Socio-Environmental Vulnerability to Drought Conditions and Land Degradation: An Assessment in Two Northeastern Brazilian River Basins

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Abstract: Over the past few decades, a significant amount of agricultural land has been lost due to soil degradation/desertification. In addition, the increasing frequency of extreme events, such as intense droughts and forest fires, has negatively impacted various ecosystem services. Two of the main Brazilian biomes—the Cerrado and the Caatinga—have been affected by increased rainfall variability, leading to desertification, increased fire frequency, and, consequently, rising concerns regarding the water and food security of the local population. In this study, we develop a methodology to assess these impacts using a Socio-Environmental Vulnerability Index (SEVI) that combines physical, environmental, and socio-economic indicators related to exposure, sensitivity, and adaptation, as well as including socio-environmental feedback. The developed SEVI is then applied to the São Francisco and Parnaíba river basins. The proposed index is based on the MEDALUS methodology and is adapted to include multiple biological, physical, and socio-economic indicators, allowing for the discrimination of areas characterized by different levels of vulnerability. We also analyze the effectiveness of governmental policies, such as the creation of conservation areas and the rural registration of properties, in reducing vulnerability. The SEVI analysis highlights that adaptive capacity is the main constraint for reducing socio-environmental vulnerability in the Parnaíba basin, while exposure and sensitivity are the greater challenges in the São Francisco basin. The results of this study are crucial for the prioritization of recovery actions in degraded areas.

Keywords: socio-environmental vulnerability; conservation units; rural environmental cadastre (CAR); Northeastern Brazil; Cerrado; Caatinga

1. Introduction

The world's population has been growing rapidly and—albeit at a slower rate—it is projected to reach 8.5 billion by 2030, around 9.7 billion by 2050, and 10.9 billion by 2100 [1]. Population growth implies a more intense use of natural resources, requiring more adequate environmental planning to meet the needs of the population without depleting these resources.

Habitat fragmentation, landscape ecology changes, soil erosion, and loss of biodiversity have critically influenced the sustainable development of regional ecosystems, and the evaluation of vulnerability has been considered as a strategy for the mitigation of environmental degradation [2]. Environmental indicators enable description of the characteristics of sociological, ecological, or environmental components in a comprehensive and understandable manner [3].

One of the main causes of biodiversity loss in South America is the increased frequency of fires [4], which is a common land management practice in subsistence agriculture [5].

Although some regions are adapted to burning—as is the case of the Cerrado biome [6]—frequent use of this technique can lead to a loss of nutrients, soil compaction, and erosion [7]. In areas with erosive potential, such as Cerrado and Caatinga, more than half of the endemic plants are threatened by extinction. Furthermore, the occurrence of uncontrolled burning favors soil erosion, increasing river sediment loads and sedimentation [8,9]. In addition, the chemical, physical, and biological characteristics of the soil are altered, further favoring soil erosion, compaction, and loss [10], thus accelerating degradation/desertification [11].

More frequent and severe droughts have been reported in the Brazilian Cerrado, leading to a decrease in agricultural productivity of around 40–45% [12–15]. The severe drought events in recent years have been associated with an increase in burned area [16], susceptibility to erosion [17,18], and intensification of soil degradation [15,19]. According to [20], the São Francisco river basin faced severe drought conditions from October 2012 to March 2021, affecting crop production and reducing the reservoir level to a critical volume of 15%. In addition, the authors of [21] used global climate models to show that, as a consequence of climate change, streamflow in the São Francisco and Parnaíba rivers is projected to decline by 46% and 26%, respectively, in the upcoming decades. Previous studies have shown that socio-environmental vulnerability may increase significantly with a high frequency of climate extremes, especially in regions where the local population lives in a situation of poverty [22].

A system (or environment) can be vulnerable to several perturbations (e.g., floods, landslides, droughts, sickness, or socio-economic issues) in various different ways [23,24]. Vulnerability can be defined as the conditions established by physical, social, economic, and environmental factors which increase the susceptibility of an individual, community, or system to the impacts of hazards [25,26]. According to [27], vulnerability is most often conceptualized in terms of components that include exposure, sensitivity, and capacity to adapt [27]. The concept of exposure refers to the degree to which a system experiences environmental or socio-political stress, evaluated using indicators related to environmental stress. Sensitivity is defined as the degree to which a system is modified or affected by disturbances and is related to its internal characteristics, leading to a more or less susceptible state. It is evaluated using indicators related to the characteristics of the physical and biotic environment [23,27]. The adaptive capacity can be defined as the ability of a system to evolve in order to accommodate environmental hazards or anthropogenic impacts, evaluated in terms of conservation and/or environmental preservation actions that reduce the pressures exerted on the environment [24,27]. Socio-environmental vulnerability simultaneously consists of environmental and social vulnerability in the same place and period of time [28].

Considering that the regions of the São Francisco and Parnaíba river basins suffer from anthropic and climatic pressures [20,21,29], improving our knowledge on social vulnerabilities has become fundamental for the development of strategic plans aimed at adapting to climate change or reducing risks in these regions.

