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Land use and land cover changes and carbon stock valuation in the São Francisco river basin, Brazil

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ABSTRACT

The São Francisco River Basin (SFRB) is one of the largest basins in Brazil and hosts several economic activities. However, it is under socioeconomic and environmental vulnerabilities. The SFRB includes part of the biomes Caatinga, Atlantic Forest, and Cerrado in Brazil, which are undergoing strong economic pressures. Changes in land use land cover (LULC) affect carbon stocks at different intensities; thus, the valuation of carbon stocks can assist in decision-making, mainly in the context of ecosystem services in areas of interest. In this study, impacts of LULC on carbon stocks in the SFRB in 1997, 2007, and 2017 were assessed. The total Carbon stocks by 2017 were estimated and evaluated for economic value to support the estimation of ecosystem services in our study area. The LULC dynamics were evaluated using data provided by the MapBiomas project. The carbon stocks, modeled as a function of LULC, were estimated using the InVEST program. Our study results showed a total estimated loss of 7,496,128 hectares in different types of native vegetation and 133,187,028 Mg in carbon stocks in the SFRB between 1997 and 2017. The Carbon loss is equivalent to US$ 3.2 billion of ecosystem services related to carbon sequestration and stocks in the study period. This information may support decision-makers to define public policies to improve environmental monitoring, recovering, and conservation in this important river basin in Brazil. This study area should be subject to new public policies focusing on the recovery and conservation of environmental quality and climate change mitigation, by considering the socioeconomic and environmental importance of that basin in the national context.

1. Introduction

The São Francisco River Basin (SFRB) is one of the largest basins in Brazil, with a drainage area that encompasses six Brazilian States (Alagoas, Bahia, Goiás, Minas Gerais, Pernambuco, Sergipe), and the Distrito Federal. It is subdivided into four geographic regions: Upper, Middle, Sub-Middle, and Lower (CBRSF, 2012). The SFRB is under socioeconomic, and environmental vulnerabilities. It encompasses regions with high population density and poverty and regions with low population density; social and environmentally diverse (biomes of Caatinga, Atlantic Forest, and Cerrado), which makes difficult and challenging to enforce any type of scientific investigation (Teixeira et al., 2020). Land use changes by anthropogenic activities in the SFRB are historical and diverse due to their extensions throughout different regions. Moreover, their importance surpasses their delimitations as it was observed by the water transfer from São Francisco River to the semiarid region in Northeastern Brazil (Lee, 2009; Stolf et al., 2012).

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It has been estimated that around 35% of the world's carbon stocks in tropical forests is in Brazil, and 52% of the GHG (Greenhouse Gas) emissions in the country are due to conversions of natural forests into pastures, and agricultural areas (Baccini et al., 2012; Cerri et al., 2009). GHG emissions reached 2 billion Mg CO_2e in Brazil by 2017, making it the seventh largest global GHG emitting country (3.4%), and deforestations were responsible for 46% of that emission (SEEG, 2018). The agriculture activity is the second greatest source of GHG emissions in Brazil (24%), followed by the energy sector (21%) (SEEG, 2018). However, GHG emissions can be underestimated due to the lack of recent studies on changes in LULC in Brazilian forest areas, which underwent major changes in the last years. Therefore, the investigation and description of data related to LULC are crucial to identify the contribution of Brazil to GHG emissions, and provide information for decision-makers to define appropriated public policies for those regions (Pavani et al., 2018).

Some researches focusing on LULC and on its dynamics and effects on carbon stocks have been conducted during the last decade, which included some within the SFRB region. However, previous studies lacked of temporal analyses that would allow understanding land use processes based on comparisons among past and current environmental conditions observed in the entire river basin (Lopes, 2014; Mascarenhas, 2008; Santos et al., 2018). In addition, current advances in technical analysis of impacts of land use changes on carbon stocks contribute to more complex analysis.

Developing countries in tropical regions are responsible for most of deforested and degraded forests in the world and, consequently, for GHG emissions (FAO, 2018; Watch, 2020). However, there is a lack of knowledge of direct and independent quantification of effects of LULC on carbon reservoirs in tropical regions (Olorunfemi et al., 2019). Moreover, local estimates are usually reported by research in specific locations, based on intensive field surveys, which are very time, labor, and money consuming. Large-scale estimates based remotely sensed data may substantially lower financial costs (Feng et al., 2020) and provide accurate estimates of land use changes and Carbon estimates. It can provide helpful information and data to support definitions of public policies to encourage changes in land uses that would contribute to improve CO_2 sequestration and increase carbon stocks in tropical forests.

In this study, we assessed the LULC dynamics and estimated their economic impacts on carbon stocks in the São Francisco River Basin, between 1997 and 2017, using the MapBiomas deforestation datasets, field data, and the InVEST program developed by Natural Capital Project (Sharp et al., 2018). Our results indicated a loss of ecosystem services in the study area, mainly due to the decrease of carbon stocks, and provided information to support definition of public policies to promote sustainable land uses in the study region.

2. Material and methods

2.1. Characterization of the study area

The SFRB flows towards the Atlantic Ocean. It encompasses 636,137.07 km^2 and part of the Brazilian states of Alagoas, Bahia, Goiás, Minas Gerais, Pernambuco, Sergipe, and the Distrito Federal, approximately 8% of the Brazilian territory (Fig.1). The SFRB includes 34 sub-basins, 12,821 watersheds (CBHRSF, 2015), 503 municipalities, and occupied by an estimated population of 20 million people in 2019 (IBGE, 2019). The SFRB also provides water for semiarid regions of Brazil through a transposition (transfer) channel, which enhances its regional socioeconomical importance and urgency for environmental efforts to recover and conserve native vegetation in the study region.

