Cost-effective restoration for carbon sequestration across Brazil`s biomes

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Keywords: CO_2e cost-effectiveness; climate mitigation, large scale restoration, pasture degradation, nature-based solution

Abstract

Tropical ecosystems are central to the global focus on halting and reversing habitat destruction as a means of mitigating carbon emissions. Brazil has been highlighted as a vital part of global climate agreements because, whilst ongoing land-use change causes it to be the world's fifth biggest greenhouse gas emitting country, it also has one of the greatest potentials to implement ecosystem restoration. Global carbon markets provide the opportunity of a financially viable way to implement restoration projects at scale. However, except for rainforests, the restoration potential of many major tropical biomes is not widely recognised, with the result that carbon sequestration potential may be squandered. We synthesize data on land availability, land degradation status, restoration costs, area of native vegetation remaining, carbon storage potential and carbon market prices for 5475 municipalities across Brazil's major biomes, including the savannas and tropical dry forests. Using a modelling analysis, we determine how fast restoration could be implemented across these biomes within existing carbon markets. We argue that even with a sole focus on carbon, we must restore other tropical biomes, as well as rainforests, to effectively increase benefits. The inclusion of dry forests and savannas doubles the area which could be restored in a financially viable manner, increasing the potential CO_2e sequestered more than 40 % above that offered by rainforests alone. Importantly, we show that in the short-term avoiding emissions through conservation will be necessary for Brazil to achieve it's 2030 climate goal, because it can sequester 1.5 to 4.3 Pg of CO_2e by 2030, relative to 0.127 Pg CO_2e from restoration. However, in the longer term, restoration across all biomes in Brazil could draw down between 3.9 and 9.8 Pg of CO_2e from the atmosphere by 2050 and 2080.

1. Introduction

As emissions from deforestation and land-use change have continued to increase over the past decades, conservation and restoration are increasingly being seen as essential to meet climate mitigation goals. Climate mitigation, safeguarding biodiversity and water security are often considered the three major motivations for ecosystem conservation and restoration (Brancalion et al., 2019b; Strassburg et al., 2020). However, global agreements on conservation/restoration targets from governments and industry are most often tied to climate mitigation (Bustamante et al., 2019a; Seddon, 2022), possibly due to the existence of an established global carbon market. The dominance of carbon sequestration potential as the main criterion for determining where these actions should take place has led to a global focus on restoring forested ecosystems (Bastin et al., 2019; Brancalion et al., 2019b; Philipson et al., 2020), especially tropical rainforests, known for their high carbon storage potential. This neglects other biomes such as tropical savannas and dry forests that cover half of the global tropics (Pennington et al., 2018), and which have been suffering extensive destruction. Moreover, there is strong evidence that these seasonally dry biomes have high value in terms of their contribution to carbon storage, plant species diversity, national water security and local livelihoods (Forzza et al., 2012; Strassburg et al., 2017a; The Brazil Flora Group, 2018).

Brazil has one of the largest global potentials for implementing ecosystem restoration (Brancalion et al., 2019b) and conservation to mitigate emissions (Griscom et al., 2020, 2017). It contains 5.3 million km^2 of tropical rainforests (i.e. Amazonia and Atlantic Forests) and 3.2 million km^2 of tropical dry forests, savannah and grasslands (Caatinga, Cerrado, Pantanal, and Pampa ecoregions), representing a significant proportion of the global extent of these biomes. However, globally, seasonally dry biomes are still treated as much lower priority for conservation and restoration, than rainforests perhaps due to the perception that they store far less carbon and harbour lower biodiversity (Dudley et al., 2020; Silveira et al., 2021; Strassburg et al., 2017b). In Brazil, agribusiness expansion has resulted in a greater extent of seasonally dry biomes undergoing land use change than rainforests, with around 50% of Brazil's dry biomes, especially in Cerrado, converted compared to 20% of Amazon Forest (MapBiomas, 2020; Pennington et al., 2018). The focus of restoration efforts in Brazil has largely been in Amazonia and the Atlantic Forest (Brancalion et al., 2019b; Guerra et al., 2020; Romijn et al., 2019; Strassburg et al., 2020), with limited action in restoring Brazil's tropical seasonally dry biomes (tropical dry forests and savannahs) (Dudley et al., 2020). However, the savannahs of the Cerrado and the dry forests of the Caatinga region in Brazil cover >2.7 million km^2 within Brazil and to date more plant species have been documented for the Cerrado than Brazil's Amazon rainforest (The Brazil Flora Group, 2018). Moreover, dry biomes have a much higher proportion of degraded and unproductive pastures (MapBiomas, 2020), 5% of dry forests and non-forested biomes, versus 3.7% in rainforests, presenting an opportunity for restoration in the dry biomes which is currently not fully explored. These degraded and unproductive lands provide an opportunity for land restoration without compromising or displacing global food production.

