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Araguaia biodiversity corridor cost benefit analysis: Large scale restoration and sustainable agribusiness in Amazon and Cerrado

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ABSTRACT

Ecosystem restoration is an important tool for reducing ecosystem loss and contribute to diminish the negative impacts from deriving from climate change, but can be very costly. This paper focuses on the cost-benefit and cost-effectiveness analysis of recovering almost one million hectares of legally protected areas in the Araguaia Biodiversity Corridor (Brazil) following the Brazilian Forest code regulation. We analyze two paths for recovery, ecological and economic (including timber and agroforestry systems). We consider the direct and indirect local costs, as well as monetized environmental benefits using the social cost of carbon and avoided soil erosion. According to our estimates, in 50 years, the recovery of the Araguaia Corridor will lead to net societal benefits with either the ecological (US$ 19.8 billion) or economic (US$ 18.9 billion) pathways in all macro-regions (north, central, and south) and rural property sizes (small, medium and large). The recovery captures 262 million tCO_2eq and avoids 527 million tons of soil erosion with the economic path; these estimates are 23% and 1.7% higher, respectively, when using the ecological path. Importantly, we show that the restoration activity is not carbon credit dependent on being profitable when based on the economic path proposed. Additionally, this study highlights the high profitability of agroforestry systems, especially in small farms. There are also relevant local impacts, from 12 to 38 thousand new direct jobs. Even considering a limited menu of ecosystem services (carbon and soil), we show that social benefits from the Araguaia biodiversity corridor restoration exceed its social costs, justifying the subsidization of ecosystem restoration. In this sense, land use policies can incorporate mechanisms for financial support, grants, or incentives to encourage and facilitate ecosystem restoration efforts in the region.

1. Introduction

Ecosystem restoration is one of the main strategies to reduce the loss of ecosystem services and thus contribute to decrease the negative impacts of undergoing climate change. In particular, forests contribute to climate change mitigation by carbon sequestration through biomass production while improving biodiversity and ecosystem conservation (Yirga et al., 2019, Murthy and Prasad, 2018). According to IPCC report 2022, sustainable land use and reforestation initiatives can reduce future emissions of between 8 and 14 billion tons of CO_2 yearly by 2050. However, national and local forest restoration projects face considerable difficulties in being implemented on the ground: land scarcity and lack of funding (Brancalion et al., 2012), participation of stakeholders, and agreement among them (Brancalion and Holl, 2020; Metzger et al., 2017), and landscape governance (Van Oosten, 2013). One crucial step to overcoming these challenges is to evaluate restoration's direct and indirect costs and benefits to society.

In this context, this study conducts an ex-ante cost-benefit and cost-effectiveness analysis of restoring 931 ha of legally protected areas in Brazil, located in the Amazon and the Cerrado biomes, the most prominent remaining tropical forest and the richest savanna in the world, respectively (Colli et al., 2020). This area (931 ha) is located along the

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Araguaia and part of the Tocantins Rivers, denominated as the Araguaia Biodiversity Corridor.[1] At the regional level, recovering a biodiversity corridor is an opportunity to strategically plan and manage conservation actions to enhance biodiversity protection at a large scale and beyond the boundaries of individual protected areas. The corridor then contributes to reducing fragmentation and natural habitat loss in accordance with the Convention on Biodiversity Aichi targets.[2]

The cost-benefit and cost-effectiveness analysis estimate the net present benefit and benefit-cost ratio, considering the direct and indirect local costs of restoration, potential revenues, ecosystem services benefits, new direct jobs, and additional government tax collection[3] at the farm level in a discounted cash flow approach. Ecosystem services considered from restoration activity are avoided soil erosion and forest carbon sequestration, respectively mainly a local and a global scale benefit. We propose two distinct recovery pathways through which the restoration of native vegetation in the Araguaia Biodiversity Corridor might occur: the "ecological" and "economic" paths. On the one hand, "ecological" paths do not consider sustainable economic use of land; that is, there is no revenue generation from the sale of either timber or non-timber products. On the other hand, "economic" paths include agroforestry and timber (logging) systems, providing revenues from the sale of non-timber and timber products. Logging systems in "economic" paths consider only one harvesting cycle,[4] while agroforestry systems consider only one crop of each non-timber product. Both "economic" and 'ecological" paths are followed by natural regeneration, making them similar in the long run. The analysis also considers the specificities of the biomes and three property sizes (small, medium, and large).

We use several data sources to proceed with the calculations, including ground cost data for farm-level restoration. Quantities and prices of inputs are collected from governmental technical reports, agricultural suppliers, and/or research institutes' reports. Carbon sequestration and avoided soil erosion are estimated from the recovery of previous pasture areas and we analyze the implications for meeting the 2015 Brazilian Nationally Determined Contribution (NDC) emission targets (Federative Republic of Brazil, 2015).

In a 50-year horizon projection (baseline scenario), we find that the recovery of the areas assessed in the Araguaia Corridor leads to net societal benefits with either the "ecological" (US$ 20 billion) or "economic" (US$ 19.3 billion) paths. The recovery captures 262 million tCO_2eq and avoids 527 million tons of soil erosion with the "economic" scenario. These estimates are 23% and 1.7% higher, respectively, in comparison with "ecological" path. There are also relevant local impacts, from 12 to 38 thousand new direct jobs, depending on the model analyzed. Considering only financial flows, "economic" paths generate a net present value (NPV) of US$ 500 million and a 14.4% internal rate of return (IRR).

This paper contributes to the recent literature on cost-benefit and cost-effectiveness analysis related to forest recovery initiatives (Raihan and Said, 2021, Van Oosterzeea et al., 2020, Iversen et al., 2019, Busch et al., 2019). We add to this literature by showing that the recovery activity is not carbon credit-dependent to be profitable, providing an important incentive to the land owner. This is an interesting achievement once carbon credit markets are still under development with low liquidity and uncertain returns, despite the expressive increase in voluntary forest and land use carbon markets in 2021.[5] We also add to the literature that evaluates positive environmental externalities. These are not easily or directly quantified, in ecological and monetary terms. While there have been efforts to quantify and value some of the benefits of ecosystem services (Strand et al., 2018; Carrasco et al., 2014), the still-nascent understanding of the provision of such services hinder their total estimation and valuation, making a cost-benefit analysis of restoration projects especially challenging.

Even considering a limited ecosystem service menu (only avoided carbon emissions and soil erosion), we demonstrate that social benefits from the Araguaia corridor restoration exceed its social costs. Therefore, our findings significantly contribute to the public policy discussions in the area. Finally, we also incorporate important features to our projected cash flows, such as: the differentiation between financial (costs, taxes and revenues) and environmental flows (monetized carbon capture and avoided soil erosion); and the use of different discount rates (the weighted average cost of capital to the financial flows[6] and the intergenerational discount rate to environmental flows.[7]

This paper is organized as follows. Section 2 describes the study region while Section 3 presents the main aspects of the Brazilian Forest code related to this study. Section 4 describes the recovery pathways proposed, and Section 5 presents the empirical strategy to estimate and project the main costs and benefits of such recovery as well as the data sources and assumptions utilized. Section 6 presents the cost-benefit and cost-effectiveness analysis and the direct job creation of implementing the recovery of the Araguaia Corridor, followed by a sensitivity analysis in Section 7 and Section 8 concludes.

2. The araguaia biodiversity corridor

As the first step of this study, we developed the corridor's mapping in order to identify and describe its main characteristics, such as its area, extension, land use, land cover features, biomes, vegetation, soil types, altitude, land tenure, types of rural properties (public, private, and others), sizes of rural private properties and, importantly, the location and extension of degraded areas to be recovered. The Araguaia Biodiversity Corridor includes 40 kilometers situated alongside the riverbanks of the entire Araguaia River and part of the Tocantins River (Fig. 1). It starts upstream at the Araguaia headwaters in central Brazil, continues north, and ends near Marajó Bay. Thus, according to the mapping realized, the resulting Corridor has 10,787,044 ha of lands (excluding inland water), with 2361 km of total length. Two very different biomes, the Amazon and the Cerrado share approximately the same area of the Corridor, 52.4%, and 47.6%, respectively, and were studied separately. The Brazilian Cerrado, a tropical savanna in the center of Brazil, boasts the richest flora of any savanna in the world, where 40% of the species are endemic (Klink and Machado, 2005). However, from 1985 to 2017, the native vegetation of the Cerrado declined by almost 750,000 ha per year (Alencar et al., 2020), one of the highest deforestation rates in Brazil. The Amazon Rainforest, the largest remaining rainforest in the world, containing about 40% of the world's tropical forests (Pack et al., 2016), has also been increasingly converted for agriculture and pasture (Silva Junior et. al, 2021). These two biomes are currently the most threatened in Brazil by deforestation due to the

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[1] Biodiversity corridors are green infrastructures that increase habitat connectivity in fragmented human-modified landscapes.

[2] See more details on https://www.cbd.int/doc/strategic-plan/targets/T5-quick-guide-en.pdf.

[3] The additional tax collection refers to direct taxation on incremental gross revenues and corporate income due to the commercialization of timber and non-timber products generated by the recovery activity. More details see Section 5.3.

[4] Between 7 and 30 years, depending on the tree species' path composition.

[5] According to EM global carbon markets hub, the voluntary forest and land use carbon market reached US$ 1.3 billion in 2021, an increase of 321% in comparison to 2020. For more details see https://www.ecosystemmarketplace.com/em-global-carbon-markets-hub/.

[6] Following recommendations of (Nordhaus, 1994; Stern et al., 2006; Dasgupta, 2008; Goulder and Williams III, 2012; Dell et al., 2014).

[7] We apply the Ramsey rule based on parameters collected by a recent survey published by Drupp et al. (2018).

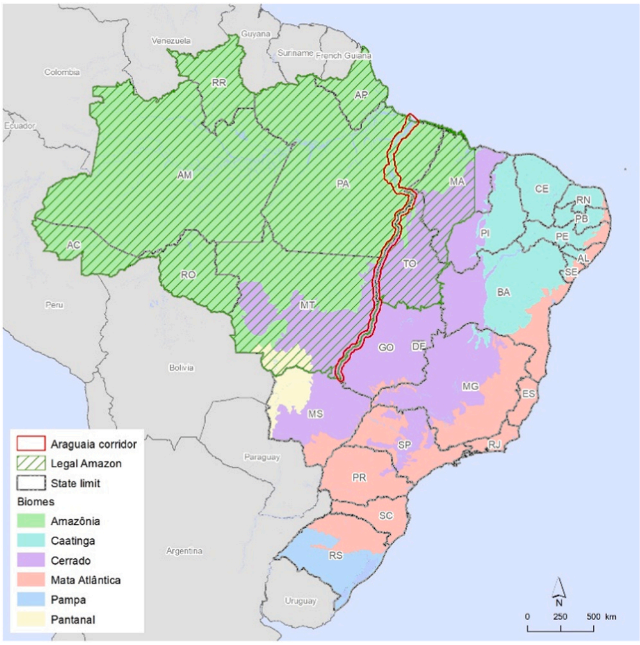

Fig. 1. Araguaia Biodiversity Corridor: states, Legal Amazon and biomes.

expansion of agricultural activities (Souza et al., 2020).

Concerning the Corridor area's location, it encompasses six different states (Mato Grosso do Sul (MS), Goiás (GO), Mato Grosso (MT), Maranhão (MA), Tocantins (TO), and Pará (PA)), being 84% of its area located in the Legal Amazon,[8] and only 0.4% of urban areas. Its limits overlap 112 municipalities, 3 entirely and 109 partially located in the Corridor, of which 73 municipalities are small, having less than 25,000 habitants and 9 have more than 100,000 habitants. According to Mapbiomas 2017 data, 46.8% of the Corridor area is covered by forests (natural/native and planted/exotic for commercial purposes), 38.7% is covered by pasture or agricultural uses (from which 22% is the area to be recovered), 13.6% is non-forest natural formation (such as grasslands), and the remaining 0.9% are non-vegetated or unclassified areas (such as urban areas).

The altitude in the Corridor varies from more than 1000 m (in Araguaia River head) to 0 m (at the Atlantic Ocean), being lower than 200 m in altitude in more than 60% of the Corridor's area, which leads to a low slope along the Corridor (USGS SRTM 1 Arc-Second Global data). Also, it is possible to identify different soils (IBGE 2018): typesacrisol and ferralsol (deep, highly weathered and acidic soils with low natural fertility; in some cases with high aluminum saturation) occupy more than 50% of the area, and soil types associated with seasonal flooding are highlighted (gleisol, histosol, fluvisol, argiluvic plinthosol, and haplic plinthosol) in order to help define areas subject to seasonal floods and the species selection for restoration strategies.