In this study, we propose a Socio-Environmental Vulnerability Index (SEVI), which is then applied to the São Francisco and Parnaíba river basins. These basins are considered crucial for both agribusiness expansion and biodiversity conservation in South America [30,31], and they are threatened by the effects of climate change [32]. As Brazilian water law defines the hydrographic basin as the unit for the planning and management of water resources, we chose the study area in accordance with the legal framework that guides the implementation of public policies in Brazil.

This is the first study to analyze the socio-environmental vulnerability in two large Brazilian hydrographic basins, which host two important Brazilian biomes threatened by the vigorous agricultural land expansion in Brazil. Most of the existing studies in the region have focused on environmental or socio-economic aspects independently, without considering the feedback between both dimensions.

An integrated and systematic view of socio-environmental vulnerability contributes not only to a more comprehensive diagnosis of the challenges which must be addressed to

achieve sustainable development in impoverished areas, but also to support the implementation of effective management policies and programs by prioritizing management actions and facilitating decision making.

2. Study Area

The study area extends over the Northeastern and Northern regions of Brazil, including two major Brazilian basins: the São Francisco river basin and the Parnaíba river basin (see Figure 1B). The region presents contrasting rainfall regimes, mostly with tropical climate with dry winter (Aw) and semi-arid climate (BSh) (Figure 1B). With an area of 962,194 km^2, this region includes part of the Caatinga (47.86%), Cerrado (49.94%), and a small fraction of the Atlantic Forests (2.20%) biome (see Figure 1A). The region has a population of about 20 million inhabitants, with 16 million living in the São Francisco basin (77% of the population is urban) and 4.15 million in the Parnaíba basin (35% of the population is in the rural areas) [33]. The natural vegetation that dominates the northeast region, known as Caatinga, is composed of shrubs and small trees that are usually thorny and deciduous, which lose their leaves early in the dry season [34]—mainly under semi-arid conditions [35]. The Caatinga soils are shallow and have low fertility, poor drainage, and high concentrations of interchangeable sodium [36]. The other dominant biome in the study area is the Cerrado, which is the second-largest Brazilian biome and is undergoing severe land-use changes due to rapid agricultural expansion. The Cerrado has high heterogeneity and strong seasonal variation, being formed by forestlands (ciliary forest, gallery forest, dry forest, and Cerradão), shrublands (Cerrado sensu stricto, park savanna, palm, and vereda), and grasslands (campo limpo, campo sujo, and campo rupestre) [37,38]. Along the coast, the dominant biome is the Atlantic Forest, characterized by a large variety of tree types and unique vegetation under severe anthropogenic pressure [39]. The Atlantic Forest consists of different vegetation types or forest formations, including seasonal deciduous and semi-deciduous forest formations, fields of altitude, and pioneer formations, such as mangroves and coastal vegetation [40].

Concerning the soil type, 29.98% of the study area is covered by Neosols (51.08% of which have a sandy texture), while Quartzarenic Neosols cover about 12% (111,509 km^2) and are considered of low agricultural aptitude and susceptible to degradation. In addition, Quartz Sands, in smooth-undulated relief between 3% and 8% (35% of the study area is on this type of relief), are very susceptible to erosion and, when they occupy drainage headwaters, they generally give rise to large gullies [41].
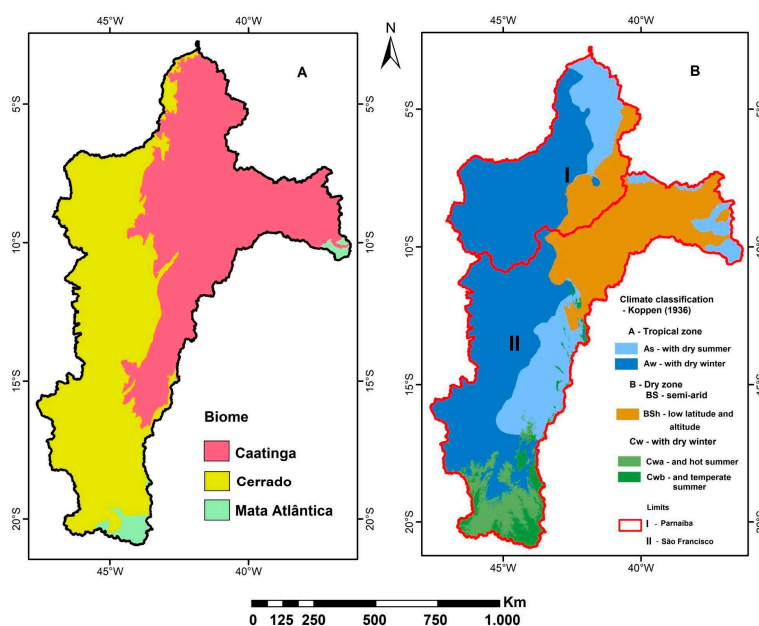
Figure 1. (**A**) Biomes included in the study area; (**B**) Köppen climate classification [42].

