Projection of spatially explicit land use scenarios for the São Francisco River Basin, Brazil

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Abstract

Future land use change in the São Francisco River Basin (SFRB) is critical to the future of regional climate and biodiversity, given the large heterogeneity among the four climate types within the basin. These changes in SFRB depend on the link between global and national factors due to its role as one of the world's major exporters of raw materials and national to local institutional, socioeconomic, and biophysical contexts. In this work, LuccME's spatially explicit land change distribution modeling framework is used, aiming to develop three models that balance global (e.g., GDP growth, population growth, per capita agricultural consumption, international trade policies, and climate conditions) and regional/ scene. Local factors (such as land use, agricultural structure, agricultural suitability, protected areas, distance from roads and other infrastructure projects), are consistent with the global structure Shared Socio-Economic Pathways (SSP) and Representative

Concentration Pathways (RCP), namely: SSP1/RCP 1.9 (sustainable development scenario), SSP2/RCP 4.5 (moderate scenario) and SSP3/RCP 7.0 (high inequality scenario). Based on detailed biophysical, socioeconomic, and institutional factors for each region of the São Francisco River Basin, spatially explicit land use scenarios to 2050 were created, considering the following categories: agriculture, natural forest, rangeland, agriculture, rangeland, and forest. mosaic plantation. The results show that the performance of the developed model is satisfactory. The average spatial fitting index between observed data and simulated data in 2019 is 89.48%, the average fitting error percentage corresponding to omissions is 2.59%, and the commission error is approximately 2.16%. Regarding the projected scenarios, the results show that three classes, agriculture, pasture, and mosaic of agriculture and pasture will continue in the same direction (increasing), regardless of the scenario considered, differently to the class of natural forest and forest plantation, which will decrease in scenarios of the middle road and strong inequality, and sustainable development, respectively.

Keywords: LuccME modeling framework, model validation, Shared Socioeconomic Pathways.

1 Introduction

Land-use and land-cover (LULC) changes are amongst the most significant global and regional socio-environmental challenges of the 21st century, impacting a wide array of natural support systems from water-energy-food (WEF) nexus security to biodiversity and ecosystem system [2], [3]. Factors such as urbanization and the implementation of agricultural policies further intensify these, leading to significant environmental alterations faced by communities [4]. Studies carried out by [5], revealed dramatic changes in global land cover and land use over the past 20 years. And highlighted by [6], the LU dynamics can exert pressure on the WEF nexus' resource potential, resulting in WEF insecurity.

The interactions between these factors are commonly modeled using globally integrated assessment models [7], e.g. LuccME modeling framework [8], which represent complex interactions and feedback on a long-term scale between the socioeconomic and natural systems.

Understanding the spatial dynamics of LULC changes is crucial for modeling interactions between socioeconomic and natural systems over the long term. However, a spatially explicit assessment of dynamics is imperative to identify not only the magnitude but also the geographic extent and location of these dynamics, thereby offering vital insights for LULC and environmental policymakers

The São Francisco River Basin Region in Brazil has become a critical area for observing the intensification of land-use and land-cover changes, largely due to a variety of socioeconomic development activities in recent years [9], [10] These changes highlight the need for a detailed examination of future land-use scenarios within the basin. Consequently, the main goal of this study is to employ a spatially explicit model to forecast these scenarios. Specifically, the research seeks to pinpoint the foremost environmental and socioeconomic factors that have been driving the LULC dynamics from 2000 to 2010 on a regional level. Additionally, it aims to scrutinize the location, intensity, and direction of land-use changes by leveraging the capabilities of the LuccME framework.

The projected scenarios represent a diverse range of biophysical, environmental, and socioeconomic assumptions about the future and capture a broad range of regional- and gridded-level uncertainties typical in current models based on the framework developed in the AMAZALERT project for the Brazilian Amazon [11], in line with the SSPs and RCPs to be useful to environmental policymakers on land use changes [12].

This paper is structured into four main sections: an introduction that sets the stage with a review of pertinent literature; a materials and methods section detailing the study area, socioeconomic context, database construction, and the structure and calibration of the LuccME model; a results and discussion section presenting the findings; and concluding remarks offering insights and recommendations for land resource conservation and protection.

2 Material and Methods

2.1 Study area brief description

This work was carried out in the São Francisco River Basin, one of the largest in Brazil, extending approximately 2,700 km, annual discharge of 94,000,000 m^3 and a flow rate between 2,100 and 2,800 m^3/s [10], [13].

The river has its source in the Serra da Canastra National Park (Minas Gerais, the southern region of Brazil) and its mouth is in the Atlantic Ocean, between the states of Alagoas and Sergipe (the northeast coast of Brazil). Therefore, the São Francisco River encompasses four different climate types: a dry subhumid climate in the southern hemisphere with a dry season coinciding with winter (Upper São Francisco), a semi-arid climate (Central São Francisco), a semi-arid and arid climate (Lower São Francisco) [14].

The climatology of the São Francisco River Basin is characterized by high spatial-temporal variability due to the action of different large-scale, meso, and local meteorological systems [15]. The average annual rainfall ranges from 1,500 mm (Hight São Francisco in Minas Gerais) to 350 mm (Lower São Francisco) [16], and soils with an aptitude for irrigated agriculture predominate in this basin.

