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# Rural Properties Supported by the Carbon Storage and Sequestration Model in the area under the Biome

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**Abstract** The carbon storage and sequestration are impacted by land use/land cover (LULC) changes, being an important ecosystem service, responsible for climate regulation. Through InVEST's Carbon Storage and Sequestration model, combined with LULC and declared areas in Cadastro Ambiental Rural (CAR) in Rondônia State, a current and two future scenarios of carbon pools with secondary forest of 5 and 80 years were created in the Amazon biome. The declared areas have a predominance of forest formation and pasture, and the pools with the highest gains in tons of carbon were aboveground and belowground biomass, with a total gain of 2% and 7%, respectively, concerning the current one. Thus, it emphasizes the importance of command-and-control tools and forest recovery incentives.

**Keywords:** Carbon Pools, Secondary Forest, Future Scenario, Model Carbon.

# 1 Introduction

The carbon sequestration and storage dynamics are intrinsically linked to changes in land use/land cover (LULC) [IPCC, 2006] since forests, grasslands, and other terrestrial ecosystems collectively store more carbon than the atmosphere [Lal, 2004], as well as being an important ecosystem service for climate regulation.

Carbon stocks can be assessed through different pools, such as aboveground biomass (AGB), which comprises forests and plantations [Baccini *et al*., 2012; Fearnside, 1997; Saatchi *et al*., 2007], the portion of the biomass belowground (BGB), composed of roots [Kuyah *et al*., 2012], the soil carbon pool (SOC) [Ferreira *et al*., 2023] and the pool composed of litter and dead matter (LDM) [Chambers *et al*., 2000]. To quantify and understand the dynamics of carbon pools, it is necessary to examine them in combination with the landscape [IPCC, 2014].

Thus, the Brazilian Amazon biome, which covers nearly 61% of Brazilian territory, supports various ecosystem services, particularly climate regulation [Saatchi *et al*., 2007]. It is the world's largest repository of forest carbon [FAO, 2010]. However, the conversion of tropical forests to agricultural use has been observed [Nepstad *et al*., 2014], and it has negative consequences, disrupting biodiversity and increasing greenhouse gas emissions [Aragão *et al*., 2018].

Application of regulations related to land, command and control instruments, assists in monitoring and understanding its LULC [Domeher and Abdulai, 2012], agricultural mainly concerning activities, Cadastro 2017, Ambiental such Rural as the (Rural Environmental Registry – CAR) [Jung *et al*., 2022]. Combining this regulation with the management of ecosystem services contributes with landscape analysis, mapping pathways reducing deforestation, and motivating sustainability in agriculture.

Secondary forests have great potential as carbon sinks, encouraging forest restoration in these areas declared Legal Reserves and Permanent Preservation, [Matos *et al*., 2020]. These secondary forest areas with natural regeneration processes have rapid growth and a high rate of primary productivity, the potential for biomass accumulation, and soil recovery [Fearnside, 2018]. These factors contribute positively to its role as a carbon pool [Aguiar *et al*., 2016]. Therefore, the main objective of this work was to quantify carbon stock and sequestration for Rondônia State within CAR declared areas, comparing current and future scenarios of forest restoration in Legal Reserve and Permanent Preservation areas.

# 2 Material and Methods

## 2.1 Study Area and Land Use/Land Cover

The study area is Rondônia, State with a total area of 237,646.10 km² (Figure 1A) under the domain of the Amazon Biome [IBGE, 2016].

The territorial limit is from the Brazilian Institute of Geography and Statistics (IBGE), as well as the limit of the Amazon biome, which was standardized for IBGE Conic Albers projection and SIRGAS 2000 datum as a metric coordinate system [IBGE, 2016].

The LULC data (Figure 1B) was obtained from the project MapBiomas, collection 7 (2021) with a spatial resolution of 30 m, produced from pixel-by-pixel classification of images from Landsat satellites and obtained through Google Earth Engine platform [Souza Junior *et al*., 2020].