3. Material and Methods

Figure 2 provides a general flowchart for the framework of the proposed method.
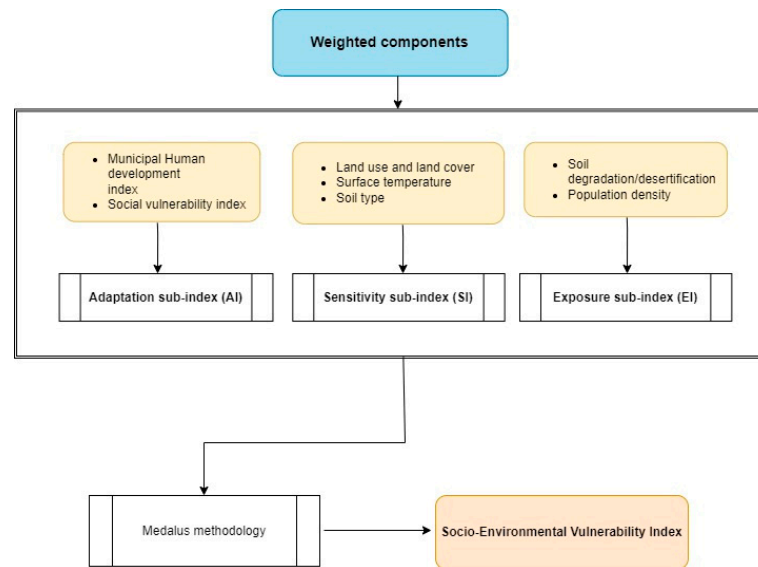
Figure 2. Framework for the socio-environmental vulnerability assessment.

The methodology used to assess socio-environmental vulnerability considers the three components of vulnerability represented by specific sub-indices (Figure 2). Each sub-index is composed of indicators that reflect various components of the environment's vulnerability, such as drought recurrence, fire frequency, soil degradation, and socio-economic aspects. The processes related to physical and social vulnerability are dynamic and, at the same time, interconnected, thus forming a feedback mechanism; for example, the same socio-economic process that causes soil fertility depletion increases the exposure of the population to the negative effects of degradation, which is unable to adapt to the new changes [43]. Previous studies have indicated that the study area is prone to episodic droughts [32,44–47], affected by soil degradation and desertification [11,34,47,48], as well as annual burning [28]. Based on this characterization, and considering the socio-economic characteristics [43], the indicators described in Table 1 were selected.

Table 1. Indicators used to calculate the Socio-Environmental Vulnerability Index (SEVI).

	Indicators	Description	Source
Adaptation sub-index (AI)	Municipal Human development index (in Portuguese, IDHM)	Geometric mean of the normalized indices of the economic, educational, and longevity conditions	[49]
	Social vulnerability index (in Portuguese, IVS)	Arithmetic mean of the sub-indices: IVS Urban Infrastructure, IVS Human Capital, and IVS Income and Labor	[50]
Sensitivity sub-index (SI)	Number of days without rain	Days with no rain (annual average period 2001 to 2018)	[51]
	Land use and land cover	Land-use and land cover classes in the year 2018 based on the MapBiomas—Collection 5.0 mapping	[52]
	Surface temperature	Average temperature (2001 to 2018)	[53]
	Soil type	Soil map	[54]
Exposure sub-index (EI)	Soil degradation/desertification	Based on NDVI images (period 1985 to 2019)	[55]
	Population density	Population density by area (2010)	[56]

To ensure that there was no correlation between the set of selected indicators, we conducted a Pearson correlation analysis to analyze the differences between groups of indicators. Indicators with significant correlation values of ≤0.50 were used. Figure S3 in the Supplementary Materials illustrates the spatial distribution of the set of indicators initially used in this study.

To calculate the number of rainless days, a daily precipitation data set from the CHIRPS project (https://developers.google.com/earth-engine/datasets/catalog/UCSB-CHG_CHIRPS_DAILY#bands (accessed on 15 June 2020)) covering the period from 2001 to 2018 was used. For each image, a binary map indicating areas with precipitation (0) and areas without precipitation (1) was calculated. The absence of daily precipitation was defined as a pixel value of less than or equal to 1 mm day^{-1}. For each year of the series, daily binary maps were summed to create a map showing the total number of rainless days in each pixel for the entire study area. Finally, the average of the annual sums of rainless days was calculated.

The soil degradation/desertification indicator was generated following the methodology described in [55], using the Normalized Difference Vegetation Index (NDVI) to derive predictive indices selected using decision tree analysis. The development of the index was based on the identification of areas following two criteria: (1) the frequency and persistence of exposed soil or areas where frequent loss of natural vegetation cover is occurring; and (2) the frequency and persistence of low annual amplitude of NDVI values ($NDVI_{maximum} - NDVI_{minimum}$), based on the fact that infertile areas do not exhibit vegetation recovery in the rainy season. Therefore, the NDVI time-series were first classified based on the annual $NDVI_{minimum}$ value and the annual NDVI amplitude (defined as $NDVI_{amplitude} = NDVI_{maximum} - NDVI_{minimum}$), resulting in two different maps per year—one with the annual minimum NDVI value and the other with the annual amplitude.