The SFRB includes several phytophysiognomies of the biomes Caatinga (39%), Cerrado (58%), and Atlantic Forest (3%). The vegetation cover includes: Atlantic Forest fragments in the headwaters and mouth of the São Francisco River; Cerrado vegetation in the Upper and Sub-Middle SFRB; and Caatinga vegetation in the Middle, and Sub-Middle SFRB. The most significant vegetation transition is located between the Cerrado and Caatinga biomes. The Atlantic Forest shows seasonal deciduous, and semi-deciduous forest formations, fields of altitude, and pioneer formations, such as mangrove, and coastal vegetation in the Lower SFRB (IBGE, 2006).

Table 1
Global accuracy of LULC classification by the Random Forest algorithm used by the MapBiomas Project for the entire territory of Brazil.

Biome	Global accuracy		
	1997	2007	2017
Caatinga	0.81	0.82	0.82
Cerrado	0.83	0.84	0.84
Atlantic Forest	0.89	0.90	0.90

2.2. Database

The geodatabase used in this study was composed by matrix (raster) and vector file formats. The Brazilian biomes limits (vector files) were provided by the Brazilian Ministry of Environment (MMA); the hydrographical data were provided by the Brazilian National Water Agency (ANA); and the territorial State and Municipality borders were provided in vector format by the Brazilian Institute of Geography and Statistics (IBGE).

The LULC was provided by the MapBiomas project (version 4.0; http://mapbiomas.org) for 1997, 2007, and 2017 in raster format. The MapBiomas datasets were originally prepared for each biome Caatinga, Cerrado, and Atlantic Forest within the SFRB. The MapBiomas classification is based on annual maps of LULC using an automatic classification approach based on the Random Forest decision tree algorithm available in the Google Earth Engine Platform. The automatic classification was applied using Landsat imagery and it has showed mapping accuracies above 80% for the different years and biomes (Table 1) (http://mapbiomas.org/pages/accuracy-analysis).

The accuracy of the LULC maps for the study area was assessed using a confusion matrix (Congalton and Green, 2008), which allows the calculation of the accuracy and the Kappa agreement index (Landis and Koch, 1977). Based on the characteristics of the LULC type distribution in the study area, 1000 samples were randomly selected from the Landsat image data for the year 2017, classified by MapBiomas. These homogeneous sample areas were easily identified through visual observation, and the same image classified by MapBiomas was used as a reference. The distribution of sample pixels was uniform and well represented throughout the study area. Randomly selected sample pixels were used to quantitatively assess the accuracy of the LULC classification using the indicators of producer accuracy, user accuracy, omission error, commission error, general accuracy, and Kappa agreement index (Congalton and Green, 2008; Mather and Tso, 2016).

Therefore, the accuracy assessment estimated 78.59% and 84.69% of the Kappa agreement index. According to (Landis and Koch, 1977), this result of the Kappa index demonstrates the performance of the classifier to be substantial and a good level of reliability of the classification results (Araya and Cabral, 2010; Keenan et al., 2015).

The hierarchy of LULC classes of the MapBiomas Project for the SFRB was used by considering the main level, which was represented by the macro classes: forest, non-forest natural formation, agriculture, no vegetation areas, and water bodies. These and the other classes of the version 4.0 of the MapBiomas Project are presented in Table 2.

The georeferenced database of each biome provided by the MapBiomas Project were mosaicked using the official cartographic standardization established by the Resolution no. 01/2015 issued by the IBGE.