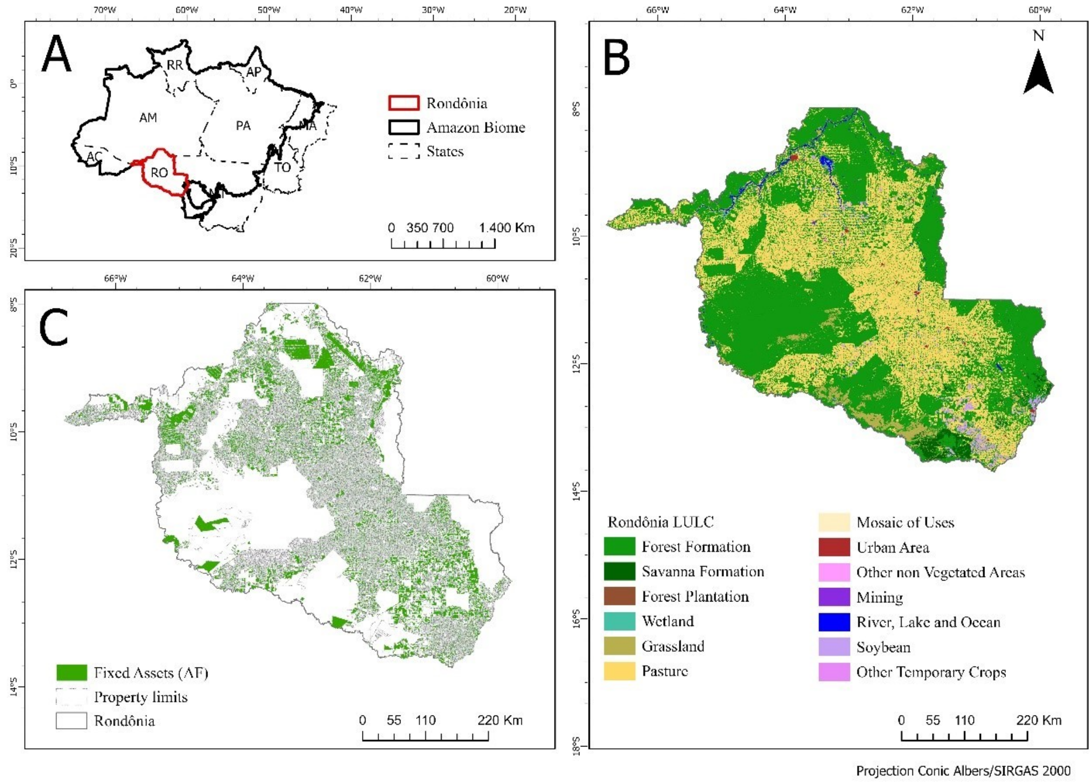


**Figure 1.** (A) Rondônia State localization in Brazilian Amazon Biome (B) Rondônia LULC and (C) CAR areas in Rondônia State..

## 2.2 Cadastro Ambiental Rural (Rural Environmental Registry – CAR)

The data on limits to rural properties in the CAR were obtained from the Embrapa Territorial database, which curated and consisted the information from the Brazilian Forest Service (SFB) through SICAR (National Rural Environmental Registry System) in 2021 (Figure 1B) [Brasco and Carvalho, 2022].

From the CAR data we extracted the areas declared as legal reserve and permanent preservation, which are part of the fixed assets (FA) (Figure 1C), i.e. areas that, according to the Forest Code, must maintain vegetation, with some exceptions [BRASIL, 2012].

Furthermore, the remaining property area corresponds to the Productive Area, which is the portion of the property available for agroforestry activities.

## 2.3 Carbon Pools

The Carbon Storage and Sequestration model within the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) software manages ecosystem services by calculating the amount of carbon stored in different areas and comparing different scenarios [Natural Capital Project, 2024]. This model requires a LULC map and a corresponding table with values of carbon pools in each LULC, to estimate the amount of carbon (tons per hectare) in different natural pools such as aboveground biomass (AGB), belowground biomass (BGB), organic soil (SOC), and litter with dead organic matter (LDM).

Areas classified as forest formation, savannah formation, wetlands, and grassland, we used the weighted average between the area and the carbon values found in different vegetation types, as outlined in the Reference Report of the Third Brazilian Inventory of Anthropogenic Emissions and Removals of Greenhouse Gases [MCTI, 2015]. When transitioning between different vegetation types, we used the carbon values average. Secondary forests, including future scenarios, we used values described by Fearnside and Guimarães [1996] for secondary forests of 5 and 80 years in the Amazon Biome.

Agriculture values considered the specific pools values of cultures such as temporary crops [Bonini *et al*., 2018], soy [Alliprandini *et al*., 2009], sugar cane [Cerri *et al*., 2013], silviculture [MCTI, 2015], pasture [Lemos *et al*., 2016], perennial crops [Pavlis and Jeník, 2000]. For the mosaic class agriculture and livestock were obtained through the average estimates used for temporary crops and pasture.

The 0-30 cm soil organic carbon pool (SOC) was obtained from Embrapa Soils maps [Marques *et al*., 2021]. For this purpose, the sum of the 0-5 cm, 5-15 cm, and 15-30 cm layers was made, and then the cut-out for each class of use so that the average of each LULC class was obtained and tabulated. As output, we obtained the estimates of each pool, total carbon and delta of the scenarios in a matrix format.