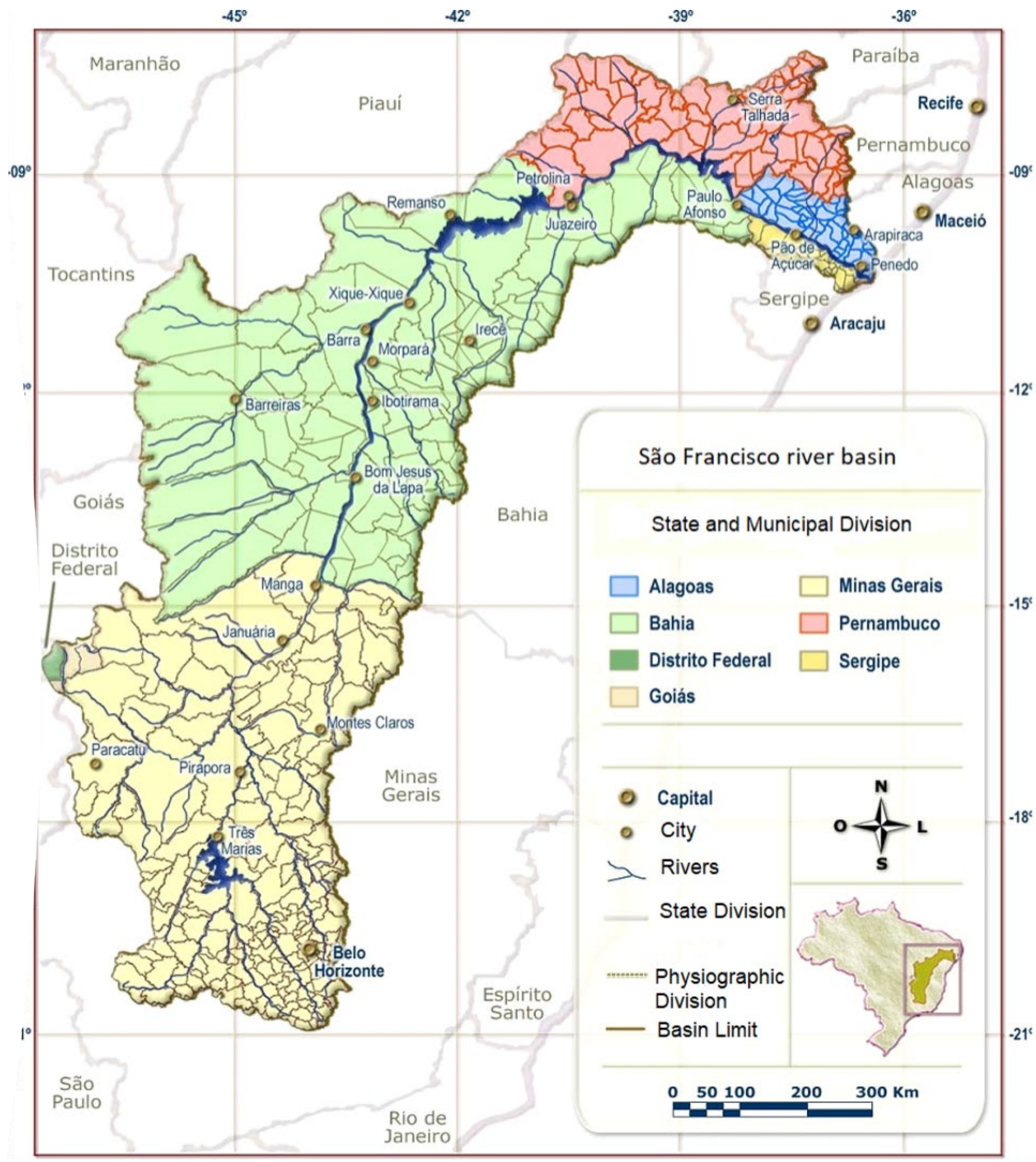

Figure 1: Geographic location map of the São Francisco River basin, Brazil.
Source: modified from Matos and Zoby (2004).

2.2. Modeling Approach

In this work, we adopted a top-down modeling approach/protocol [17], whose conceptual structure for the projection of the scenarios of land-use change for the SFRB region through the LuccME framework, is presented in Figure 2.

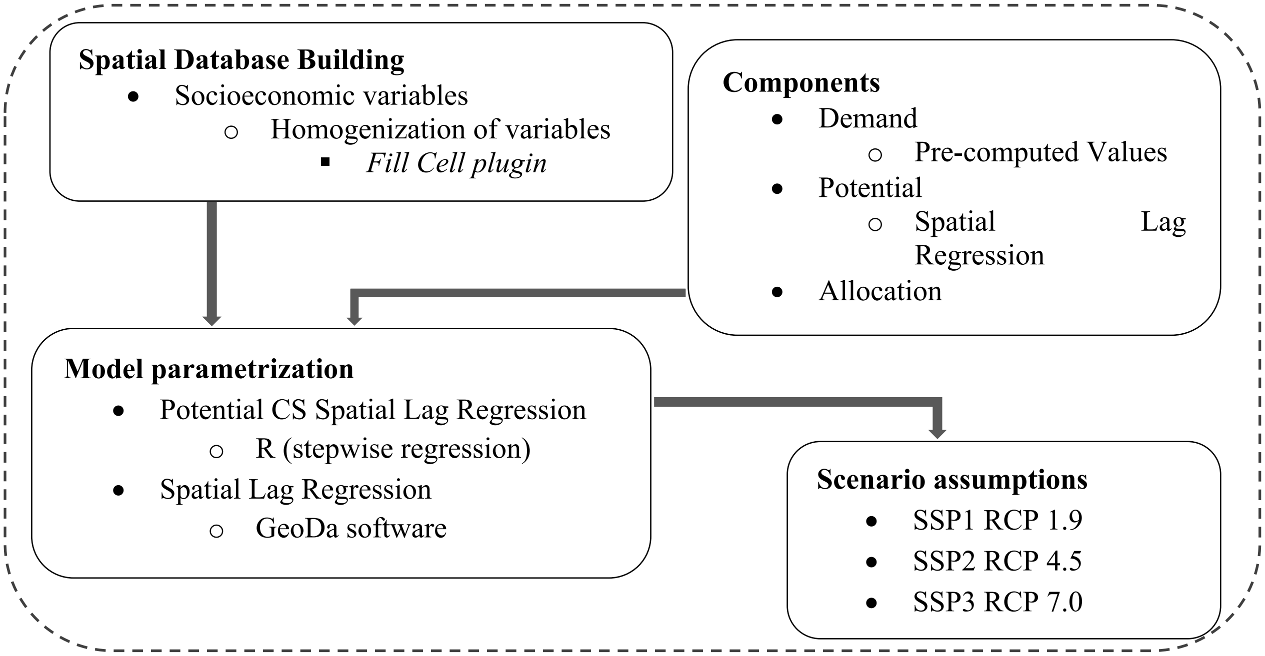

Figure 2: A conceptual structure for projecting the scenarios of land use changes through the LuccME framework.