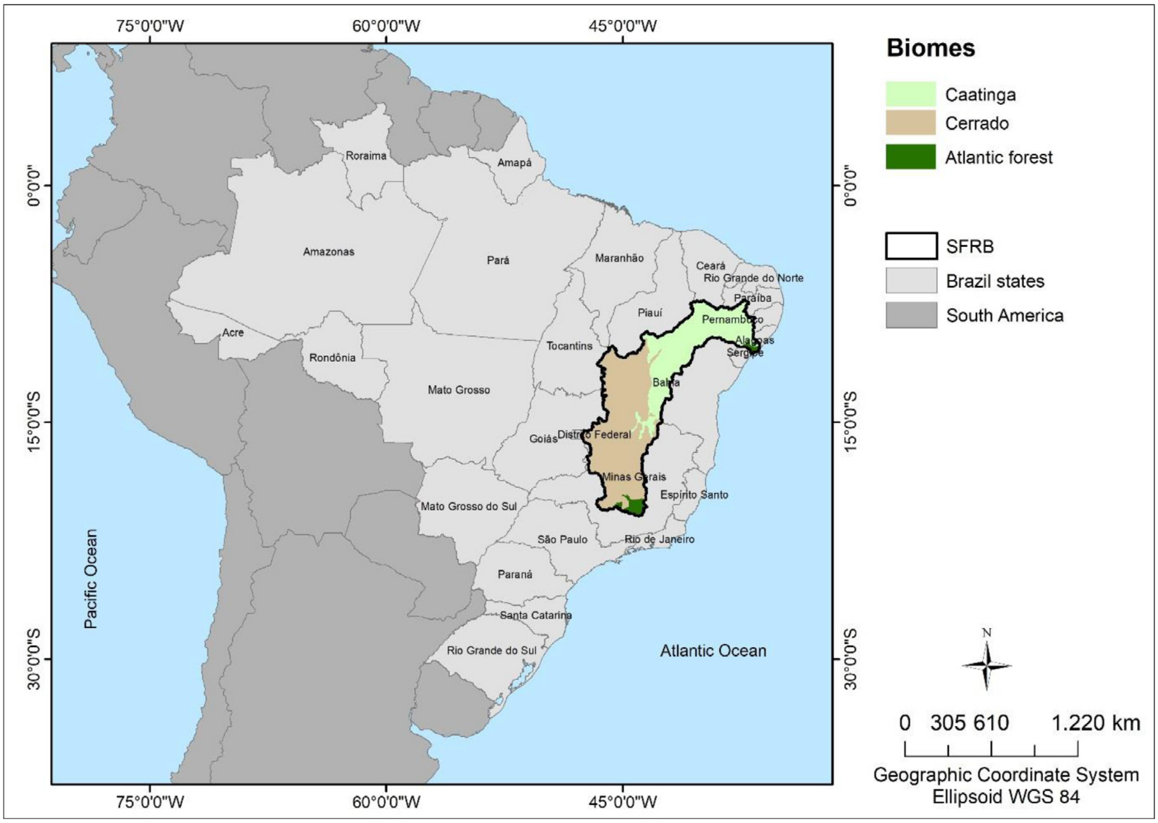

Fig. 1. Spatial location of the study área.

Table 2
Classes of LULC in the version 4.0 of the MapBiomas Project.

1. Forest	1.1. Natural forest
	1.1.1. Forest formation
	1.1.2. Savanna formation
	1.1.3. Mangrove
2. Non-forest natural formation	1.2. Planted forest
	2.1. Natural non-forest humid area
	2.2. Field formation
	2.3. Swamps
	2.4. Other non-forest natural formations
3. Agriculture	3.1. Pastures
	3.2. Agricultural plantations
	3.2.1. Annual and perennial crops
	3.2.2. Semi-perennial crops
	3.3. Crop and pasture mosaic
4. Areas with no vegetation	4.1. Beach and dune
	4.2. Urban structure
	4.3. Rock outcrop
	4.4. Mining areas
	4.5. Other areas with no vegetation
5. Water bodies	5.1 River, lake, and ocean
6. Not observed	6. Not observed

The final LULC mosaicked datasets used in this analysis were converted to UTM projection, Datum WGS84.

2.3. Geoinformation processing

The geoinformation were processed using the QGIS 2.18 software (QGIS Development Team, 2017), including its plugins, and extensions. The matrix (raster) files containing the mosaicked LULC of the Brazilian Biomes of interest were clipped using the limits of SFRB. The clipped LULC raster file was converted into a polygon-type vector file. The vector files containing the LULC for 1997, 2007, and 2017 were used to set a color range for the LULC classification by assuming the standards adopted by the MapBiomas project. The LULC classes were quantified, and the data were properly arranged for the analysis of each biome area and year within the SFRB.

2.4. Forest cover dynamics

The spatial-temporal dynamics of LULC were assessed based on the LULC maps. The forest cover changes were estimated for three periods: 1997–2007, 2007–2017, and 1997–2017. The forest dynamics data were arranged by the analysis of the areas acquired for each two sequential periods, in which deforestation, native forest, forest regeneration, and other anthropogenic classes were assessed. The LULC was generated by the intersections of the 1997, 2007, and 2017 layers using the QGIS software.

The forest cover dynamics in the two intermediate periods (1997–2007 and 2007–2017) were assessed to estimate changes in LULC occurred within the two periods of analysis. The period 1997–2017 was assessed to estimate changes in LULC throughout the entire period of analysis.

The maintenance of native forests was evaluated by considering intersections of areas that were initially covered by forests and forested at the end of that period of analysis. The deforestation areas were assessed using the intersections of areas that were initially covered with forests and were composed by other LULC classes at the end of that period of analysis. Forest regeneration areas were assessed by considering intersected areas initially classified as different classes of forest formations and were converted into forested areas. The maintenance of other anthropogenic classes was assessed by considering intersected areas that did not change same classes within that period of analysis.

Table 3
The LULC changes in the São Francisco River Basin in 1997, 2007, and 2017.

LULC Classes	1997 ha	2007	2017	1997 (%)	2007	2017
Forest formation	30,719,865.27	29,347,903.19	28,841,903.59	48.29%	46.13%	45.34%
Non-forest native formation	9,573,925.72	9,509,007.14	8,456,270.55	15.05%	14.95%	13.29%
Agriculture	21,620,104.20	23,075,873.34	24,903,181.24	33.99%	36.27%	39.15%
Area with no vegetation	1,021,711.74	916,286.60	925,451.10	1.61%	1.44%	1.45%
Water bodies	667,767.90	755,281.04	479,540.10	1.05%	1.19%	0.75%
Not observed	11,927.62	10,951.13	8,955.86	0.02%	0.02%	0.01%
Total	63,615,302.44	63,615,302.44	63,615,302.44	100%	100%	100%

2.5. Carbon stocks valuation

The valuation of carbon requires information on its stocks. Carbon stocks were estimated using the Carbon Sequestration Storage Model (CSSM) using the InVEST program, developed by the Natural Capital Project of the University of Stanford, which consists of a compilation of theoretical models that allow the evaluation of several ecosystem services (Sharp et al., 2018). In the CSSM, the carbon stocks in the different reservoirs are dependent on the aboveground biomass (aerial vegetation), dead biomass (dead branches and litter fall), underground biomass (roots), and soil organic matter. The CSSM considers the quantity of carbon stored in those pools, based on LULC maps. The intertemporal analysis of changes in LULC, using the CSSM, enables the evaluation of the carbon sequestration capacity of an area. The information to estimate the carbon stocks were based on the LULC and carbon reservoir maps using the CSSM.