## 2.4 Current and Future Scenarios

Three scenarios were compared, their carbon stock and sequestration values, which were obtained from LULC data, and the carbon pool values. The first scenario, the current one, contemplates the carbon stocks of the existing LULC MapBiomas collection 7 of 2021.

**Table 1.** Estimated carbon stock (total, in aboveground living biomass, in belowground living biomass, in litter and dead organic matter, and in the 0-30 cm deep soil layer) in land use/land cover classes in Rondônia State.

| **Current Scenario (2021)** | | | | | | |
|---|---|---|---|---|---|---|
| **Rondônia** | **SOC** | **AGB** | **BGB** | **LDM** | **Area (km²)** | **Percentage (%)** |
| Not Observed | 0 | 0 | 0 | 0 | 1.27 | 0 |
| Forest Formation | 37.74 | 93.41 | 10.39 | 11.97 | 132,385.1[illegible] | 55.71 |
| Savannah Formation | 36.8 | 67.24 | 13.63 | 17.99 | 4,440.13 | 1.87 |
| Silviculture | 43.9 | 30.76 | 18.16 | 5.44 | 7.76 | 0 |
| Wetland | 38.1 | 74.22 | 14.26 | 18.89 | 309.69 | 0.13 |
| Grassland | 36.14 | 82.67 | 15.64 | 20.48 | 7,512.10 | 3.16 |
| Pasture | 36.68 | 4.1 | 2.9 | 1.2 | 86,355.09 | 36.34 |
| Mosaic Agriculture and Pasture | 44.7 | 2 | 0.97 | 0.85 | 18.71 | 0.01 |
| Urbanized Area | 37.3 | 0 | 0 | 0 | 495.42 | 0.21 |
| Other non-vegetated areas | 44.96 | 0 | 0 | 0 | 25.97 | 0.01 |
| Mining | 35.7 | 0 | 0 | 0 | 132.36 | 0.06 |
| River, Lake, and Ocean | 0 | 0 | 0 | 0 | 2,258.90 | 0.95 |
| Soy | 38.24 | 8.9 | 2.2 | 0 | 3,186.03 | 1.34 |
| Other Temporary Crops | 38.2 | 2.1 | 0.04 | 0.5 | 517.56 | 0.22 |
| | | | | **TOTAL** | 237,643.1[illegible] | 100 |
| **Future Scenarios** | | | | | | |
| Secondary Forest 5 years | 37.74 | 33.2 | 13.8 | 11.97 | 994.97 | 23.88 |
| Secondary Forest 80 years | 37.74 | 143.4 | 28.5 | 11.97 | 994.98 | 23.89 |

The future scenarios (5 and 80 years) simulate the restoration of declared areas as Fixed Assets (AF) in the CAR with secondary native vegetation. To achieve this, the pixels within the AF areas in the LULC data were reclassified, and the carbon reservoir values for secondary vegetation aged 5 and 80 years were inserted [Fearnside and Guimarães, 1996].

### 2.5 InVEST model

The InVEST Software is a set of free, open-source software models used for evaluating and determining the value of the natural resources that sustain human life. One of the models, the Carbon Storage and Sequestration model, calculates the current amount of carbon stored in a landscape and estimates the value of the sequestered carbon over time [Natural Capital Project, 2024]. This simple carbon model only requires four carbon pools and a land cover map as inputs. It maps carbon pool values to the land cover map but does not include biophysical complexities or dynamics. In this context, it is used secondary data, such as data from biomass reservoirs above and belowground and dead matter and litter extracted from the third Report 'National Inventory of Anthropic Emissions and Removals of Greenhouse Gases' [MCTI, 2015], which uses methodologies suggested by IPCC [2006].

## 3 Results and Discussion

### 3.1 LULC and Carbon Pools

The forest class occupies the most prominent area and naturally stores the most significant volume of carbon. The most expressive aboveground biomass pool is native forests with values between 93.41 t $ha^{-1}$ and 67.24 t $ha^{-1}$. These are highly affected areas by human actions contemplating the classes of forest formation, grassland, wetland, and savannah formations [Berenguer *et al*., 2014]. In agricultural production, the AGB has values of 8.9 t $ha^{-1}$ for soybeans, 4.1 t $ha^{-1}$ for pasture, and 2.1 t $ha^{-1}$ for temporary crops (Table 01).