Despite land-use change emissions, Brazil has significant National Determined Contributions (NDCs) as part of the Paris Climate Change agreement to reduce greenhouse gas emissions, that are underpinned by large scale restoration goals. Brazil is the world's fifth biggest greenhouse gas emitting country with 2.18 Gt of $CO_2\,e$ emitted in 2019, a 9.5% increase from 2018 (SEEG, 2019), largely due to deforestation and land-use change. To meet its NDC Brazil will require a carbon sink of almost 900 $MtCO_2\,e\ yr^{-1}$, with an even greater demand to achieve the 43% reduction by 2030 (relative to 2005 emissions). To achieve these targets, a goal was established to restore 12 million hectares (Mha) of native vegetation in Brazil by 2030 (Crouzeilles et al., 2019). In addition to this, in the 26th Conference of the Parties (COP 26), Brazil signed an agreement to halt and reverse deforestation and land degradation by 2030(COP26: UN Climate Change Conference, 2021). To address these shortfalls and achieve its NDC and COP 26 commitments, there is an urgent need to provide guidance for conservation and cost-effective large-scale restoration in Brazil. Significant investments in advancing our capacity to restore tropical ecosystems are urgently needed, as restoration, in contrast to avoided deforestation, is the most scalable and cost-effective way to reduce current atmospheric CO_2 concentrations and reverse emissions from previous deforestation, something which is now essential to stay below critical 1.5 ºC and 2 ºC climate warming targets (Griscom et al., 2020, 2017; IETA, 2021; Seddon, 2022). Slowing the rate of climate change undoubtedly requires a rapid reduction in fossil fuel emissions, however in countries like Brazil where a majority of emissions are from land use change, using conservation and restoration as climate solutions is vital to both address the root cause and reverse historic damage. Given this the aim of our study is to provide the first estimates across all of Brazil's biomes of the potential for cost-effective restoration for carbon sequestration. Achieving Brazil's NDC targets will require a broad perspective of how much $CO_{2\text{-}}e$ emissions can be avoided from halting deforestation and from restoration, including in this last one how and where cost-effective restoration can be most beneficial (i.e., combining land opportunity-cost, restoration cost and $CO_{2\text{-}}e$ sequestration). Here we use a combination of remotely sensed datasets and government reports for each of Brazil`s 5475 municipalities, and we produce estimates of the emission reductions that restoration could generate relative to its cost (USD per $tCO_2e$) in order to understand how C cost-effective restoration opportunities are distributed across all Brazil`s biomes. Then, integrating these data with a model of how rapidly restoration could be implemented and the annual CO_2e uptake, we provide new insights into how planning restoration within and across different Brazilian ecoregions could maximise its contribution to Brazil`s NDC. Finally, we evaluate the extent to which restoration could contribute to reducing emissions for Brazil to reach its NDC by 2030 and compare this with the amount of CO_2 *e* emissions that can be avoided by halting deforestation at the national level.

