 3.69% in the stock, which is equivalent to approximately 78.5 million MgC emitted into the atmosphere during the analyzed period. The portion of the watershed inside Bolivia, Paraguay and Mato Grosso (Brazil) showed negative variations of -42.3×10^6 , -37×10^6 and -7.2×10^6 MgC, respectively, while Mato Grosso do Sul (Brazil) showed an increase of 8×10^6 in the carbon stock. The aboveground carbon stock varied positively in 48 out of the 108 municipalities examined. The mapping of carbon variations in the UPRB allowed us to locate where attitudes towards reducing emissions from deforestation and changes in land cover should be implemented or intensified. Thus, the application of the proposed methodology can serve as one of the parameters for determining the variations in aboveground carbon stock in the research region.

Keywords: Cerrado; Chaco; carbon emissions; dry forests; Pantanal; remote sensing.

Mudanças na cobertura vegetal e estoque de carbono na América do Sul central: uma análise usando dados de campo e sensoriamento remoto

Resumo

A região central da América do Sul, onde está localizada a Bacia do Alto Paraguai (UPRB), é considerada um dos maiores reservatórios de carbono acima do solo do planeta. No entanto, a superfície ocupada por essas formações vem diminuindo consideravelmente, o que exige ações estratégicas para a preservação desses recursos. Nesse contexto, o presente estudo teve como objetivo estimar o estoque de carbono nas formações florestais e savânicas da UPRB, analisando as variações ocorridas nos anos de 2013 e 2018, utilizando dados de campo, sensoriamento remoto e geoprocessamento. A abordagem proposta para a área tri-nacional da bacia é inédita e possibilitou a quantificação do carbono na vegetação da UPRB, apresentando uma redução de 3,69% no estoque, o que equivale a aproximadamente 78,5 milhões de MgC emitidos na atmosfera durante o período analisado. A porção da bacia dentro da Bolívia, Paraguai e Mato Grosso (Brasil) apresentou variações negativas de $-42,3 \times 10^6$, -37×10^6 e $-7,2 \times 10^6$ MgC, respectivamente, enquanto Mato Grosso do Sul (Brasil) apresentou um aumento de 8×10^6 no estoque de carbono. O estoque de carbono aéreo variou positivamente em 48 dos 108 municípios examinados. O mapeamento das variações de carbono na UPRB permitiu localizar onde as atitudes de redução de emissões por desmatamento e mudanças na cobertura do solo devem ser implementadas ou intensificadas. Assim, a aplicação da metodologia proposta pode servir como um dos parâmetros para determinar as variações do estoque de carbono acima do solo na região pesquisada.

Palavras-chave: Cerrado; Chaco; emissões de carbono; florestas secas; Pantanal; sensoriamento remoto.

1. Introduction

Deforestation in central South America is currently the biggest cause of loss of natural areas on the planet and is the second largest source of carbon emissions into the atmosphere, second only to emissions caused by burning fossil fuels (FAO, 2018). In this region, the highest rates of deforestation are in the areas of agricultural expansion (Houghton et al., 2012; De Sy et al., 2015; FAO, 2016) and, therefore, related to the anthropization of natural areas, causing changes in cover and land use.

One of the direct consequences of deforestation is the reduction of the forest carbon stock in native biomes across the region in areas such as the Amazon, Pantanal, Cerrado, Chaco and Chiquitano Dry Forests (Andersen et al., 2016; Tejada et al., 2016; Baumann et al., 2017; Noojipady et al., 2017; Rappaport et al., 2018). The direct impact on the increase in emissions is caused not only by the felling and burning of vegetation, but also later emissions caused by the decomposition of residual phytomass and carbon release from the soil must also be taken into account (Fearnside, 2008; Guillaume et al., 2015), since they can further aggravate the negative effects of climate change.

In addition to the diversity of forest and savanna formations, another striking feature of the central region of South America is the abundance of water resources and hydrographic basins, among which the Upper Paraguay River Basin (UPRB) stands out (Fig. 1) with the Paraguay River as its main river drainage axis. In UPRB there are approximately 1642 water bodies and its area covers the largest floodplain on the planet, the Pantanal, a site designated as an area of significant international importance by the RAMSAR Wetlands Convention in 1993, Biosphere Reserve by the United Nations Educational, Scientific and Cultural Organization (UNESCO) in 2000 (ANA, 2017), and considered a priority area for biodiversity conservation actions by the Brazilian government (MMA, 2007).

Because it is an extensive area between three countries (Brazil, Paraguay and Bolivia), where most of it belongs to rural landowners, with some Conservation Units and Indigenous Lands, the territorial management of UPRB is a great challenge. Considering the hydrographic basin as a basic unit for implementing management strategies, regardless of political boundaries, can be the starting point for achieving socio-environmental and economic balance. Thus, the consolidation of environmental indicators, such as the quantification of carbon in vegetation, preferably via non-destructive methods, constitutes a strategic component for valuing the ecosystem services that forests provide for climate balance, providing information for understanding the carbon flow at a local scale, allowing the assessment of the

impacts of carbon emissions in relation to global climate changes (Chave et al., 2014; Temesgen et al., 2015; Tejada et al., 2016; Bonini et al., 2018; Paul et al., 2018).

In this context, the present study aimed to estimate the carbon stock in forest and savanna formations in the Upper Paraguay River Basin using field data, remote sensing and geoprocessing. The methodological proposal is unprecedented for the tri-national area of the basin, and its application made it possible to quantify the carbon stock in 2013 and 2018, in addition to comparing the variations that occurred in the two years analyzed. According to Timothy et al. (2016), the use of remote sensing to quantify biomass and carbon on a large scale is an advantageous alternative when compared to conventional approaches, which are laborious, time-consuming and sometimes inapplicable due to the lack of accessibility.

In addition to the alternative methodological proposal for remote quantification, the results obtained here will contribute to the understanding of the dynamics of the carbon stock in the region, revealing priority areas for conservation.

The carbon estimates made in this study may also serve as an indicator for which other initiatives, such as the program for Reducing Emissions from Deforestation and Forest Degradation (REDD+), can be implemented or optimized. Thus reflecting the possibility of Payment for Environmental Services (PES) to the owners of native forest areas for the maintenance of the remnants and/or recovery of areas inadequately deforested in their properties – contributing to the achievement of global goals and agreements for sustainable development.