The CSSM was applied for the study area and for the LULC classes considered in the study (forest formation, natural formation, non-forest formation, and agriculture) for 1997, 2007, and 2017. The estimates of changes in carbon stocks were based on mean values reported in the literature (MCTI, 2015; Menezes et al., 2012; Scolforo et al., 2016; Villela et al., 2012). The carbon stocks were estimated for each LULC class, and for the four carbon sets considered in this analysis: aboveground biomass (aerial vegetation), dead biomass (dead branches and litter fall), underground biomass (roots), and soil organic matter.

The economic valuation of carbon stocks was based on estimated values for each year and for each biome of the SFRB, and on the estimated social cost of carbon for Brazil, proposed by (Ricke et al., 2018). The estimates indicate values between US$ 14 and US$ 41, with a mean of US$ 24 per Mg CO_2e. The social cost of carbon provided an estimate linked to socio-environmental costs of climate changes, therefore, more consistent with the reality. The market prices for carbon credit denote only the payment of agents, and they did not include the socio-environmental costs of climate changes to the society.

3. Results

3.1. Changes in LULC classes

The LULC found in the SFRB in 1997, 2007, and 2017 are presented in Table 3. These results indicate decreases in forest and non-forest natural formation, an average of 2.95% for the 1997–2007 and 1.76% for 2007–2017. The forest and other native formations showed the largest decreases in the study area. The forest and native formation decreased almost 3 million hectares between 1997 and 2017. Contrastingly, anthropogenic areas converted to agriculture and pastures for livestock (agriculture class) increased more than 3 million hectares in the study area and period.

The results show an increase in agricultural areas, mostly, over native vegetation areas. Our field observations indicated an advance of agriculture areas in the West region of the state of Bahia, within the Cerrado biome, and in irrigated agricultural areas in the Caatinga biome, mainly in the municipalities of Juazeiro (Bahia) and Petrolina (state of Pernambuco) in the study area.

3.2. Dynamics of forest cover

The dynamics of forest cover in the SFRB is shown in Table 4. The Cerrado biome in the SFRB showed the largest deforestation areas, native forests and regeneration, and other land use classes, followed by the Caatinga, and Atlantic Forest, which showed the smallest areas of deforestation, native forests, and regeneration.

The deforestation in the Caatinga biome increased 2.87% in the study period: from 36.56% (1997–2007) to 39.43% (2007–2017). The total forest area within the Caatinga biome showed no changes. The forest regeneration decreased from 40.17% (1997–2007) to 32.15% (2007–2017) in that biome. The other land use classes showed small variation in the study period in the Caatinga biome (Table 4 and Fig. 2).

The deforestation in the Atlantic Forest biome decreased from 2.08% (1997–2007) to 1.57% (2007–2017). The total area with forest cover increased from 1.29% (1997–2007) to 1.41% (2007–2017). The area with forest regeneration increased 0.31% from 1997 to 017. The other land use classes decreased from 5.14% (1997–2007) to 4.91% (2007–2017) (Table 4).

The forest areas within the Cerrado biome decreased 2.38%: from 61.37% (1997–2007) to 58.99% (2007–2017). The maintenance of forest areas and maintenance of other land use classes showed small variation over the study period. The area of forest regeneration increased 7.71% between 1997 and 2017 (Table 4).

3.3. Valuation of carbon stocks

The results of the carbon stocks for each LULC class in the different biomes in the study area, modeled using the InVEST program, are presented in Table 5

The estimated carbon stocks for the Caatinga biome within the SFRB was 849,320,918 Mg in 1997. It decreased to 825,678,297 Mg in 2017, a total loss of 23,642,621 Mg, an average of annual loss of 1,182,131 Mg of carbon in the study period. Based on the social cost of carbon estimated for Brazil by Ricke et al., (2018), the average of the carbon stocks in the Caatinga biome was US$ 20.4 billion in 1997 (minimum of US$ 11.9 billion and maximum of US$ 34.8 billion). This estimate decreased in 2017 to US$ 19.1 billion (minimum of US$ 11.6 billion and maximum of US$ 33.6 billion), based on values of 2018. Based on it, we estimated that the Caatinga biome lost US$ 1.3 billion in the study period.

The carbon stocks estimated for the Atlantic Forest biome within the SFRB were 68,941,664 Mg in 1997, and 74,067,267 Mg in 2017. This increase he must to the recovery of some degraded areas, which contributed to increase 5,125,603 Mg in carbon stocks, representing an average of annual gain of 256,280 Mg.

The carbon stocks estimated for the Cerrado biome within the SFRB were 1,553,463,256 Mg in 1997, and 1,438,793,260 Mg in 2017. The results showed a decrease of 114,669,996 Mg in carbon stocks, an average of annual loss of 5,733,499 Mg. That biome showed the highest loss

Table 4
Dynamics of land use and cover in the São Francisco River Basin in the 1997–2007, 2007–2017, and 1997–2017 time-periods.

