Carbon Storage and Sequestration in Amazonian Rural Properties Supported by the Carbon Storage and Sequestration Model

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Abstract. *Changes in land use and land cover in the Amazon Biome directly impact carbon reservoirs, making it a crucial ecosystem service for climate regulation. Therefore, quantifying and spatializing these reservoirs is essential. Using the Carbon Storage and Sequestration model from InVEST, combined with Land Use and Land Cover (LULC) data and areas declared in the Rural Environmental Registry (CAR) in the state of Rondônia, we created a current scenario and a future scenario with 5-year-old secondary forest. Forest formation and pasture predominated in the declared areas, and the reservoirs with the most significant gains in carbon tons were Aboveground Biomass (AGB) and Belowground Biomass (BGB), resulting in a total gain of 2% compared to the current state. This underscores the importance of command-and-control tools and incentives for forest restoration.*

1. General Information

Amazon biome occupies a vast portion of Brazilian territory (61% of the country), making it the world's largest repository of forest carbon [FAO, 2010]. It stores significant carbon (C) above and belowground, serving as a crucial ecosystem service for climate regulation [Saatchi et al., 2007]. The extensive land cover change driven by rural development has been responsible for converting tropical forests into agricultural landscapes [Macedo et al., 2012] [Nepstad et al., 2014], negatively impacting biodiversity composition within this ecosystem and increasing greenhouse gas emissions [Aragão et al., 2018].

Managing ecosystem services such as carbon stock in landscape is fundamental for climate regulation. The dynamics of carbon sequestration and storage are intrinsically linked to changes in land use and land cover (LULC) [IPCC, 2006] [Pagiola, 2008] [Stern, 2007]. Forests, pastures, and other terrestrial ecosystems collectively store much more carbon than the atmosphere [Lal, 2004].

This carbon stock can be assessed through different reservoirs, including aboveground biomass, which encompasses forests and plantations [Baccini et al., 2012] [Houghton et al., 2001][Potter, 1999]. Belowground biomass, consisting of roots [Kuyah et al., 2012], soil carbon reservoir [Ferreira et al., 2023], and the reservoir composed of dead organic matter and litter, all of which provide essential ecosystem services for climate regulation [Chambers et al., 2000]. A landscape examination and land use analysis are required to account for these carbon pools [IPCC, 2006].

Deforestation and wildfires results in carbon stock losses in land use and changes in land cover in the Amazon biome [Nogueira et al., 2015]. Therefore, implementing land-related regulations, such as Rural Environmental Registry (CAR), helps monitor and understand LULC, especially concerning agricultural activities [Jung et al., 2022, 2017]. Combined with ecosystem service management, these command-and-control instruments aid landscape analysis and developing strategies to reduce deforestation, promoting sustainability in agriculture.

The main objective of this study is to quantify carbon stock and sequestration for the state of Rondônia within the areas declared in the CAR, comparing the current scenario with a future scenario of forest restoration in Legal Reserves and Permanent Preservation areas.

2. Material and Methods

The study area is the state of Rondônia, with a total area of 237,646.10 square kilometers (Figure 1). It is within the Amazon and Cerrado biomes [IBGE, 2019]. The territorial divisions obtained from the Brazilian Institute of Geography and Statistics (IBGE) include the boundaries of the Amazon biome and other limits. These boundaries were standardized for the IBGE Conic Albers projection and SIRGAS 2000 datum using a metric coordinate system.

The land use and land cover data were sourced from the MapBiomas Project Collection 7, with data from 2021 and a spatial resolution of 30 meters. These data were generated through pixel-by-pixel classification of Landsat satellite images, and access to data is facilitated through the Google Earth Engine platform [Souza et al., 2020].

