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Geosciences

Viability of a carbon credit project supported by nature-based solutions in rural settlements in Santa Catarina state, Brazil

Viabilidade de projeto de crédito de carbono apoiados em soluções baseadas na natureza nos assentamentos do INCRA de Santa Catarina, Brasil

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ABSTRACT

This study aimed to analyze carbon market opportunities for forest remnants located in settlements of the National Institute for Colonization and Agrarian Reform (INCRA) in Santa Catarina State, Brazil, as a nature-based solution for mitigating climate change. The methodology comprised four steps: (i) mapping of forest remnant areas in INCRA settlements, (ii) characterization of forest remnants, (iii) establishment of criteria and classes for viability analysis of carbon credit generation; and (iv) estimation of carbon sequestration credits. The results confirmed the viability of generating carbon credits in forest remnants located in INCRA settlements in Santa Catarina. Projected gains were estimated at 1,568,238.05 USD per year, considering a total area of 28,743.366 ha for two viability criteria (Cv1 and Cv2). Adopting integrated approaches to nature-based solutions focused on annual carbon stock increments and tailored to the specificities of each class enables conservation projects to realize their climate and environmental objectives and offers long-lasting benefits to local communities and the ecosystem.

Keywords: Carbon market; Climate change; Forest remnants

RESUMO

Este estudo tem por objetivo analisar as oportunidades do mercado de carbono nos remanescentes florestais dos assentamentos do Instituto Nacional de Colonização e Reforma Agrária (INCRA) em Santa Catarina, como solução baseada na natureza para mitigação da mudança no clima. A metodologia foi norteada por quatro etapas: (1) Mapeamento de áreas de remanescentes florestais nos assentamentos; (2) Caracterização dos remanescentes florestais; (3) Estabelecimento de critérios e classes para a viabilidade de geração de créditos de carbono; (4) Estimativa da projeção de créditos de remoção de carbono. Os resultados evidenciam a viabilidade da geração de créditos de carbono nos remanescentes florestais situados em assentamentos do INCRA em Santa Catarina, com ganhos projetados de USD

1.568.238,05 por ano, considerando uma área total de 28.743,366 hectares para os critérios Cv1 e Cv2. A abordagem integrada das SbN, focada no incremento anual de carbono e adaptada às especificidades de cada classe, não apenas possibilita que os projetos de conservação atinjam seus objetivos climáticos e ambientais, mas também oferece benefícios duradouros às comunidades locais e ao ecossistema.

Palavras-chaves: Mercado de carbono; Mudanças climáticas; Remanescentes florestais

1 INTRODUCTION

The synthesis report of the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) (IPCC, 2023) states that a global warming of 1.1 °C has already triggered dangerous changes to natural ecosystems and human well-being, underscoring the urgent need for actions to mitigate these impacts. In Brazil, sectors related to land use changes, such as deforestation and forest fires, are the primary contributors to carbon dioxide (CO_2) emissions, which are estimated at 1.12 billion tonnes and account for 48% of national emissions (SEEG, 2023). According to the MapBiomas Project - Collection 9 (1985–2023), deforestation driven by the expansion of pasture and agriculture is the leading cause of biome changes, negatively affecting biodiversity, water resources, carbon emissions, and climate stability. Concerningly, the latest edition of the Atlas of Forest Remnants of the Atlantic Forest (2024) reported a loss of 14,697 ha of native forests during the 2022–2023 period. Santa Catarina was one of the four states with areas of forest fragmentation and deforestation exceeding 1 ha (SOS Mata Atlântica, 2024).

Nature-based solutions (NbS) have been widely discussed as key strategies for climate change mitigation. NbS approaches are particularly promising in tropical forests, as they accumulate expressive amounts of carbon, provide social and environmental benefits, and generate sustainable financial assets. However, research assessing the potential of these solutions within the Atlantic Forest biome is still scarce. Nevertheless, some studies have demonstrated the sink capacity of these forest remnants. In the current context of worsening climate impacts, NbS approaches have become increasingly popular for generating carbon credits, requiring a deep understanding of climate dynamics for prioritizing conservation and restoration areas (TNC, 2023).