2.2.1 Spatial Database Building

One of the relevant steps for the development of the model presented in this work was the construction of the database, containing biophysical and anthropic factors as potentially important factors in the process of land-use change for the entire São Francisco River basin.

From the Water Resources Plan of the São Francisco River Basin (2016–2025) [18], and based on the literature review stating that, in the Northeast of Brazil, land-use changed minimally during the 2000 – 2016 period with greater agricultural expansion in the southwestern zone [19], [20], a spatial database with over 30 variables was built. Within this set of variables, we have two types of data:

i. Variables were dependent on land use and land cover: from the classes established in the "MapBiomas Project – collection 5 of the Annual Series of Land Cover Maps of Brazil", through the link: https://mapbiomas.org/produtos, where data from LULC were organized into six (6) classes of interest: agriculture, planted forest, natural vegetation, mosaic, pasture, and the unobserved area and others were reclassified to the class "other". The data periods of land use and occupation changes analyzed were from 2010 to 2050, being used

2010-2015 (for calibration), 2015-2019 (for validation), and 2020-2050 (for land use scenarios).

ii. Independent variables related to socioeconomic, environmental, and political factors that influence the land-use change.

Both variables were integrated into a spatial resolution cellular space of 100km^2 (10 km x 10 km), created in the TerraView GIS environment using the Fill Cell Plugin [12]. The use of cellular space made it possible to homogenize the factors described above, regardless of their source format (vector data, matrix data, etc.), aggregating them in the same space-time basis, through operators (e.g., percentage of each class, minimum distance, etc.) used according to the geometric representation and semantics of the attributes of the input data.

2.2.2 Model description

An open-source modeling framework, LuccME (http://luccme.ccst.inpe.br/luccme/), originally developed on the TerraME computational environment at the Earth System Science Center of the National Institute for Space Research (CCST/INPE) and partners [12], [21], was adopted in this work to build a new spatially explicit LUCC model to project future scenarios of land use/cover changes for the São Francisco River Basin.

Through LuccME framework modeling, the modelers can combine (existing and/or creating new) different components, such as demand (quantifying the changes), potential (calculation of the suitability of change for each cell), and allocation (spatial distribution of changes based on land demand and each cell's potential to change), to create different land use and land cover change (LUCC) models at different space-time scales [8].

The adapted generic structure of the main spatially explicit land use/cover change models [22], shows that this open-source modeling framework, LuccME, follows several well-known LUCC models' structures that use a range of different approaches and techniques for their three components.

However, the LuccME modeling framework [21], allows the building of new models, combining the elements of demand, potential components, and allocation, which are designed according to the concepts of the main LUCC models found in the literature, CLUE [23]–[25], Dynamic EGO [26], GEOMOD [27], which are classified according to the purpose, scale, approach or underlying theory.

The demand component is responsible for determining the amount/intensity of the changes of each use change that is intended to be allocated for each time step [8]. In this case, the *LuccME Precomputed Values component was adopted* to calculate the annual demand considering the amount of land use and occupation change for each transition period [28], how much will be able to change annually from each class in the period from 2010 to 2050, according to equation 1.

$$C_{ca} = \frac{L_{ctf} - L_{cti}}{n_t} \qquad \text{Eq. 1}$$

where C_{ca} corresponds to the annual change in the area of the land use class L_c between the initial t_i and t_f end year of the chosen period, and n_t refers to the number of years of the period.

Among the various ways of calculating the annual demand D_{cat_k}, in the present study, the demand was calculated for the period 2010 and 2050 (presented in Table 1), considering the difference in the area (km^2) of each of the classes of land use and cover and redistributed equally for each year, in the period considered, according to equation 2.

$$D_{cat_k} = L_{ct_{k-1}} + C_{ca}, \qquad \text{Eq. 2}$$

where D_{cat_k} corresponds to the annual demand of a given land use class in a year t_k, calculated from the sum of the class area in the previous year t_{k-1}, and the annual change C_{ca}

Table 1: Land-use demand parameters

Precomputed values		SSP1 RCP 1.9		SSP2 RCP 4.5		SSP3 RCP 7.0	
Agriculture	from	47,046	km^2 (2000)	47,046	km^2 (2000)	47,046	km^2 (2000)
	to	24,725	km^2 (2050)	64,441	km^2 (2050)	214,305	km^2 (2050)
Natural Forest	from	283,932	km^2 (2000)	283,932	km^2 (2000)	283,932	km^2 (2000)
	to	318,615	km^2 (2050)	223,982	km^2 (2050)	176,665	km^2 (2050)
Pasture	from	30,302	km^2 (2000)	30,302	km^2 (2000)	30,302	km^2 (2000)
	to	33,573	km^2 (2050)	50,502	km^2 (2050)	53,815	km^2 (2050)
Mosaic of Agr. /Pasture	from	105,791	km^2 (2000)	105,791	km^2 (2000)	105,791	km^2 (2000)
	to	137,164	km^2 (2050)	209,918	km^2 (2000)	178,687	km^2 (2050)
Forest plantation	from	4,214	km^2 (2000)	4,214	km^2 (2050)	4,214	km^2 (2000)
	to	2,024	km^2 (2050)	5,274	km^2 (2000)	1,592	km^2 (2050)

In the initial year, the demand value corresponds to the observed value of the land use class, calculated based on the land use and land cover data used; in this case, MapBiomas LULC data.

For the potential module, the LuccME / São Francisco model used a component alternative based on *Spatial Lag Regression*, which considers the spatial autocorrelation between the determining factors (explanatory factors) [8], and dependence to estimate the potential of cellular space to change at each time step [28], and can be translated by equations 3 and 4.

$$Potential_{x,y,t,u} = \%\, of\ estimated\ usage_{\,x,y,t} - \%\, of\ the\ usage_{\,x,y,t-1} \qquad \text{Eq. 3}$$

$$Potential_{x,y,t,u} = \%\, use_{x,y,t}\ estimate \qquad \text{Eq. 4}$$

where: u is related to the type of land use or cover; x and y correspond to the location of the cell in the cellular plane in time t.