	Caatinga	%	Atlantic Forest	%	Cerrado	%	Total (ha)
1997 to 2007							
Deforestation	1,885,155.66	36.56	107,155.89	2.08	3,164,668.65	61.37	5,156,980.20
Forest Maintenance	11,693,274.75	41.91	358,667.46	1.29	15,845,678.55	56.80	27,897,620.76
Forest Regeneration	1,464,903.00	40.17	95,130.00	2.61	2,086,381.17	57.22	3,646,414.17
Maintenance of other classes	10,926,117.18	37.51	1,496,740.86	5.14	16,702,330.77	57.35	29,125,188.81
2007 to 2017							
Deforestation	2,070,410.58	39.43	82,614.06	1.57	3,097,440.36	58.99	5,250,465.00
Forest Maintenance	11,087,747.82	42.17	371,183.94	1.41	14,833,743.93	56.42	26,292,675.69
Forest Regeneration	1,263,162.51	32.15	114,866.91	2.92	2,551,542.03	64.93	3,929,571.45
Maintenance of other classes	11,548,089.81	38.05	1,489,027.23	4.91	17,314,321.32	57.05	30,351,438.36
1997 to 2017							
Deforestation	2,778,218.10	37.06	128,711.34	1.72	4,589,199.18	61.22	7,496,128.62
Forest Maintenance	10,800,871.02	42.26	337,115.25	1.32	14,420,218.59	56.42	25,558,204.86
Forest Regeneration	1,550,683.98	33.24	148,937.49	3.19	2,965,062.06	63.56	4,664,683.53
Maintenance of other classes	10,840,595.67	38.57	1,442,933.55	5.13	15,822,546.21	56.30	28,106,075.43

Table 5
Temporal changes of Carbon stocks (Mg of C) and LULC classes in different biomes in the São Francisco River Basin during the study period.

Biome	Year		Forest formation Mg of C	Agriculture	Non-forest natural Formation	Total
Caatinga	1997	(A) C Stock	11,427,794	83,971,727	753,921,397	849,320,918
	2007	(B) C Stock	11,561,896	85,113,948	742,289,432	838,965,276
		B – A	134,102	1,142,221	-11,631,965	-10,355,642
	2017	(C) C Stock	11,227,155	89,518,062	724,933,080	825,678,297
		C - A	-200,639	5,546,335	-28,988,317	-23,642,621
Atlantic Forest	1997	(A) C Stock	10,589	20,265,122	48,665,953	68,941,664
	2007	(B) C Stock	12,799	19,785,023	51,019,556	70,817,378
		B – A	2,210	-480,099	2,353,603	1,875,714
	2017	(C) C Stock	12,847	19,131,020	54,923,401	74,067,267
		C - A	2,258	-1,134,102	6,257,448	5,125,603
Cerrado	1997	(A) C Stock	33,673,839	128,617,890	1,391,171,527	1,553,463,256
	2007	(B) C Stock	31,781,430	145,192,889	1,306,753,261	1,483,727,579
		B – A	-1,892,409	16,574,999	-84,418,266	-69,735,677
	2017	(C) C Stock	26,364,612	164,191,370	1,248,237,277	1,438,793,260
		C - A	-7,309,227	35,573,480	-142,934,250	-114,669,996

in ecosystem services related to carbon stocks, estimated an average of US$ 37.3 billion (minimum of US$ 21.7 billion and maximum of US$ 63.7 billion) in 1997, and an average of US$ 34.5 billion (minimum of US$ 20.1 billion and maximum of US$ 59.0 billion) in 2017.

The carbon stocks estimated for the whole SFRB represent a social cost of carbon of an average of US$ 59.3 billion (minimum of US$ 34.6 billion and maximum of US$ 101.3 billion) in 1997, and an average of US$ 56.1 billion (minimum of US$ 32.7 billion, and maximum of US$ 95.9 billion) in 2017. Our results indicate an average of total loss of US$ 3.2 billion, which was estimated based on the social cost of carbon in the study area.

The spatial distribution of carbon stock variation in the SFRB is presented in Fig. 3. Carbon stocks per hectare ranged from negative values that represent a decrease of -3.9123 to positive values that represent an increase up to 11.1825.

4. Discussion

Changes in LULC occur due to natural and anthropogenic factors, which significantly influence the provision of various ecosystem services, such as provisioning services (drinking water and fisheries resources), regulatory services (carbon capture and storage, flood control and climate regulation) and sociocultural services (scenic beauty and tourism). Due to the scale of intervention, major changes in LULCs in agriculture and in vegetation cover promote significant changes in ecosystem services, as observed by Talukdar et al., (2020), for example, on the Ganga River plain in India. In the SFRB from 1997 to 2017, the results show that there was an increase in the agricultural area, responsible for a lower carbon stock per hectare compared to native forest cover, in addition to a reduction in natural non-forest and forest areas, responsible for a greater stock of carbon per hectare.

In the Caatinga included in the SFRB, Menezes et al., (2021) observed, for example, a reduction of more than 50% in carbon stocks per hectare from the conversion of forest formation to livestock or agricultural use. In this region, Fernandes et al., (2020) observed a 14% increase between 1992 and 2017 in agricultural activities and a reduction in carbon stocks.

This dynamic of loss of forest cover and natural areas in the last two decades and the consequent reduction in carbon stocks has been observed in other parts of the world. Mannan et al., (2019) observed loss of forest cover and reduced carbon stocks from 1998 to 2018, for example, in the foothills of the Himalayas, in the temperate subtropical and humid forests of Pakistan, brought about by increased urbanization and livestock.

An alternative to the loss of carbon stock due to changes in LULC and reduction of forest cover in the SFRB would be the creation of more conservation units. However, Nogueira et al., (2018) observed that even the carbon stock being protected in protected areas in the Brazilian Amazon, there was in 2014 a loss of 2.3%, due to deforestation. In this sense, the creation of conservation units should be accompanied by greater effectiveness of inspection actions carried out by the responsible authorities, for example, federal police, IBAMA (Brazilian Institute of the Environment and Renewable Natural Resources) and subnational institutions, such as secretariats of the environment.