After selection of the indicators detailed in Table 1, they were sub-divided into categorical classes receiving a weight factor from 1 (low) to 2 (high), thus producing eight maps. The weights were assigned based on previous studies [34,57–60]. The range (1, 2) is compatible with the composite Socio-Environmental Vulnerability Index and the formulation of sub-indices, which were estimated in terms of the geometric mean. Many studies utilize averages between components to maintain a synthetic index, as this provides a simple and easily reproducible procedure [37,49–54].

As adaptive capacity presented an inverse relationship, when compared to the other sub-indices (including vulnerability), lower weights (closer to 1) were assigned to values of the indicators within the range of high adaptive capacity, while weights closer to 2 were assigned for the ranges indicating low adaptive capacity. Table S1 in the Supplementary Materials provides details of the weights assigned to the different ranges of each indicator.

Finally, the indicators were standardized and re-projected into the Albers/SAD69 geographic coordinate system, as well as converted to a spatial resolution of 30 m, using the Google Earth Engine Platform.

3.1. Socio-Environmental Vulnerability Index (SEVI)

To estimate the SEVI, we adopted the Environmentally Sensitive Areas (ESA) approach developed under the MEDALUS project [55]. This methodology has been widely used in desertification risk studies [34,59–61], and is based on the multi-factorial integration of environmental variables related to factors such as climate, soil, vegetation cover, and natural resource management [62]. One of the benefits of this approach is that its parameters can be modified according to the data available in each case [63].

The exposure, sensitivity, and adaptive sub-indices were estimated as the geometric means of the indicators, as defined by their corresponding weights, using Equations (1)–(4):

$$EI = (POP \cdot D)^{\frac{1}{2}} \tag{1}$$

Here, *EI* is the exposure sub-index, *POP* is the population density (number of inhabitants/km^2), and *D* represents the area affected by land degradation/desertification (km^2).

$$SI = (SO \cdot T \cdot LULC \cdot NDR)^{\frac{1}{4}} \tag{2}$$

Here, *SI* is the sensitivity sub-index, *SO* is the soil type, *T* is the mean annual temperature (in degrees Celsius), *LULC* is the land use and land cover, and *NDR* is the number of days without rain.

$$AI = (HDMI \cdot IVS)^{\frac{1}{2}} \tag{3}$$

Here, *AI* is the adaptation sub-index; *HDMI* is the geometric mean of the normalized indices of the economic, educational, and longevity conditions; and *IVS* is the arithmetic mean of the sub-indices of the urban infrastructure, human capital, and income and labor. In this case, values closer to 1 indicate high adaptive capacity, while higher values of AI (close to 2) correspond to low adaptive capacity.

Finally, the *SEVI* is calculated as a combination of the previous sub-indices:

$$SEVI = (EI \cdot SI \cdot AI)^{\frac{1}{3}} \tag{4}$$

3.2. Analysis of the Contribution of the Indicators

After generating the SEVI, we performed a sensitivity analysis to assess the contribution of each indicator to the index. For this, we used an Information Value (IV) based on the following equation:

$$IV = \sum_i (Si/N - Ni/N) \cdot lnln\left(\frac{Si/N}{Ni/N}\right) \tag{5}$$

where *IV* is the Information Value for an independent variable, *i* is the index variable, *Si* is the number of land units with the occurrence of a given class of the independent variable, *Ni* is the number of land units without the occurrence of a certain class of the independent variable, and *N* is the total number of land units in the study area.

The IV values can be interpreted according to the assumptions presented in Table 2 [64].

Table 2. Score range for Information Value (IV).

IV	Predictiveness
Less than 0.02	Not useful for prediction
0.02 to 0.1	Weak predictive power
0.1 to 0.3	Medium predictive power
0.3 to 0.5	Strong predictive power
Greater than 0.5	Suspicious predictive power

3.3. Spatial Analysis of Socio-Environmental Vulnerability on Conservation Units and in Rural Properties

In order to analyze the pressure of socio-environmental vulnerability on areas intended for the preservation of natural resources, such as Conservations Units (UCs) [65], buffers of 5, 10, and 15 km adjacent to existing UCs in the study area were generated. This analysis was carried out for two types of UCs: UCs of integral protection, which are areas of natural preservation, only allowing the indirect use of its natural resources; and UCs of sustainable protection, where the exploitation of natural resources is allowed as long as the biodiversity and ecological attributes are not significantly altered [65].