Carbon markets have emerged as essential tools for promoting sustainable finance and addressing the global climate crisis. As pointed out by Keohane (2017) and Seymour (2021), such markets offer an innovative approach that can attract large investments and encourage forest conservation, especially in the global south. A significant example is Reducing Emissions from Deforestation and Forest Degradation (REDD), a framework to reduce greenhouse gas (GHG) emissions through forest conservation strategies. Although REDD has proved effective in preventing the destruction of several areas of vegetation, it has limited applicability in regions where deforestation has been reduced, such as southern-central Brazil. Such areas are often economically unfeasible or ineligible for REDD projects. It should be noted, however, that these “excluded” areas of vegetation play a role in climate mitigation by sequestering carbon through biomass production, holding potential for other conservation methodologies. Examples include permanent preservation areas and legal reserves (Brazil, 2012), which are ineligible for REDD but can be contemplated by new offsetting schemes based on annual carbon stock increments. Thus, both private properties and rural settlements become potential generators of carbon credits, benefiting residents and smallholder farmers in a manner that promotes sustainability and socioeconomic inclusion.

Bordin et al. (2023) noted that the Subtropical Atlantic Forest acts as a carbon sink across all forest ages, showing no relationship between biodiversity and net carbon change. Vibrans et al. (2022) concluded that secondary forests are important for carbon absorption, biodiversity recovery, and income generation for rural communities. Carbon credit generation methodologies based on estimates of annual carbon sequestration, rather than avoided deforestation, represent an effective solution for incorporating numerous forest remnants currently excluded from the carbon market. Such an approach creates significant opportunities for employment and income through environmental services. In Brazil, new regulations are revolutionizing the carbon market, such as the National Emission Reduction System (SINARE) (Brasil, 2023), the Brazilian Emission Reduction Market (MBRE) (Brasil, 2021), and the Brazilian

Emission Trading System (SBCE) (Brasil, 2015). Additionally, recent laws are prioritizing climate change mitigation through NbS (Brasil, 2024).

Carbon credit projects based on forest conservation are recognized as nature-based solutions (NbS) capable of delivering multiple benefits beyond biodiversity protection. These benefits include climate regulation, improved water quality, soil stability, and increased resilience of local communities to extreme weather events. Evidence indicates that natural climate solutions can contribute up to one-third of the global mitigation needed to limit warming to 1.5°C, provided large-scale disruptions are avoided (Griscom et al., 2017). Furthermore, forest restoration and conservation in tropical and subtropical areas are associated with complementary benefits, such as improved agricultural productivity through microclimate regulation and regional water security (Seddon et al., 2020).

In the Brazilian context, such initiatives can also act as instruments for sustainable rural development by promoting economic alternatives based on ecosystem services and expanding the socioeconomic inclusion of small farmers and settlers (Sparovek et al., 2019; Metzger et al., 2010). Thus, by aligning climate mitigation, ecosystem services, and social benefits, carbon projects in rural settlements constitute an integrated strategy for conservation and territorial development.

In view of the foregoing, this study aimed to demonstrate the viability of a carbon credit project in forest remnants of settlements of the National Institute for Colonization and Agrarian Reform (INCRA) in Santa Catarina as a NbS for mitigating climate change.