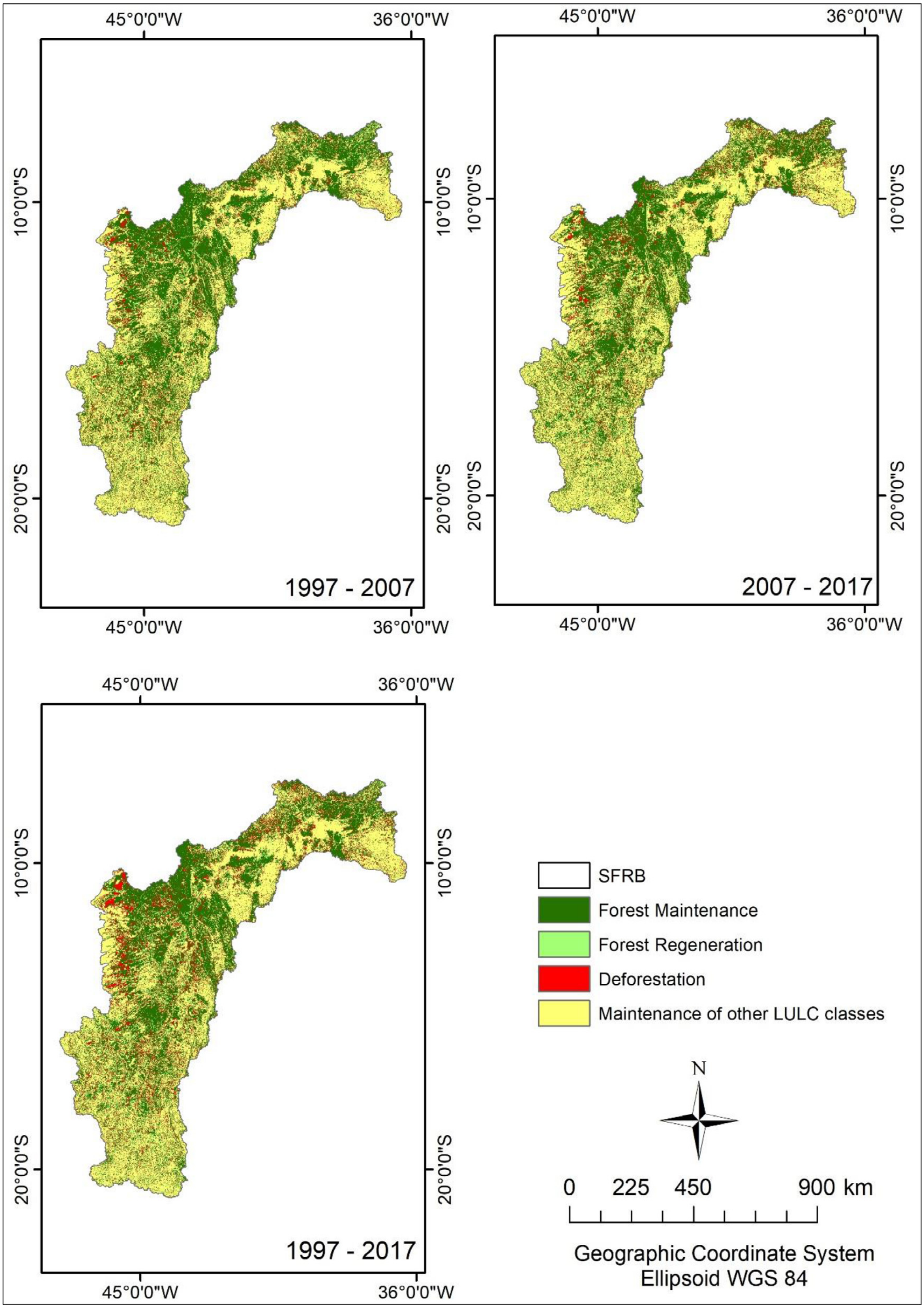

Fig. 2. Dynamics of LULC in the São Francisco River basin during the 1997–2007, 2007–2017, and 1997–2017 time-periods.

Our results showed that the SFRB is a significant area covered by forest formations, estimated in approximately 45% by 2017, despite the observed increasing deforestation trend in during the study period. However, forest remnants are spatially concentrated and distributed heterogeneously. Santos Júnior et al., (2017) estimated that 9.5% of forest formations are in the Atlantic Forest within the state of Sergipe, which is part of the Lower SFRB. By considering the whole SFRB, the percentage of Atlantic Forest area is even smaller.

However, the results showed increasing trends of deforestation and uneven distribution of forest fragments, indicating an uncomfortable sit-