We also analyzed the pressure of socio-environmental vulnerability on rural properties. For this, we used data from the Rural Environmental Registry (CAR), considered the main policy mechanism for environmental management in rural properties in Brazil [66], which

are a set of polygons delimiting private properties (https://www.car.gov.br/publico/municipios/downloads (accessed on 7 April 2021)). We identified a substantial number of discrepancies between the actual property boundaries and those reported in the CAR database. For this reason, before analyzing the spatial pattern of vulnerability, the data were corrected by eliminating inconsistencies in the database: for example, properties that were counted twice, duplicated lines, and so on. After these corrections, our analysis was based on fiscal modules (MF in Portuguese), a unit of measurement that indicates the minimum extension of rural properties considered as economically viable productive areas. In accordance with Article 4 of Act 8629/93, the rural properties, in terms of size, were classified as small (area of less than 4 MF), medium (area between 4 and 15 MF), or large (total area greater than 15 MF) [67].

4. Results and Discussion

Figure 3 illustrates the spatial distribution of each of the sub-indices, as well as the SEVI map. The range used to determine the degree of vulnerability intensity was derived based on the standard deviation.
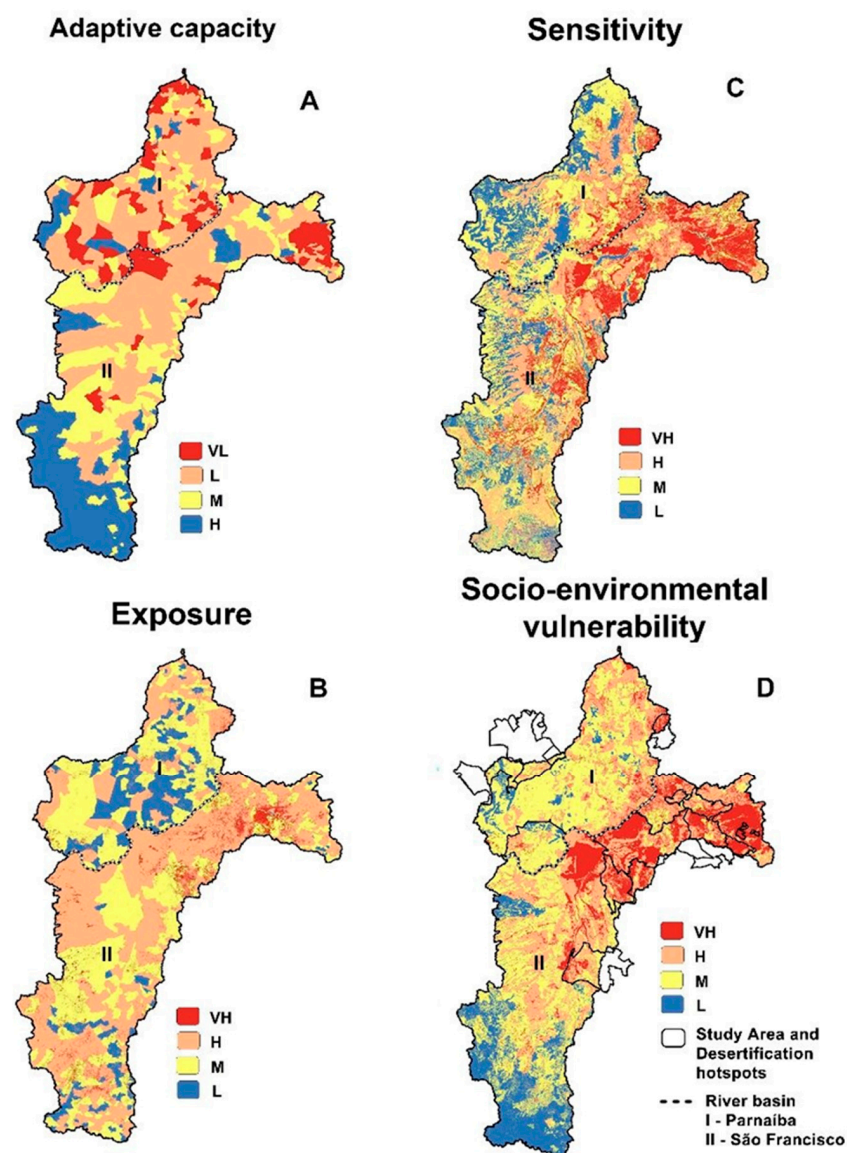
Figure 3. Spatial distribution of sub-indices of adaptive capacity (**A**), sensitivity (**B**), exposure (**C**), and socio-environmental vulnerability (**D**). VH, very high values; H, high values; M, moderate values; VL, very low values; L, low values.