3. The Brazilian forest code

The Brazilian Forest Code (Law nº 12,651/2012)[9] establishes standards for the protection, restoration, and sustainable use of native vegetation and defines legally protected areas within rural private properties - Permanent Preservation Areas (PPA) and Legal Reserves (LR). PPAs include riparian areas, springs, hilltops, high altitudes, and steep slopes that have specific ecological functions in the landscape and are more vulnerable to ecological degradation. Landowners are legally responsible to maintaining the native vegetation cover in a PPA. Any intervention or native vegetation suppression is only allowed in cases of public utility, social interest, or low environmental impact. Landowners are required to promote the restoration of vegetation in case of previous or unauthorized deforestation.

LR areas consist of a percentage of each private rural area that needs to be set aside for native vegetation conservation. For most of the country, the LR percentage is 20%. However, for rural properties located in the Legal Amazon municipalities, this percentage increases and varies according to the area's native vegetation: 80% for properties located in forested areas, 35% for savanna areas, and 20% for those established in open fields. In general terms, PPA has a more restricted preservation character due to its vulnerability, while LR areas have conservation as their primary objective. Both areas are defined to ensure sustainable economic use of natural resources in line with the promotion of ecosystem services.

According to the Brazilian Forest Code, there are two main alternatives for landowners that are not in compliance with PPA and LR requirements: (i) restoring the area through natural regeneration or reforestation, which has to be done with native species or with native and exotic species intercropped in an agroforestry system, as long as the exotic species do not exceed 50% of the total reforestation area; or (ii) offsetting LR deficit through, for example, paying for the conservation of land in another area (usually in the same biome). Additionally, the Forest Code also considers some special cases for RL/PPA deficit regularization, especially those related to small rural properties.[10]

Imaflora's data (Freitas et al., 2018) allows the identification of land tenure of 80% of the Corridor's territory,[11] corresponding to 23,997 rural properties (located totally or partially inside the Corridor), of which 96% are private (including rural settlements) and 4% are public lands.

Finally, considering the Forest Code rules and all special cases, our estimates show that 13,148 rural private properties located in the Corridor present 930,704 ha of LR/PPA deficit to be regularized (Fig. 2). As already mentioned, this study proposes two recovery pathways that combine, in different proportions, natural regeneration and active restoration with native and exotic species in order to suit the small,

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[8] Though called Legal Amazon, this region accomplishes nine states (AM, PA, AC, RR, AP, RO, part of TO, MT and MA) and has three different biomes (Amazon, Cerrado, and Pantanal). It was created to apply a special regulation to a crucial area in terms of natural resources and biodiversity. Therefore, laws such as the Forest Code have different rules when it comes to the Legal Amazon.

[9] This is the revised version of the Forest code which decreased some aspects of forest preservation regulation. The original version of the Brazilian Forest code date from 1965 (Law 4771 /1965). For instance, the revised Forest code granted amnesty for farmers that had illegally deforested permanent preservation areas until July 2008. For more details see Roriz et al. (2017) and Schielein and Borner (2018).

[10] Some special cases are: (i) PPA is accepted in the LR percentage if there is no new land conversion; (ii) small rural properties with LR deficit are allowed to use an alternative LR definition: area occupied with native vegetation existing on July 22, 2008, with new conversions for alternative land use being prohibited; and (iii) small rural properties with consolidated use of PPA on July 22, 2008, will be required to restore PPA only up to 20% of the property size as PPA (and 10% if the small property is less than two fiscal modules in size). These and other special cases can be clarified in art. 68 of Law 12,651.

[11] Imaflora's database merges different georeferenced land tenure databases by an overlapping hierarchy resulting in one unified database thatcovers 82.6% of the Brazilian territory. Our land tenure identification corresponds to 80% of the Corridor's territory mainly due to Imaflora'smissing data and partially due to some geometry errors during processing.

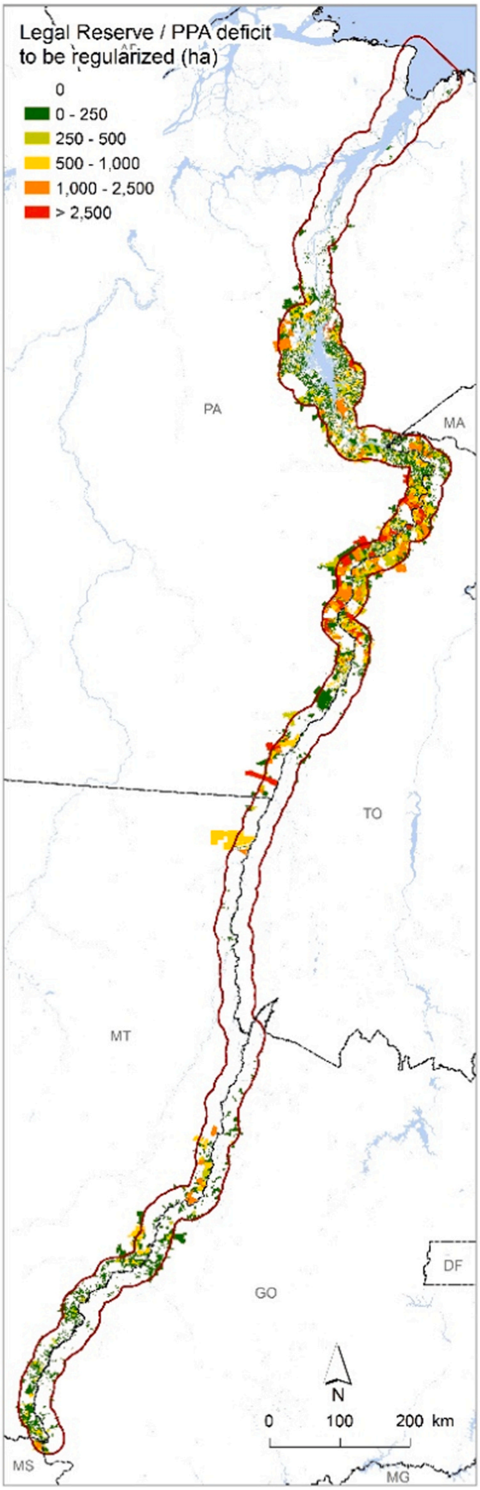

Fig. 2. Legal Reserve / PPA deficit to be regularized in rural properties under FC regulation in Araguaia Biodiversity Corridor.

medium, and large properties' legal and social conditions.

4. Recovery paths

Recovery paths can be defined as systematic designs or arrangements for forming a new ecosystem and its ecological sustainability. Some of the guiding elements for designing a recovery pathway include, among other factors, ecological succession concepts, abiotic environment characteristics, and local infrastructure. In this study, paths directly focusing on native ecosystem restoration are named “ecological”. Paths that also include sustainable economic land use are named “economic”. In this study we assume that “economic” and “ecological” paths are mutually exclusive, that is, we calculate all the results assuming that the corridors' recovery will be based solely in one path (e.g. ‘economic”) or in the other (e.g. ”ecological”).

The species composition of the recovery pathways was defined based on the available information about the species composition of each phytogeographical domain (Amazon and Cerrado) prevailing in the Corridor, which allowed to identify the species or genera potentially more suitable for restoration in each proposed recovery path.[12] The recovery paths' definition also considered specificities of state level environmental laws (of the six Brazilian states located in the Corridor) and the ecological differences of forests and savanna ecosystems.

Thus, recovery may be carried out strictly aiming at ecosystem restoration or combining ecological features with timber and non-timber products for exploitation through sustainable forestry or agroforestry management in LRs and the PPAs of small properties, with some caveats. Importantly, species choices and system management in “economic” paths take place so as not to mischaracterize biome vegetation physiognomy and minimize the changes in species community composition and ecosystem functions.

To spatially assign the distribution of the proposed recovery pathways, we considered three macro-regions (North: Amazon, Central: Ecotone (transition between Amazon and Cerrado biomes) and South: Cerrado) and three property sizes (small, medium and large),[13] obtaining 9 region/property size combinations: Amazon/Large (81,875 ha), Amazon/Medium (123,368 ha), Amazon/Small (68,419 ha), Ecotone/Large (326,525 ha), Ecotone/Medium (179,181 ha), Ecotone/Small (59,153 ha), Cerrado/Large (53,020 ha), Cerrado/Medium (33,634 ha) and Cerrado/Small (5528 ha).

The “ecological” paths were defined according to three different regeneration potential classes (based on the Brazilian Environment Ministry (MMA, 2017)): (i) passive regeneration management for sites with high regeneration potential, requiring no interventions beyond area isolation; (ii) guidance, enrichment and densification techniques for sites with medium regeneration potential[14]; and, (iii) direct seeding andseedlings planting for sites with low regeneration potential.

Differently, the “economic” paths were based on (i) property size[15]: large properties - pathways based on timber systems; medium properties - pathways combining timber (main part) and agroforestry systems; and, small properties - pathways based on agroforestry systems; and (ii) region: species composition of timber system and agroforestry system differs by region due to biome and site characteristics, existent local markets, and potential natural regeneration. Thus, we have proposed seven different timber systems and seven different agroforestry systems, that include different combinations of 19 different non-timber products, depending on the region (such as açaí, cocoa, banana, mangaba, taperebá, bacuri, guariroba, baru, araticum, among others). Notably, at the end of each timber harvesting cycle (between 7 and 30 years, depending on the pathway composition and tree species growth rate)

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[12] The biodiversity planning, recovery path's species composition and paths' spatial distribution were developed in association with Biodendro Forest Consultancy (www.biodendro.com.br). More details can be obtained upon request.

[13] Based on fiscal module units (Law 6746/1979), defined by the National Institute of Colonization and Agrarian Reform (INCRA), whose reference value in hectares varies by municipality. Municipalities located within the Corridor have fiscal modules varying from 5 to 7 ha to 75–80 ha.

[14] Consists in of mowing in a radius of 0.5 m to 1.0 m in the surroundings of each naturally regenerated native species or the seedlings introduced by enrichment or densification techniques.

[15] In large and medium properties, we also considered the utilization of ecological paths to recover APPs, approximately 8.8% of total corridor area.

and each non-timber agroforestry harvest, passive regeneration is implemented to induce natural regeneration, making "economic" and "ecological" paths similar in the long run.

5. Methods and data

To calculate the cost and benefits of recovering the LR and PPA deficit areas within the Araguaia Corridor, we estimate and project the main costs and benefits related to the recovery activity and apply the discounted cash flow (DCF) approach, which involves free cash flow forecasting over time (Damodaran, 1996). Importantly, the projected cash flows are differentiated into (i) financial flows, which encompass costs (both "ecological" and "economic" paths), taxes and timber and non-timber revenues (only to "economic" paths), based on the rural property owner's perspective; and, (ii) environmental flows, which pertain to monetized environmental benefits accrued from avoided social cost of carbon and avoided soil erosion (in both "ecological" and "economic" paths). As for the environmental flow, we consider the benefit of avoided soil erosion as local (related to on-site impacts),[16] and the avoided social cost of carbon as a global benefit as it contributes to global climate change reduction.[17] In addition to distinguishing between economic and environmental aspects, we also account for regional perspectives by calculating the results on a state-level. Regional revenues and costs are used to evaluate local outcomes.

In the DCF approach, the time discount rate provides the degree to which the future is devalued. An academic debate on time discounting in environmental valuation analysis contrasts ethical considerations (relative importance of future generations) and market considerations (Nordhaus, 1994; Stern, 2006; Dasgupta, 2008; Goulder and Williams, 2012; Dell et al., 2014). In this sense, this study considers different discount rate scenarios (based on standard economic approaches) to financial and environmental flows. Related to the environmental flows, we apply the Ramsey rule based on parameters estimated by a recent survey published by Drupp et al. (2018) and obtain an intergenerational discount rate of 2.5%, in line with the measures calculated for the SCC[18] (IWG US, 2015).

Concerning the financial flows, we use the opportunity cost of capital as the discount rate to understand the Brazilian market conditions for implementing this recovery activity. We calculate the opportunity cost using the WACC (weighted average cost of capital) approach. We also estimate the CAPM (capital asset pricing model) model to the forest recomposition sector as a benchmark for the cost of equity within the WACC calculation. The calculated opportunity cost considers the simple average of the estimated WACC from 2016 to 2019, or 7.7% per year.[19]

We assume that the Corridor's recovery activity will be completed after 20 years (reaching the total of 930,704 ha), with the last hectares being restored in the 20th year of the flow, following the Forest Code, which determines that the LR recovery deficits must be completed in 20 years. However, revenues derived from timber and agroforestry systems (in "economic" paths) as well as social benefits related to the forest growth in both "economic" and "ecological" paths take a longer time horizon to be accomplished. It is noteworthy that the implementation schedule is not linear as we apply a polynomial curve[20] and the number of hectares in each region/property size implemented by year is defined proportionally to the corresponding participation in total corridor area. All regions/property sizes' implementation starts in year one and ends in year 20, since the recovery must be completed in 20 years, according to the Forest Code. Different implementation schedules are considered in the sensitivity analysis (see Section 7).