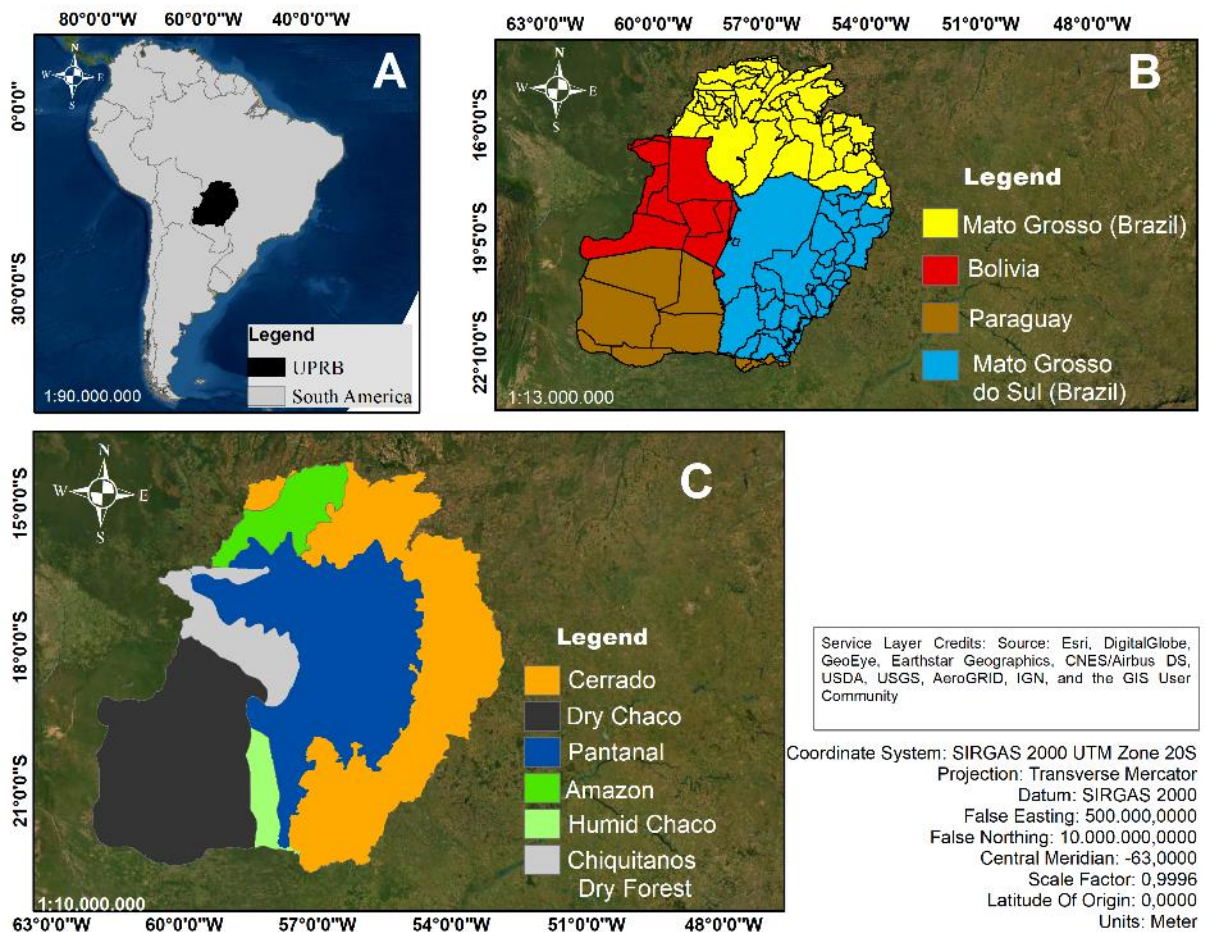
2. Material and Methods

Study site

The Upper Paraguay River Basin (UPRB), better known as the Upper Paraguay Basin, is located in central South America and occupies an area of approximately 660,000 km² (Figure 1A), with 61% of this area over the Brazilian territory, 22% in Paraguay and 17% in Bolivia (Figure 1B) (ANA, 2017). Altogether, there are 108 municipalities with at least 1.0% of their territory within the limits of UPRB, of which 60 are fully inserted in the basin. The population is approximately 10 million inhabitants (INE, 2017; IBGE, 2018; DGEEC, 2018).

The UPRB area covers six biomes: Pantanal, Cerrado, Amazon, Dry Chaco, Humid Chaco and Chiquitano Dry Forests (MPD, 2006; MADS, 2014; MMA, 2019) (Figure 1C). The natural vegetation cover is composed of several phytophysiognomies of forest and savanna formations, non-forest shrubland and grassland formations, while for the areas of

anthropic use, those destined for agriculture occupy the largest area (MapBiomias, 2018).



*The biome map (C) was prepared with vectorial geographic data from MMA (2019) for Brazil, MPD (2006) for Bolivia and MADS (2014) for Paraguay.

Figure 1 – Location of UPRB in South America (A), boundary of municipalities (B) and biomes (C).
Source: Elaboration by the authors, 2022.

In the Köppen-Geiger classification, the predominant climate in UPRB is of the Aw type (megathermic tropical with dry season in winter), with small portions to the southeast of the basin with Am climate (tropical monsoon climate) and the BSh type (hot semi-arid tropical) in the southwest region in the territory of Paraguay. The rainfall in the region can vary from 420 to 800 mm per year in the southeastern part of the UPRB, in the central portion from 1100 to 1400 mm per year, and, in the most eastern region, it can vary from 1300 to 1978 mm. The average annual temperature ranged from 21 to 27°C between 1970 and 2000, with an average 33°C in the hottest month and 14°C in the coldest (WorldClim, 2019).

Field data and carbon stock estimation

Field data was collected between April and November 2012, in 116 plots of 10 x 10 m installed under the domain of the Pantanal and Cerrado biomes in the state of Mato Grosso do Sul. 2,293 live plants with diameter at breast height (DBH) from 1.6 cm were measured. The plots were established within five conservation units called *Fazenda Rio Negro* (RN), *Dona Aracy* (DA), *Fazenda São Geraldo* (SG), *Buraco das Araras* (BA) and *Gavião de Penacho* (GP) (Table 1), classified as a Private Reserve of Natural Heritage (PNHR), according to the system of conservation units in Brazil (Brasil, 2000).

Table 1 – Location, biome, altitude, number of plots and plants measured in Private Natural Heritage Reserves (PNRH).

PNHR	Coordinates	Biome	Altitude plots (m)	n° plots	n° plants*
<i>Fazenda Rio Negro</i> (RN)	19°33'11" S; 56°13'44" W	Pantanal	106 – 121	40	498
<i>Dona Aracy</i> (DA)	19°55'15" S; 56°22'16" W	Pantanal and Cerrado	109 – 164	28	681
<i>Fazenda São Geraldo</i> (SG)	21°15'48" S; 56°33'36" W	Cerrado	321 – 369	24	559
<i>Buraco das Araras</i> (BA)	21°29'37" S; 56°25'08" W	Cerrado	306 – 328	15	328
<i>Gavião de Penacho</i> (GP)	19°56'53" S; 55°03'36" W	Cerrado	407 – 511	9	227
Total				116	2,293

* With DBH ≥ 1.6 cm. Source: Elaboration by the authors, 2022.