2 MATERIAL AND METHODS

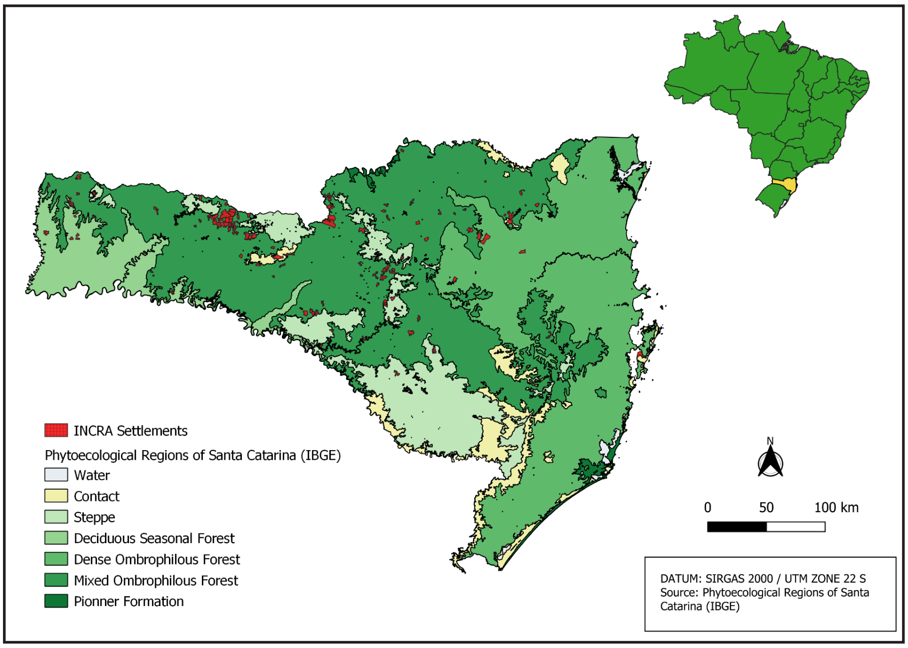
2.1 Study area

Santa Catarina, located in the southern region of Brazil, encompasses an area of 95,730 km2 completely located within the Subtropical Atlantic Forest. This biome is divided into different phytoecological regions, such as Mixed Ombrophilous Forest, Dense Ombrophilous Forest, Deciduous Seasonal Forest, Altitude Fields, and coastal vegetation (IBGE, 2012). The state retains 16% of its native vegetation (Ribeiro et al., 2009). Most remnants are experiencing loss of forest cover and fragmentation, particularly Mixed Ombrophilous Forests (Rosa et al., 2021).

As described by Oliveira and Quadro (2024), Santa Catarina is located between latitudes 26°S and 29°S and longitudes 48°W and 53°W and is geographically delineated by distinct geosystems and geofacies that shape its relief and climate. The most recent and robust climate classification (Novais and Machado, 2023) identified four climate types in the state. The coast was classified as tropical mild humid coastal southern Brazilian climate, the central areas as subtropical southern Brazilian climate, the lowland regions in the extreme west as tropical mild humid southern Brazilian climate, and the highest areas of Planalto Serrano as temperate humid southern Brazilian climate.

The study area (Figure 1) comprises 143 settlement projects distributed in 53 municipalities, with a total resident population of 4749 people and an area of 93,872 ha (INCRA, 2023). Inserted in the Atlantic Forest, most of these settlements provide protection to forest remnants, while also encompassing agricultural fields.

Figure 1 – Map showing the phytoecological regions of Santa Catarina State and the distribution of the 143 rural settlements analyzed in the study



Source: Authors (2024)

The methodological approach comprised the following four steps:

1. Mapping of forest remnants in Santa Catarina settlements. Public data from the INCRA national land collection (2023) were used for identification of settlement areas. The boundaries of settlement areas in vector format (polygons) were overlapped on classified and georeferenced images of land use and cover (raster) using the geoprocessing software QGIS version 3.28.

2. Characterization of native forests and their remnants according to the MapBiomas methodology. Automated tools available in QGIS software version 3.28 were used for characterization of native forests and their remnants. This procedure allowed identifying potential areas for carbon credit generation. The analysis was based on Collection 7 of the MapBiomas Project, published in August 2022, which offers annual land use and cover data for the 1985–2021 period. Although Collections 8 and 9 have been released, Collection 7 was chosen for its greater stability. Vector layers with measurable data were generated for all vegetation areas, including those with reduced, increased, and stable vegetation cover over the past 10 years.

3. Establishment of criteria and classes for the viability study of carbon credit generation in forest remnant areas. The approach used in this step considered the effort to evaluate other project stages/phases, going beyond the viability study of carbon credit generation and including aspects of governance strategy. Thus, the following criteria and classes of analysis were defined:

• Viability criterion 1 (C_{v1}): Forest remnant area (ha), regardless of settlement area. Remnants were classified into area classes (<100, 100–500, and >500 ha), and the number of areas per class was determined.