Based on ground data,[21] the proposed polynomial curve is more plausible than an exponential or linear models, both also evaluated in this study (Fig. 3). The linear model (constant rate of 5% per year over 20 years) is unlikely to be used due to the difficulties of meeting the initial conditions necessary to reach the target of 50,000 ha per year in the early years (based on Forest Code guidelines[22]). In turn, the exponential model evaluated will reach approximately 20% of the area to be recovered in the 15th year imposing a very high proportion of the project execution between years 16 and 20 of the flow. Therefore, the corridor's recovery better fits a polynomial curve of implementation. Despite it begins with modest goals, it presents in the initial years an area annual rate of increase greater than the exponential model. In this scenario, the annual recovery rate of 50,000 ha is reached in the 12th year and the maximum annual area for intervention is 133,000 ha in the 19th year (approximately half of the area proposed in the last year of the exponential model).

Due to the recovery paths' characteristics, we consider a 50-year time horizon projection as the baseline scenario because, so that the economic benefits from the logging systems can be fully accounted. At the end of 50 years, all slow-growing trees planted since the beginning of project implementation up to the 20th year of the flow (in "economic" paths) will be cut at age 30 (for more details, see Section 5.4).[23] After the timber harvesting, those areas are set aside to natural regeneration, and revenues (or costs) are no longer obtained derived from the logging activity.

We also project 31 and 155-year time horizons. At the end of 31 years, all moderate-growing trees planted in the 10th year of the flow will be approximately 20 years old and will be harvested (also in this case the area is then left to natural regeneration). In 155 years all carbon capture benefits from natural regeneration that followed a timber harvesting can be estimated: we have approximated a log curve on the results of Poorter et al., (2016) and considered that it takes 105 years to achieve a fully recovery of secondary forest, i.e. 100% of its original old-growth values. As the last timber harvesting occurs in the 50th year of the flow, secondary forests that naturally regenerated after this harvest will have reached their old-growth values of biomass and carbon

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[16] The complete valuation of all benefits from soil protection includes the positive impacts on both on-site and off-site soil ecosystem services. However, those known benefits from soil relate to several ecological processes and outcomes in different scales, from local agricultural production to regional impact on hydropower generation, which makes complete valuation of soil benefits very complex and full of uncertainties. Therefore, in this study we estimate only the local scale benefits from soil protection.

[17] Given that carbon emissions and their impacts transcend national borders, the social cost of carbon operates within a global context. Although there are no official local measures of carbon pricing, we consider two alternative measures in our robustness analysis.

[18] We also utilized parameters defined by Nordhaus (2018), to calculate the measure of SCC, to verify the sensitivity of the results. These results are similar to those presented in Section 6. More details can be obtained upon request.

[19] The assumptions behind the WACC calculation can be obtained upon request.

[20] The implementation schedule is set as follows: 558.48 ha in the first two years (based on ground data) and then the polynomial formula $\text{Area(year)} = 0.930704 \cdot (-692.37 \cdot \text{year} + 404.84 \cdot \text{year}^2)$ from the third to the 19th year. Year 20 is set to equal the difference between the total area to be recovered (930,704 ha) and the cumulative sum of the implemented area since the first year (809,394 ha).

[21] Biodendro Forest Consultancy (www.biodendro.com.br). Mare details can be obtained upon request.

[22] Recomposition of 1/10 of the deficit present in each rural property every 2 years.

[23] We understand that an important step when realizing a cost benefit (CBA) or cost effectiveness analysis (CEA) is to determine its time frame and how the costs and benefits will change over the established time horizon, as the results can vary depending on the time frame applied. Usually, the time frame of the CBA or CEA is determined based on: (i) the life of the intervention, if applicable, or (ii) sufficient time to capture most of the costs and benefits of the intervention. Therefore, we have projected the discounted cash flows considering three different time horizon scenarios based on the proposed recovery activity main characteristics.

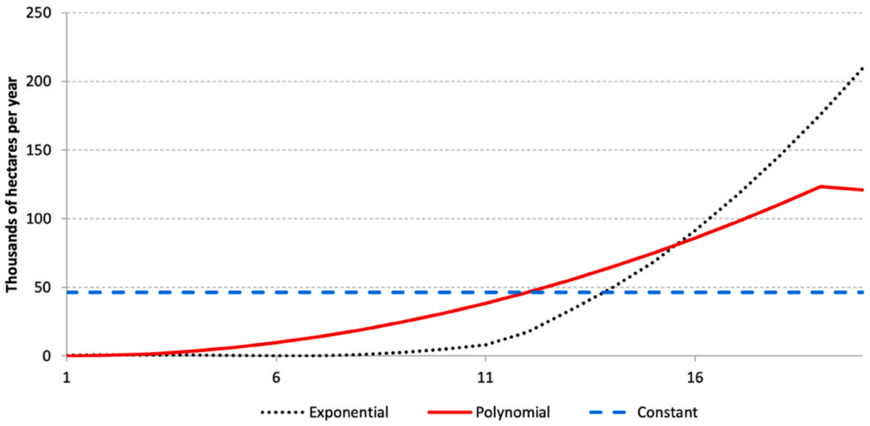

Fig. 3. Implementation schedule curves.

stock in the 155th year. Concerning agroforestry systems, we also considered one non-timber harvest in all time horizon projections, also followed by natural regeneration, with revenues or costs no longer accruing from these systems after all harvest cycles.

Additionally, we estimate the number of new direct jobs resulting from the recovery activity, focusing on the year with the highest demand for labor in each macro-region/size.[24] This typically occurs during the 19th or 20th year of the project, depending on the region/size, as the implementation schedule reaches its peak in these years, resulting in an increased need for assistants and tractor drivers. Our assumption is conservative since we did not consider any commuting time (to access different implementation sites) during working hours; we assumed workers are always hired locally.[25]

The following subsections present the methods and data utilized to estimate the environmental benefits and costs (related to "ecological" and "economic" paths), taxes and revenues (only "economic" paths), enrolled in the cost-benefit analysis.

5.1. Carbon capture

Carbon capture estimates vary by macro-region (Amazon, Cerrado, and Ecotone), and recovery path, considering the carbon contained in above and below-ground biomass[26] and all results are converted into CO_2eq. For "ecological" paths, we use an annual growth log curve based on the results of Porter et al. (2016) and assume that 100% of the carbon stock from the area's original vegetation is going to be recovered after 105 years,[27] having no additional carbon capture after that. We also use data from the Ministry of Science, Technology, and Innovation (2016) on the original vegetation carbon stock for Amazon (531 tCO_2/ha), Ecotone (467 tCO_2/ha), and Cerrado (117 tCO_2/ha) macro regions, corresponding to the weighted average of carbon stock for different vegetation types in these areas.

Considering "economic" paths, carbon capture occurs according to timber systems and agroforestry systems characteristics. Timber systems' carbon capture is based on MAI (mean annual increment) average growth (in m^3/tree/year), being converted to carbon using the equation of Pearson et al. (2014) which relates wood density values (in g/cm^3) (from Almeida et al. 2013, Dias et al. 2018 and Ribeiro et al. 2017) to extracted log emissions (MgC/m^3) in selective log harvesting in tropical forests. We then assume that 100% of the captured carbon will be released back to the atmosphere at the time of harvest, following the Intergovernmental Panel on Climate Change (IPCC) Tier 1 conservative approach (committed emissions approach), overestimating emissions in the year of harvest and ultimate total emissions.[28] After the harvest, the area is recovered by natural regeneration, and hence, the carbon capture occurs at the same rate as in the "ecological" pathways.

In turn, agroforestry systems' carbon capture rates are based on Brancher (2010), which studies agroforestry species composition (banana, açaí, cocoa, rubber, taperebá, paricá, and macacaúba) in the Amazon region, being very similar to the agroforestry composition proposed in our recovery paths. The above-ground carbon stock is assessed after 15 years, and we approximate a log curve to obtain the carbon capture per year. Below-ground carbon stock is estimated considering 18% of above-ground biomass in the Amazon biome (National Forest Information System, SNIF). The MAI productivity factor is used to correct for growth differences among regions. The resulting average carbon capture used for the agroforestry systems ranges from 9.0 to 12.7 tCO_2eq/ha/year.

Additionally, in both "ecological" and "economic" paths, avoided GHG emissions (except CO_2) from pasture burning are also counted, assuming that the majority of the recovery is going to occur in previous pasture areas, which are exposed to maintenance burns every 2–3 years for 10–20 years before they are abandoned or converted into other uses.

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[24] The total man-hours required for planting, maintenance, and implementation activities of the paths were converted into the number of workers by dividing the total hours by 176 (which means an 8-hour working day for 22 working days per month).

[25] We consider the assumption that the workers needed for the recovering activity will be hired locally is a plausible one once local agricultural employment equals 224,736 jobs in 2017 (estimated as the sum of each of the 112 municipalities' employment level weighted by the share of their area within the corridor based on IBGE 2017 data). According to IBGE data, there were over 206,200 workers engaged in "certified seed and seedling production" and "forestry production (planted or native forests)" across the six states of the Araguaia Corridor in 2017. However, in the year we consider to calculate labor demand (the year with the highest demand for labor) the numbers are significantly lower. For instance, in the baseline scenario we estimate 37,898 ("economic" paths) or 12,171 ("ecological" path) direct new positions.

[26] Deadwood and litter carbon are not considered due to their low share in total carbon stock (around 2% according to National Forest Information System estimates, SNIF). Soil organic carbon is also not considered since there is no change in soil carbon sequestration when land-use changes from grassland or pasture to forest (Post and Kwon, 2000; Martin et al., 2013).

[27] Our annual growth log curve considers 64.3% recovery after 20 years and 100% after 105 years. An underlying assumption is that the silviculture practices of our pathways will compensate for less suitable conditions so that all paths can achieve natural regeneration growth patterns.

[28] We have opted for a conservative and simpler approach to avoid making assumptions on the use and on the life cycle of the harvested timber.

We use estimates from Bustamante et al. (2012) in CO_2eq/ha, considering that pasture burning would continue for eight years on average[29] and 35% of the pasture areas in the Corridor are degraded (and therefore, not exposed to pasture burning anymore).

Finally, the economic value of the CO_2 capture is calculated based on annual estimates of the global social cost of carbon (SCC), from the US government, varying from 62 US\$/tCO_2 in 2020 up to 95 US\$/tCO_2 in 2050 (2.5% discount rate[30]) (IWG - Interagency Working Group on Social Cost of Carbon, U.S.G, 2015). For the period 2046–2050, SCC was estimated keeping the linear trend. Carbon emission by land use utilized in the analysis is available in Appendix II (Table A8). We also estimate two additional scenarios for carbon price in Appendix I (Table A1): a) country-level social cost of carbon for Brazil (Ricke et al., 2018), and b) average price in the voluntary forest carbon credit market.

5.2. *Soil erosion reduction*

It is well known that an effective natural way of controlling soil erosion is to increase vegetation cover to protect soil particles from wind and rain. In this sense, the recovery of the Araguaia Corridor through replacing large pasture areas, mostly degraded, by natural forests, timber systems, and agroforestry systems contribute to enhancing soil protection and, consequently, decreasing the loss of soil.

One frequent approach to evaluate the benefit of soil protection[31] is to use the replacement cost method by estimating the number of nutrients lost when soil is displaced and calculating the equivalence between these lost nutrients and fertilizer prices, as a way to estimate the monetary value of avoiding soil loss (Pimentel et al., 1995; San and Rapera, 2010; Graves et al., 2015). The main assumption is that the replacement cost can be used to measure the benefit provided by the good being analyzed.

In this case, we assume that soil nutrients can be infinitely replaced and disregard that soil has physical properties that are not restored by adding fertilizers. These assumptions are acceptable when soil is accomplishing its support function. If this function is reduced or lost (e.g., in the case of gullies), these assumptions are no longer valid.[32] We also assume that erosion varies across the corridor area, mainly in response to vegetation cover differences. So, in order to estimate soil erosion across the areas to be recovered and along the restoration process, we used reference values of soil loss (tons per hectare per year) for different land uses (including pasture, young plantation, mature plantation, shrubland, tree dominated land use and Amazon Forest) described in the literature (Merten and Minella, 2013; Sun et al., 2018; Labrière et al., 2015; Rodrigues, 2005; Barbosa and Fearnside, 2000).

Besides the original pasture land use category, we merge the proposed recovery paths in this study into three land-use change categories: agroforestry, timber, and native vegetation. We also consider that land-use transitions possibly impacting soil erosion outputs would occur in two or three steps, from pasture to final land-use conversion. Therefore, to estimate the amount of soil preserved by the avoidance of soil erosion, we subtracted the amount of soil expected to be lost through erosion at each land transition step for each proposed pathway (i.e., for each prospected year) from the amount of soil that would have been lost if the area had continued as pasture.[33]

We convert the amount of avoided lost soil per hectare into nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) quantities and then into the equivalent volume of a correspondent frequently sold fertilizer (Pereira et al., 2015; Bellinazi Junior et al., 1981, cited in Marques, 1998). We used average market prices (data from National Supply Company, CONAB) for each fertilizer to estimate the amount of money that would be needed

to replace those nutrients by fertilizer application plus the cost of application itself (based on technical references). Finally, we estimate the benefit of avoiding soil losses by reducing soil erosion for each land use conversion proposed, for each year, up to 31, 50, or 105 years according to the time horizon of the projection. Table A9 in Appendix II shows the reference values for soil loss applied in this study.