Finally, the allocation component used in the LuccME/São Francisco model was based on components of the CLUE Like [23] implemented by the INPE [8] to generate annual maps of land use and occupation changes.

This module distributes spatially and interactively the land use changes according to the previous components (demand and potential), based on the competition between the types of land uses in each cell and within a previously established maximum error, according to equation 5, proposed by [28] that describes the allocation process for each type of land use/cover.

$$L_{c,\,x,\,y,\,t} = L_{c,\,x,\,y,\,t-1} + Pot_{c,\,x,\,y,\,t} * ITF_c \qquad \text{Eq. 5}$$

where the amount of area allocated from a given class of land use L_c at a given xy location in the cell plane at time t is determined in an iterative process of the sum of $L_{c,\,x,\,y}$y at time $t-1$ and the potential $Pot_{c,\,x,\,y,\,t}$ multiplied by an adjustment factor proportional to the difference between the allocated area, the reported demand, and the direction of the change ITF_c.

2.2.3 Model parameterization

After compiling the database, a statistical analysis was performed to select the set of variables to be considered in the model. First linear regression was carried out using R software (stepwise regression included), and then the variables considered significant in this analysis were submitted for spatial correlation analysis between them, through the GeoDa software [29], which identified *Spatial Lag Regression* as the appropriate regression, based on the correlation coefficient (R^2) and the significance of each variable presented in Table 1.

When the spatial correlation was identified, the *Potential CS Spatial Lag Regression* was used, according to equation 6, which is based on and adapted from the spatial lag model [29], [30], and based on the correlation coefficient (R^2), whose significance of each variable was selected for the model setup.

In this component, it is considered that the influence of neighboring areas occurs, a characteristic that is intrinsic to changes in land use and land cover [12]. In addition, this component allows this potential to be dynamic over the modeled period, that is, every year.

$$Pot_{c,\,x,\,y,\,t} = \%RegL_{c,\,x,\,y,\,t} - \%L_{c,\,x,\,y,\,t-1} : \{Pot_{cxyt}\, \epsilon \mathcal{R} \parallel\ -1 \leq Pot_{cxyt} \leq 1\} \qquad \text{Eq. 6}$$

where $Pot_{c,\,x,\,y,\,t}$ corresponds to the potential for the occurrence of a given land use class L_c in a given location xy in a given time step t. To determine the potential, the percentage of land use estimated by the regression $Reg\, L_{c,\, x,\, y,\, t}$ is subtracted from the percentage of existing use $L_{c,x,y}$ at time $t-1$.

Table 2 details the general parameters, spatial lag regression parameters, and final components of LuccME, such as Spatial Lag Regression, *Clue Like* Allocation Saturation, and Pre-Computed Values, in which we externally calculate demand and inform the expected area for each land use class annually from 2010 to 2050.

Table 2: Description of model components, temporal, and spatial resolution, selected determinant variables, and scenario assumptions regarding land use projections

General parameters	**Spatial scale**	**Extent**		**Entire São Francisco River basin**
		Resolution (Cellular Space)		10 km x 10 km (100km²)
	Temporal scale	Extent		2010 – 2050
		Resolution		Yearly
		Period	Calibration	2010 – 2015
			Validation	2015 – 2019
			Scenarios	2020 – 2050

SPATIAL LAG REGRESSION PARAMETERS

POTENTIAL:

	Drivers	Metric	Regression coefficient	std Error	Significance
Agriculture (R-squared: 0.795721)	Temporary protection	Area	6.45455e-008	6.8895e-009	0.00000
	Livestock	Area	-5.99827e-008	1.26092e-008	0.00000
	Permanent protection	Area	3.26743e-007	1.16139e-007	0.00490
	Population	Average (in the year 2010)	2.59976e-008	7.6434e-009	0.00067
	Railroad	Distance	1.30584e-007	1.78403e-008	0.00000
	State highways	Distance	-3.95903e-007	7.68316e-008	0.00000
	Priority areas	Area	-0.0205208	0.00213161	0.00000
	Conservation areas	Area	-0.0166808	0.00316594	0.00000
	Settlement	Area	-0.0307039	0.00902494	0.00067
	Aptitude (good)	Area	0.0345094	0.00541664	0.00000
	Regular areas	Area	0.0324042	0.00332226	0.00000
	Restricted areas	Area	0.0124764	0.00314856	0.00007
Forest Plantation (R-squared: 0.557428)	Priority areas	Area	-0.00415734	0.000970073	0.00002
	Regular area	Area	0.00462673	0.00166935	0.00558
	Restricted areas	Area	-0.00347557	0.00166454	0.03680
	Sugarcane mills	Distance	-2.0069e-008	2.87803e-009	0.00000
	ag_pv	Average	0.00796724	0.00175907	0.00001
	Unsuitable areas	Area	-0.00933544	0.00210178	0.00001
Natural Forest R-squared: 0.808121	Livestock enterprises	Number	-6.76544e-006	2.32028e-006	0.00355
	Temporary protection	Area	-4.23389e-008	1.30666e-008	0.00119
	Livestock	Area	2.00632e-007	2.77826e-008	0.00000
	Gini index	Average	0.263603	0.0362989	0.00000
	Priority areas	Area	0.0461646	0.00395371	0.00000
	Conservation areas	Area	0.0388826	0.005736	0.00000
	ag_pv	Average	0.0708852	0.00752883	0.00000
	Unsuitable areas	Area	0.161762	0.00847408	0.00000
	Regular area	Area	0.0736055	0.00645427	0.00000
	Restricted areas	Area	0.0796189	0.00642088	0.00000
	Priority areas	Average	0.00129813	0.000147786	0.00000
	State highways	Distance	6.63987e-007	1.28749e-007	0.00000
Mosaic of Agriculture and Pasture (R-squared: 0.782430)	State highways	Distance	-9.99207e-008	3.29047e-008	0.00239
	Regular area	Area	0.00369373	0.00149181	0.01329
	Restricted areas	Area	0.0130552	0.00153997	0.00000
	avprech	Average	-8.05443e-005	1.80587e-005	0.00001
	arem	Area	0.00841796	0.00137817	0.00000
	Livestock	Area	-5.23291e-008	1.71047e-008	0.00222