• Viability criterion 2 (C_{v2}): Total area (ha) of forest remnants in each settlement. Similarly, the total area of forest remnants was classified into three area classes (<100, 100–500, and >500 ha), and the number of areas per settlement was determined.

4. Estimation of carbon removal credits per criterion/class. This step comprised the calculation of the annual carbon stock increment (AIc), projected CO2 removal

(RVy), projected carbon credits (PCC), and projected carbon credit revenue (PCCR). AIc was calculated using Equation 1:

$$AI_c = (AGB + BGB) \times F_c \tag{1}$$

Where:
AI_c is the annual increase in carbon stocks (Mg CO_2e ha^{-1} year^{-1});
AGC is the net aboveground carbon change (1.55 Mg C ha^{-1} year^{-1}) (Bordin et al., 2023);
BGC is the belowground carbon change, corresponding to 20% AGC (0.31 Mg C ha^{-1} year^{-1}) (IPCC, 2006); and
F_c is a conversion factor for CO_2 equivalents (CO_2e), given by the ratio of the molecular weight of CO_2 (44 g mol^{-1}) to that of carbon (12 g mol^{-1}), i.e., 44/12 or 3.66.

By entering these values in Equation 1, one finds $AI_c = (1.55\ Mg\ C\ ha^{-1}\ year^{-1} + 0.31\ Mg\ C\ ha^{-1}\ year^{-1}) \times 44/12 = 6.82\ Mg\ CO_2e\ ha^{-1}\ year^{-1}$.

Equation 2 was used to determine the projected CO_2 removal (RV_y) for each class. In this case, 1 carbon credit is equivalent to 1 Mg CO_2e.

$$RV_y = AI_c \times A \tag{2}$$

Where:
RV_y is the CO_2 removal estimated for each class of vegetation cover during year *y* (Mg CO_2e year^{-1});
AI_c is the annual carbon stock increment (6.82 Mg CO_2e ha^{-1} year^{-1}), and
A is the total area of the respective forest remnant class (ha).

Risk assessment of carbon credit generation was performed following the Social Carbon Methodology for Carbon Removal in Private Conservation Areas (SCM0003 version 3) from Social Carbon . The leakage risk was set at 0% and the non-permanence risk at 20%, both applied to the potential credit generation per year (Social Carbon, 2023). Leakage refers to an increase in deforestation arising from the displacement of deforestation areas to other regions. Leakage was disregarded (0%) in the current study, since project implementation is not expected to result in the clearing of new areas or the displacement of activities (such as deforestation), given that the project area is legally protected by legal provisions. It should also be noted that the project's primary focus is the conservation of forest remnants and the natural regeneration of vegetation. By contrast, the non-permanence risk is included as a buffer for the loss of carbon credits due to natural disasters, such as fires and cyclones. Even though forest fires are not common in the study area, it was chosen to assume a non-permanence risk of 20% as a safeguard against the natural loss of forest remnants.

The monetization potential of carbon credit generation was estimated using Equation 3:

$$PR = RV_y \times (LR + (1 - NPR) \times AP \tag{3}$$

Where:
PR is the projected annual revenue from carbon credits (USD);
RV_y is the CO_2 removal estimated for each class of vegetation cover during year *y* (Mg CO_2e year^{-1});
LR is the leakage risk (0%), NPR is the non-permanence risk (20%), and AP is the average price per carbon credit (10 USD).

For calculation of the projected carbon credit generation (PCC) and projected carbon credit revenue (PCCR) (Equations 4 and 5, respectively), the minimum project duration was set at 50 years, as recommended by the Social Carbon Standard version 6.2 (2024).

$$PCC = NPR \times PL \tag{4}$$

Where:
PCC is the projected carbon credit generation (Mg CO_2e);
NPR the non-permanence risk (20%), and
PL the project longevity (in this case, a minimum of 50 years).

$$PCCR = PR \times PL \tag{5}$$

Where:
PCCR is the projected carbon credit revenue (USD);
PR the projected annual revenue (USD), and
PL the project longevity (minimum of 50 years).