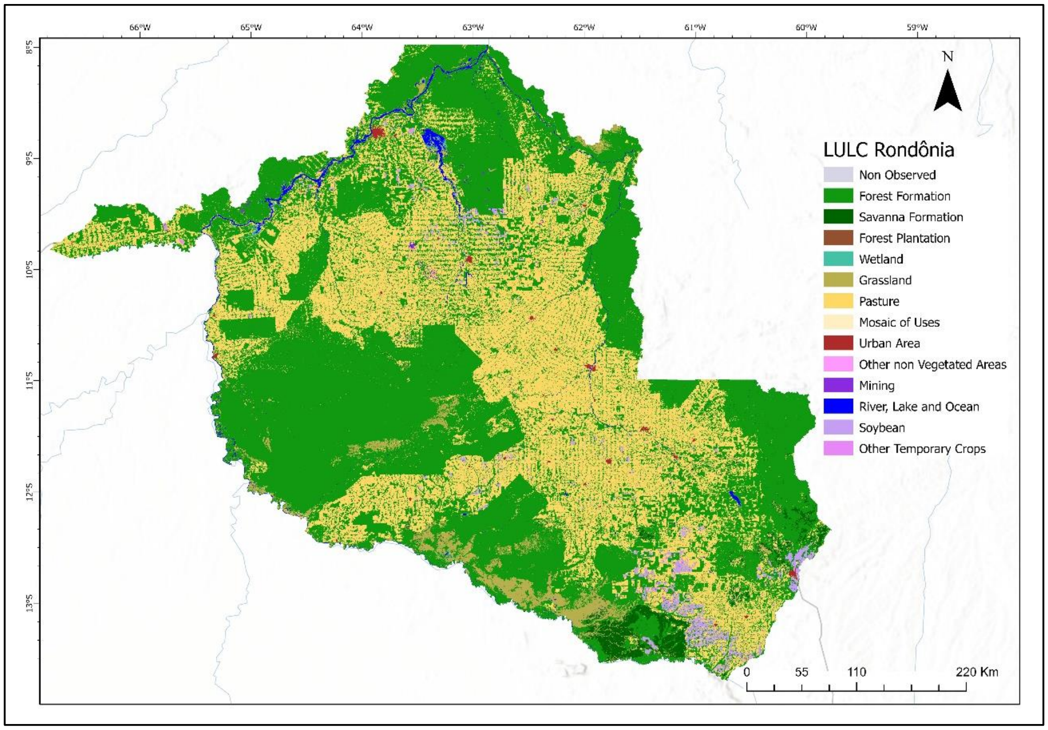

Figure 01: Boundaries and land cover of Rondônia, Brazil.

2.2. Carbon Pools

Carbon Storage and Sequestration model within the Integrated Valuation of Ecosystem Services and Tradeoffs - InVEST software aims to support ecosystem service management by quantifying existing carbon pools and their spatial distribution and comparing different scenarios. The model requires estimates of carbon quantities for the aboveground biomass, belowground biomass, organic soil, dead organic matter, and litter reservoirs, expressed in metric tons per hectare (t/ha). Inputs for the InVEST tool [Mandle and Natural Capital Project, 2023] included LULC maps and the carbon storage quantities (in CSV format), while the outputs consist of raster files for each reservoir, total carbon, and delta between scenarios.

Estimated values for the aboveground and belowground biomass reservoirs, dead organic matter, and litter for forest formation, savanna, wetland, and swamp areas, represented by land cover classes 3, 4, 11, and 12, respectively, were obtained through a weighted average. This approach considers the area covered by each land cover type and the specific carbon values associated with each biome, resulting in an adjusted value. Carbon pool values were extracted from the Reference Report of the Third Brazilian Inventory of Anthropogenic Greenhouse Gas Emissions and Removals [MCTI, 2015] for each specific biome [IBGE, 2019]. Average values of corresponding biomes were calculated for areas with transitional land uses and vegetation types.

To create a future scenario, carbon values for secondary forests in the Amazon Biome at five years were used, as described by Fearnside [1996].

Carbon values for agriculture were obtained from various sources for different crops, including temporary crops [Bonini et al., 2018], soybean [Alliprandini et al., 2009] [Carvalho et al., 2007], sugarcane [Cerri et al., 2013] [Oliveira et al., 2010], silviculture [MCTI, 2015], pasture [Lemos et al., 2016] [Santos, 2003], and perennial crops [Pavlis & Jeník, 2000]. For the mosaic land cover class of agriculture and livestock, estimates were obtained by averaging values used for temporary crops and pasture.

The organic soil carbon reservoir (0-30 cm) (SOC) was derived from Embrapa Solos maps [Marques et al., 2021]. The SOC values were obtained by summing the layers from 0-5 cm, 5-15 cm, and 15-30 cm and then cutting them for each land use class. The average for each LULC class was calculated and tabulated.