Pasture (R-squared: 0.837762)	Gini index	Average	-0.135681	0.0253183	0.00000
	State highways	Distance	-5.95004e-007	9.75338e-008	0.00000
	Priority areas	Area	-0.0144852	0.00286281	0.00000
	Conservation areas	Area	-0.0263836	0.00435291	0.00000
	ag_pv	Average	0.0289874	0.00565199	0.00000
	Regular area	Area	0.0276702	0.00432994	0.00000
	Restricted areas	Area	0.0330068	0.00426209	0.00000
	aveap	Average	-0.000291749	6.60039e-005	0.00001
	avtmh	Average	0.00409536	0.000460744	0.00000

2.2.4 Model validation

For the validation of the models implemented in the LuccME, two routines are available: multiresolution of the entire area (ext.) and multiresolution of the areas where there were changes (dif.). The two routines compare the difference between the actual data and the simulated data.

For the validation of the model, the adjustment validation metric was adopted by multiple resolutions [31], to compare the results of the model and the changes in land use and occupation observed between 2015 and 2019.

Centrally, the common metric is the level of similarity between the simulated and original map at different levels of coincidence on a scale of 1 to 10 [28], [31].

Therefore, this approach allows the evaluation, of both localization errors in the resolution of the model itself and spatial pattern errors, degrading the resolution of maps [12]. The similarity level can be calculated based on equation 7:

$$NSi = 1 - \left[\frac{\sum_{j=1}^{n}(|\sum_{c=1}^{k} dif_{sim,c} - \sum_{c=1}^{k} dif_{real,c}|)}{2 * \sum_{j=1}^{n}\sum_{c=1}^{k} dif_{real,c}}\right] * 100 \qquad \text{Eq. 7}$$

where *NS* corresponds to the level of similarity between the actual and simulated maps at a given resolution i; j is the window considered; n establishes the number of windows/cells to be considered; tex.tit **c** is the number of cells in a *resolution* $k(i*i)$; and $dif_{real} = \%real_{tf} - \%real_{ti}$ and $dif_{sim} = \%sim_{t-final} - \%real_{inicial}$, being t_i, and t_f the initial and real years, respectively, considered in the validation.

The results are shown in percentages of hit considered through resolution windows (multiresolution), according to the similarity between the maps observed and simulated in various resolutions (1x1, 2x2, 3x3, 4x4, 5x5, 6x6, 7x7, 8x8, 9x9 and 10x10) [4], [32], through the sampling windows that increase in each period, having adopted the permission of 0% error per cell. This metric is particularly useful for characterizing land use and land cover change and for validating land use and land cover change models [33].

2.3 Scenario assumptions

The scenarios developed in the present study were based on assumptions suggested by [12], i.e.:

- SSP1 RCP 1.9 (sustainable development scenario) – is a scenario that assumes that all existing environmental laws are in force and policies to reduce deforestation, encourage environmental restoration, and preserve conservation units and indigenous lands, providing an initial framework for our analysis of sustainability pathways.
- SSP2 RCP 4.5 (intermediate scenario) – this scenario assumes maintaining some of the positive trends of the last decade).
- SSP3 RCP 7.0 (scenario of strong unevenness) – which reflects a weakening of efforts in recent years, especially in the socio-environmental dimension.

3 Results and Discussion

3.1 Model performance

The distribution of land-use classes and dissimilarities between the observed and simulated data in the validation year 2019 are presented in Figures 3 and 4. In Figure 3, the class referring to agriculture shows that the modeling well simulated the areas occupied by agriculture in the basin, especially in the western extremities of the basin and in a smaller area to the east. These areas occupy a total that varies from 0.24 to 0.98% in the aforementioned portions. Regarding commission and omission error for this class, the variation was low, indicating a good adjustment of the map that was simulated in relation to what was observed. Similarly, this also occurred for the natural forest and pasture classes, where the omission error was -30 to 0 and the commission error was around 0 to 60, represented across the entire basin. In all classes in Figure 3, it is observed that omission and commission errors are higher when the total area (%) varies between 0.61 and 0.98.

In Figure 4, referring to the agriculture/pasture and planted forest mosaic classes, it is observed that although the model can estimate the total occupied area well, the omission and commission errors are greater, especially in the agriculture/pasture mosaic class, whose omission error varies around 0 - -50 and commission error from 0 – 50. The model was not able to simulate as well, compared to the other classes, the central portion of the basin referring to the agriculture/pasture mosaic class.

The model presented satisfactory performance compared to previous studies [12], with an average spatial adjustment index between observed and simulated data in 2019 corresponding to 89.48%, as shown in Table 3.

Table 3: Percentage of spatial adjustment and errors

Adjustment	Spatial adjustment		Errors	
	Patterns	Modified areas	Omissions	Commission
Land use class.		%		
Agriculture	88.75	61.53	1.60	2.27
Natural Forest	97.13	56.47	2.35	0.53
Pasture	94.48	49.44	2.99	2.83
Mosaic of Agr. /Pasture	78.13	49.85	3.12	2.05
Forest plantation	88.93	55.62	2.88	3.14
Average	89.48	54.58	2.59	2.16

When considering only the areas where some change occurred, the average adjustment index was 54.58%. The average percentage of adjustment errors corresponding to omissions was 2.59%, while commission errors were approximately 2.16%. The lowest omission and commission errors were observed in the Agriculture and Natural Forest classes, with 1.60% and 0.53%, respectively. Among all classes of land use, the highest general values of spatial adjustment were observed for natural forest and pasture, with 88.75% and 97.13%, respectively, if considered pattern changes.

When considering the areas where changes occurred, the average of the adjustment index of all classes was 54.58%; and among the classes that presented the highest values of spatial adjustment, agriculture, natural forest, and forest plantation stand out, with 61.53%, 56.47%, and 55.62%, respectively.