3 RESULTS AND DISCUSSION

Mapping showed that INCRA settlements had a total forest remnant area of 28,700 ha, with 4295 fragments (Table 1). Fragments with areas lower than 100 ha were the most numerous (n = 4193, 98.7%), accounting for 53% of the total area. Among these fragments, the mean area size was 3.7 ha. The 100–500 ha class accounted for 30% of the total area but comprised only 1.1% of fragments. The >500 ha class comprised the largest but fewest remnants, accounting for about 17% of the total area.

Table 1 – Projected generation of carbon credits according to viability criterion 1 (Cv_1) in settlements encompassing forest remnants of different size classes located in the National Institute for Colonization and Agrarian Reform (INCRA), Santa Catarina State, Brazil

Size class	Area (ha)	NR	RV*y* (Mg CO_2e year^{-1})	0% LR (Mg CO_2e year^{-1})	20% NPR (Mg CO_2e year^{-1})	PR (USD)
>500 ha	4972.10	4	33,909.715	0.00	27,127.772	271,277.72
100–500 ha	8532.03	49	58,188.445	0.00	46,550.756	465,507.56
<100 ha	15,239.24	4242	103,931.596	0.00	83,145.277	831,452.77
Total	28,743.366	4295	196,029.756	0.000	156,823.805	1,568,238.05

Abbreviations: NR, number of forest remnants; RV*y*, CO_2 removal for each class of vegetation cover (carbon credits); LR, leakage risk; NPR, non-permanence risk; PR, projected annual revenue from carbon credits
Source: Authors (2024)

Regarding NbS, the <100 ha class contributed the most to the generation of carbon credits (53%) and annual credit revenue (53%), despite being the most numerous. Although these smaller fragments are highly productive in terms of credits and revenue, management and monitoring are more complex and costly, given the large number of remnants. The 100–500 ha and >500 ha classes together accounted for 47% of carbon credits and revenue. Although these classes encompass fewer fragments, their management can be more efficient and centralized.

The large fragmentation and quantity of fragments in the <100 ha class can limit the effectiveness of NbS. Ecological micro-corridors can help connect these small areas and improve ecological integrity. The 100–500 ha and >500 ha classes may provide a more efficient NbS implementation, including large-scale restoration and maintenance of ecological corridors. The governance of these fragments is less complex, facilitating the application of standardized practices and achieving a significant reduction in environmental impacts.

The results for Cv_2 (Table 2) were similar to those for Cv_1. However, this criterion aimed to demonstrate different perspectives on operation, as Cv_2 evaluates the number of settlements in each size class. As shown in Table 2, unlike in Cv_1, the 100–500 ha class accounted for 57% of the total area and comprised the largest number of settlements (n = 77, 54%). The <100 ha class represented only 10% of the total area, comprising 39% of the total number of settlements. The >500 ha class contained 10 settlements representing 33% of the total area (9,700 ha).

Table 2 – Projected generation of carbon credits according to viability criterion 2 (Cv_2) in settlements encompassing forest remnants of different size classes located in the National Institute for Colonization and Agrarian Reform (INCRA), Santa Catarina State, Brazil

Size class	**Area (ha)**	**NS**	**RV*y* (Mg CO_2e year^{-1})**	**0% LR (Mg CO_2e year^{-1})**	**20% NPR (Mg CO_2e year^{-1})**	**PR (USD)**
>500 ha	9718.33	10	66,279.00	0.00	53,023.20	530,232.00
100–500 ha	16,238.10	77	110,743.84	0.00	88,595.07	885,950.70
<100 ha	2786.94	56	19,006.92	0.00	15,205.53	152,055.30
Total	28,743.366	143	196,029.76	0.00	156,823.80	1,568,238.05

Abbreviations: NS, number of settlements; RV*y*, CO_2 removal for each class of vegetation cover (carbon credits); LR, leakage risk; NPR, non-permanence risk; PR, projected annual revenue from carbon credits
Source: Authors (2024)