5.3. *Costs and taxes*

We estimate the costs by macro-region, property size, and type of recovery path/technique. In both “ecological” and “economic” paths, the operating costs include labor, materials, machinery and equipment, and technical assistance. We also incorporate an opportunity cost of land in both pathways. This opportunity cost represents the rent paid for land usage in each region, as documented by Bullard and Straka (2011). To calculate the rents, we initially considered different selling prices for each state and agricultural or livestock use, obtained from Lima Filho et al., (2016). The price range varied from US\$ 736 (pasture in Maranhão state) to US\$ 4995 (agriculture in Mato Grosso do Sul) per ha.[34] To derive overall averages, we applied weighted averages that considered the proportion of agricultural producers within the region and the respective contributions of the agriculture and livestock sectors.[35] Furthermore, based on the selling price, we calculated an annual rent by multiplying the annual discount rate (WACC) by the selling price. This approach allows us to address the opportunity cost of land while considering spatial heterogeneities. In addition, we include an estimated insurance expense based on Prata (2012), but only for large and medium properties in the “economic” paths.

Material, labor, and machinery costs are expected to be incurred in four stages, considering different operational coefficients in each stage: (i) pre-implementation; (ii) implementation; (iii) plantation maintenance; and (iv) forest management.

The material costs are related to direct consumable goods, whose quantities are based on governmental technical reports and/or research institutes reports. Costs of seedlings and seeds, limestone and fertilizers, herbicides, formicides, among others, vary by area or by species/recovery path. Costs incurred with fences and infrastructure for processing non-timber products vary according to property size, shape, and the

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[29] Average case for a pasture area planned to be exposed to maintenance burns for 15 years and has already been through half of this period.

[30] Values from 2007 corrected to 2019 using CPI index.

[31] The valuation of all benefits from soil protection would need to include the positive impacts on both on-site and off-site soil ecosystem services. However, those known benefits from soil relate to several ecological processes and outcomes in different scales, from local agricultural production to regional impact on hydropower generation, which makes complete valuation of soil benefits very complex and full of uncertainties. In this sense, in this study we are only estimating (and monetizing) local scale benefits from soil protection.

[32] In the Araguaia Basin, the soil is more vulnerable to the high level of erosion in the marshy areas, plateaus, and where Entisols (Quartzipsamments) are present (Castro, 2005). Those vulnerable areas are mainly outside the Corridor recovery area but may be important in a larger regional scale evaluation.

[33] We recognize that previous land uses can affect current soil conditions, for instance intensive agricultural activities usually include soil conservation techniques, so similar pasturelands may vary in terms of soil conservation. However, although we have not mapped previous land uses in the studied area, there is solid evidence that pasture activity occupation takes place over native forested areas in a known deforestation dynamic that occurs in South America (Graesser et al., 2015). Thus, we can confidently expect that the studied pasturelands have a similar history of occupation and were native areas right before the conversion to pasture.

[34] Values corrected to 2019 using IPCA inflation index and then converted to USD dollars. According to Lima Filho et al. (2016), the values are R\$ 2066 and R\$ 17,657 per ha, respectively, in 2016 Brazilian reais.

[35] The largest proportion of the corridor's area to be recovered is located in the state of Pará (62%), where land prices are US\$ 1056 (livestock) and US\$ 1386 (agriculture), in 2019 values. The states of Maranhão and Mato Grosso do Sul accounts only to 0.27% and 0.32%, respectively, of the total area to be recovered.

number of discontinuous areas, obtained from agricultural suppliers and government institutions, such as IEA (Institute of Agricultural Economics) and CONAB (National Company of Food Supply), among others. Machinery and equipment costs include all indirect consumable goods related to mechanized operations, such as fuels, oils, lubricants, preventive and corrective maintenance, tractor and implement depreciation, interest on capital and insurance, and are calculated by Machine Hour Rate (MHR). We estimate these costs based on the operational cost of agricultural tractors[36] provided by the Office to Coordinate Integral Technical Assistance (CATI) of the São Paulo State Department of Agriculture and Supply. Diesel prices are collected from the National Petroleum Agency.

Labor costs vary by rural property size and recovery path. We consider in-house labor in “ecological” paths, small properties in “economic” paths, and agroforestry systems in medium properties under “economic” paths. Outsourced labor is considered for timber systems in large and medium properties under “economic” paths once wages of outsourced labor are approximately 30% higher than in-house labor due to invoice taxes and administrative

costs. We collect wage data by occupation[37] from the General Register of Hiring and Dismissal (CAGED) of the Ministry of Labor and Employment (MTE). We also consider social and labor charges. According to its operational coefficients, a field team (composed approximately of 30 people, including rural workers, tractor operators, and one agricultural/forestry technician) can plant approximately 30 ha per month. Finally, due to cost variations in the different macro-regions (North, South, and Central) of the Araguaia Corridor, we estimate a weighted average cost per region, considering local unit costs.

Large properties under “economic” paths pay direct taxes based on their gross revenue (Contribution to the Social Integration Program – PIS and Contribution to Finance Social Security - COFINS) and corporate income tax and social contribution on net profit are calculated based on net income. Medium and small properties, also under “economic” paths, pay lower income tax based on revenues (Simples Nacional regime). There is no incidence of taxes when using “ecological” paths since there is no generation of revenues. The main parameters utilized to estimate costs can be found in Appendix II (Table A3, Table A4, Table A5 and Table A10).

5.4. Timber and non-timber products’ revenues

The expected revenues related to timber and non-timber products in “economic” paths are obtained based on: (i) the estimates of the mean annual increment (MAI) of the tree species considered (native and non-native); (ii) the productivity of non-timber products in the agroforestry systems proposed; and, (iii) the prices per cubic meter of native and non-native timber species and non-timber products prices.

Based on the timber systems productivity factors, we establish their average productivity and group the native and non-native timber species into three growth rate groups. In the “fast” group trees grow six years before being harvested (i. e., clear-cutting in the 7th year of the projected cash flow). Trees in the “moderate” growth group are clear-cut 21 years after being planted (i. e, the 22nd year of the cash flow) but also allows for thinning cuts at age 14 (the 15th year of the cash flow). Finally, trees in the “slow” group can be harvested only after 30 years of growth (i. e., clear-cutting in the 31st year of the cash flow). The productivity factors of native species are obtained from Arco-verde and Schwengber (2003), Brienza Junior et al. (2008), Souza et al. (2008) and Rolim and Piotto (2018) and the productivity of the non-native timber species is obtained from Souza et al. (2020), Silva et al. (2021), Grupioni et al. (2018), Schnell et al. (2010) and Demolinari et al. (2007), adjusted by the potential productivity map of eucalyptus in Brazil (based on Alvares et al. 2011).

Prices per cubic meter of native timber species are determined according to the minimum price guidelines of the state fiscal departments of Tocantins, Mato Grosso, Goiás and Pará. Prices of non-native species are based on the National Supply Company (CONAB) and the Institute of Man and Environment of the Amazon (IMAZON). Additionally, we assume that the timber and non-timber markets are competitive, meaning that the increase in supply might lower prices depending on the price elasticity of demand and on the size of the increase relative to the total existent market. Based on the literature (Nogueira et al. 2013, Amaro 2010, Nogueira et al. 2009, Santana 2015, Santana et al. 2011, Almeida et al. 2009, and Cartaxo et al. 2004), we attribute estimates for the elasticity of demand of timber and non-timber products (or similar products). In turn, the total market size (in metric tons, or thousand cubic meters) was collected in the Agricultural Census (2017) and Forestry Production Survey (PEVS) of 2017, both calculated by the Brazilian Institute of Geography and Statistics (IBGE). Therefore, we calculate the change in prices using the price elasticity of demand of product j (ε_j^d) and the initial quantity of the market from the Agricultural Census ($q_{0,j}$). Eq. (1) summarizes the final price ($p_{1,j}$):

$$p_{1,j} = p_{0,j}\left[1 + \frac{\left(\frac{q_{1,j}-q_{0,j}}{q_{0,j}}\right)}{\varepsilon_j^d}\right] \tag{1}$$

where $q_{1,j}$ is the total market in 2017 plus the supply change from the production within the Corridor. We assume that prices decrease, at most, until they achieve 20% of the initial value (as the price elasticity of demand changes over time, but different values of the elasticities along the demand curve are not observed). The price-elasticity and average price of timber and non-timber products utilized in this study are available in Appendix II (Tables A6 and A7, respectively).

6. Results and discussion

6.1. Cost-benefit and cost-effectiveness analysis

All results are presented for both “ecological” and “economic” paths (in US$ 2019 values), considering the assumptions discussed in the above sections. According to our estimates, the recovery of the Araguaia Biodiversity Corridor presents a net benefit either when utilizing “economic” or “ecological” paths in all macro-regions (Amazon, Ecotone, and Cerrado) and property sizes (large, medium, and small). Table 1 shows that based on “economic” paths, the overall result indicates a net benefit of US$ 19.3 billion and 76% social IRR, while based on “ecological” paths, the figure is US$ 20.0 billion and 294% social IRR, both considering a 50-year horizon projection (baseline scenario).

Analyzing the net benefit composition (Table 1), one can observe that monetized carbon capture corresponds to the most relevant part of the net benefit present value: US$ 17.4 billion and US$ 19.6 billion in “economic” and “ecological” paths, respectively, emphasizing the high carbon sequestration potential of forest recovery activity. Specifically, in the case of “economic” paths, timber and non-timber revenues (US$ 2.7 billion) also represent a significant portion of the total net benefit, followed by the monetized soil erosion reduction (US$ 1.4 billion,

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[36] We consider the use of 80 HP tractors for light-duty and 110 HP for heavier operations such as soil preparation.

[37] The occupations considered are: rural workers (field hands, fence installers, and other rural workers which perform activities with manual tools or semi-mechanized equipment); tractor drivers (farm tractor operators, forest tractor operators); supervisors (forest area supervisors, agricultural/livestock supervisors, farm managers, responsible for supervision of field team, distribution of tasks and logistics); engineers (agronomists or forest engineers responsible for the project) and technicians (agricultural, forest production, reforestation or agronomy technicians, responsible for technical guidelines of the operational activities in the different implementation stages).

Table 1
Net benefit by recovery path (50-year horizon projection).

	Economic models	Ecological models
Net Benefit (US$ million)	19,266	19,973
Total expenses	-2,213	-1,028
Timber and non-timber revenue	2,713	0
Carbon capture	17,353	19,566
Avoided soil erosion	1,414	1,435
Social IRR (%)	*76%*	*294%*

Notes: Net benefit is calculated as timber and non-timber revenues plus environmental benefits (carbon capture and avoided erosion) subtracted from total expenses (ecological models do not include timber and non-timber revenues). Total expenses include operational costs, investment, opportunity cost of land, insurance and taxes (ecological models do not include taxes). All monetary values are expressed in USS 2019 million and represent 50-year time horizon present values. Social IRR is the social internal rate of return.

approximately the same amount for both "ecological" and "economic" paths). The avoided erosion value indicates that even not fully accounting for the impacts of erosion, as we considered only the local effects,[38] converting land use from degraded pasture to more adequate agricultural activities and then to native vegetation cover promotes the retention of high amounts of soil.

Regarding total expenses, "ecological" paths register US$ 1.0 billion (or US$ 22 per ha/year), 54% lower in comparison to "economic" paths (US$ 2.2 billion or US$ 48 per ha/year). Overall, "ecological" paths are less costly since operational costs to induce natural regeneration demands, on average, fewer working hours, material and machinery costs compared to the timber systems and agroforestry systems proposed to compose the "economic"paths. Also, there is no incidence of income taxes or insurance expenses in "ecological" paths (on the other hand, there are no revenues related to the sale of timber and/or non-timber products, as in "economic" paths). Neither path include an incremental cost relative to the ecosystem crossing the forest-savanna tipping point. In our projections, Brazil and other Amazon countries will reduce significantly deforestation rate in the next years.[39]

Although expenses differ between "ecological" and "economic" pathways, in both cases, our estimated restoration costs lie below the range of values obtained for other tropical regions. We found costs equal to US$ 83 per hectare/year for "economic" paths and US$ 57 for "ecological" paths, when considering 20 years of projection. For a tropical rain forest in Australia, the recovery costs lied between US$ 161–255 per hectare/year (Van Oosterzeea et al., 2020). The cost values we obtained are also smaller in comparison to Raihan and Said (2021) estimates to recover tropical and subtropical forests in peninsular Malaysia, which totals US$ 234 (forest conservation), US$ 298 (natural regeneration) and US$ 327 (afforestation) per hectare/year considering 50-year time horizon projection and 3% discount rate.[40] Finally, a global review pointed out restoration costs to be approximately US$ 306–612 per hectare/year, when considering a 20 years period (De Groot et al., 2013).