2.3. Rural Environmental Registry

The rural property data for the Rural Environmental Registry (CAR) were obtained from the Embrapa Territorial database, which curated and validated the information provided by the Brazilian Forest Service (SFB) through the National Rural Environmental Registry System (SISCAR) in the year 2021 [Brasco, A. M.; Carvalho, 2022]. From this database, the following areas were extracted: Legal Reserve (RL) and Permanent Preservation Area (APP), which are part of the Fixed Assets (AF), as well as the productive area (AP), which represents the portion of the property available for agricultural and livestock activities (Table 01).

Table 01: Areas declared in the Rural Environmental Registry in the State of Rondônia.

Areas	Area (km²)	$Area_{RO}$(%)	$Area_{CAR}$(%)
State of Rondônia Area	237,646.10	100%	-
Registered Properties	122,735.40	51.65%	100%
Productive Area (AP)	84,340.20	35.49%	68.72%
Fixed Assets (AF)	38,395.20	16.16%	31.28%
Fixed Assets (AF)			
Legal Reserve	32,248.90	13.57%	26.28%
Permanent Preservation Area (APP)	6,146.30	2.57 %	5.01%

2.4. Current and Future Scenario

Two scenarios were created using land use data from MapBiomas and carbon reservoir values to compare and obtain carbon sequestration values. The current scenario encompasses carbon stocks within the existing land cover classes of Collection 7 (2021), while the future scenario projects different land uses and carbon stocks while complying with current environmental regulations.

The future scenario involves converting the entire Fixed Assets (AF) area into secondary native vegetation, as per Fearnside (1996), while leaving the productive area (AP) unchanged. This conversion will be achieved through pixel reclassification within the Fixed Assets areas, following the Forest Code's requirement these areas be composed of native vegetation.

3. Resulted and Discusses

3.1. Land Use and Land Cover and Carbon Pools

The state of Rondônia exhibits 13 land use and land cover classes, with the predominant class being forest formation, covering 55.71% of the total area, followed by the pasture class at 36.34% (Figure 02). The agricultural classes (soybean and temporary crops) represent 1.57% of the total area. The urbanized area of the state corresponds to 0.21% of its territory, ranking ahead of only Sergipe, Roraima, Acre, and Amapá [IBGE, 2019b].

Values for carbon stocks in the four assessed reservoirs, measured in tons per hectare (t/ha), were obtained from the literature for each land use and land cover class, as presented in Table 01. Aboveground biomass reservoir (AGB) is most significant in native forests, with values ranging from 93.41 t/ha to 67.24 t/ha for the land cover classes of forest formation, grassland, wetland, and savanna formation; it is highly affected by anthropogenic activities [Berenguer et al., 2014]. In the agricultural production sector, the reservoir shows 8.9 t/ha values for soybeans, 4.1 t/ha for pasture, and 2.1 t/ha for temporary crops.

The belowground biomass compartment (BGB) follows a similar pattern to AGB, being more pronounced in vegetation-rich classes, ranging from 18.16 t/ha to 10.39 t/ha. Since it is directly related to tree roots and remains below ground after fires and clear-cutting, it decomposes more slowly, even in such situations [Aguiar et al., 2012]. The dead organic matter and litter compartment, present only in forest formations and agriculture, ranges from 20.98 t/ha to 0.50 t/ha, respectively. The organic soil carbon reservoir (SOC) ranges from 35.70 t/ha to 44.96 t/ha for the classes in Rondônia.

Table 02: Estimated carbon stock (total, in aboveground live biomass, in belowground live biomass, in dead biomass - litter - and in the soil layer at a depth of 0-30 cm) in land use and land cover classes in the state of Rondônia.