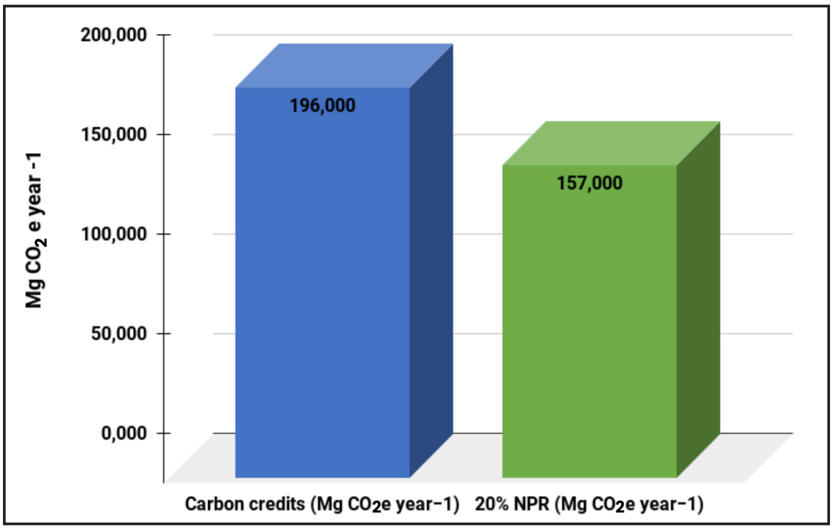
Larger areas may generate a greater volume of carbon credits, but a small number of settlements may represent a lower governance risk. Many feasibility studies ask individual landowners about their preferences regarding forest carbon credit programs. Nevertheless, it would likely be necessary to aggregate small land parcels into larger projects to enable the widespread participation of small forest owners in the carbon offset market (Kerchner; Keeton; 2015).

As shown in Table 2, the 100–500 ha and >500 ha classes together accounted for 96% of carbon credits and 97% of revenue. This finding shows that these larger areas are responsible for most of the financial and carbon sequestration benefits. Therefore, NbS may be more efficient in medium to large areas, as these facilitate the implementation of large-scale conservation projects.

Large areas (>500 ha) offer the highest efficiency for NbS implementation, enabling large-scale restoration projects and the maintenance of large ecological corridors. Centralized governance facilitates the management of these areas and maximizes positive environmental effects, such as water regulation and biodiversity conservation. Medium-sized fragments (100–500 ha) can also promote efficient NbS implementation, allowing for a relatively centralized management and the installation of important conservation projects. The combination of medium- and large-sized areas generates numerous positive impacts. Although small fragments (<100 ha) contribute less to credit and revenue generation, they are still relevant. Implementing NbS in small areas may contribute to connecting small ecological fragments and integrating smaller areas into broader landscape planning.

For both Cv_1 and Cv_2, the projected generation of carbon credits was 196,000 per year. However, when considering a non-permanence risk of 20%, the adjusted estimate was 157,000 carbon credits per year (Figure 2).

Figure 2 – Projected generation of annual carbon credits according to viability criteria



Source: Authors (2024)

This large volume demonstrates the strategic potential of NbS actions. Such results are in line with the definition proposed by the International Union for Conservation of Nature (IUCN), which describes NbS as "actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al., 2016, p.2).

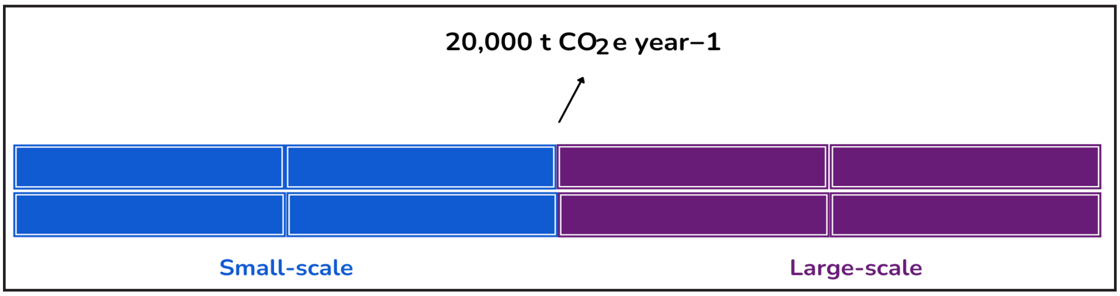
The estimated annual carbon credit (156,823.805 Mg CO_2e year^{-1}) may account for a significant part of the global mitigation potential associated with NbS, estimated at 10 Gt CO_2 per year. This value corresponds to about 27% of current annual global emissions (Girardin et al., 2021). Considering an average price of 10 USD, the annual revenue from carbon credits was projected at 1,568,238.05 USD. A conservative approach was adopted in the projection, with 1 ha estimated to generate about 6.8 carbon credits. Investing in forest protection, natural capital, and continuous provision of ecosystem services through carbon projects is a financially viable and sustainable means of addressing socioeconomic and environmental issues beyond climate change (Sarira, 2022).