4.1. Adaptive Capacity Analysis

Concerning adaptive capacity, 57% (549,830 km^2) of the study area presented low to very low values. Although adaptive capacity was low in almost this entire area (436,620 km^2), the area with a very low degree of adaptive capacity was 113,209 km^2, with 66,594 km^2 in the Parnaíba river basin and 46,615 km^2 in the São Francisco river basin (Figure 3A). IVS was the indicator that most contributed to the low adaptive capacity. In fact, the Parnaíba river basin region is the poorest in the country and is socially vulnerable [62,63], due to restrictions related to accessing land, health, education, and basic sanitation [68]. People living in social vulnerability and poverty tend to settle in places that are more exposed to risks, without infrastructure for immediate decision making, having negative impacts on the rural population that depends on agriculture and ecosystems [69]. Analyzing Figure 3A, we can observe larger areas with low values of adaptive capacity to the south of the Parnaíba river basin. These areas are close to the Gilbués desertification hotspot, the largest continuous desertified area in Brazil [70].

Thus, to increase the adaptive capacity, infrastructure development and the improvement of economic and social capital should be considered. Preventing the poorest populations from settling in vulnerable areas, improving their quality of life, and restoring and protecting the most vulnerable natural areas are some of the measures that can be considered to improve adaptation [69].

4.2. Exposure Analysis

The São Francisco river basin presented a larger area (62.86%) than the Parnaíba river basin (30.71%) with high and very high values for "exposure". Population density and soil degradation/desertification were the indicators that most contributed to increased exposure.

The Brazilian semi-arid region has a population of 53 million inhabitants and a density of approximately 34 inhabitants per km^2. Rapid population expansion has increased the need for food, fuel, and housing, which increases pressure on natural resources and has been recognized as a driver of soil degradation [11]. The Parnaíba river basin has contributed decisively to the economic development of the Brazilian northeast, at the expense of the over-exploitation of soil and water resources. The lack of water and soil management practices have resulted in soil degradation and siltation of water courses [71]. Previous studies have indicated that the soil degradation process is increasing in the study area [11]; for example, an area of 72,708 km^2 was classified for soil degradation/desertification in the period of 2000 to 2016, with an accelerated trend after 2014, for the northeast region of Brazil within the study area. In the same region, the authors of [47], using the Enhanced Vegetation Index 2 (EVI2) multi-temporal series, observed a 175% increase in potentially degraded/desertified areas in the same period (2000–2016), with a significant increase from 2009 to 2014. In this study, we identified an area of 54,645 km^2 characterized by land degradation/desertification (Figure S4) in Supplementary Materials), distributed between the São Francisco basin (45,465 km^2) and the Parnaíba basin (9180 km^2).

4.3. Sensitivity Analysis

Figure 3C shows that, in the São Francisco basin, the area of sensitivity was higher than that in the Parnaíba basin (341,726 km^2 and 123,666 km^2, respectively). The number of days without rain was the indicator that most contributed to increased sensitivity in the region, which directly influences the risk of forest fires during the dry season. According to the São Francisco River Basin Committee, in 2021, some regions of the country had more than 150 days without rain, with 2100 fires being recorded in the Caatinga—more than twice as many as in 2020, which was 805 fires. Fires are one of the main causes of desertification [10,16,63], deforestation, and climate change.

4.4. SEVI Analysis

The spatial distribution of the SEVI can be seen in Figure 3D. The largest proportion of areas with high and very high vulnerability are concentrated in the São Francisco basin,

presenting a combined area of 337,569 km² (53%), while that in the Parnaíba basin is 121,990 km² (37%). We observed that 40% of high vulnerability values occurring in the São Francisco basin coincided with desertification hotspots officially recognized by the Ministry of the Environment (Figure 3D).

Since the Brazilian colonial period, the São Francisco river basin has been used for extensive cattle raising, mining, and the implementation of large steel industrial action, promoting the clearing of native vegetation from the land for charcoal production. More recently, increases in agricultural production—mainly soybean, corn, and sugarcane–have been observed, leading to intensified land clearing in both Cerrado and Caatinga biomes, and associated to the increased soil erosion rates observed in the São Francisco river basin [71]. Both biomes have been affected by intensive anthropogenic pressure [72,73]. According to [52], in 2021, the deforested area in Cerrado was 500,537 ha (30.2%), while that in Caatinga was 116,260 ha (7%). Land clearing occurred mainly in savanna (66%) and grassland (12%) areas [52]. Consequently, when comparing the SEVI map with the land-use and land cover change map of MapBiomas, the savanna and grassland classes presented the highest vulnerability values (22.86% and 12.22%, respectively).

4.5. Analysis of SEVI in the Conservation Units and Buffer Zones

Figure S5 (in the Supplementary Materials) illustrates the spatial distribution of UCs in the study area, as well as their situation in relation to the SEVI. In the case of the Parnaíba basin, with a greater distance from the UCs of integral protection, the more the area and the intensity under environmental vulnerability increased. We estimated areas of 6339 km² (19.6%) and 7854 km² (19.8%) with high environmental vulnerability when considering buffers of 10 and 15 km, respectively.