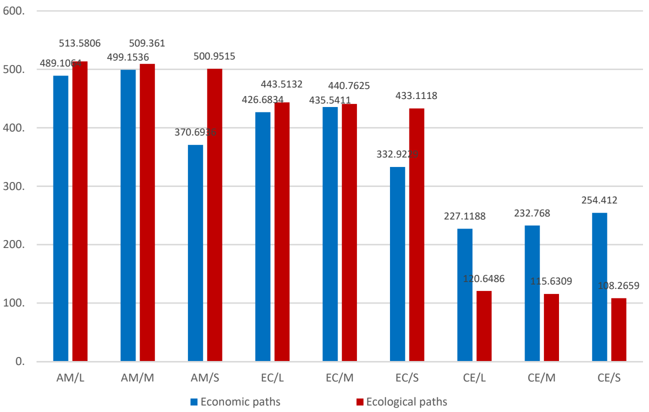
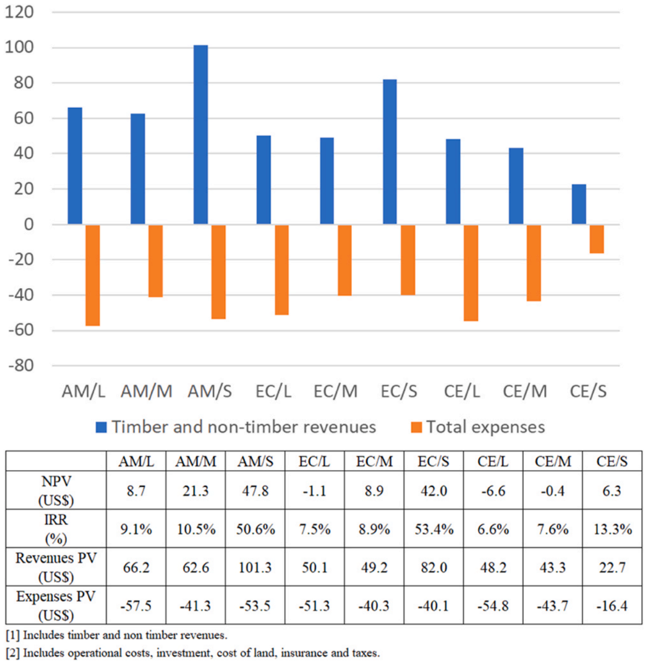


Fig. 4. Net benefit per ha/year (50 years projection, US$).



	AM/L	AM/M	AM/S	EC/L	EC/M	EC/S	CE/L	CE/M	CE/S
NPV (US$)	8.7	21.3	47.8	-1.1	8.9	42.0	-6.6	-0.4	6.3
IRR (%)	9.1%	10.5%	50.6%	7.5%	8.9%	53.4%	6.6%	7.6%	13.3%
Revenues PV (US$)	66.2	62.6	101.3	50.1	49.2	82.0	48.2	43.3	22.7
Expenses PV (US$)	-57.5	-41.3	-53.5	-51.3	-40.3	-40.1	-54.8	-43.7	-16.4

[1] Includes timber and non timber revenues.
[2] Includes operational costs, investment, cost of land, insurance and taxes.

Fig. 5. Economic paths - Total expenses and revenues per ha/year (50 years projection, US$).

Importantly, despite the relevance of carbon capture in total net benefit, analyzing only financial flows (timber and non-timber revenues versus total expenses) in "economic" paths, the overall result is still positive with US$ 500 million of NPV and 14% IRR (see Table 3), indicating that the recovery activity proposed in this study is not carbon credit-dependent when adopting such paths. Currently, this is an important result, especially considering the low development stage of forest carbon credit markets. In the same direction, despite not analyzing the impact of the forest code regulation, Silva et al. (2022), point out that the emergence of new agricultural technologies may raise land opportunity cost in the region against carbon stocking, indicating that the potential benefits from alternative land uses tend to be higher than the benefits from the standing forest. In turn, analyzing alternative policy interventions to avoid deforestation, Souza-Rodrigues (2019) shows that a perfectly enforced tax of US$ 42.5/ha/year will induce farmers to maintain 80% forest coverage on private properties in the Amazon region. Comparing to our baseline result (in "economic" paths), we advocate that the recovery of the Araguaia corridor average cost is equal to US$ 22/ha/year (or specifically US$ 49/ha/year in the Amazon macro region) and generates an average revenue of US$ 58/ha/year (or

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[38] We did not account for the regional impacts of soil erosion (for instance, the impacts on the hydroelectric power generation system and on coral reefs).

[39] According to Franklin and Pindyck (2018), the average incremental social cost of deforestation ranges between US$ 9000/ha to US$ 35000/ha depending on the Amazon deforestation rate in the next 12 or 80 years, respectively. If deforestation rate reaches the tipping point in one year, the average incremental social cost is estimated in US$ 52000/ha.

[40] The comparison of costs between different projects, regions, recovery paths, time horizon projection and discount rates must be carried out sparingly. All values are 2019 dollars. In order to minimize these differences, we focused on tropical forests' recovery projects with the same time horizon and similar discount rates.

Table 2
Scenarios - Net benefit (31, 50 and 155-year horizon).

Total	Economic models		Ecological models	
	Net benefit	Social IRR	Net benefit	Social IRR
	(US$ million)	(%)	(US$ million)	(%)
Less Costly first	19,587	86%	19,946	378%
More profitable first	19,562	85%	20,085	371%
Labour market adjustment	19,440	74%	20,224	294%
Ecotone-> Cerrado-> Amazon	19,208	82%	19,950	343%
Baseline (50-year)	**19,266**	**76%**	**19,973**	**294%**
31 year-horizon	*18,170*	*76%*	*15,794*	*294%*
155 year-horizon	*23,955*	*76%*	*23,813*	*294%*

Notes: Net benefit is calculated as timber and non-timber revenues plus environmental benefits (monetized carbon capture and avoided erosion) subtracted from total expenses (ecological models do not include timber and non-timber revenues). All monetary values are expressed in USS 2019 million and represent cash flow present values.

US$ 73/ha/year in the Amazon macro region), indicating that, beyond greater government inspection and penalties to inhibit deforestation, well designed recovery paths contribute to the compliance of quantitative limits to deforestation.

Focusing on environmental flows, “ecological” paths present higher monetized carbon and soil values once they generate 21% higher physical carbon capture (323 million tCO$_2$eq) and 1% higher physical erosion reduction (371 million tons) in comparison to “economic” models (268 million tCO$_2$eq and 367 million tons, respectively). These differences in favor of “ecological” paths are due to the absence of timber systems (which in our study is subject to harvesting according to IPCC’s committed emissions approach) and agroforestry systems (that register lower CO$_2$ capture factors[41]) in their composition. Additionally, passive regeneration processes (initially more frequent in “ecological” paths) are expected to rapidly increase soil surface protection, lowering soil erosion rates (see Section 5.2).

Accordingly, the net benefit by region/size per ha/year (Fig. 4) mainly follows the physical CO$_2$ capture (tCO$_2$eq) by region/size: the Amazon region presents the highest net benefit per ha/year (between US $ 371–514/ha/year), followed by Ecotone (between US$ 333–444/ha/year) and Cerrado (between US$ 108–254/ha/year). Two main factors probably explain this: the higher incremental annual average growth of trees in the Amazon region (in paths with timber harvesting) and the differences in the carbon capture factors by region and pathway (see Section 5.1). In particular, in Cerrado region, “economic” paths’ carbon sequestration values are higher compared to “ecological” paths because agroforestry systems and forest formation induced by natural regeneration, subsequent to timber harvesting, present higher carbon capture factors in comparison to the cerrado *strictu sensu* vegetation adopted in the “ecological” paths. In this sense, after 105 years, Cerrado’s “economic” paths’ carbon stock is on average 190 CO$_2$ ton/ha versus 117 CO$_2$ ton/ha to “ecological” paths in the same macro-region. In turn, the quantity of avoided erosion per hectare is very similar in all regions/sizes and pathways: between 394 and 395 tons/ha in “economic” paths and 397–402 tons/ha in “ecological” paths.[42,43] Interestingly, when considering only financial flows and “economic” paths (Fig. 5), small properties register the highest NPV per ha/year and IRR in each macro-region, due to the profitability of agroforestry systems, since small properties’ recovery paths are based solely (100%) on agroforestry systems. Among all property sizes and regions, Amazon/small and Ecotone/small present the highest revenue per ha/year and Cerrado/small is the most profitable among all property sizes in the Cerrado region. Concerning large and medium properties recovery in “economic” paths - mainly based on timber systems (between 85% and 91% of total hectares, depending on the macro-region) -, Fig. 5 shows that properties’ revenues are higher for Amazon, medium for Ecotone, and lower for Cerrado properties. This pattern relates to timber systems in the Amazon being more productive (upper annual average increment equal to m^3/year tree growth) than timber systems in the Ecotone region, which in turn are more productive than Cerrado timber systems.[44]

As for cost-effectiveness analysis, carbon capture costs US$ 8.3 per tCO2eq or US$ 3.2 per tCO2eq considering “economic” or “ecological” paths, respectively and a 50-year horizon projection. Avoided soil erosion totals US$ 6.0 per ton or US$ 2.8 per ton to replace soil nutrients (this is Nitrogen, Phosphorus, Potassium and Calcium, contained in one ton of soil lost per hectare), in “economic” or “ecological” paths, respectively.

“Ecological” paths present lower cost-effectiveness values for both carbon and erosion because, as already mentioned, they produce higher physical carbon capture and erosion reduction rates than “economic” paths and register lower expenses to be implemented. Also, it is important to mention that the cost-effectiveness calculations consider total expenses for both carbon capture and soil erosion reduction since it is not possible to distinguish expenses to obtain each environmental benefit separately.

As a basis for comparison, the costs of carbon savings in the projects studied by Swisher (1991) in Central America were between US$2.8 and US$7.3 per tCO2eq, depending on the type of the project, the climate and the opportunity cost of land.[45] In turn, the estimated cost of soil erosion on rice cultivated and abandoned land plots in Myanmar in 2006, using the replacement cost method with similar assumptions, was US$11.5 for a ton of soil lost per hectare, US$ 70.5 per ha/year for cultivated plots and US$ 143.5 per ha/year for abandoned plots (San and Rapera, 2010). Our estimation, as San & Rapera’s results, is underestimated not only because micro-nutrients are not considered but also due to physical soil conditions that can undergo local degradation and off-site impacts such as sedimentation of lakes and rivers, and adverse effects on water treatment and electrical energy generation (Telles et al., 2013). Graves et al. (2015) estimate that 39% of on-site soil degradation costs are due to compaction (changing soil structure), while off-site impacts account for 80% of total soil degradation costs. Both impacts were not considered in our study, meaning that values obtained for the Araguaia Corridor’s avoided soil erosion do not account for the full benefits of soil conservation.

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[41] This occurs due to the lower number of trees per hectare when compared to natural regeneration in Amazon and Ecotone region.

[44] It is important to notice that when considering the results per hectare in a 31-year time horizon, that is, not considering the project as a whole, but considering representative properties (by macro-region and size), NPV and IRR are positive to all regions and properties sizes and it takes between one (small properties) to eight (large and medium properties) years to present net positive results (which lasts during the remaining 30 or 22 years of the flow). These results can be obtained upon request to the authors.

[42] In Figs. 4 and 5, “AM/L“ stands for “Amazon/Large”, “EC/M” for “Ecotone/Medium”, “CE/S” for “Cerrado/Small”, and so on.

[43] We have estimated avoided soil erosion considering that the area would have continued as pasture. However, it would be possible for one to expect an alternative trajectory for this land parcel such as the conversion to agriculture. Mean erosion rates for degraded pasture, agriculture and forested areas are respectively 12.00, 8.59 and 0.23 ton/ha/year (Merten et al., 2013). Thus, if this was the case, and instead of persisting as pasture our estimated hectare had been changed to agriculture, then avoided soil erosion service would have been approximately 29% smaller.

[45] Original values from the study converted to 2019 US$ values and tCO$_2$eq; costs include establishment, maintenance, management, monitoring costs and opportunity cost for the land.

6.2. Direct jobs creation and government tax collection

In the year with the highest labor demand in each macro-region/size (usually the 19th or 20th year of the implementation schedule, depending on the region/size), "economic" paths create approximately 38 thousand direct jobs, while "ecological" paths create 12 thousand jobs. Since "ecological" paths do not include labor-intensive agroforestry systems, direct jobs created are 68% lower than in "economic" paths. As already mentioned in Section 5, we do not consider any commuting time (to access different implementation sites) in the working hours, assuming that workers are always hired locally.

Analyzing by occupation, in both "economic" and "ecological" paths, most of the created jobs correspond to field hands and tractor operators (96% and 92%, respectively), followed by agricultural/forestry technicians (3% and 8%, respectively) and forestry engineer (0.2% and 0.4%, respectively). Additionally, in "economic" paths, 295 positions (1%) are related to agricultural/forestry supervision.