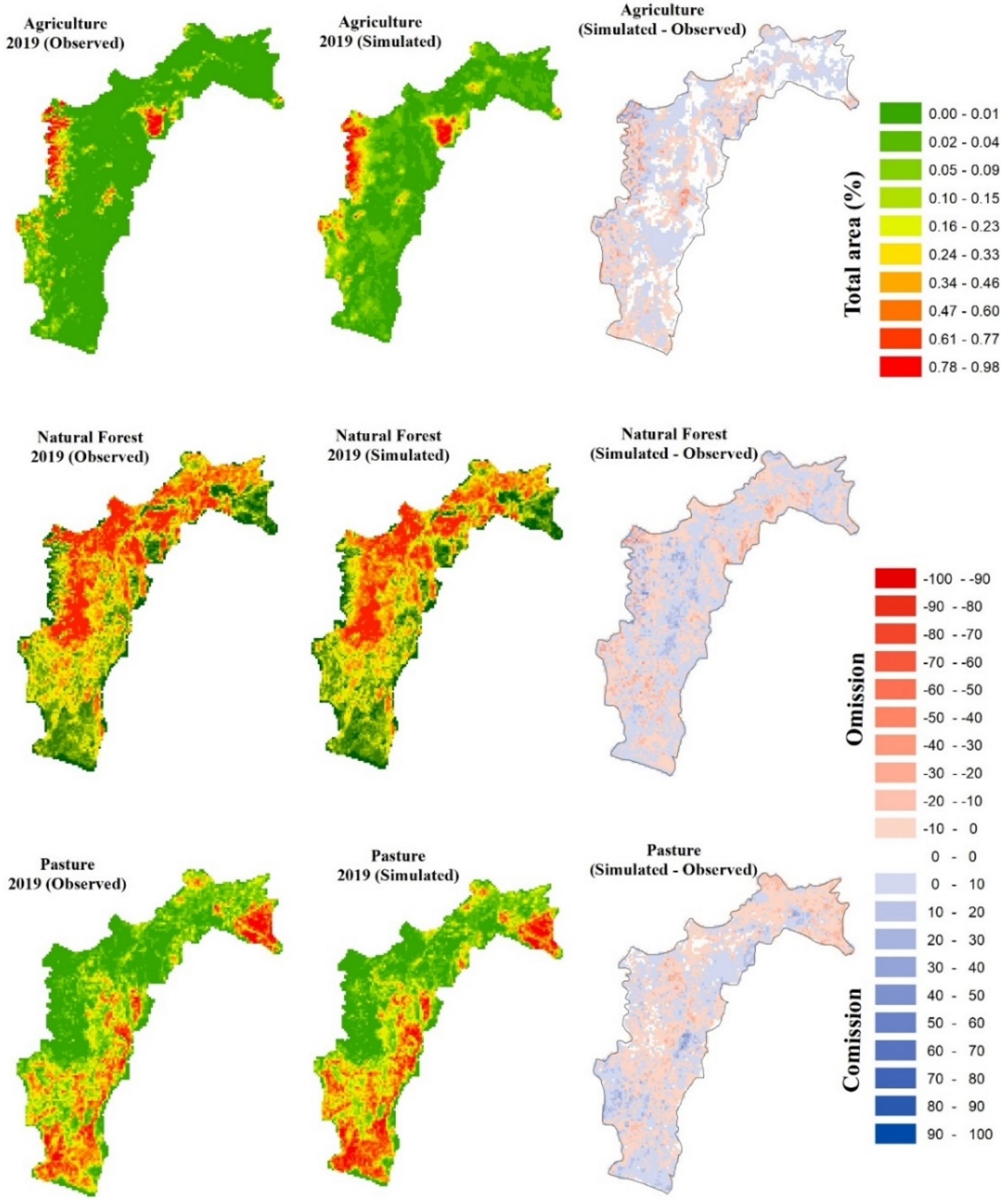

Figure 3: Percentage of agriculture, natural forest, and pasture observed versus simulated in 10 x 10 km2 cells in 2019, and the spatial distribution of omission and commission errors