In the São Francisco river basin, high vulnerability values occurred within the 5 km buffer, in which approximately 32.4% of the area (12,477 km²) was highly vulnerable, indicating human pressure in the UCs of integral protection. The Lapa Grande State Park (integral protection) is the most well-preserved conservation unit in the region, with much of its area presenting a low degree of vulnerability, 130 km² (84.6%). However, when considering a 10 km buffer, about 28% of the UC (285 km²) already presented moderate vulnerability (Figure 4B).
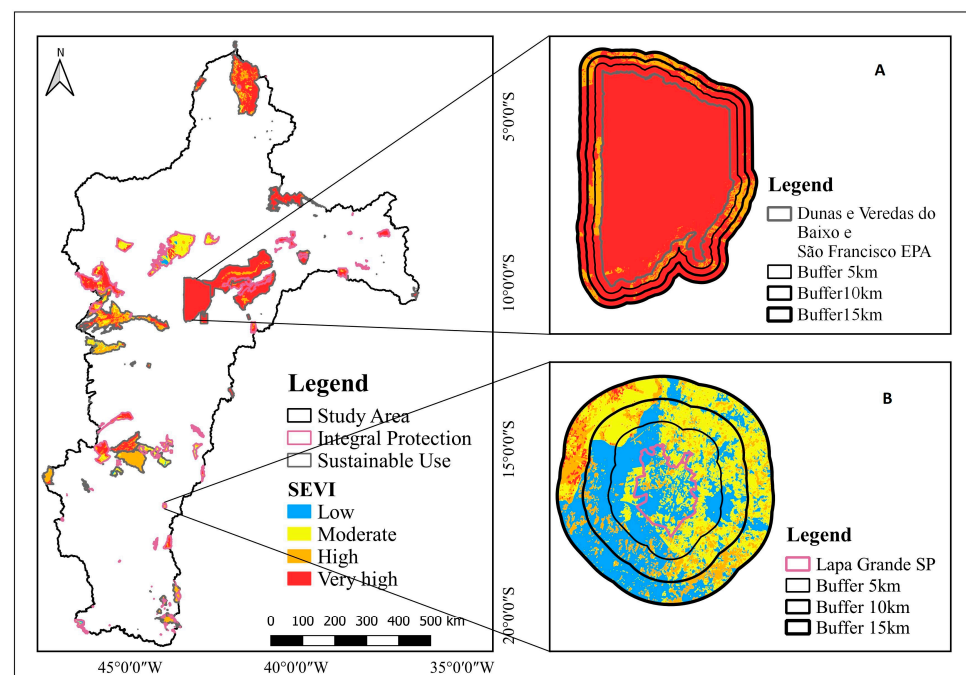
Figure 4. Analysis of SEVI pressure with 5, 10, and 15 km buffers in dunes and veredas of São Francisco basin (**A**) and Lapa Grande State Park (**B**).

Within the UCs under the sustainable use regime, the dunes and veredas (palm marshes) of the São Francisco basin were those that had the largest area characterized by very high environmental vulnerability, 9781 km^2 (95.4%), as shown in Figure 4A.

The creation of recent protected areas in the Caatinga has had a negative effect on the UCs, due to the intensification of land clearing and degradation in the buffer zones [74]. In addition, the low investments into conservation in the Caatinga and social inequalities (e.g., high rates of poverty) have increased the vulnerability of the protected areas. The MapBiomas project estimated that an area of 6737 ha (5.8%) was deforested during 2021 in the Caatinga in UCs [52].

4.6. Analysis of SEVI in Relation to the Size Defined by the CAR

Small rural properties were characterized by high and very high environmental vulnerability (Figure 5), with the majority being located in the semi-arid region. The rural families and smallholders in this region face high social risks due to drought, and migration is often adopted as a survival strategy [13,75]. In areas where there is a predominance of subsistence agriculture, episodic droughts lead to crop failure, land conflicts, and increased poverty [13]. The pressure of environmental vulnerability around rural properties is a critical element affecting the social vulnerability classification and the solution space for adaptation measures. Considering the rural properties classified with high and very high vulnerability, subsistence agriculture is highly affected by the environmental vulnerability, being a key driver of social vulnerability. Thus, adopting diversified and sustainable agricultural systems could improve the resilience of crops and enhance the wellbeing of small-scale farmers. Implementing such practices could reduce the exposure to extreme climatic events and soil degradation in the Cerrado and Caatinga regions [68,69].
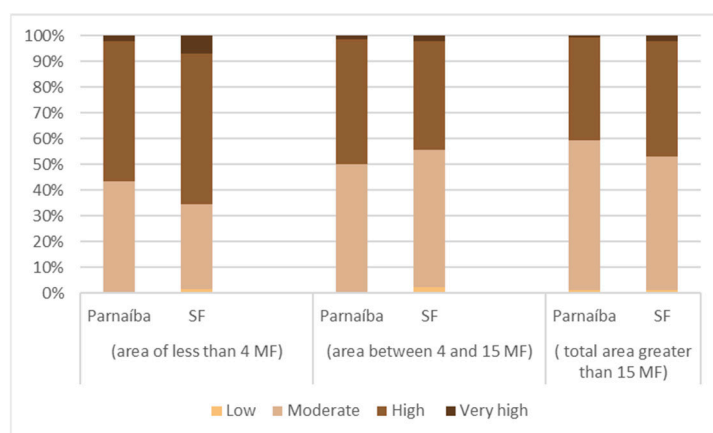
Figure 5. Relationship between the size of rural properties and socio-environmental vulnerability.