The belowground biomass behaves similarly to AGB, showing higher values in areas with abundant vegetation, ranging from 18.16 t $ha^{-1}$ to 10.39 t $ha^{-1}$ as it is directly related to forest roots. The BGB maintains itself after fires and deforesting and, being below ground, tends to decompose more slowly, even in these situations [Aguiar *et al*., 2012].

The compartment of litter and dead matte is found only in forest formations and agriculture, and it presents values between 20.98 $ha^{-1}$ and 0.50 $ha^{-1}$, respectively. In Rondônia, the soil organic carbon pool ranges from 35.70 $ha^{-1}$ to 44.96 $ha^{-1}$ for different classes.

**Table 2.** Land use and land cover (LULC) classes and areas in the state of Rondônia.

| **Areas** | **Area (km²)** | **AreaRO (%)** | **AreaCAR (%)** |
|---|---|---|---|
| Area of the State of Rondônia | 237,646.10 | 100% | - |
| Registered Properties | 122,735.20 | 51.65% | 100% |
| Productive Area | 84,340.20 | 35.49% | 68.72% |
| Fixed Assets (FA) | 38,395.20 | 16.16% | 31.28% |
| | **Fixed Assets(FA)** | | |
| Legal Reserve | 32,248.90 | 13.57% | 26.28% |
| Permanent Preservation Area | 6,146.30 | 2.57% | 5.01% |
| **LULC classes within the FA** | **Area (km²)** | **PercentageFA (%)** | |
| Forest Formation | 26,792.10 | 69.78% | |
| Pasture | 9,762.98 | 25.54% | |
| Grassland | 748.23 | 1.96% | |
| Savannah Formation | 597.26 | 1.56% | |
| Soy | 124.90 | 0.33% | |
| River, Lake, and Ocean | 104.14 | 0.27% | |
| Other Temporary Crops | 36.36 | 0.10% | |
| Wetland | 28.00 | 0.07% | |
| Mining | 17.45 | 0.05% | |
| Non observed | 2.80 | 0.01% | |
| Mosaic Agriculture and Pasture | 1.78 | 0.00% | |
| Other non-vegetated areas | 1.43 | 0.00% | |
| Silviculture | 1.23 | 0.00% | |
| Urbanized Area | 0.76 | 0.00% | |

## 3.2 Areas of the Rural Environmental Registry (CAR)

The properties declared in CAR cover an area of 122,735.40 km², which is equivalent to 51.65% of Rondônia state. The Legal Reserve accounts for 26.28% of the property areas, and the Permanent Protection Area covers 5.01%, as shown in Table 02. Forest formation corresponds at 69.78%, followed by pasture at 25.54%, and other LULCs make up 4.35%. The CAR, as suggested by [Jung *et al*., 2017], could be a promising approach to reducing deforestation. The expansion of livestock in the CAR areas is leading to a decrease in carbon stocks, due to changes in LULC, which directly affect gas emissions. It underscores the necessity to mitigate and adapt to climate change through integrated and low-carbon production systems, as highlighted by MAPA [2012].

## 3.3 Current Scenario and Futures

Figure 02 illustrates that in the 5-year future scenario, there will be an increase in carbon stocks, depicted in yellow. Moreover, in the 80-year scenario, there will be a more uniform and robust secondary forest, represented by green, spreading across settlement areas and pasture lands.

The regeneration of secondary forests can help reduce gas emissions, as discussed by Heinrich *et al*. [2021]. However, the loss of old-growth forests remains the most critical factor in determining the carbon balance in the Brazilian Amazon [Poorter *et al*., 2016].

The native vegetation of the state is crucial for various aspects, including pools AGB, BGB, litter, and dead matter, which play a significant role in the overall carbon stock and the conservation of species [Nelson *et al*., 2008]. It is important to advocate for public policies related to ecosystem services [BRASIL, 2012, 2021] that contribute systematically to the conservation and preservation of forests. This can lead to an increase in carbon stocks, especially in the AGB pool, even though they are lower than natural forests [Nave *et al*., 2019].

When we look at the current and future total carbon stock, we have 2,720 million tC, 2,774 million tC (in 5 years), and 2,906 million tC (in 80 years), indicating that reforestation of declared areas as legal reserves and permanent preservation areas could result in a gain of 54 thousand tC/ha. This is equivalent to 2% increase in the total existing carbon today. Additionally, in areas with native vegetation, there would be an increase of 4%, with secondary forests contributing to the recovery of carbon stocks [Bustamante *et al*., 2019].

Furthermore, the presence of these forests contributes to the protection and maintenance of water resources [Filoso *et al*., 2017] as well as to the preservation of biodiversity [Matos *et al*., 2020].