Regarding government tax collection present value, we estimate a total of US$ 402.6 million considering "economic" paths and 50-year horizon, representing 18% of estimated tax collection in the Araguaia Corridor municipalities in 2018 (US$ 2019 values).[46] We discriminate between two regimes: "Lucro Real", for large properties, makes up 61% of this value (US$ 245.6 million) while "Simples Nacional" represents small and medium properties 14.9% (US$ 59.8 million). The remaining 24.1% (US$ 97.1 million) corresponds to PIS/Cofins revenue, a direct tax based on the enterprise's turnover that large properties also have to pay. It is important to notice that total municipality revenues include tax collection and transfers from the federal and state governments. Our calculations consider only tax collection derived from agro sector profits or revenues.

7. Sensitivity analysis

We estimate four different scenarios described as: (i) the least costly methods are initially adopted, changing the implementation schedule over the years, when compared to the baseline scenario; (ii) the most profitable methods are adopted first, also changing the order of implementation when compared to the baseline scenario; (iii) higher implementation rate in intermediate years and lower in initial and final years to allow for workforce to adjust and to mitigate the risk of labor market collapse[47]; and, (iv) implementation schedule by macro-region, being the areas located in the ecotone region the first to be recovered, followed by cerrado and then amazon macro-region areas. We consider the 50-year time horizon for all scenarios and additional 31 and 155 years time horizon projections for the baseline scenario as explained in Section 5.

The net benefit of all scenarios ranged between US$ 19.2 and US$ 19.6 billion for "economic" paths and between US$ 19.9 and US$ 20.2 billion for "ecological" paths (Table 2) and is very similar to the baseline in both "economic" and "ecological" paths (US$ 19.3 and US$ 19.9 billion, respectively - see Table 1). This can be explained by the monetized carbon capture, which, as already mentioned, is the major component of the net benefit and barely varies between the proposed scenarios. Social IRR ranges between 74% and 86% in "economic" paths and 294% and 378% in "ecological" paths.

Table 2 also shows the net benefit when considering 31 and 155-year time horizon projections. In 31 years-time projection, "economic" paths' net benefit reaches US$ 18.2 billion, 15% higher than "ecological" paths, as in the former most of the logging and its consequent emissions do not occur before the 31st year.[48] When it comes to 155 years the "economic" net benefit present value (US$ 24.0 billion) is slightly higher than the "ecological" (US$ 23.8 billion). Despite the fact that "ecological" paths present higher monetized benefits in both carbon capture and avoided soil erosion, the addition of timber and non-timber revenues in the "economic" paths compensate for this difference and make both pathways very similar in the long run. Importantly, in 155 years carbon sequestration is similar in both paths: "economic" and "ecological" paths capture 405 million tons of CO2eq (US$ 21.0 million) and 421 million tons of CO2eq (US$ 22.4 million), respectively (Fig. 6). Assuming that the complete recovery of an area takes 105 years after the natural regeneration that followed the last timber harvesting (and therefore, no additional net carbon capture would occur after that), results from 155-year time horizon reflect the maximum carbon capture in the restored area (see Section 5.1 for details).

The difference between 50 and 155-year time horizon net benefit is due mainly to the fact that the carbon capture benefits increase at decreasing rates (see Section 5.1) and, on a smaller proportion, because there are no revenues from timber and non-timber products from the year 50th on (see Section 5).

Focusing on financial flows, we also calculated the net present value (NPV), internal rate of return (IRR), government tax collection and direct jobs created compared to the baseline and same alternative scenarios, over a 50-year time horizon, for both "economic" and "ecological" paths. Table 3 shows that regarding "economic" paths, the early adoption of more profitable methods (scenario ii) leads to the highest NPV among all the projected scenarios, being 66% higher than the baseline. However, there are no significant changes related to IRR or government tax collection. Scenarios (i. less costly first) and (iii. labor market adjustment) register similar NPV, which is approximately 25% higher when compared to the baseline scenario. Choosing the implementation schedule by macro-region (scenario iv) turned out to be the worst option since it shows the lowest NPV among the projected alternatives. As regard to social impact, the maximum number of direct jobs created in the year with the highest labor demand in each macro-region/size increases significantly in scenarios (i) and (ii), followed by scenario (iv). This occurs due to the anticipation of labor-intensive recovery methods in the mentioned scenarios. In turn, scenario (iii) demands 16% fewer employees than the baseline scenario. Regarding government tax collection, only scenarios (iii) and (iv) present a higher tax present value than the baseline.

Concerning the 31-years' time horizon, NPV is negative (-US$ 509 million) meaning that total expenses are higher than timber and non-timber revenues. Observing Fig. 7 we see that total revenues only overcome total expenses from the 21st projection year on as most of the logging and timber revenues occur after this point. In turn, Table 3 does not include 155-year time horizon results because all expenses and revenues are estimated to end in the 50th year of the flow. From the 51st year on, all paths are solely based on natural regeneration. When it

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[46] Araguaia corridor's tax collection (US$ 2243 million) is estimated as the sum of each of the 112 municipalities' revenue weighted by the share of their area which is located inside the corridor, based on SICONFI 2018 data (Sistema de Informações Contábeis e Fiscais do Setor Público Brasileiro). Values corrected to Dec 2019.

[47] This scenario adjusts the implementation schedule to ensure a slower pace of forest recovery in the early years, aligning with the available workforce and mitigating the risk of labor market collapse. It takes into account that the restored area experiences increasing expansion rates in the initial years and decreasing rates in the later years. By designing it this way, the scenario allows for a slower pace of recovery in the early years, which aligns better with the available workforce for the project. As a result, it helps mitigate the risk of a collapse in the forest labor market at the project's conclusion."

[48] In the 31 years-time projection, all slow-growing trees planted from the 2nd year of the flow cannot be harvested, meaning that it is not possible to consider an earlier logging operation. The same happens to moderate growing trees from the 18th year of the flow (assuming that those planted between the 11th and 17th year of the flow will be cut at age 14. It is important to emphasize that the rationale behind the 31-years-time projection is that at the end of 31 years, all moderate-growing trees planted in the 10th year of the flow will be approximately 20 years old and will be harvested.

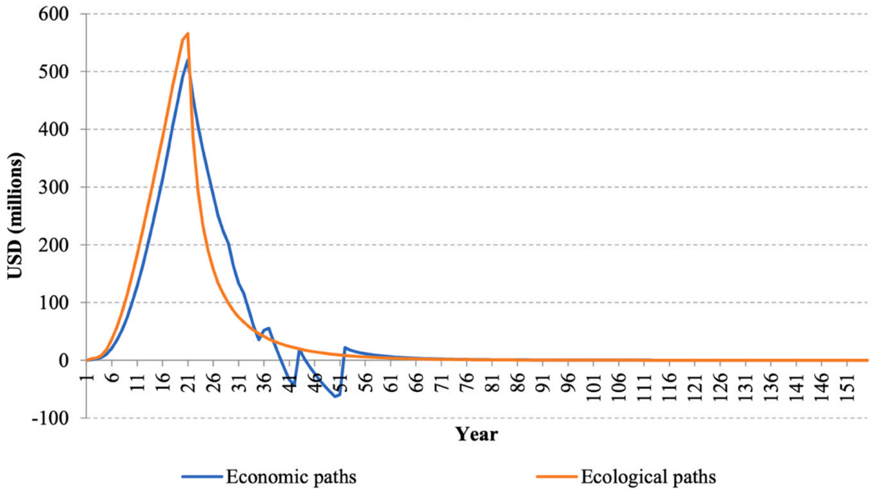

Fig. 6. Carbon capture (present value).

Table 3
Scenarios (50-year horizon projection).

Total	Economic models						Ecological models	
	NPV (US$ million)	IRR (%)	Expenses PV (US$ million)	Revenues PV (US$ million)	Gov tax collection (US$ million)	Direct Jobs (n of jobs)	Expenses PV (US$ million)	Direct Jobs (n of jobs)
i. Less Costly first	619	13.4%	2,110	2,729	322	124,460	1,074	27,126
ii. More profitable first	830	13.9%	2,162	2,991	321	106,010	1,045	29,552
iii. Labour market adjustment	624	14.7%	2,397	3,021	449	31,998	1,106	10,529
iv. Ecotone-> Cerrado-> Amazon	408	13.4%	2,227	2,636	434	79,077	1,056	18,895
Baseline	**500**	**14.4%**	**2,213**	**2,713**	**403**	**37,898**	**1,028**	**12,171**

Notes: Net present value (NPV) is calculated as timber and non-timber revenues present value subtracted from total expenses present value. Total expenses include operational costs, investment, opportunity cost of land, insurance and taxes (ecological models do not include taxes). All monetary values are expressed in USS 2019 million and represent 50-year time horizon present values. IRR is the internal rate of return.

comes to the “ecological” paths, all projected scenarios register similar expenses present value, but scenarios (i), (ii), and (iv) are the most labor-intensive. Total expenses include operational costs, investment, the opportunity cost of land, insurance and taxes (“ecological” paths do not include taxes). All monetary values are expressed in USS 2019 million and represent 50-year time horizon present values. IRR is the internal rate of return. Number of jobs refer to the year with the highest labor demand.

We have also taken into consideration the different scenarios for the opportunity cost of land. We have considered a scenario in which degraded areas would be converted to agricultural land, taking into account the local land price for agricultural activities. Additionally, we have explored another scenario in which the degraded lands are converted to pastures, considering the pasture value for the area. However, the results remain the same, with no significant changes and can be assessed in Appendix I (Tables A1 and A2).

Finally, we have varied carbon value, considering the average carbon price in the voluntary forest carbon credit market[49] and the country-level SCC estimated by Ricke et al. (2018). The results for the estimated scenarios are also available in the Appendix I (Tables A1 and A2). Overall, the profitability of the models considered remains the same, with only the magnitude of the results changing.

8. Final remarks

Restoration science has advanced toward comprehending the main drivers of the restoration process (Crouzeilles et al., 2017) and the advantages and limitations of different restoration methods (Crouzeilles et al., 2020). Nevertheless, restoration of native ecosystems is site and context-specific. Cost-benefit analysis based on ecosystem services modeling and valuation is needed to scale up from local to regional implementation. This kind of analysis is scant for most parts of the world and is also the case in our studied region.

We find that the recovery of the Araguaia Biodiversity Corridor indicates promising results, with positive net benefit values for all regions and property sizes as well as low costs per captured tCO_2eq and ton of erosion reduction. “Ecological” paths present lower expenses to be implemented, while the “economic” paths present revenues derived from timber and non-timber products. Moreover, in terms of carbon capture, “ecological” paths register 21% higher results than “economic” paths in the 50-year horizon projection. However, when extending the time to 155 years, both pathways present similar results, achieving 405 billion tons and 421 billion tons of CO_2eq for “economic” and “ecological” paths, respectively. It is worth noting that most of the benefits are related to the environmental ones, empowering the argument in favor of public funding for the restoration activity.

Nonetheless, results for the “economic” paths provide an important argument for rural landowners to join restoration projects in the region as agroforestry and timber systems proved to be profitable and economically sustainable, even when environmental social benefits are not considered. The proposed production changes benefit landowners by increasing revenues and by allowing the compliance with the Brazilian Forest Code. In this sense, our “economic” recovery path proposition

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[49] According to EM global carbon markets hub, the voluntary forest and land use carbon credit average price was US$ 5.8/tCO2eq in 2021. We corrected that average price to 2019 using CPI inflation index and consider it constant over time as a conservative assumption. For more details see https://www.ecosystemmarketplace.com/em-global-carbon-markets-hub/.

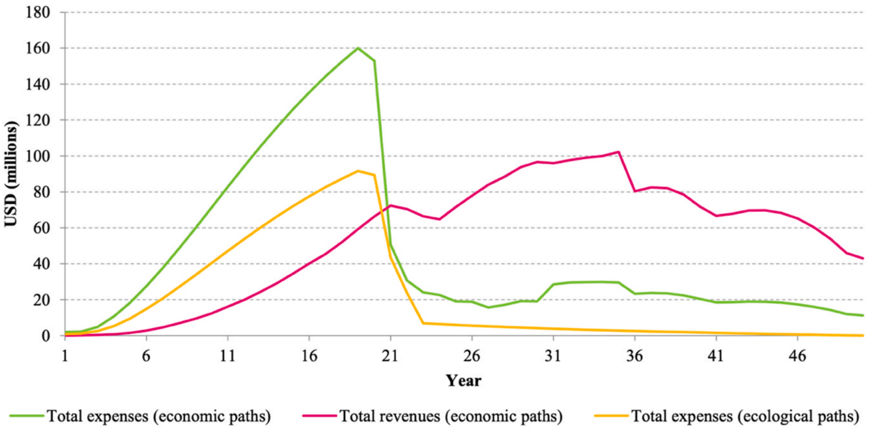

Fig. 7. Total projected expenses and revenues (present value) – Economic and ecological paths.

contributes to the Brazilian government in order to enforce the current Forest Code. As Roriz et al. (2017) point out, legislation per se does not imply the best performance, especially in an environment with low supervision. It is well known that command and control policies, such as the Brazilian forest code, demand concerted monitoring and supervision by the related government agencies to produce the expected results. When properly managed, better law enforcement leads to diminish deforestation and favors intensive land use, replacing extensive livestock by agriculture, such as experienced, between 2010 and 2020, by Tocantins state,[50] part of the arc of deforestation, area with high deforestation pressure (Feitosa et al., 2023; Schielein and Borner, 2018). On the other hand, with low supervision there is a significant trade-off between forest conservation and livestock technology improvements (Cattaneo, 2001).