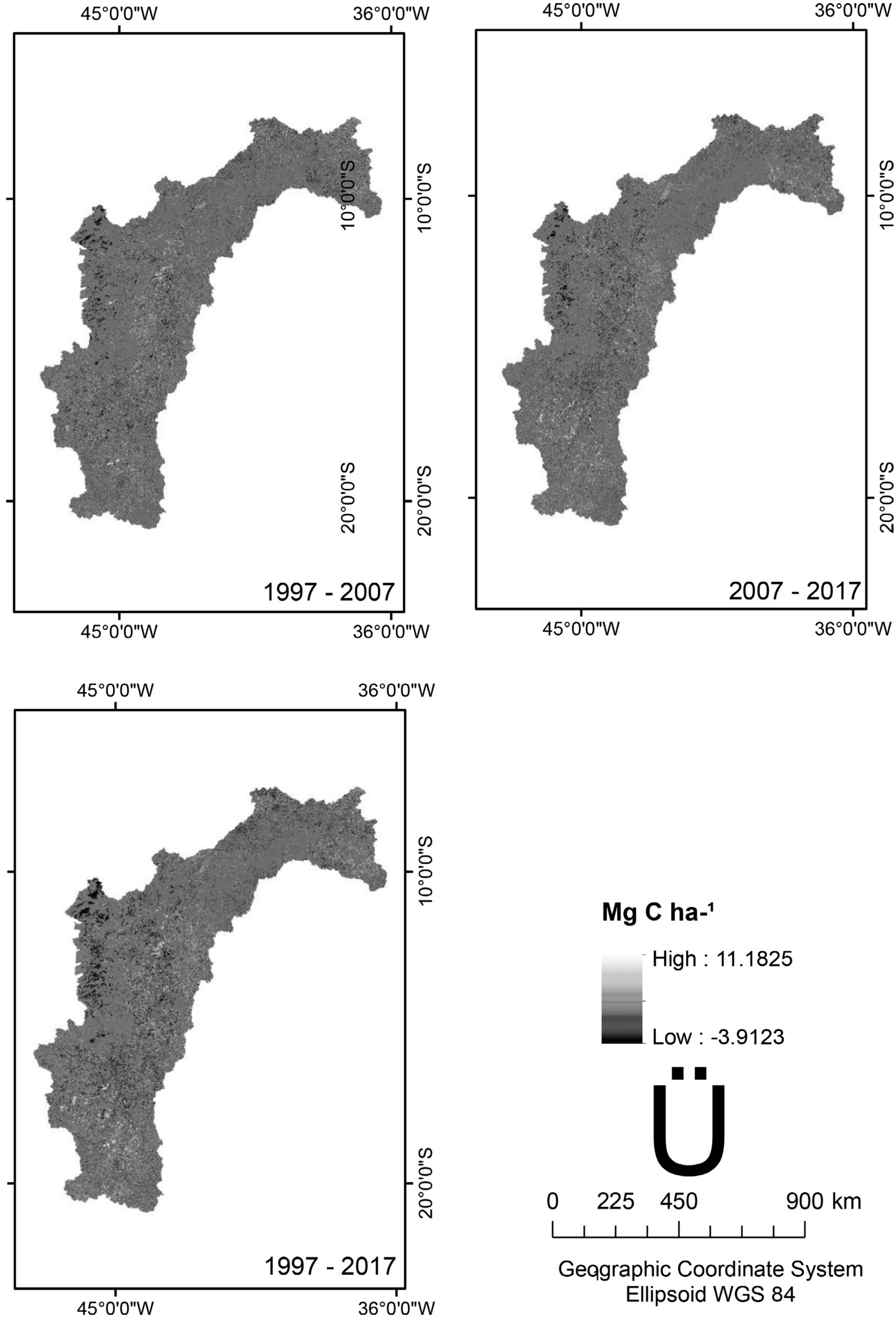

Fig. 3. Dynamics of carbon stock in the São Francisco River basin during the 1997–2007, 2007–2017, and 1997–2017 time-periods.

uation from the ecological point of view when considering the general context of the SFRB. Forests are responsible for important ecosystem services, but their maintenance requires the preservation of a certain percentage of forest cover.

The area of the Caatinga biome within the SFRB has been subjected to a historical process of intense human occupation, with deforestation for implementation of industries, firewood extraction, and agricultural activities. This occupation process was favored by the water availability for irrigation in regions near the São Francisco River, mainly in the municipalities of Petrolina (Pernambuco), and Juazeiro (Bahia) (CBRSF, 2012). Those regions host important agricultural production centers based on irrigation systems. However, a large area with soil degradation, and desertification processes was mapped in the central São Francisco River Valley in 2001 to 2012, with conversions of natural vegetation areas into irrigated agricultural areas (Schulz et al., 2017).

Although biomass per unit area is normally low in arid regions of the planet, such as the Caatinga Biome, the large extension of the arid lands on the planet gives it an important role as a carbon reservoir and for the provision of ecosystem services related to changes climate (Zandler et al., 2015). Studies demonstrate a strong link between desertification and CO_2 emission from soil and vegetation to the atmosphere (Issa et al., 2020; Lal, 2001).

Besides, deforestation has been affecting forest regeneration over time. Deforestation in the Caatinga biome has showed an increasing trend between 1990 and 2010, with an estimated rate of 0.3% (liquid loss) and 25,335 km^2 (gross loss) per year (Beuchle et al., 2015). Fernandes et al., (2015) also observed an intense deforestation (26%) of Caatinga biome areas in the state of Sergipe between 1992 and 2013 due to conversion of native vegetation into pasture lands. Forest regeneration measures are considered a complex activity in the Caatinga biome because of its local edaphoclimatic and socioeconomical characteristics.

The advance of agribusinesses in the Cerrado biome within the SFRB is due to environmental factors in that region, such as flat topography and deep soils (Oxisols), which allow for mechanization, in addition to the presence of different water sources (rainfall, rivers, and underground waters) (Oliveira et al., 2017). The growth of agriculture activities in the West region of Bahia (Cerrado biome within the SFRB) contributed to increase deforestation and reached 795,502.61 ha in 1998 and 2,804,679.75 ha in 2011 (Oliveira et al., 2016). The municipality of São Desidério (Cerrado biome within the SFRB) showed 4% of agricultural area in 1984, and reached 32.5% in 2008, which indicates a direct impact on the native vegetation, which decreased from 93.43% (1984) to 57.19% (2008) (Spagnolo et al., 2012). This regional LULC dynamic affects ecosystem services of climate regulation and it has been potentially harmful to energy production and water cycles (Arantes et al., 2016).