The plots were distributed based on the following criteria: ease of access by land, minimum distance of 50 m between plots, coverage of only one

type of plant physiognomy per plot and coverage of the greatest possible diversity of plant physiognomies (Figure 2).

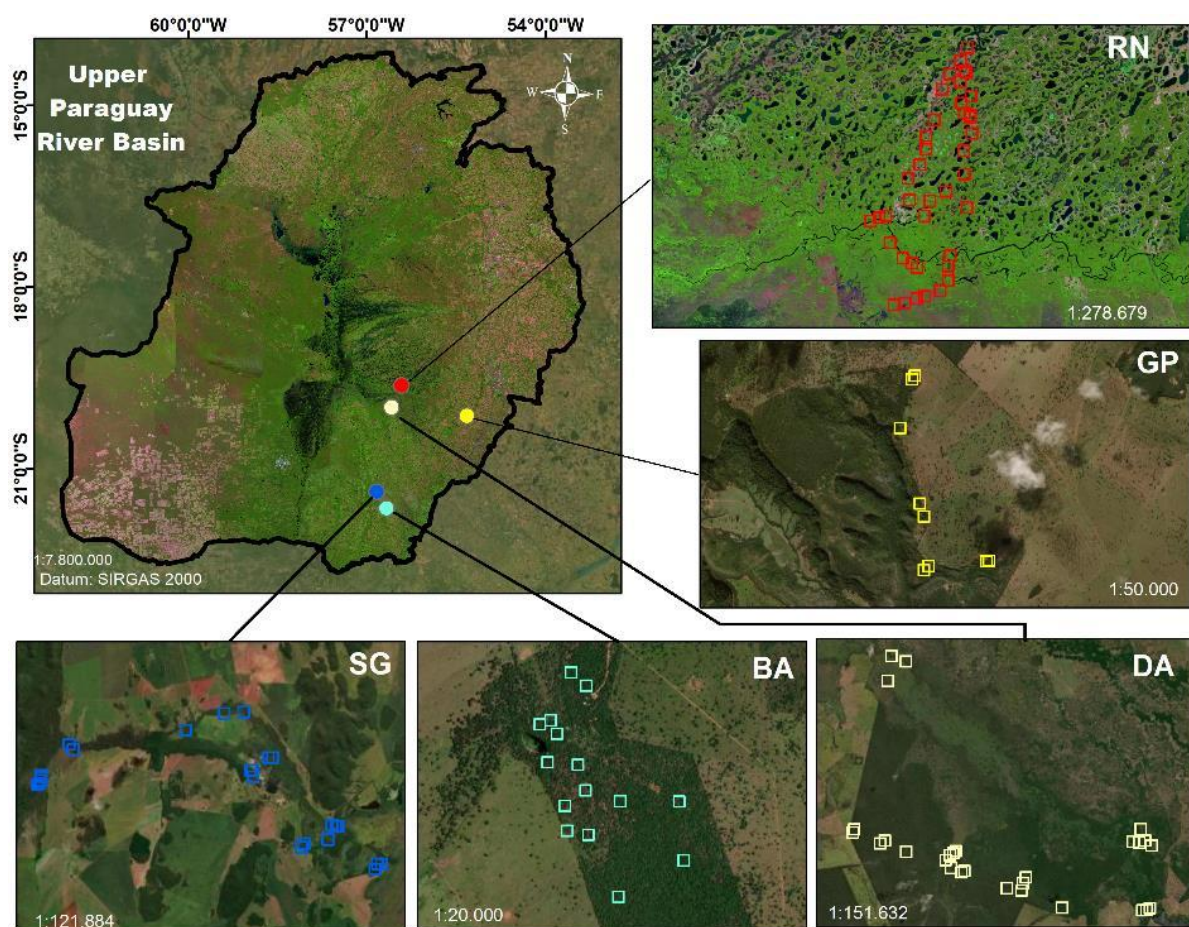


Figure 2 – Location of sample plots within Private Natural Heritage Reserves in the Upper Paraguay River Basin. Source: Elaboration by the authors, 2022.

In the area where the plots were planted there are forest and savanna phytophysognomies. The forests are represented by riparian forest, forested savanna, wooded savanna, stricto sensu cerrado, deciduous and semideciduous seasonal forests, while the savannas are represented by grassy-woody savanna and park savanna (Ribeiro and Walter, 1998; Silva et al., 1998; Silva et al., 2000; WWF-Brasil, 2017).

According to the Köppen climate classification, the climate in the sample area can be classified as Am type (tropical monsoon) and Af type (equatorial tropical) (Alvares et al., 2013). Rainfall ranges from 1200 to 1400 mm.year⁻¹, with the highest rainfall occurring from October to March (CPRM, 2018). Soils of the type ultisols, spodosols, entisols and alfisols can be found under the plots (Santos et al., 2011). The slope of the relief is flat, smoothly wavy or wavy (Ladeira Neto, 2010).

To estimate the biomass in the plots, three variables were used: diameter at breast height (DBH) and total height of each plant, which were measured in the field, and the average specific density of wood from tropical species (0.645 g.cm⁻³), adopted by Chave et al. (2006). The three independent variables were used in the allometric equation by Chave et al. (2014), developed for the estimation of above ground biomass in tropical regions (Equation 1).

$$AGBest = 0.0673 * (\rho D^2 H)^{0.976} \quad (1)$$

where, ρ = wood density equal to 0.645 g.cm⁻³ for tropical trees (Chave et al., 2006); D = DBH and H = height.

The non-specific allometric equation adopted performed well in all types of tropical forests and bioclimatic conditions (Chave et al., 2014). Thus, its use was an alternative in the absence of specific local equations for each phytophysognomy of the area studied. In addition, the development of allometric equations depends on the availability of data for destructive collection and, in areas protected by law such as the Pantanal and Cerrado biomes, the suppression of vegetation is restricted.

The vegetation carbon stock was obtained by multiplying the aboveground forest biomass by 0.50, considering that carbon represents 50% of dry biomass (Brown, 1997; Chave et al., 2005).

The information on vegetation cover in the Brazilian portion of UPRB, obtained from the monitoring report of changes in vegetation cover and land use by UPRB (WWF-Brasil, 2015, 2017), helped in the identification of forest and savanna areas, as well as in the description classes of vegetation cover. The concept of forest formation was based on the

Technical Manual of Brazilian Vegetation (IBGE, 2012). For Bolivia, information on vegetation cover and ecoregions was accessed on the *GeoBolivia Portal* (<http://geo.gob.bo/portal/>), for Paraguay, on the portal of the *Dirección General de Estadística, Encuestas y Censos* (<https://bit.ly/2ksXM0y>).