Rondônia (RO)	LULC	Carbon Pools (ton/ha)				Area (km²)	Percentual (%)
		Soil organic carbon 0-30 cm (SOC)	Aboveground biomass (AGB)	Belowground biomass (BGB)	Litter and Dead Wood		
Non-Observed	0	0	0	0	0	1.27	0.00
Forest Formation	3	37.74	93.41	10.39	11.97	132,385.11	55.71

Savanna Formation	4	36.8	67.24	13.63	17.99	4,440.13	1.87
Forest Plantation	9	43.9	30.76	18.16	5.44	7.76	0.00
Wetland	11	38.10	74.22	14.26	18.89	309.69	0.13
Grassland	12	36.14	82.67	15.64	20.48	7,512.10	3.16
Pasture	15	36.68	4.1	2.9	1.20	86,355.09	36.34
Mosaic of Uses	21	44.70	2.00	0.97	0.85	18.71	0.01
Urban Area	24	37.30	0	0	0	495.42	0.21
Other Vegetated Areas	25	44.96	0	0	0	25.97	0.01
Mining	30	35.70	0	0	0	132.36	0.06
River, Lake and Ocean	33	0	0	0	0	2,258.90	0.95
Soybean	39	38.24	8.90	2.20	0	3,186.03	1.34
Other Temporary Crops	41	38.20	2.10	0.04	0.50	517.56	0.22
					TOTAL	237,646.1	100.00
Future Scenario							
Secondary forest (5years)	55	37.74	33.2	13.8	11.97	-	-

3.2. Rural Environmental Registry Areas

Regarding managing and planning changes in LULC, the Rural Environmental Registry (CAR) is an essential tool. Its purpose is to integrate information from rural properties for control, monitoring, environmental and economic planning, and combating deforestation. It enables the understanding of the location of properties (Figure 04) and, when combined with other databases, facilitates the management of ecosystem services [Jung et al., 2022][Tambosi et al., 2015].

Declared property areas cover 122,735.40 square kilometers, equivalent to 51.65% of the state of Rondônia. The Legal Reserve (RL) totals 26.28% of the declared property areas, and Permanent Preservation Areas (APP) cover 5.01%, as shown in Table 02. Since Legal Reserves can include APP, the concept of "Fixed Assets" (AF) has been created to consider both areas. According to Law 12,651/2012, every rural property must maintain an area with native vegetation cover. In the case of the Legal Amazon, this requirement is 80% of the property in forest areas. It is important to note that Rondônia has areas within the Cerrado biome where the Legal Reserve requirement is 35%. It is worth mentioning that there are consolidated areas and excess areas for small properties.

The land use and land cover classes within the Fixed Assets predominantly consist of forest formation at 69.78% and pasture at 25.43%, with other uses accounting for 4.79%. Presents a promising pathway to reduce deforestation through CAR [Jung et al., 2017]. The expansion of cattle ranching is observed within CAR areas, leading to a reduction in carbon stocks through LULC changes, directly impacting greenhouse gas emissions. Consequently, mitigate and adapt to climate change through integrated and low-carbon emission production systems is needed.