The non-permanence risk must be taken into account, which is common in this type of project. Here, a risk of 20% was used. Moreover, a leakage risk of 0% was adopted, not altering final projections. Therefore, the adjusted projection was 5.44 credits ha^{-1}, resulting in an annual revenue of about 54.4 USD ha^{-1} year^{-1}.

For carbon credit projects to be minimally feasible, they must demonstrate sufficient scale and financial viability to cover operational costs, such as audits, periodic verifications during each credit generation cycle, and the submission of information to registration platforms.

According to the feasibility assessment approach developed by Social Carbon v6.2 (2024) (Figure 9), large-scale projects are those that generate at least 20,000 tCO2 per year (Figure 3). Based on the projected credits generated for Cv_1 and Cv_2, the approach is feasible and shows potential for large-scale application. The exception is in the Cv_2 (<100 ha) classes, whose carbon removal estimates indicate values below the large-scale threshold, thus being classified as small-scale. The proposed areas can generate about 157 thousand carbon credits or 157 Mg CO_2e year^{-1} (Social Carbon, 2024).

Figure 3 – Standard for determining project scale and feasibility



Source: Social Carbon Standard version 6.2 (2024)

Table 3 provides an analysis of the contribution of the three size classes to the generation of carbon sequestration credits over 50 years. Fragments of different sizes play key roles in the sequestration of greenhouse gases. The Social Carbon Standard v. 6.2 (2024) recommends a project duration of at least 50 years. Thus, the fragments can generate approximately 7.8 million credits over this period, with a mean of 157 thousand credits per year, as demonstrated in Table 3.

Table 3 – Projected generation of carbon credits over the project life cycle (50 years) according to feasibility criterion 1 (Cv_1)

Size class	PCC	PCCR (USD)
>500 ha	1,356,388.607	13,563,886.07
100–500 ha	2,327,537.784	23,275,377.84
<100 ha	4,157,263.854	41,572,638.54
Total	7,841,190.245	78,411,902.45

Abbreviations: PCC, projected carbon credits; PCCR, projected carbon credit revenue
Source: Authors (2024)

The >500 ha class was projected to generate 1,356,388.607 credits over 50 years, with an annual mean of 27,000 credits (Table 3). The 100–500 ha class could generate 2,327,537.784 credits, at an annual rate of 46,000 credits. Fragments belonging to the >100 ha class were projected to generate 4,157,263,854 credits over

50 years, with an annual mean of about 83,000 credits, significantly increasing CO_2 removal despite their smaller size.

Table 4 shows the results of the projections made according to criterion Cv_2. Although the results were similar, it was observed that the 100–500 ha class had a total projection of 4,429,753,680 credits over 50 years, with an annual mean of 88,000 credits. The other classes combined (<100 ha and >500 ha) accounted for 43.5% of the total credits generated over 50 years.