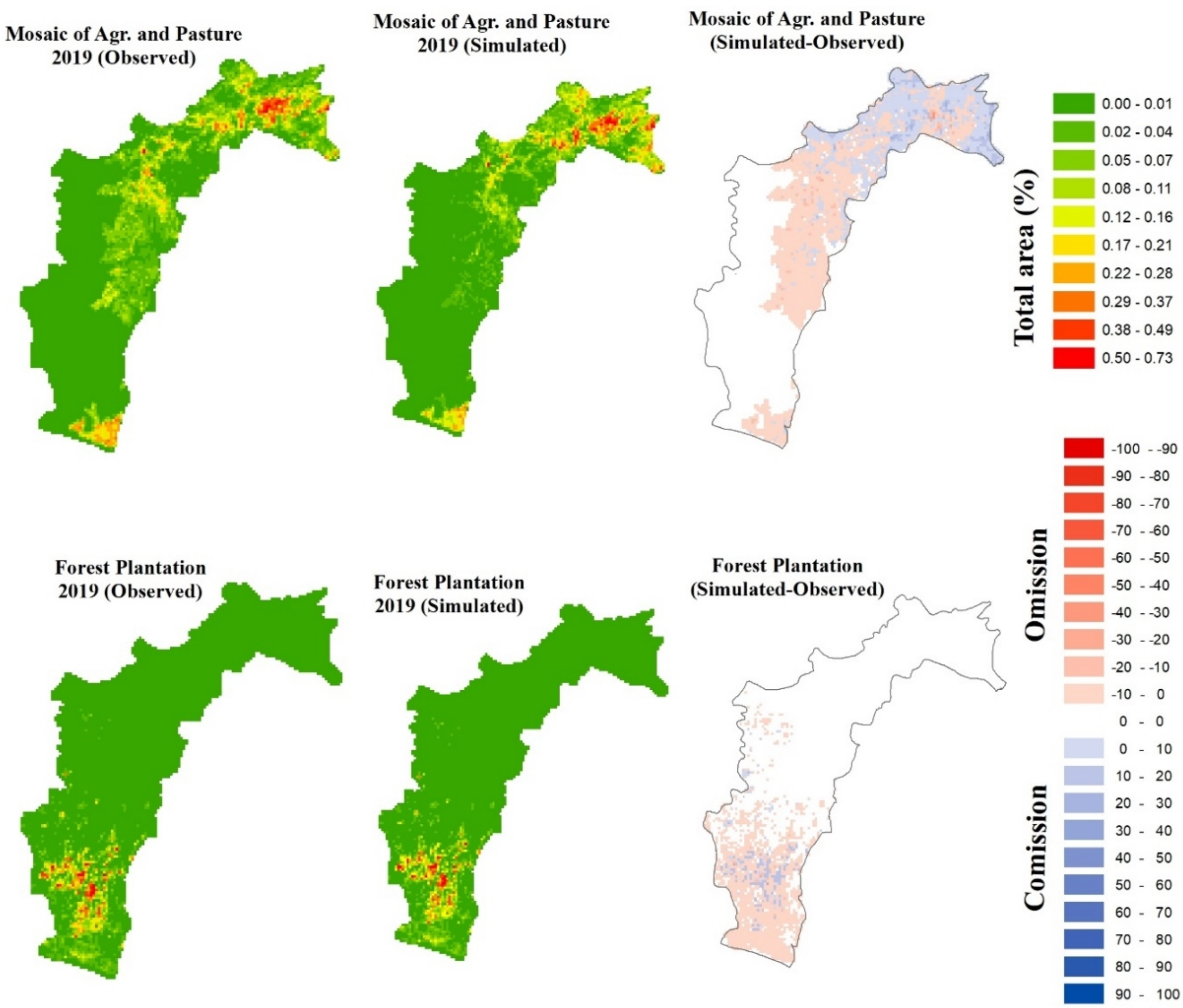

Figure 4: Percentage of the mosaic of agriculture and pasture, forest plantation observed versus simulated in 10 x 10 km2 cells in 2019, and the spatial distribution of errors of omission and commission

3.2 Scenarios of land-use Change

Figure 5 shows the spatially explicit distribution of the classes of land use in the initial year of the simulation (2010) and the three scenarios considered in this work (for the year 2050). In Figure 5 it can be seen that in 2010 the areas of agriculture, mosaic of agriculture/pasture and planted forest are predominant classes in the São Francisco basin. Natural forest areas are more concentrated in the north and south extremities of the basin and in some portions of its border. Pasture areas are more present in the middle and sub-middle portion of the basin. When analyzing the projected scenarios, it is clear that there will be a more representative increase in natural forest and pasture in relation to other classes, in the three scenarios analyzed, with a variation of 0.81 – 1.0 (Figure 5). The agriculture/pasture mosaic class will decrease, according to projections, in the three scenarios analyzed, as well as agriculture and planted forest, but on a smaller scale.

Table 4 shows the direction of change in land use and coverage, according to classes and scenarios between 2010 (observed year) and 2050 (final year).

Analyzing the dynamics of land use change (Table 4), according to the scenarios considered, has been observed that agriculture, pasture, and natural forest, will continue in the same direction, regardless of the scenario considered.

Regarding the class of agriculture, this will triple from one scenario to another by 2050. These results corroborate with estimated increase of irrigated areas by 130,323 ha between 2018 and 2025 [34], more than double the expansion of agriculture by the year 2035 [35]. Similar results of the expansion of agriculture over the next two decades were also observed [36], [37], with the clearest expansion and water demand increase occurring in Upper and Middle São Francisco.

Table 4: The direction of change in land use change, according to classes and scenarios between 2010 and 2050 Legend: ↗ = Increase and ↘ = Reduction.

	Agriculture	Natural Forest	Pasture	Forest Plantation	Mosaic of Agr. /Pasture
SSP1 RCP 1.9	↗	↗	↗	↘	↘
SSP1 RCP 4.5	↗	↗	↗	↗	↘
SSP1 RCP 7.0	↗	↗	↗	↗	↘

As shown in Table 4 and Figure 5, the expansion of the agriculture class will be led by the decrease of conservation areas, protection (temporary and permanent), and the regular suitability of these areas for the practice of agriculture.

Differently to the class of forest plantation, which will increase in these two scenarios (SSP1 RCP 4.5 and SSP1 RCP 7.0), the class of natural forest in the middle road and strong inequality scenarios, corroborating with an accelerated modification of the natural conditions of the basin reported by between 1985 and 2015 [36], specifically in Upper São Francisco due to the observed urbanization process and planted forest area growth.

According to scenarios of halfway and strong inequality (SSP1 RCP 4.5 and SSP1 RCP 7.0), the natural forest will suffer an increase of approximately 59,950 km² and 69.627 km², respectively, until 2050, mainly in Upper and Middle San Francisco. However, in the sustainable development scenario (SSP1 RCP 1.9), the natural forest will increase by 34,683 km². This increase occurs mainly in the Sub-middle and Lower São Francisco, as shown in Figure 5.

Figure 5 presents the spatial distribution of areas and land use according to the scenarios from 2010 to 2050.