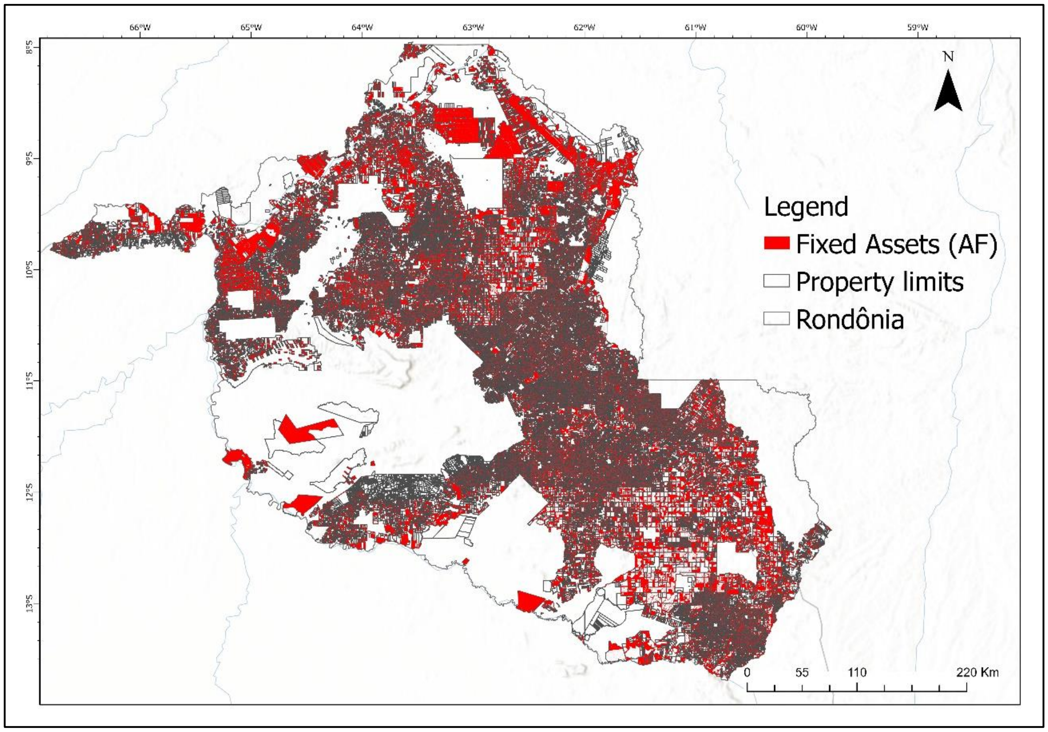

Figure 04: Limits of the CAR areas and area of Fixed Assets (AF) in the state of Rondônia.

3.3. Current and Future Scenario

Trough data from the reservoirs (Table 01) and the LULC map (Figure 02) it was possible to calculate the total carbon quantity for the current (2021) and future (5 years) scenarios for each carbon pool (Table 04), along with spatialization of the scenarios (Figure 05). The future scenario was created based on secondary forest values in the Amazon Biome provided by Fearnside (1996). It represents a future scenario for five years of secondary forests (Table 01) in the Fixed Assets area where there were no existing forest formations, savannas, grasslands, wetlands, and swampy areas (classes 03, 04, 11, and 12), excluding urban areas and rivers, lakes, and oceans (classes 24 and 33). In Figure 05, the future scenario shows that the carbon gain, represented by the increased yellow shading, is uniform throughout the state and extends into areas with settlement characteristics and pasture areas.