Image processing

Thirty-six scenes from the Operational Land Imager (OLI) sensor, multispectral bands 3, 4, 5 and 6 of the Landsat 8 satellite, referring to the years 2013 and 2018, were used. The American satellite was launched in February 2013 and since then, scenes are made available for free download by the United States Geological Survey (USGS) on the Global Visualization Viewer (GloVis) platform (USGS, 2019).

The OLI sensor scenes have medium spatial resolution (30m), 16 bits of radiometric resolution and the radiometric and geometric quality of data are technically superior to data acquired by past Landsat missions, dispensing with adjustments due to the orthorectification of the images, emphasizing the agility and simplicity of using the data (Loveland and Irons, 2016). In addition, the amplitude of the imaging (175 km long towards North-South and 183 km towards East-West), together with the improved noise rates, offer a high-quality primary data source, desirable for the accurate aboveground biomass estimation, especially in environments with a lack of data (Dube and Mutanga, 2015).

Considering the frequency of revisiting the satellite every 16 days, the scenes were obtained between the first day of June and the last day of August, both for the year 2013 and 2018, which corresponds to the period of lowest probability of rain and cloud cover in the region.

For the initial processing of the scenes, the composite bands tool of the software ArcGIS 10.6.1 (ESRI, 2018) was used, which performed the colorful composition of bands 3, 4, 5 and 6, which allowed for greater contrast between water, soil and vegetation. With the colored images, the mosaics of 2013 and 2018 were elaborated and then their redesign for the southern hemisphere, at the SIRGAS 2000 Zone 20S Datum, using the Erdas Imagine 2013 software (Hexagon Geospatial, 2013).

The next step consisted of combining the near infrared (NIR) and red (R) bands of each mosaic to generate the Normalized Difference Vegetation Index (NDVI) (Equation 2) and collect information related to the land cover and calculation of UPRB vegetation indexes (VI). The application of NDVI generates values from -1 to +1 for each pixel of the image, which made it possible to create classes for the different

spectral responses of the surface, in which values below zero indicate absence of vegetation and the closer to +1, indicate greater presence, density and vigor of vegetation (Rouse et al., 1974).

$$NDVI = \frac{NIR - R}{NIR + R} \quad (2)$$

where, $NDVI$ = Normalized Difference Vegetation Index, NIR = Near Infrared, and R = Red.

From the central geographical coordinates of each plot, it was possible to obtain the vegetation index (VI) of the pixel in which the plot was allocated, used as a parameter for correspondence with the carbon estimates in the field. From the correspondence between the values, the Reclassify Raster algorithm of the ArcGIS software (ESRI, 2018) was used to group the spectral responses to vegetation in 6 classes, with each class indicating an average amount of aboveground carbon. The maps in Raster format were converted into polygons (shapefile format) for the quantification of carbon per unit area.

Validation of remote sensing data

The accuracy analysis was carried out in two stages: the first aimed to verify the accuracy of the classification based on the vegetation indexes using carbon stock data from the field plots as a reference. The second aimed to analyze the accuracy of the classification of maps for 2013 and 2018 using high resolution images as reference.

For the second stage, images of 2013 and 2018 made available by Google Earth with a maximum spatial resolution of 2.5 m were used as a reference. For each vegetation class 50 sampling points were marked totaling 300 points for each year of analysis. The points marked in the 2013 and 2018 images are different, however, they were marked based on the representativeness of each vegetation class in all sub-regions. The sample points were marked on Google Earth Engine application and exported to ArcGIS (ESRI, 2018), which made it possible to compare representative samples and map classification.

Thus, it was possible to elaborate the error matrices and, from these, obtain the overall accuracy (OA) using equation 3; and Kappa coefficient (K)

(Cohen, 1960), using equation 4 (Congalton and Green, 2008), for each stage of analysis.

$$OA = \frac{\sum_{i=1}^r x_{ii}}{n} 100 \quad (3)$$

$$K = \frac{n \sum_{i=1}^r x_{ii} - \sum_{i=1}^r (x_{i+} + x_{+i})}{n^2 - \sum_{i=1}^r (x_{i+} + x_{+i})} \quad (4)$$

where, n = number of samples (pixels); r = number of rows in the error matrix (classes); x_{ii} = number of agreements (main diagonal); x_{i+} = row total; x_{+i} = column total.

According to Congalton (2001), the creation of an error matrix is the key element of a quantitative accuracy assessment and can then be used as a starting point for a series of descriptive and analytical statistical techniques. An error matrix is a very effective way to represent accuracy in that the accuracies of each category are plainly described along with both the errors of inclusion (commission errors) and errors of exclusion (omission errors) present in the classification.

The Kappa coefficient makes it possible to measure the degree of agreement between the processed map data (predicted) and the real soil cover, in nominal scales, considering all the elements of the error matrix, different from the total accuracy, which uses only the main diagonal. The ranges for characterizing the accuracy of the Kappa coefficient range from 0 to 1, the classification being considered poor (0.0 – 0.2), reasonable (0.2 – 0.4), good (0.4 – 0.6), very good (0.6 – 0.8) and excellent (0.8 – 1.0) (Congalton and Green, 2008).

3. Results

The results of the accuracy analysis (Table 2) demonstrated that the classification, based on vegetation indexes and field data, was excellent ($K = 93.13$) and with a percentage of probability of error below 7% ($OA = 93.13\%$). The classification of the 2013 map showed greater total accuracy compared to the 2018 map (Table 2), however, both maps obtained a very good classification ($K = 0.79$ and 0.63 respectively) considering the Kappa coefficient.

Table 2 – Overall accuracy (OA), Kappa coefficient (K), total samples (N) and total agreements (NA) of the field plots, 2013 and 2018 classified maps.

Classification	OA (%)	K	N	NA
Field Plots	93.13	0.91	131	122
2013	83	0.79	300	249
2018	77.66	0.73	300	233

Source: Elaboration by the authors, 2022.

The vegetation indexes of 2013 and 2018, referring to the pixel in which the plot was allocated, did not show significant differences when compared by the Student's t-test at 95% confidence interval

(Table 3). Therefore, the carbon stock attributed to each vegetation class was the same for the classified maps of 2013 and 2018 (Table 4).

Table 3 – Minimum, maximum, average values and the comparison between the average of the vegetation indices (NDVI) of the plot pixel, obtained from the mosaics of 2013 and 2018.