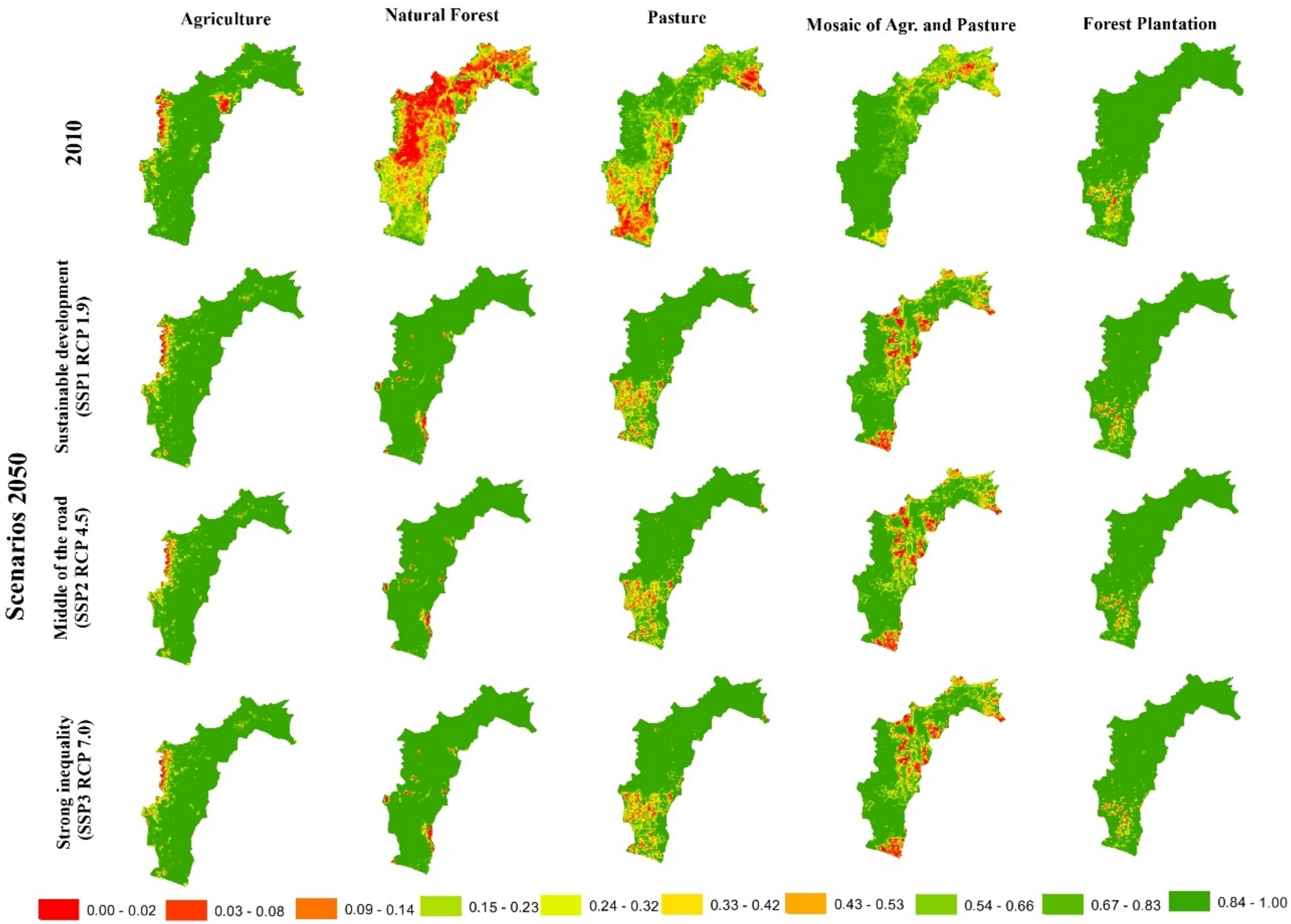

Figure 5: Spatial distribution (%) of areas and land use according to the scenarios from 2010 to 2050

Total loss estimates of 7,496,128 ha in different types of native vegetation between 1997 and 2017 reported live up to what will happen with natural forests [38], which will tend to reduce its length in the scenarios of the middle of the road and strong inequalities (59,950 and 107.267 km², respectively). Differently from the sustainable development scenario, there will be an increase of 34,683 km².

Although the results have shown an increase in agriculture, pasture, and mosaic of agriculture and pasture, regardless of the scenario considered, the increase will occur with greater intensity in the scenarios of the middle of the road and strong inequalities for the class of mosaic and pasture, unlike the agriculture that will register the largest increase in the scenario of the middle of the road; with a difference of about 149,863 km², when compared to the scenario of strong inequality.

The set of scenarios presented in this work provides important information, which can help establish public policies that can contribute to biodiversity conservation and reduce emissions from deforestation and degradation, especially those resulting from land use/cover changes. In addition, this set of scenarios with extension throughout the São Francisco region makes it possible to understand how decision-making and the demands of all States that compose this region can influence different processes, including hydrologic, along the São Francisco river basin.

4. Conclusion

The results regarding model performance showed relatively low commission and omission errors, indicating a good spatial adjustment of the simulations of land use classes in the São Francisco basin. The classes that performed best in the simulated information were agriculture and natural forest, in which errors were lowest. Given the results obtained, the simulations showed the effectiveness of the LuccME model in generating products that well represent the use of the soil of a river basin, in this case the São Francisco basin, becoming an important tool in aiding management for control and analysis of areas with significant dynamics of land use changes.

Furthermore, in this research, we assess land use change in the SFRB by building a spatially explicit land use change model that considers drivers of deforestation, different land needs, land policies, and governance arrangements, and operates under three Scenarios running to 2050: optimistic), intermediate (similar to "business as usual") and fragmented (worst). In the last two cases (road-centric and fragmented), we observed a tendency for the agriculture category to increase. It was observed that the classes defined by natural forest and planted forest tend to increase in this three scenarios (road-centric and fragmented).

Significant and increasing changes in land use in the SFRB were agriculture and pasture for the three scenarios, which will be, probably, led by the reduction of conservation units, protection (temporary and permanent), and regular adaptation of these areas for the practice of agriculture.

In this way, it is understood that preventing the expansion of the agricultural practices in the SFRB cannot ensure biodiversity conservation or carbon savings in the absence of complementary measures committed to land use efficiency, controlled land use expansion, and new economic alternatives. In this perspective, recognizing land-use systems as open and human-driven systems is a first and central challenge in designing more efficient land-use policies. Therefore, for this research, it is recommended carrying out future studies to analyze the changes considering more classes of land-use and other land-use databases, instead of the 5 land-use classes from the MapBiomas initiative adopted in the present study.

Land-use change scenarios are useful in showing how present and future decisions could affect land change trends in the São Francisco region. A real-life scenario could be a combination of the three scenarios presented in this study. Observing the potential impacts of land use in a spatially explicit way, as a valuable discussion on the existing laws of the three scenarios considered in this work, can help to prevent (or reduce) and influence policy markers' actions to improve land-use governance.

It is expected that this work can contribute to adequate planning and better management of water resources in the SFRB since changes in LULC can directly interfere with the regime of monthly average flows of the region.

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