Table 4 – Projected generation of carbon credits over the project life cycle (50 years) according to feasibility criterion 2 (Cv_2)

Size class	PCC	PCCR (USD)
>500 ha	2,651,159.878	26,511,598.78
100–500 ha	4,429,753.680	44,297,536.80
<100 ha	760,276.686	7,602,766.86
Total	7,841,190.245	78,411,902.45

Abbreviations: PCC, projected carbon credits; PCCR, projected carbon credit revenue
Source: the authors (2024)

The results show the feasibility of generating carbon credits in remnant forests located in INCRA settlements in Santa Catarina State, Brazil. The projected gains were 1,568,238.05 USD per year, considering a total area of 28,743.366 ha for Cv_1 and Cv_2 criteria. These data corroborate the analysis carried out by White et al. (2018), who found that similar programs can provide revenue to small-scale forest owners, while encouraging sustainable forest management, contributing to carbon sequestration, and offering a viable alternative to deforestation and conventional development (White et al., 2018).

When NbS initiatives do not take into account the resilience of the targeted areas, they can become susceptible to the very climate changes they aim to mitigate. This is because such initiatives are generally based on current local conditions, without considering the potential impacts of future climate change. Increased temperature, drought, and disturbances, such as insect outbreaks and forest fires, can negatively affect the photosynthetic potential of forests, thereby impacting carbon sequestration and compromising the integrity of conserved or restored forests over time (TNC, 2023). Maia et al. (2020) observed a declining trend in the carbon sink, marked by increasing losses and decreasing gains, with the hottest and driest forests experiencing the greatest declines. The study shows that, even outside the Amazon, tropical/seasonal forests are already under climate stress that compromises their carbon sequestration capacity.

Although studies on the potential of carbon credit projects in the Atlantic Forest biome are scarce, it has been demonstrated that NbS can mitigate about 80% of Brazil's net-zero goals by 2050 (Soterroni et al., 2024). However, implementation of the Forest Code alone is not sufficient to achieve Brazil's long-term goals. According to Soterroni et al. (2024), this legal framework, focused on protected areas in private properties, could cover only 38% of the national net-zero goal by 2050. Although only 12.4% of its original vegetation remains, the Atlantic Forest holds significant potential to act as a carbon sink (SOS Mata Atlântica, 2022). The estimated sink capacity of primary forests of the Subtropical Atlantic Forest is greater than that of the Andean (Duque et al., 2021), African (Hubau et al., 2020), and Amazonian (Brienen et al., 2015) biomes, albeit in a much smaller and fragmented area compared to tropical forests.

The results of projections based on annual carbon stock increments for REDD+ projects demonstrate the potential of Atlantic Forest remnants, which are mainly located on private land (Liang, 2016). This opportunity has direct implications for offsetting mechanisms in climate change mitigation efforts within REDD+ projects.

4 CONCLUSIONS

The results demonstrated that, although small forest fragments (<100 ha) are significant for the generation of carbon credits and revenue, they face challenges related to governance and management complexity, as well as high administrative costs. By contrast, medium to large forest fragments (100–500 ha and >500 ha) can generate a much greater amount of carbon credits and revenue. The governance of these areas is less complex; however, there is a greater reliance on landowners and fewer fragments, increasing risks that need to be carefully managed. The proposed NbS approach represents an effective strategy to maximize environmental and social benefits.

In comparing viability criteria, it was found that the most adequate criterion for maximizing NbS benefits was forest remnant area (Cv_1) rather than forest remnant area per settlement project (CV_2). The implementation efficiency of conservation projects would be greater in medium to large areas (100–500 ha and >500 ha), allowing for centralized governance, standardization of management practices, and generation of significant environmental benefits. By contrast, in small areas (<100 ha), such projects would face considerable governance challenges. The high concentration of small remnants implies complex management and high administrative costs, in addition to risks associated with ecological fragmentation and variability in management practices. This scenario would require tailored governance strategies to ensure long-term effectiveness and sustainability.

Finally, it is concluded that the integrated NbS approach, focused on annual carbon stock increments and adapted to the specificities of each size class, can help conservation projects achieve their climate and environmental objectives, while providing lasting benefits to local communities and the ecosystem. NbS are therefore essential for the construction of resilient and sustainable landscapes, playing a crucial role in combating climate change and protecting biodiversity, particularly in biomes such as the Atlantic Forest. The results of this study confirm that carbon credit programs in the Atlantic Forest represent an important opportunity to engage small forest owners in the growing market of carbon offsetting, promoting both emission mitigation and revenue generation, thereby benefiting the environment and the local economy.

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