Additonally, Wortley et al. (2013) noted the importance of the socioeconomic attributes of restoration, advocating that it should be also the focus when evaluating restoration projects. Socioeconomic outcomes are essential for understanding ecological restoration's full societal benefits and costs and supporting its application in natural resource management. In this sense, the "economic" paths proposed in this study present a viable option to ecologically restore degraded forest areas once they are not dependent on forest carbon credits obtained in low-developed payment schemes with uncertain returns to be profitable.

Analyzing the results by region and property size show that small properties (in all regions) are the ones with the highest profitability due to the presence of agroforestry systems. Our results are in line with the ones reviewed by Wainaina et al. (2020), in which among 17 different restoration types, agroforestry is the one that consistently presents positive NPV, in contrast to natural regeneration, reforestation, and afforestation. Among the possible agricultural activities to be adopted, agroforestry systems are the most similar to the natural tropical forest ecosystems that naturally thrive in Northern Brazil. This may explain the high potential economic return and the successful carbon and soil services estimations for the proposed pathways. Nevertheless, migrants from both the South and the Northeast who have settled in the Araguaia corridor's region have naturally adopted the agricultural techniques from their places of origin to which they are familiar, unaware of a more suitable alternative possibility. Nor is it easy to switch from a familiar system to a new unknown one. So, intensive technical support is needed to help producers move from the well-known pasture system towards the agroforestry system they do not dominate. Current land titles and financing options are important factors for this transition (Schembergue et al., 2017). Although the Federal Government has been making some effort to promote the adoption of agroforestry systems since the 2000 s and has implemented a set of different measures to increase land regularization and credit for low-carbon agricultural systems, the lack of qualified local technical assistance hinders the rise of this new and promising agricultural use across the country, especially in the North of Brazil.

The corridor recovery also shows significant local impacts (50-year horizon): (i) the number of direct jobs created represents 17% (4%) and 5% (1%) of local agro (total) sector employment; (ii) local income increase due to job creation represents 6% and 3% of local agro sector GDP[51]; and (iii) timber and non-timber production raises represent 9.8% and 6.5% of national supply (based on IBGE 2017 data), all numbers for "economic" and "ecological" paths, respectively. Finally, (iii) the impacts on local government tax collection (US$ 24 million, considering the year with the highest tax collection in each region/property size) register an increase of 1.1% on local municipalities revenues.[52] Also, at the national level, the Araguaia corridor recovery contributes to both the Brazilian government's Bonn Challenge commitment - to restore 12 million hectares up to 2030 -, and the iNDC Br goals to reduce greenhouse gas emissions. The Araguaia project could account for 8% of the Brazilian Bonn Challenge goal.

In turn, the impact of the Araguaia Biodiversity Corridor implementation on hydrological systems might be significant and a future avenue of research. Hydrological modeling deals with complex interactions and processes in different spatial and temporal scales associated with several uncertainty sources (Wei et al., 2013). Large and heterogeneous basins, such as the Araguaia, are yet more difficult to model (Cavalcante et al., 2019) because regional and global changes, e.g., neighbor land use and global climate changes, are difficult to isolate from the effect of the corridor restoration activities. Besides, there are several other additional ecosystem services, for instance, hydropower efficiency gains, fishery benefits, coral reef conservation, and biodiversity protection, to mention a few, that could also be considered as local,

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[50] According to Feitosa et al. (2023), in 2004 the Tocantins state government adopted the "Tocantins Forest Protection Project", which combined to the Plan for the Protection and Control for deforestation in the Amazon (PPPCDAm), led to a decrease in deforestation and criminal forest fires in the area. In this way, forest formation areas increased in Tocantins state and the number of forest fires was the lowest among the states of the Amazon region between 2010 and 2020. Feitosa et al. (2023) also show that, due to the government greater inspection to inhibit deforestation, the projection of land use and land cover change for 2050 for the Amazon Forest in Tocantins registers a significant increase of forest formation.

[51] Local agro sector GDP (US$ 991.5 million) is estimated as the sum of each of the 112 municipalities' agro GDP weighted by the share of their area, which is located inside the corridor, based on IBGE 2017 data.

[52] As already mentioned, it is important to notice that total municipality revenues include municipality tax collection and transfers from the federal and state governments, not included in these calculations.

regional, and global benefits from the Araguaia Biodiversity Corridor implementation. If these additional services were considered, then the overall estimated benefits of such an extensive restoration project would certainly be much greater than the results we estimate.

Finally, the results of this study provide valuable insights for the formulation of land use policies in Araguaia and Brazil. The findings emphasize the economic, environmental, and social benefits associated with large-scale restoration initiatives. This information can inform public policies by promoting sustainable land management practices, incentivizing the implementation of agroforestry systems, and supporting ecosystem restoration projects. The social benefits derived from these restoration efforts outweigh the associated costs, thereby justifying the need for subsidies to support ecosystem restoration. Public policies can incorporate various mechanisms, such as financial support, grants, and incentives, to encourage and facilitate ecosystem restoration activities in the region. Specifically, land use policies can focus on encouraging and providing incentives for small-scale farmers to adopt agroforestry practices, leading to positive economic and environmental outcomes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The authors do not have permission to share data.

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Appendix I. Additional scenarios

In this appendix we present the results based on additional scenarios considering alternative opportunity costs of land and alternative carbon price. Concerning the opportunity cost of land, in our analysis, we utilized weighted average selling price of land for each state and agricultural or livestock use, as sourced from Lima Filho et al., (2016). To calculate the overall weighted price averages, we have taken into account the proportion of the area within the region and the respective contributions of the agriculture and livestock sectors. In this Appendix we have included two additional scenarios exploring different land prices, based on the conversion to 100% of agricultural areas, or 100% of pasture areas and then calculated an annual rent corresponding to the annual discount rate (WACC) multiplied by the selling price. We also calculated the results considering a scenario in which the opportunity cost of land is the average selling price of land (weighted by state location and agricultural or pasture usage). The overall results remain profitable and can be observed in Table A1 and Table A2.

Related to the carbon price, we assume that the carbon capture impact as a global benefit (despite its costs being local in the project) as it contributes to global climate change reduction. In addition, modeling the impacts of carbon capture deals with complex interactions and processes in different spatial and temporal scales associated with several uncertainty sources, being very difficult to isolate its local effect. In any case, we estimate the monetized benefit accruing from carbon capture applying the country-level social cost of carbon to Brazil (US$ 24/tCO_2eq) estimated by Ricke et al. (2018) and the average price in the voluntary forest carbon credit market in 2021 (US$ 5.8/tCO_2eq). It is possible to interpret the revenues obtained in the carbon credit market as a local effect, however, we understand that it is not the fully effect of carbon capture benefit as intended to be computed in a cost benefit analysis. Overall, the profitability of the models considered remains the same, with only the magnitude of the results changing (Table A1 and Table A2).

Table A1
Scenarios: Net benefit alternative opportunity costs and carbon prices (50-year horizon)

Scenarios	Economic paths		Ecological paths	
	Net benefit (US$ million)	Social IRR (%)	Net benefit (US$ million)	Social IRR (%)
A. Alternative opportunity costs of land:				
100% Pasture	19,268	76%	19,975	294%
100% Agriculture	19,256	75%	19,962	288%
Average price of land	18,910	58%	19,602	159%
B. Alternative carbon price:				
Country-level SCC (Brazil)	6,018	28%	4,852	52%
Voluntary forest carbon credit	2,905	18%	1,481	4%
Baseline (50-year)	**19,266**	**76%**	**19,973**	**294%**

Notes: Net benefit is calculated as timber and non-timber revenues plus environmental benefits (monetized carbon capture and avoided erosion) subtracted from total expenses (ecological models do not include timber and non-timber revenues). All monetary values are expresses in US$ 2019 million and represent cash flow present values.

Table A2
Scenarios: NPV (50-year horizon)

Scenarios	Economic paths						Ecological paths	
	NPV (US$ million)	IRR (%)	Expenses (US$ million)	Revenues (US$ million)	Tax (US$ million)	Direct Jobs (no. of jobs)	Expenses (US$ million)	Direct Jobs (no. of jobs)
A. Alternative opportunity costs of land:								
100% Pasture	501	14.4%	2,212	2,713	403	37,898	1,027	12,171

(continued on next page)

Table A2 (*continued*)

	Economic paths						Ecological paths	
Scenarios	NPV	IRR	Expenses	Revenues	Tax	Direct Jobs	Expenses	Direct Jobs
	(US$ million)	(%)	(US$ million)	(US$ million)	(US$ million)	(no. of jobs)	(US$ million)	(no. of jobs)
100% Agriculture	490	14.3%	2,223	2,713	402	37,898	1,039	12,171
Average price of land	143	10.8%	2,569	2,713	388	37,898	1,399	12,171
B. Alternative carbon price:								
Country-level SCC (Brazil)	500	14.4%	2,213	2,713	403	37,898	1,028	12,171
Voluntary forest carbon credit	500	14.4%	2,213	2,713	403	37,898	1,028	12,171
Baseline (50-year)	**500**	**14.4%**	**2,213**	**2,713**	**403**	**37,898**	**1,028**	**12,171**

Notes: Net present value is calculated as timber and non-timber revenues present value subtracted from total expenses present value. Total expenses include operational costs, investment, opportunity cost of land, insurance and taxes (ecological ptahs do not include taxes). All monetary values are expressed in US$ 2019 million and represent 50-year time horizon present values. IRR is te internal rate of return.

Appendix II. Costs and revenues parameters

In this appendix we present the main costs and revenues utilized in the analysis. The main components of operational costs are: labor, machinery and equipment, direct materials (seedling and seed, fertilization and soil correctives, herbicide, formicide, hydrogel) and indirect materials (fuel, oil, lubricant). Table A3 presents the main costs by macro-region in US$ 2019 values:

Table A3

Costs by macro region (US$ 2019 values)

Cost items	unit	Amazon	Ecotone	Cerrado
Labor (in-house)				
Field assistant	hour	2.71	2.88	3.43
Tractor operator	hour	3.66	3.58	4.29
Agricultural/Forestry supervisor	hour	5.15	5.49	6.50
Agricultural/Forestry technician	hour	5.56	6.39	6.55
Forest Engineer	hour	13.82	15.18	13.66
Labor (outsourced)				
Field assistant	hour	3.88	4.11	4.90
Tractor operator	hour	5.22	5.11	6.13
Agricultural/Forestry supervisor	hour	7.35	7.84	9.28
Agricultural/Forestry technician	hour	7.94	9.12	9.36
Forest Engineer	hour	19.75	21.69	19.52
Machines and equipments (in-house)				
Semi-manual equipment	hour	1.59	1.59	1.68
Tractor-implements - 80 hp	hour	19.28	18.95	19.08
Tractor-implements - 110 hp	hour	25.66	25.21	25.39
Machines and equipments (outsourced)				
Semi-manual equipment	hour	2.27	2.27	2.40
Tractor-implements - 80 hp	hour	27.54	27.07	27.25
Tractor-implements - 110 hp	hour	36.66	36.01	36.27
Material and inputs				
Inputs of the fences (6 ×6 w/4 wires)	km	1644.08	1644.08	1644.08
Pos-emergent herbicide (Glifosate)	liter	6.42	6.12	4.97
Selective pre-emergent herbicide	liter	14.39	14.39	14.39
Herbicida Pré-emergente (Isoxaflutole)	liter	212.00	212.00	212.00
Water retaining gel (hydrogel) during planting	kg	8.22	8.22	8.22
Water retaining gel (hydrogel) - after planting	kg	16.70	16.70	16.70
Formicide in grain (Sulfuramida)	kg	3.08	3.08	3.08
Eucalyptus seedling	container	0.13	0.13	0.13
Native species seedlings	bag	0.51	0.51	0.51
Native species seedlings	container	0.39	0.39	0.39
Seeds (Tree native species)	kg	12.85	12.85	12.85
Seeds (Green manure species)	kg	3.08	3.08	3.08
Acacia mangium seedlings	container	0.33	0.33	0.33
Pupunha seedlings	container	0.26	0.38	0.51
Açaí seedlings	container	0.31	0.17	0.00
African mahogany seedlings	container	0.90	0.90	0.90
Banana seedlings	container	0.51	0.51	0.51
Cupuaçu and cocoa seedlings	container	0.51	0.51	0.40
Teak seedlings	container	0.77	0.77	0.77
Dolomitic-limestone	tons	33.41	32.23	34.40
Fertilizer NPK 06–30–06	kg	0.46	0.46	0.42
Fertilizer NPK 20–05–20 + Micro	kg	0.46	0.47	0.46
Fertilizer NPK 10–28–20	kg	0.46	0.46	0.46
Fertilizer NPK 10–10–10	kg	0.45	0.45	0.45
Fertilizer NPK 00–18–00	kg	0.37	0.37	0.37
Fertilizer NPK 20–00–20	kg	0.46	0.46	0.46

(*continued on next page*)

Table A3 (*continued*)

Cost items	unit	Amazon	Ecotone	Cerrado
Fertilizer NPK 20–10–10	kg	0.48	0.48	0.48
Fertilizer NPK 20–00–10	kg	0.44	0.44	0.44

Sources: Caged, MFRural, Agristore, Agrolink, Conab and Institute of Agricultural Economics (IEA).