Private Natural Heritage Reserves	NDVI						
	2013			2018			<i>p-value*</i>
	Min	Max	Mean	Min	Max	Mean	
<i>Fazenda Rio Negro</i> (RN)	0.017	0.236	0.132	0.013	0.248	0.158	0.059
<i>Dona Aracy</i> (DA)	0.058	0.24	0.165	0.051	0.23	0.174	0.379
<i>Fazenda São Geraldo</i> (SG)	0.128	0.272	0.192	0.069	0.261	0.187	0.664
<i>Buraco das Araras</i> (BA)	0.055	0.215	0.133	0.079	0.226	0.159	0.099
<i>Gavião de Penacho</i> (GP)	0.058	0.178	0.132	0.064	0.188	0.123	0.630

*Student's t-test for comparison between the means at 95% confidence interval. Source: Elaboration by the authors, 2022.

Table 4 – Description of classes and correspondence between the values of the vegetation index (NDVI) and the mean amount of the aboveground carbon per hectare, estimated in the field plots.

Classes	n° plots.class ⁻¹	NDVI values	Mean of Carbon (MgC.ha ⁻¹)	Description of classes
1	-	< 0.0	0	Soil with little or no vegetation cover.
2	12	0 a 0.072	12.24 ± 4.14	Predominantly grassy-shrub vegetation with density less than 80 trees* per hectare
3	45	0.073 a 0.176	39.41 ± 12.77	Typical wooded savanna vegetation of ecotones between forest and savanna with density of 80 to 180 trees* per hectare
4	35	0.177 a 0.203	85.77 ± 16.11	Forested savanna with density of 180 to 280 trees* per hectare
5	14	0.204 a 0.223	140.33 ± 20.4	Tree vegetation with density of 280 to 450 trees* per hectare
6	10	0.224 a 1	204.3 ± 90.25	Tree vegetation with density greater than 450 trees* per hectare

* Height ≥ 3.0 m. Source: Elaboration by the authors, 2022.

Based on the classification, UPRB land cover maps for the years 2013 and 2018 were prepared, with colors representing each class of vegetation (Figure 3).

This representation helped to identify changes in the vegetation pattern between the two years analyzed.

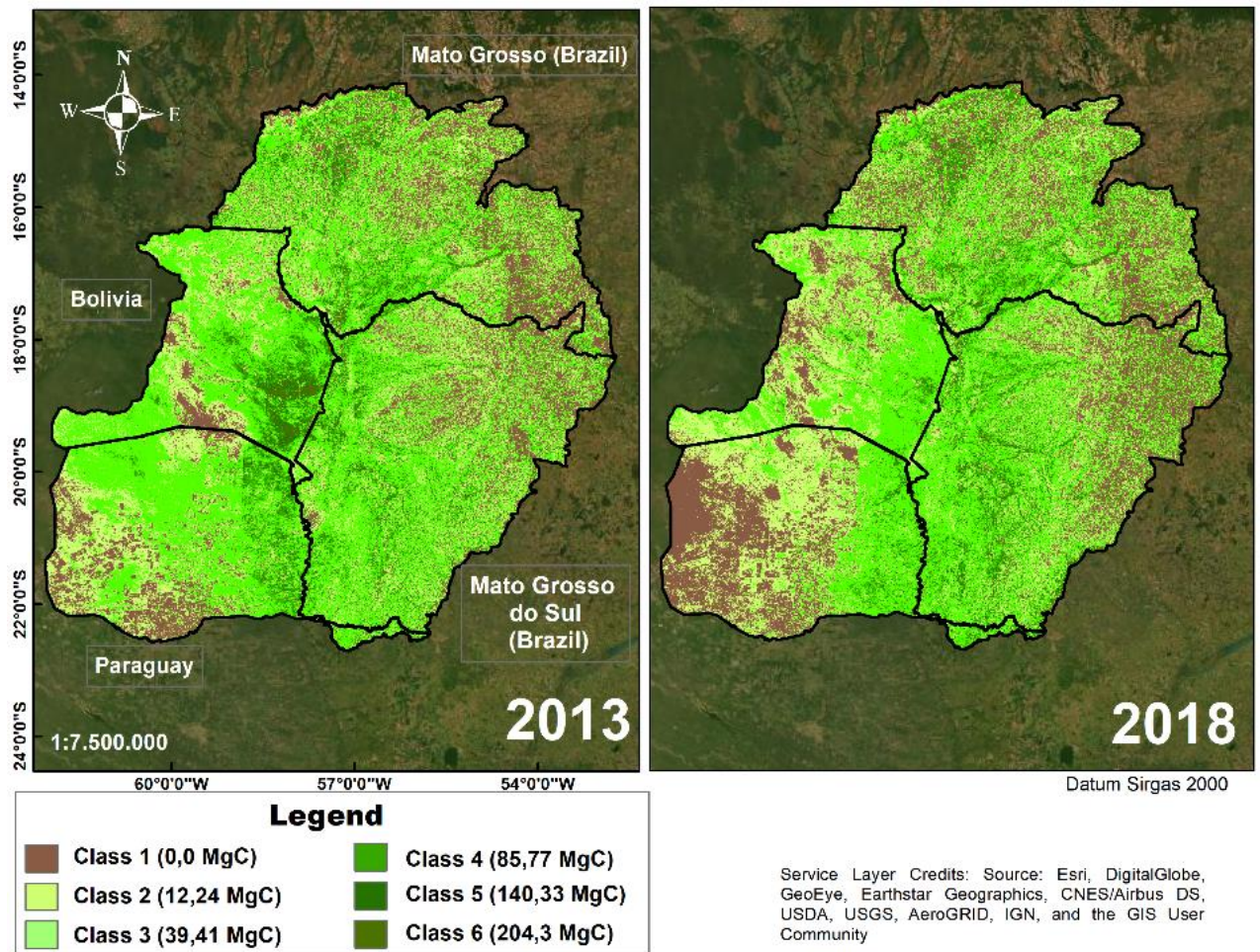


Figure 3 – Variations of area and carbon stock by vegetation class in the sub-regions Bolivia (BO), Mato Grosso (MT), Mato Grosso do Sul (MS) and Paraguay (PY).
Source: Elaboration by the authors, 2022.

Considering that the UPRB covers some regions of Brazil, Bolivia and Paraguay, the comparative results between the years evaluated were separated and organized in four sub-regions: Mato

Grosso (MT) and Mato Grosso do Sul (MS) in the Brazilian portion, Paraguay (PY) and Bolivia (BO), shown in Table 5. Results by municipality can be found in the supplementary materials.

Table 5 – Representation of the vegetation cover classes elaborated from the application of the Vegetation Index (NDVI) in the mosaics of 2013 and 2018 in the Upper Paraguay River Basin, territories of Bolivia, Brazil and Paraguay.