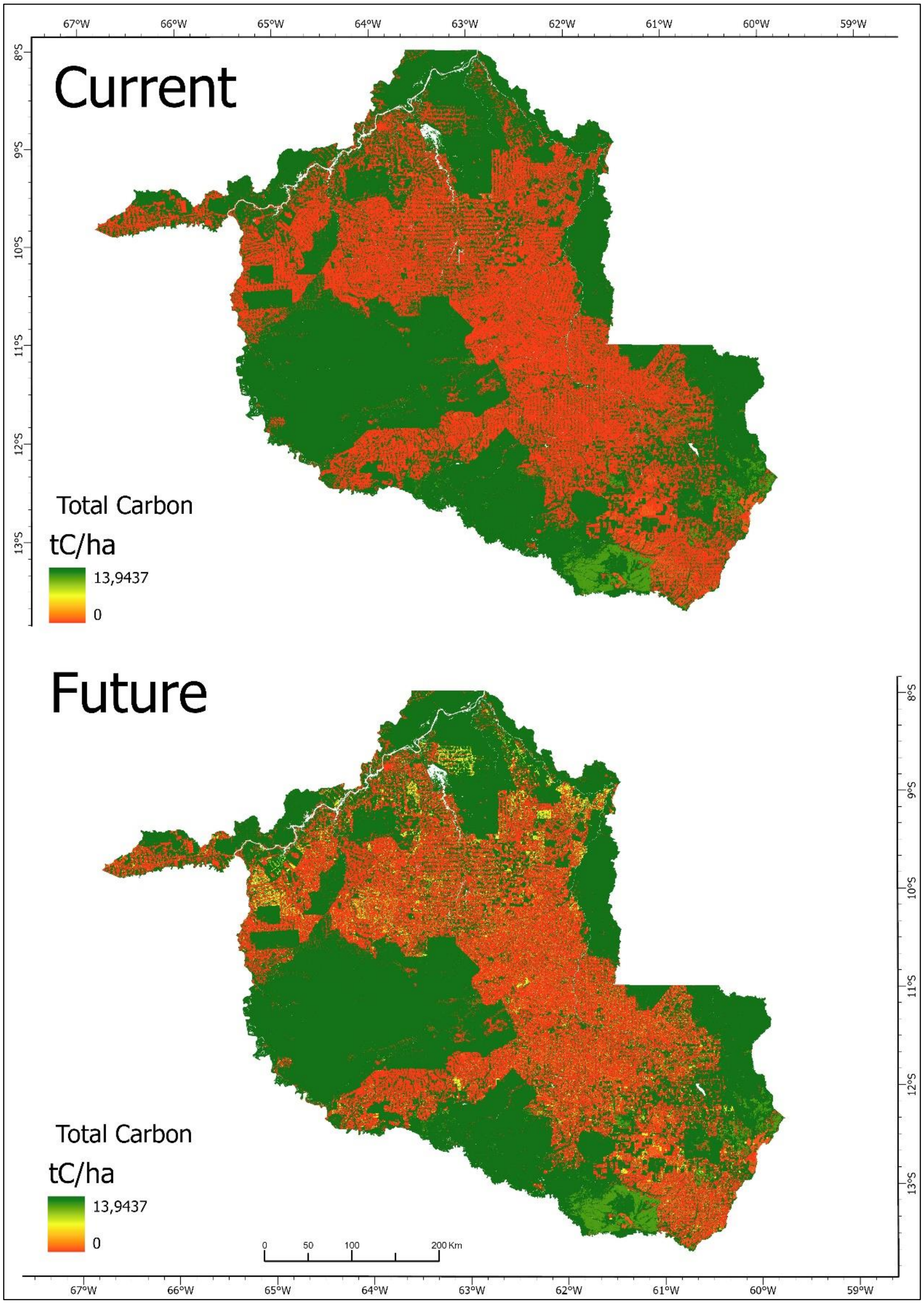

Figure 05: Current and 5-Year Future Scenario for Carbon Stocks in the State of Rondônia.

Natural vegetation in the state is significant for the AGB and BGB reservoirs, as well as for the dead organic matter and litter reservoirs. These carbon pools significantly increase total carbon stock and are vital for conserving various species [Nelson et al., 2007]. This emphasizes the crucial role of government policies concerning ecosystem services [BRASIL, 2021, 2012] in methodically aiding the safeguarding and maintenance of forests.

Table 04: Contribution of each carbon reservoir to the current and future scenarios and their gains in carbon tons (C) in the state of Rondônia.

Carbon Pools (ton C)	Current	Future	Gain
ABG	1,420,994,018.60	1,451,522,961.06	30,528,942.46
BGB	188,474,414.61	199,953,415.17	11,479,000.57
SOC	910,870,292.75	911,955,526.01	1,085,233.26
Litter and dead wood	200,207,875.42	211,546,227.06	11,338,351.64
Total	**2,720,546,601.37**	**2,774,978,129.29**	**54,431,527.92**

The increases in carbon stocks are primarily in the AGB reservoir, although they are lower than those in natural forests [Nave et al., 2019]. When looking at the current and future total carbon stocks, we have 2,720,546,601.37 tC and 2,774,978,129.29 tC, respectively (Table 04). In other words, with the reforestation of areas designated as legal reserves and permanent preservation areas, there will be a gain of 54,431,527.92 tC, equivalent to 2% of the current total carbon or a 4% increase in native vegetation areas. Secondary forests, in addition to restoring carbon stocks [Nunes et al., 2020], also contribute to the protection and maintenance of water resources [Ellison et al., 2017;] and biodiversity [Matos et al., 2020].

6. Conclusions

In the state of Rondônia, it is evident that forest formations cover 55.71% of the total area. However, the significant extent of pastureland at 36.34% is a cause for concern, especially considering that the soy moratorium only curbed soy cultivation in the Amazon Biome. At the same time, pasture expansion remains a prominent driver of deforestation and a significant emitter of greenhouse gases if not managed correctly. Therefore, implementing the integration of crop-livestock forests could serve as a sustainable alternative, particularly for Rondônia, which has a substantial expanse of pastureland.

Another crucial aspect is the carbon stocks in the AGB reservoir, primarily representing the biomass of forest canopies, making it the most significant reservoir in the state. Consequently, monitoring and enforcing regulations in these areas is of utmost importance for the ecosystem service of climate regulation, carbon stock and sequestration in addition to other services provided by forest formations. When combined with the InVEST tool, these reservoirs aid in understanding changes in Land Use and Land Cover. They can help shape public policies related to carbon emissions and even regulate the carbon market.

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