2. Materials and methods

We based our study regions on the Brazilian Institute of Geography and Statistics (IBGE) classification of vegetation in Brazil (IBGE, 1992) separating Brazil into six ecoregions: the Amazon rainforest, the Atlantic rainforest, the Cerrado, the Caatinga, the Pantanal and the Pampa. We note that this region-based classification does not represent the diversity of biomes (i.e. the global concept of biomes), within each ecoregion. For example, whilst the Cerrado is dominated by savannah and grasslands, these are interdigitated with smaller areas of tropical dry forest and, along rivers, rainforest (gallery forest) (Bueno et al., 2018; Dexter et al., 2018; Silva de Miranda et al., 2018). In the Amazon, tropical rainforests are dominant, but there are also areas of savannah. The Pantanal is a mosaic of rainforest, savannah, grasslands, and wetlands. In contrast, the Pampa is mostly dominated by grasslands and the Caatinga region by dry forest.

We synthesized data on land availability for restoration, land degradation status, restoration costs, area of native vegetation remaining, carbon storage potential and CO_2e costs across all biomes in Brazil. The steps for this analysis are detailed below and the data products used are summarized in Table S1 (see Supplementary Information).

2.1. Defining potential scenarios to restore

To calculate the potential area for restoration we used the atlas of degraded pasture, from 2020 (MapBiomas, 2023). This product uses a pasture degradation index, which is produced using a temporal filter applied to the pastureland enhanced vegetation index (EVI) to classify pasturelands into three categories: not degraded, medium and severe (Laerte Ferreira et al., 2021; MapBiomas, 2023). We used all pastureland classified as medium and severely degraded as potential restorable area in our first scenario (S1), and only the severely degraded pastures in our second scenario (S2). We selected these degradation categories to create our lower (S2) and an upper (S1) value for pastureland available, as these more degraded pastures generally have a low stocking density of cattle. We believe these areas would be associated with lower opportunity costs when compared to productive sites. The degradation data were disaggregated to the municipality level for 5380 of the 5570 municipalities across the six ecoregions in Brazil, with an average (± error) municipality size of 152.8 ± 7.5 thousand ha (full range of 356 ha – 16 Mha) (IBGE, n.d.) . Our analysis was performed at the municipality level because it was the smallest level at which we could resolve most of the data required for this analysis and provide a spatially meaningful unit for restoration planning. For the municipalities registered in more than one ecoregion (i.e. the ones that occur in the boundaries between two or more regions), we used the percentage of total area in each to attribute a proportion of the restorable land.

2.2. Potential C storage from restoration

To evaluate the potential Above Ground Biomass (AGB) that could be gained from restoring native vegetation across the Brazilian ecoregions we used the European Space Agency (ESA) CCI Biomass AGB product (100m resolution) (The European Space Agency, 2018). The potential AGB of restored vegetation is taken to be the same as remaining local native vegetation. To produce local estimates of the potential AGB stocks of restored vegetation, we centred a ~25 km2 moving window (radius ~ 2.5 km) on each potential restoration pixel (areas classified as medium or severe degradation level, see methods 2.1) and we calculated the mean AGB of surrounding native vegetation (remaining grassland, savanna, forests and wetland) within this window. After this, we extracted the average AGB (Mg per hectare) per municipality. This was used to represent the maximum potential AGB, which could be obtained from restoring the degraded pasture in each municipality.

For the Below Ground Biomass (BGB) we extracted the AGB and BGB from data available in the literature for forest and non-forest dominated ecoregions (see Table S2). We calculated the BGB following a root: shoot ratio from the amount of AGB (see Figure S1). For the Cerrado, Pantanal and Pampa we used a logarithmic equation based on data obtained from the literature for non-forested ecoregions; and for Amazon, Atlantic Forest and Caatinga forests we used a linear relationship between AGB and BGB. The average BGB was then predicted for each municipality, using the AGB data. The total biomass (AGB + BGB) was multiplied by 0.5 to obtain the carbon (C ha^{-1}), which could be stored from restoring native vegetation (Braz et al., 2013). For the potential carbon restored we consider 95% of the previous value could be stored over a 100-years period. Then, we multiplied the potential carbon restored per hectare by the number of hectares of degraded pasture in order to obtain the total carbon storage potential from restoring the degraded pasture in each municipality, for both scenarios S1 and S2.