Location	Area in UPRB (ha)	Classes	Area 2013 (%)	Area 2018 (%)	Carb 2013 (Mg)	Carb 2018 (Mg)	Carbon Variation (Mg)
Mato Grosso (MT) - Brazil	18,404,042	1	24.27	27.32	0.00	0.00	0.00
		2	25.70	24.80	52,738,876.64	50,891,740.09	-1,847,136.56
		3	34.08	31.24	225,177,535.18	206,461,459.44	-18,716,075.74
		4	7.98	8.45	114,726,722.25	121,527,278.46	6,800,556.20
		5	4.13	4.17	97,159,119.82	98,037,193.42	878,073.60
		6	3.85	4.02	131,799,174.84	137,476,805.43	5,677,630.59
Total MT				621,601,428.75	614,394,476.84	-7,206,951.91 (-1.16%)	

Mato Grosso do Sul (MS) - Brazil	21,976,105	1	16.20	17.90	0.00	0.00	0.00
		2	26.35	20.22	61,155,250.62	56,726,609.59	-4,428,641.02
		3	39.22	43.78	293,043,707.17	305,264,121.44	12,220,414.27
		4	9.82	9.44	159,739,781.86	159,129,089.56	-610,692.30
		5	4.24	4.33	112,730,571.87	113,276,224.73	545,652.86
		6	4.17	4.33	161,616,409.45	161,911,165.21	294,755.77
			Total MS	788,285,720.97	796,307,210.54	8,021,489.57 (+1.01%)	
Bolivia (BO)	11,510,557	1	11.33	21.89	0.00	0.00	0.00
		2	42.87	41.02	51,307,015.40	42,854,094.60	-8,452,920.80
		3	21.64	27.90	83,392,331.20	84,060,088.40	667,757.10
		4	12.96	6.65	108,699,099.50	97,832,766.40	-10,866,333.10
		5	6.66	1.51	91,309,052.30	77,746,273.00	-13,562,779.30
		6	4.54	1.02	90,597,887.50	80,490,754.50	-10,107,133.00
			Total BO	425,305,386.20	382,983,977.10	-42,321,409.10 (-9.95%)	
Paraguay (PY)	14,275,315	1	27.62	24.38	0.00	0.00	0.00
		2	32.39	55.17	52,111,64.39	62,181,561.96	10,069,913.57
		3	36.34	17.79	188,287,467.97	141,287,548.82	-46,999,919.15
		4	2.55	1.60	28,804,654.22	28,387,687.45	-416,966.77
		5	0.73	0.61	13,405,173.50	13,515,486.06	110,312.56
		6	0.36	0.45	9,759,030.67	9,951,209.39	192,178.72
			Total PY	292,367,974.75	255,323,493.68	-37,044,481.08 (-12.67%)	
			Total UPRB	2,127,560,510.69	2,049,009,158.15	-78,551,352.54 (-3.69%)	

Source: Elaboration by the authors, 2022.

The quantification for 2013 showed that UPRB's total carbon stock was 2.1 billion MgC, with the highest value in the sub-region of Mato Grosso do Sul (MS) Brazil (Table 5). Considering the area of each sub-region, Bolivia had the largest stock per hectare (36.9 MgC.ha⁻¹), followed by Mato Grosso do Sul – Brazil (35.8 MgC.ha⁻¹), Mato Grosso – Brazil (33.7 MgC.ha⁻¹), and the lowest value was obtained in the Paraguay sub-region (20.4 MgC.ha⁻¹).

In relation to losses, between 2013 and 2018, there was a net reduction of 3.69% in UPRB's carbon stock, totaling the emission of 78.5 million MgC into the atmosphere. The biggest losses occurred in the Bolivia sub-region, 42.3 million MgC, more than half of the total emissions, equivalent to a reduction of 3.67

Mg.ha⁻¹. The Paraguay sub-region, despite having a lower total emission compared to Bolivia, had a reduction of 12.67% of the carbon stock in the period considered, approximately -2.6 Mg.ha⁻¹, which deserves attention compared to the lowest value initially presented.

In the Brazilian portion of UPRB, the sub-region Mato Grosso showed a reduction of 1.16% in the carbon stock, which corresponds to the emission of 0.39 MgC.ha⁻¹. In contrast, there was a positive variation in the sub-region Mato Grosso do Sul, that is, a stock increase in the proportion of 1% in 2018 compared to 2013. The result of the analysis of variations in the carbon stock in the municipalities of UPRB is represented in Figure 4.