5. Conclusions

Several socio-environmental indicators have been developed for Brazil for different purposes, most of them being related to natural threats such as disasters related to hydrogeometeorological phenomena in metropolitan areas [68–70].

In this study, we presented a new approach to characterize and quantify the socio-environmental vulnerability over the Sao Francisco river basin and Parnaíba river basin, integrating socio-demographic indicators with climate and environmental indicators to define the SEVI index.

This study provided an innovative approach for the São Francisco and Parnaíba river basins, using an integrated analysis considering the SEVI to understand the spatial variability of vulnerability in these two large hydrographic basins which are representative of the Cerrado and Caatinga biomes.

The SEVI was applied to the São Francisco and Parnaíba river basins, and we observed that SEVI maps indicated areas of high and very high vulnerability coinciding with hotspots

of desertification and where social and economic development indices were low—mainly to the west of the study regions—indicating that the index is suitable for mapping areas of socio-environmental vulnerability.

The use of adaptation, exposure, and sensitivity indicators to map fragile regions has the potential to contribute effectively to various global programs, such as the World Economic Forum and the United Nations Environment Program, for the restoration of ecological and ecosystem functions. In addition, as a measure of adaptation, Brazil's strategic planning should prioritize areas indicated as being at high or very high vulnerability for long-term landscape restoration and sustainability actions.

We found that adaptive capacity was the main constraint for reducing socio-environmental vulnerability in the Parnaíba basin. At the same time, exposure and sensitivity were the more significant drivers of vulnerability in the São Francisco basin. The high and very high SEVI value areas were also more extensive in the São Francisco basin.

The UCs of integral protection were less vulnerable in the Parnaíba basin than in the São Francisco basin, where spots of high vulnerability were found within a 5 km buffer adjacent to the UCs. Although UCs are effective landscape components for maintaining local ecosystem services and biodiversity, anthropogenic activities in the buffer zones pose significant pressure regarding their integrity. Therefore, extending the areas of UCs while adopting sustainable land management practices in the buffer zones are critical, and it is urgent that management strategies for maintaining vital ecosystem services and to protect those areas are developed.

Our analysis demonstrated that small farms were located in regions of high socio-environmental vulnerability, generally associated with a lack of financial resources and inadequate soil management. Therefore, policies aiming to reduce unequal land distribution are likely to fail if they are not accompanied by the modernization of land management practices to ensure the long-term sustainability of ecosystem services and soil productivity. It is clear that many of the traditional land-use practices of smallholders are depleting natural resources and aggravating poverty.

A major contribution of this study is the identification of indicators of socio-environmental vulnerability, taking into account regional climate, fire, soil degradation/desertification, and social characteristics. This assessment supports programs, such as the National Plan for Adaptation to Climate Change (PNA), in providing information related to the exposure and sensitivity of natural systems, which is frequently disregarded in the formulation of climate mitigation policies.

In addition, the results can help to identify areas characterized by environmental degradation, thus facilitating prioritization of the distribution of financial resources for the recovery of these areas.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15108029/s1, Figure S1. Variables Correlation Matrix; Figure S2. Pearson´s Chi-square tests; Figure S3. Spatial distribution of the set of variables used to compose the sub-indices.; Figure S4. Desertification areas mapped. The areas delineated in purple indicate desertification hotspots recognized by the Brazilian environment ministry; Figure S5. Conservation units colored according to their degree of socio environmental vulnerability within the (A) Parnaíba basin and the (B) São Francisco basin. Table S1: Weight table.

Author Contributions: Conceptualization, R.M.d.S.P.V., J.T., and A.P.M.d.A.C.; methodology, R.M.d.S.P.V., J.T., and A.P.M.d.A.C.; validation, R.M.d.S.P.V., J.T., A.P.M.d.A.C., A.A.B., J.P., Y.F., and F.C.S.; writing—original draft preparation, R.M.d.S.P.V., J.T., A.P.M.d.A.C., A.A.B., J.P., Y.F., F.C.S., L.M.A., and J.O.; writing—review and editing, R.M.d.S.P.V., J.T., A.P.M.d.A.C., J.P., L.M.A., and J.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We are grateful for the support and guidance received during this research project from a number of leaders at the ECOMETRICA and the Foundation for Science, Technology and Space Applications (FUNCATE) for administrative support. This study had support from the Forests 2020 project, part of the UK Space Agency's International Partnership Programme (IPP), funded by the UK's Global Challenges Research Fund (GCRF). We are also grateful for the support of FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo), grant 2017/22269-2. Finally, the second author is also grateful for the support of the National Council for Scientific and Technological Development (CNPq).

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

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