In addition, for the Future Scenario of 80 years, the difference compared to the Current Scenario would be 185 thousand tC, which is almost 7% of the gains in carbon pools achieved through the implementation of the CAR and the regeneration of secondary forests. According to Heinrich *et al*. [2021], in Rondônia state, the age of the forest is the most important factor for the ability of forests to sequestration of carbon from the atmosphere.

These preservation areas demonstrate the importance of secondary forests in the context of carbon sequestration, environmental preservation, biodiversity conservation, and ecosystem services [Bungenstab *et al*., 2019]. Renewing secondary forests is beneficial, providing essential ecosystem services such as soil protection, increased fertility, and timber and non-timber resources.

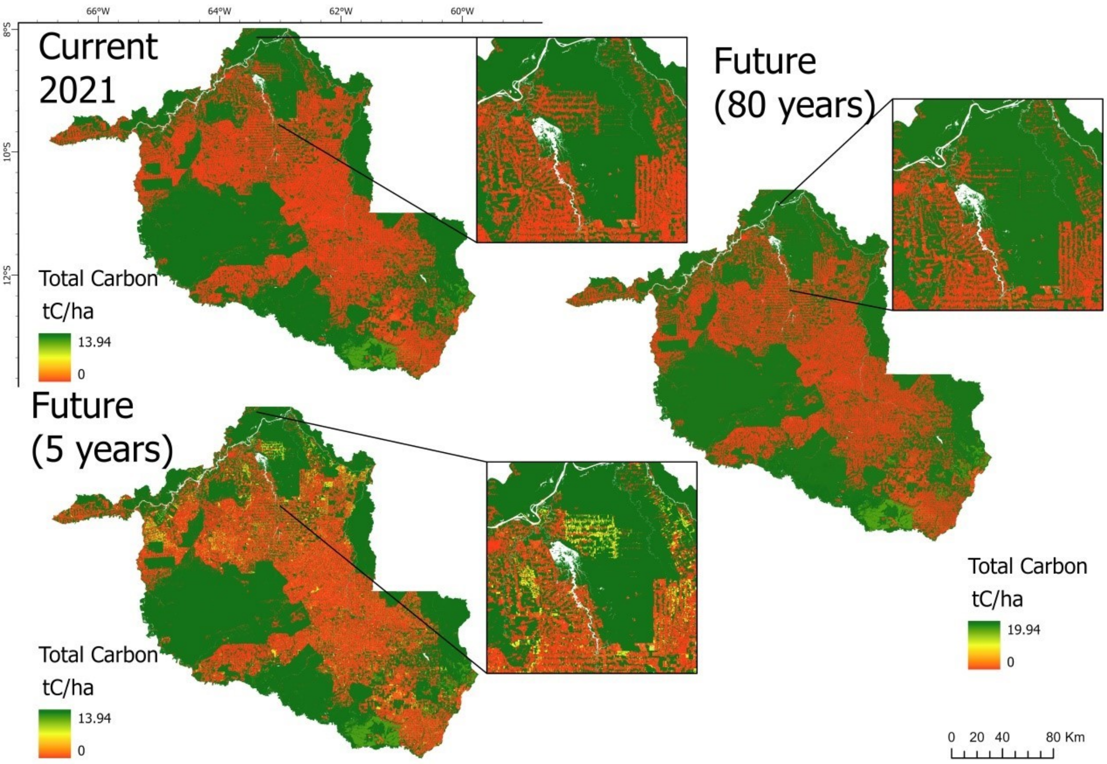


**Figure 2.** Current, Future 5 years and 80 years scenario for carbon stocks in Rondônia.

The presence of secondary vegetation can also contribute to small-scale agricultural systems, promoting the concentration of this cover and enhancing the integration of agricultural practices with environmental conservation. However, the expansion of industrial agriculture can pose a threat to the regeneration of secondary forests, as it can lead to the conversion of these areas to permanent uses such as monocultures, highlighting the importance of policies and practices that encourage the preservation and restoration of these ecosystems [de Carvalho *et al*., 2019].

# 4 Conclusions

Overall, keeping designated areas as Fixed Assets (FA), including the legal reserve and permanent protection area outlined in Brazilian Forest Code in Rondônia, would result in benefits as carbon sinks.

Another important finding is the significant carbon stocks of the AGB pool, which represents the biomass of the forest canopies in the state. Therefore, it is crucial to prioritize monitoring these areas for their role in regulating the climate and recognize the significance of secondary forests as carbon stocks.

Using the InVEST Carbon Storage and Sequestration model, we can better understand LULC changes and the potential of secondary forests, which can inform public policies related to carbon emissions and even contribute to regulating the carbon market.

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