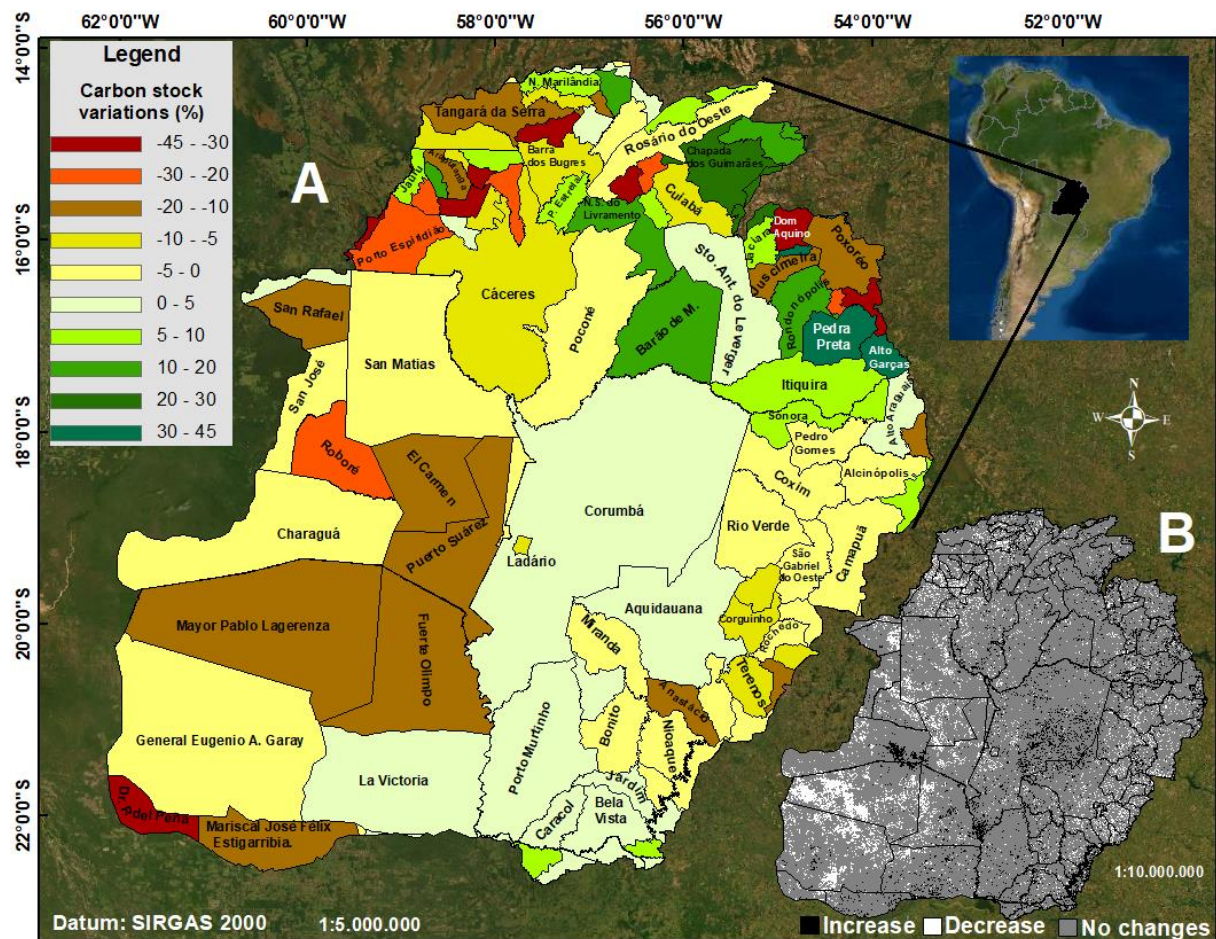


Figure 4 – Representation map of aboveground carbon stock variations by municipality (A) and points where carbon stock variations occurred in the Upper Paraguay River Basin (B).
Source: Elaboration by the authors, 2022.

4. Discussion

All Bolivian municipalities with more than 5% of the territory within the UPRB showed a negative variation for the carbon stock. Losses were more accentuated in classes 4, 5 and 6, while class 1 suffered a substantial increase (10.6%), denoting the conversion of forest areas into exposed soil or with little vegetation. Some studies have shown that over the years, Bolivian native forests have suffered considerable losses of area due to three main causes: expansion of mechanized agriculture, growth of small-scale agriculture and the expansion of cattle ranching in forest areas (Müller et al., 2012; Müller et al., 2014; Tejada et al., 2016).

Deforestation in Bolivia increased by 78% between 1990 and 2000, and from 2000 to 2010, the increase was 54%, which corresponded to 5,160,939 hectares of forest suppression. The department of Santa Cruz, which has 31% of its territory within the limits of UPRB, was the region that suffered the most deforestation in this period, totaling 4,016,342 hectares in 2010 (Bolivia, 2013). Between 2011 and 2016, deforestation continued to increase in this region, with an approximate loss of 231,905 hectares

of native forests in the five-year period, considering only the Bolivian region (Santa Cruz department) belonging to UPRB (GeoBolivia, 2019a, b).

The deforestation data presented for the Bolivia sub-region corroborate the results obtained in the present study, which found the greatest loss of plant carbon in the municipalities where there were more records of deforestation. The municipalities of Roboré, El Carmen and Puerto Suárez, for example, had a reduction in carbon stocks of 24, 17 and 10%, respectively, totaling approximately 36 million MgC. In El Carmen and Puerto Suárez, area losses are mainly related to the reduction of, respectively, 36.7 and 27.6% of classes 5 and 6 combined. In this region, the highest deforestation rates from 2011 to 2016 were detected, a total of 76,175 hectares (GeoBolivia, 2019a, b). The area that covers transition zones between the Chaco and Chiquitano Dry Forests deserves attention because of the speed with which changes in vegetation cover have occurred, especially since the year 2000 (Tejada et al., 2016; Devisscher et al., 2016).

In the Paraguay sub-region, class 3 suffered the greatest reduction in area (-18.5%) and carbon compared to the other classes and sub-regions,

resulting in the emission of approximately 4.7 million MgC (Table 5). The retraction of class 3 was concomitant to the 22% increase in the area occupied by class 2 vegetation, denoting the conversion of wooded savannah areas into grassy-shrubby areas, which have less tree density and carbon.

According to the report published in 2015, deforestation in Paraguay has been constant over the past 40 years, however, it has intensified since the 1990s, mainly due to the expansion of agriculture in the eastern region of the country which is within the limits of UPRB (Paraguay, 2015).

Deforestation and carbon emissions in the Paraguay sub-region are also associated with factors such as: 1) land tenure - poor distribution and lack of legal regularization of tenure for small producers, evidenced by factors such as the growth of the area destined for soy production and the decrease in the number of farms, that is, land tenure is being concentrated; 2) undervalued environmental goods and services from forests - lack of profitable alternatives for owners of native forests to join conservation and sustainable development programs; 3) the need to strengthen national capacities, especially in aspects related to the prevention and control of deforestation - non-compliance with laws and the State's deficiency in inspection and control; 4) unsustainable patterns of production and consumption - the production model is centered on exports and the demands of the international market (mainly grains and beef); 5) population growth and urban expansion - direct increase in the area occupied by cities to the detriment of rural areas; and 6) increasing energy demand - domestic and industrial use of firewood and charcoal (Paraguay, 2015; Elgert, 2016; Paraguay, 2019).

Recent studies have sought to relate the causes of deforestation, especially in the Chaco regions of Bolivia and Paraguay, with agricultural activities, demonstrating that the growing world demand for soy and beef has driven the conversion of forests into areas of monocultures or pastures in the region (Baumann et al., 2016; Baumann et al., 2017; Fehlenberg et al., 2017).

In the Brazilian portion of UPRB, the results showed that in the municipalities of the sub-regions Mato Grosso and Mato Grosso do Sul, the dynamics of the carbon stock occurred differently in the physiographic regions of lowland (Pantanal biome) and plateau (Cerrado biome), in which emissions were more expressive.

In the Brazilian Pantanal region, negative variations in the carbon stock occurred predominantly in the northern region, in the Mato Grosso sub-region, in areas belonging to the municipalities of Cáceres (-7.84%) and Poconé (-1.7%). In the Mato Grosso do Sul sub-region, of the municipalities that have most of

their territory in the Pantanal, only Ladário presented losses in the carbon stock (7.77%), the highest quantified for the biome. On the other hand, the municipalities Barão de Melgaço, Corumbá, Aquidauana and Porto Murtinho deserve to be highlighted for having presented positive variations in the five years considered, resulting in a positive balance for the Brazilian Pantanal and for the MS sub-region, despite the emissions that occurred in the plateau.