Pasture lands are the predominant anthropogenic land use in the Cerrado biome, occupying approximately 60 million of hectares, followed by annual crops (17 million of hectares) (IBGE, 2019). A large portion of the Cerrado biome in the state of Minas Gerais is located within the SFRB, which encompasses approximately 12 million hectares of annual crops, mainly soybean, maize, and cotton (Scaramuzza et al., 2017).

The Cerrado biome encompasses the largest area within the SFRB: 58% of the total area. The SFRB includes two administrative regions within the Cerrado biome: in the Middle SFRB in the state of Minas Gerais, and in the West region of the state of Bahia. Based on our results, native forests were converted mainly into pastures in the Cerrado biome between 1997 and 2017. There was an increase of 21 million ha of pasture in the Cerrado biome between 1985 and 2017 (Parente et al., 2019), which was observed in the Cerrado biome in the SFRB, which contributes to the increase in deforestation rates and decrease in forest cover native.

The Atlantic Forest biome has shown an overall transition process with increases in forest areas. According to Costa et al., (2017), the Atlantic Forest within the state of Rio de Janeiro showed low rates of deforestation, which was mitigated by the observed forest regeneration. This forest dynamics is mainly due social and economic factors that favored the decrease of deforestation.

Some environmental laws were crucial to increase forest maintenance in the Atlantic Forest biome. For instance, the Federal Law 9605/1998 that establishes administrative sanctions and punishment for environmental crimes, also includes further restriction for land use in the Atlantic Forest biome. In addition, the Brazilian Law 9985/2000 created the National System of Conservation Units (SNUC) to create new protected areas by adding up at least 10% of the Atlantic Forest into those areas (Campanili and Schaffer, 2010). The use and protection of native vegetation of the Atlantic Forest biome, established by the Law 11428/2006, and the adoption of payments for environmental services (PES), established by the water production program of the National Water Agency (ANA, 2018), in the headwaters of the SFRB within the Atlantic Forest biome also contributed to decrease deforestation rates and increase maintenance and regeneration of forest areas in that biome.

Some initiatives, such as PES (payment environmental services) and sustainable forest management of non-timber forest products may combine nature conservation and increase of agricultural production by generating income and socioeconomic development (Brum et al., 2019). In January 2021, the National Policy for Payment for Environmental Services was created (Law n° 14,119). The adoption of more advanced agricultural practices, development of secondary forests, and especially the adoption of more restrictive types of land uses are alternatives to slow down the deforestation process, decrease the loss of carbon stocks, and increase forest regeneration in the Caatinga biome within the SFRB, which could significantly contribute to increase levels of carbon sequestration (Garrastazú et al., 2015). Agroforestry systems and creation of new protected areas are practices that have been adopted and have already promoted increases in the maintenance of forests in the SFRB.

The Atlantic Forest was the biome that showed the highest carbon stocks per hectare (Colombo and Joly, 2010) and the only that showed gains in carbon stocks by reaching US$ 1.7 billion in 1997 (minimum of US$ 965.1 million and maximum of US$ 2.8 billion) and US$ 1.8 billion in 2017 (minimum of US$ 1.0 billion and maximum of US$ 3.0 billion). Despite the small percentage of native vegetation within that biome in the SFRB, the ecosystem services related to carbon stocks annually increased approximately US$ 100 million.

Regardless of forest protection by agroforestry systems, PES, or other arrangements, the adoption of policies that encourage rural land owners to maintain and manage forests may generate economic, social, and ecological benefits (Garrastazú et al., 2015). According to Saraiva Farinha et al., (2019), ecosystem services, such as carbon sequestration in the Cerrado biome, may result in greater economic value than the agricultural production based on corn and/or soybean crops.

The economic evaluation of natural capital and ecosystem services can be seen by two perspectives: costs of opportunity and information for the society, which can support decision makers to define strategies and policies of LULC. Therefore, the increasing forest degradation in the SFRB would financially represent an average increase cost of opportunity of US$ 3.2 billion over 20 years for the society by considering the GHG emissions due to deforestation. This information could support the formulation of more appropriated environmental policies to that study region and promote the adoption of innovative instruments of environmental policy, such as PES (Sobrinho et al., 2019).

This study showed a multidisciplinary ecosystem evaluation of the changes in LULC and that regulation services provided by the sequestration and stocks of carbon in the SFRB between 1997 and 2017. Moreover, the Brazilian government had adopted of actions focused on the recovery, and protection of natural environments, increasing the need of the society for access to better information.

5. Conclusions

Our results indicate a decrease in native vegetation, mostly forest types, in the SFRB, an average deforestation of 7,496,128 hectares of native vegetation and 133,187,028 Mg of carbon from 1997 to 2017. The deforestation in the Caatinga biome over the 20 years of our analysis, mainly in the irrigated perimeter region of São Francisco River Valley, resulted in an estimated loss of 1,182,131 Mg $year^{-1}$ of carbon, which is equivalent to estimate of US$ 1.3 billion of social cost due to loss of carbon. The largest deforested area was observed in the Cerrado biome, which was related mainly to increases of areas with agricultural crops and pastures. The deforestation in the Cerrado biome was responsible for the loss of 114,669,996 Mg of carbon in the study period, equivalent to US$ 2.8 billion. The Atlantic Forest was the only biome that showed an increase of forest cover, which was related to the conservation of native vegetation, regeneration of forests, and decreases of deforestation rates in the study period. It contributed to increase 5 million of Mg of carbon stocks, which is equivalent to US$ 100 million in social gains. Despite the positive result in the Atlantic Forest biome, the net result for the SFRB was negative, which was estimated in a loss of US$ 3.2 billion in ecosystem services related to carbon sequestration and stocks between 1997 and 2017.

Declaration of Competing Interest

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

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