Occupations are based on Brazilian Classification of Occupations (CBO). Average wages include taxes (68.17% of labor-related taxes, such as 13th wage, vacation INSS, FGTS). If labor is outsourced, a premium of 30% was considered (12% of taxes, 15% of profits and 3% of administrative costs of the service-provider). Wages were converted to MH (man-hour) considering 44 hours per week or 176 hours per month.

Machinery and equipment costs vary by recovery path: the operation of all "economic" paths is mechanized, while the operation of "ecological" paths can be mechanized or not. Machinery costs includes the following items:

- Farm tractors: consider the use of 80 hp engine tractors for light duty and 110 hp for heavier operation, for example, for soil preparation (operating yield - machine hour);
- Semi-manual machinery: manual grass cutter machine, manual holler digger machine, chainsaw (operating yield - machine hour)

Machinery and equipment costs includes: (i) fixed costs: purchase price of machinery and implement, depreciation, interest on capital, insurance; and, (ii) variable costs: fuel, lubricant, preventive and corrective maintenance.

Material and inputs costs vary by region and recovery models and its main items are: seedlings and seeds, concealers and fertilizers; herbicides, pesticides and formicides; water retaining gel and fencing.

The opportunity cost of land was estimated based on weighted average selling price of land according to Table A4 and land use (Table A5):

Table A4

Average Price of land (US$/ha) in 2019 values

	Amazon	**Ecotone**	**Cerrado**
	(north)	(central)	(south)
agriculture	1386	1464	3465
livestock	1056	1121	1575
weighted average	1061	1129	2187

Source:Lima Filho et al. (2016)

Table A5

Average land use by macro region

	Amazon		**Ecotone**		**Cerrado**	
	livestock	agriculture	livestock	agriculture	livestock	agriculture
area (ha)	269,223	4,439	551,486	13,373	62,316	29,867
%	98%	2%	98%	2%	68%	32%

Table A6 summarizes the price elasticity estimates from the specific literature:

Table A6

Price elasticity estimates from the literature by product.

Product	Price elasticity	Region	Period	Method	Reference
Açaí	-0.779	Pará	1994–2009	Simultaneous equations	Nogueira et al. (2013)
Banana	-0.862	Roraima	1995–2007	Simultaneous equations	Amaro (2010)
Barú, Buriti and Pequi	-0.5 (average)	Vale do Urucúia, Minas Gerais		Literature survey	Nogueira et al. (2009)
Brazilian nut	-0.222	Amazônia	1990–2010	Simultaneous equations	Santana (2015)
Fruits, Pineapple, banana, coconut, guava, orange, passion fruit, watermelon and other fruits.	-0.679	Pará	1985–2005	Simultaneous equations	Santana et al. (2011)
Timber	-0.550	Paraná	1988–2004	Simultaneous equations	Almeida et al. (2009)
Cassava	-1.512	Ceará	1985–2000	Simultaneous equations	Cartaxo et al. (2004)

Source: elaborated by the authors.

Table A7 presents timber average prices and non-timber average prices, respectively, in the first and 15th year of the flow, by macro region, in US$ 2019 values.

Table A7
– Average timber and non-timber prices (US$ 2019 values)

Species	macro region	logging (years)	baseline price	price in 15th year of the flow
Timber products				
Native trees	All	7	30.84	23.33
Native trees	All	14	65.78	49.78
Native trees	All	21	146.99	111.22
Native trees	All	30	249.26	188.61
Eucaliptus Uro x grandis	All	7	16.06	15.79
Eucaliptus Uro x grandis	All	14	21.97	21.60
Eucaliptus slow growth	All	6	14.78	14.52
Eucaliptus slow growth	All	9	15.16	14.90
Eucaliptus slow growth	All	15	30.84	30.31
TeKa	Ecotone and Cerrado	7	17.99	13.61
TeKa	Ecotone and Cerrado	14	96.62	73.11
TeKa	Ecotone and Cerrado	21	146.99	111.22
African Mahogany	All	10	69.38	52.50
African Mahogany	All	15	147.76	111.80
Paricá	Amazon and Ecotone	6	28.78	21.78
Acacia mangium	All	3	10.28	7.78
Acacia mangium	All	6	22.61	17.11
Acacia mangium	All	10	56.53	42.78
Non-timber products				
Açaí (fruit)	Amazon	-	0.37	0.36
Açaí (palm heart)	Amazon	-	0.69	0.68
Andiroba (seed)	Amazon and Ecotone	-	0.27	0.05
Araticum-marolo (fruit)	Cerrado	-	1.09	0.22
Bacuri (pulp)	Amazon and Ecotone	-	2.18	0.44
Banana (fruit)	Amazon and Ecotone	-	0.60	0.60
Banana da terra (fruit)	Amazon	-	0.54	0.54
Baru (nut)	Ecotone and Cerrado	-	2.22	0.45
Cocoa (nibs)	All	-	1.31	0.76
Brazil nut (nut)	Amazon and Ecotone	-	0.17	0.10
Cupuaçu (pulp)	Amazon and Ecotone	-	1.41	0.28
Guariroba (palm heart)	Cerrado	-	1.40	1.40
Macaúba (pulp)	Ecotone and Cerrado	-	0.10	0.02
Cassava (root)	Amazon and Ecotone	-	0.06	0.06
Mangaba (fruit)	Cerrado	-	0.53	0.39
Pequiá (fruit)	Amazon	-	0.23	0.08
Pequi-anão (fruit)	Ecotone and Cerrado	-	0.13	0.06
Pupunha (palm heart)	Amazon	-	0.77	0.18
Tapereba (pulp)	Amazon and Ecotone	-	0.48	0.10

Source: elaborated by the authors.

Table A8 presents an overview of above and belowground carbon capture per hectare per year for comparison purposes.

Table A8 –
Carbon stock or emissions by land use (per hectare)

Activity		**Stock (tCO2eq/ha)**	**Period (years)**	**Carbon capture (or avoided emissions) per year (tCO2eq/ha/year)** [1]
Pasture burning		0.73[2]	8	0.19[3]
Ecological restoration[4]	Amazon	341.78	20	17.09
	Ecotone	300.50	20	15.03
	Cerrado	75.30	20	3.77
Logging[5]	1 - Amazon	353.01	22	16.05
	2 - Ecotone	314.18	22	14.28
	3 - Cerrado	275.35	22	12.52
	4 - Amazon	418.54	15	27.90
	5 - Ecotone	372.50	15	24.83
	6 - Cerrado	326.46	15	21.76
	7 - Amazon	420.05	16	26.25
	8 - Ecotone	373.84	16	23.37
	9 - Cerrado	327.64	16	20.48
	10 - Ecotone	277.41	22	12.61
	11 - Cerrado	243.12	22	11.05
	12 - Amazon	451.38	16	28.21
	13 - Ecotone	401.72	16	25.11
	14 - Cerrado	352.07	16	22.00
	15 - Amazon	304.08	31	9.81
	16 - Ecotone	270.63	31	8.73
	17 - Amazon	304.08	31	9.81
	18 - Ecotone	270.63	31	8.73
	19 - Cerrado	237.18	31	7.65
Agroforestry	All AFSs except for AFS IV (Brancher's AFS 1)	173.49	15	11.57
	AFS IV (Brancher's AFS 2)	191.05	15	12.74

[1] Annual rates obtained as a linear approximation using stock and period.

[2] Emissions from 1 ha of pasture burned in a given year.

[3] Considering that pasture is burned every 2.5 years and that 35% of pasture is degraded and therefore not subject to maintenance burning.

[4] Ecological restoration models consider that 64.35% of the carbon stock from the original vegetation is achieved after 20 years (or 66% in 90 years, using a log approximation).

[5] Carbon capture in models that include logging refers to the maximum carbon stock in each model (considering trees destined for timber harvesting) and its corresponding year. Carbon capture per year is presented just for comparison, since all captured carbon from these trees is considered to be released back to the atmosphere when harvested (committed emissions).

In order to estimate soil erosion, we used reference values of soil loss (tons per hectare per year) for different land use types, gathered from the scientific literature (Table A9):

Table A9

Reference values for soil loss

Land Use	Correspondence to Araguaia pathways	Soil loss (ton ha^{-1} y^{-1})	Source
Pasture	Original land use	12	Merten and Minella, (2013)
Young plantation	Initial 3 years for both agroforestry and treeplantations	3.9	Sun et al., (2018)
Mature plantation	Timber systems from 5 to 29 y (i.e. usp to the end of timber exploitation)	1.1	Sun et al., (2018)
Shrubland	Young native regeneration (up to year 4)	0.36	Labriere et al., 2015
Tree dominated land use	Agroforestry systems (no timber systems)	0.27	Labriere et al., 2015
Amazon forest	Native forest	0.23	Barbosa and Fearnside, (2000)

Source: elaborated by the authors.

We calculate the WACC for the Forest Recomposition as the simple average of the WACC from 2016 to 2019 as can be observed in Table A10:

Table A10

WACC calculation and its components, 2016–2019

Capital Structure			**2019**	**2018**	**2017**	**2016**
E	Proportion of equity	Optimal capital structure - companies from paper and forest products sector - emerging markets (Damodaran)	58%	63.2%	61.3%	60.4%
D	Proportion of debt		42%	36.8%	38.7%	39.6%
Cost of Equity			**2019**	**2018**	**2017**	**2016**
R_f	risk-free rate	Average of T-Bond 10 y daily income series for the United States of America over the past 10 years	2.45%	2.52%	2.64%	2.89%
P_{MR}	market risk premium	Average of the premium (difference) of the average return of the S&P500 daily series (i. e. 10 years) on the risk free rate (R_f) of the last 10 years.	10.05%	6.32%	4.07%	3.86%
P_{CR}	Country risk	Average of EMBI + Brazil daily series in July of each year	2.49%	2.66%	2.89%	4.07%
β	leverage beta	Average value of the leveralized beta of companies from the Paper and Forest products sector (Damodaran).	0.97	0.96	0.82	0.98
D/E			72.4%	58.1%	63.1%	65.5%
T	corporate tax risk	Brazilian tax rate = 34% (25% of income tax/IRPJ + 5% of CSLL)	34%	34%	34%	34%
k_E	nominal cost of equity	In USD, nominal	14.60%	11.26%	8.84%	10.73%
i_{EUA}	inflation rate	Average annual US inflation measured by CPI over the past 10 years	1.77%	1.33%	1.64%	1.66%
k_E*	real cost of equity	Deflated by CPI	12.68%	9.80%	7.09%	8.92%
Cost of Debt			**2019**	**2018**	**2017**	**2016**
Rc	Credit risk	Rate charged for loans to projects that support reforastation, recovery and sustainable use of forests (BNDES FINAME Fundo Clima - Subprogram " Florestas Nativas")	4%	4%	4%	4%
$k_D$nom	nominal cost of debt	Sum of risk-free rate, country risk and credit risk	8.94%	9.19%	9.53%	10.96%
T	corporate tax risk	Brazilian IRPJ + CSLL	34%	34%	34%	34%
k_D	nominal cost of debt (after tax)	In USD, nominal	5.90%	6.06%	6.29%	7.23%
k_D*	real cost of debt (after tax)	Deflated by CPI	4.06%	4.67%	4.57%	5.48%
Weighted Cost of Capital			**2019**	**2018**	**2017**	**2016**
E	Proportion of equity		58%	63.2%	61.3%	60.4%
D	Proportion of debt		42%	36.8%	38.7%	39.6%
k_E*	real cost of equity		12.68%	9.80%	7.09%	8.92%
k_D*	real cost of debt (after tax)		4.06%	4.67%	4.57%	5.48%
WACC	weighted cost of capital (after tax)	Real rate (per year)	9.06%	7.91%	6.11%	7.56%
WACC	weighted cost of capital (after tax)	Nominal rate (per year)	10.99%	9.35%	7.86%	9.35%
WACC average 2016–2019						**7.7%**

Source: elaborated by the authors.

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