A factor that may have contributed to the increase in carbon stock in the plain was the publication of Law No. 12,651 of 2012, known as the Brazilian Forest Code, which started to consider the Pantanal biome as a restricted use zone, being under the responsibility of the environmental policy of the state of Mato Grosso do Sul (Brasil, 2012). In 2015, Decree N° 14,273 of the state of Mato Grosso do Sul, Brazil was published, which determines the protection of at least 50% of forest phytophysiological, in areas of remnant of native vegetation, of rural properties within the restricted use zone of the Pantanal, and the owner must reconstitute this percentage if it has been suppressed (Mato Grosso do Sul, 2015).

Despite this positive variation, several studies have shown that the anthropization of natural areas in the Brazilian portion of UPRB, has occurred more significantly in the plateau regions (Silva et al., 1998; WWF-Brasil, 2015; Peres et al., 2016; WWF-Brasil, 2017; Miranda et al., 2018; WWF-Brasil, 2018), and that the consequences of these changes propagate directly in the lowland region, mainly due to the increase in sediment transport caused by erosion processes in extremely sandy soils in the regions of river springs, directly impacting the Pantanal's flood and drought regimes, which guarantee the biome's socio-biodiversity (Alho and Sabino, 2011; Bergier, 2013; WWF-Brasil, 2018).

In the plateau of the sub-region Mato Grosso do Sul, east of UPRB, the history of degradation, due to changes in land cover, has caused environmental impacts of great magnitude in the areas of lower altitude, especially in river systems (Assine, 2005; Galdino et al., 2006; ZEE-MS, 2014; ANA, 2017; WWF-Brasil, 2018). This region covers most of the municipalities of Coxim, Alcinoópolis, Camapuã and São Gabriel do Oeste, which suffered reductions of 1 to 4% in the carbon stock in the analyzed period, indicating that the environmental impacts related to land use continue to occur. In this context, incentive programs for sustainable agriculture, together with monitoring and inspection actions, supported by scientific studies, must be implemented or intensified in the UPRB plateau areas, in order to avoid local impacts and in lowland regions.

Considering the Mato Grosso sub-region as a whole, despite positive variations in the carbon stock

in classes 4, 5 and 6 (Table 5), the sum of gains in these classes was equivalent to approximately 13.3 million MgC, while the decrease in stock, referring only to class 3, was 18.7 million MgC. Another factor that contributed to emissions was the increase in the class 1 area, where any increase reflects a loss in the carbon stock. Of the municipalities fully inserted in the UPRB, Pedra Preta, in the Mato Grosso sub-region, presented the greatest increase in the carbon stock (33.8%), while the municipality of Jangada, in the same sub-region, had the greatest decrease (-41%). Both are located in the plateau region.

In general, the changes in land use that influence the carbon stock dynamics occurred unevenly in the four sub-regions, as expected, given the great sociocultural, environmental and geopolitical diversity of the basin. In multinational regions, the difference between the environmental policies of each country is a factor that can harm environmental management (Espíndola and Ribeiro, 2020). In this context, considering the basin as a political-administrative unit independent of geopolitical boundaries can be a strategy for an efficient management of the UPRB's natural resources. Therefore, terms of cooperation between the three countries could unify them under the same legislation applicable to the extension of the basin, considering the potential and vulnerabilities of each biome and the existing sociocultural diversity.

Many basins still lack well-developed instruments for cross-border cooperation (Stefano et al., 2017), which represents a major challenge for integrated management. However, despite the difficulties, cooperation between countries is essential for the regulation, monitoring and inspection of socioeconomic activities that use natural resources or that could potentially cause negative environmental impacts on the UPRB.

5. Conclusions

The combination of field information with vegetation indexes, obtained from the Landsat 8 satellite images, made it possible to estimate the carbon stock in the Upper Paraguay River Basin in 2013 and to analyze the variations that occurred in relation to 2018, quickly and at low cost. The mapping of carbon variations in UPRB allowed us to locate where actions to reduce emissions from deforestation and changes in land cover should be implemented or intensified. Thus, the use of the method applied as a standard form for estimates, can serve as one of the parameters for determining the variations of aboveground carbon in the research region, contributing both to inspection and control actions, as well as to the carbon valuation of primary tropical

forests, especially in natural areas bordering agricultural expansion.

However, it is important to consider that the applied method is limited to obtaining scenes without atmospheric elements that could interfere with the surface spectral responses, such as the presence of clouds or smoke. Another important issue is the time between scene collections, which should be as little as possible to avoid significant differences in vegetation vigor and consequently in vegetation indices since the mosaic formed by the scenes is the main remote database of the method. Therefore, the application of the proposed method is limited to regions with low cloud cover during the dry season, as is the case in the study area.

In 2018, the Upper Paraguay River Basin showed a 3.69% reduction in the aboveground carbon stock compared to 2013, totaling approximately 78.5 million MgC emitted into the atmosphere in five years. However, from our analysis, we conclude that the carbon stock dynamics in the UPRB were quite different in relation to the area of the countries within the basin.

The highest carbon emissions from vegetation occurred in the territory of Bolivia within the basin, which lost 42.3 million MgC, equivalent to $-3.67 \text{ MgC.ha}^{-1}$ of variation in the period considered. This result was due to a large reduction in forest area (classes 4, 5 and 6) and an increase in the area of exposed soil or with little vegetation (class 1). On the other hand, the Mato Grosso do Sul - Brazil sub-region showed a positive variation of 1% for the carbon stock, however, this positive balance was mainly influenced by the areas within the Pantanal, while in the plateau region, the negative variations had greater magnitude.

Of the 108 municipalities belonging to the Upper Paraguay River Basin, 48 showed positive variation in the carbon stock and, therefore, fulfilling potential requirements for receiving financial incentives to assist in the sustainable management of forests.

In this context, cooperation between the countries involved in the UPRB is essential for the creation and implementation of coordinated public policies that allow the development of economic activities, such as agriculture and tourism, respecting the socio-cultural and environmental diversity of the basin. In this sense, studies on the valuation of ecosystem services in the region, such as carbon stock, should be encouraged, as they will contribute to adding value to the remnants of native vegetation, promoting its preservation and, consequently, that of all the biodiversity involved.

Statements and Declarations

The authors have no competing interests to declare that are relevant to the content of this article.

Authors Contribution

João Henrique de Souza Barros: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review and Editing, Supervision and Project administration. Paula Martin de Moraes: Conceptualization, Validation, Investigation and Writing - Review and Editing. Fábio Martins Ayres: Conceptualization, Methodology, Validation, Investigation, Resources, Data Curation, Writing - Review and Editing and Supervision. Leandro Skowronski: Formal analysis and Writing - Review and Editing. Michel Constantino: Validation, Formal analysis and Writing - Review and Editing. Wellington Santos Fava: Validation and Writing - Review and Editing. Reginaldo Brito da Costa: Conceptualization, Methodology, Validation, Investigation, Writing - Review and Editing, Supervision and Project administration.

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