In this paper, the soil carbon gains only account for Below Ground Biomass (BGB). We do not include Soil Organic Carbon (SOC) changes when calculating the potential carbon gain from restoring pasture to native vegetation, despite the potentially high soil carbon stocks in these regions (Figure S2a). We explored published data (Supplementary Information, Figure S2 and Table S3) to evaluate the change of SOC on conversion from native vegetation to pasture, but because of the variability in results across studies and ecoregions we opted to not include these data in the main analysis (See Supplementary Information, section 2).

2.3. Restoration costs

Restoration can be achieved through various techniques, ranging from more passive, including complete natural or assisted natural regeneration, requiring minimal anthropogenic assistance, to fully active, requiring substantial anthropogenic assistance. Active restoration normally requires intensive soil preparation and either seed or seedling planting. The greater the degradation the higher the likelihood that more expensive active restoration approaches are needed relative to passive approaches (Holl and Aide, 2011). The more degraded pasture areas we focus on are normally less amenable to passive restoration approaches. We did not include agricultural areas, because this would directly affect food production, substantially increasing the opportunity cost of the land for restoration, requiring a much more complex economic analysis, for which limited data is available across all ecoregions.

To evaluate the restoration approach needed and estimate costs, we used two metrics: 1) natural regeneration potential and 2) topography. The regeneration potential in each municipality was extracted from a Brazilian Environmental Ministry report (Ministerio do Meio Ambiente, 2017), which considered climate, landscape characteristics (i.e. proportion of land use change such as pasture and agriculture, connectivity and proximity to intact native vegetation) and topography to determine natural regeneration capacity. However, each ecoregion considered other parameters, depending on their specificities (e.g. soil characteristics) to improve analysis (Ministerio do Meio Ambiente, 2017). However, it is possible this reference over-estimates the natural regeneration potential, as a recent study (Crouzeilles et al., 2020) for Atlantic Forest found a maximum potential of ~ 21.6 M ha to be under regeneration potential in the most optimist scenario (stopping any activity that interrupts this process), which compare with about 36 M ha under high and medium natural regeneration potential (~ 8 M and 28 ha, respectively) predicted by the models we used. However, it is complex to compare both methods and say this for all biomes, as there are not many studies evaluating natural regeneration potential across different Brazilian biomes.

In the Brazilian Environmental Ministry report (Ministerio do Meio Ambiente, 2017), the regeneration potential was modelled within planning units (e.g. water micro-basins with a mean area of 5,000 ha), classifying them with a low, medium or high potential for regeneration. To scale from the planning unit to municipality level, we calculated the proportional area of each category (low, medium and high) within the municipality. We then assume these values are representative of the proportion of regeneration classes across pasture sites within each municipality.

The second metric used to calculate the restoration cost was the slope of the terrain, calculated from the ASTER Global Digital Elevation Model V003 (DEM resolution 100 m) (Hulley and Hook, 2015) . Slope has a substantial impact on the restoration techniques that can be applied. Steeper slopes decrease the capacity to use machinery and therefore some cheaper active restoration approaches (i.e. direct seeding) (Antoniazzi et al., 2016). Consequently, a steeper slope generally increases the cost of restoration. For each municipality, we calculated the percentage of areas with the slope above and below 12%, a threshold beneath which the use of heavy machinery is viable (Antoniazzi et al., 2016) . We combined this metric with the natural regeneration potential to estimate the average restoration cost per hectare in each municipality. If the natural regeneration potential was high, we assumed that more passive restoration techniques were possible, such as assisted natural regeneration and enrichment planting, and we estimated the restoration cost as USD 566 ± 222 ha^{-1} (Brancalion et al., 2019a). If the natural regeneration potential was low or medium, we assumed active restoration would be necessary. For medium potential for natural regeneration, we combined costs of soil preparation, fencing and enrichment planting resulting in a value of approximately USD 1280 ± 718 ha^{-1} (Antoniazzi et al., 2016; Brancalion et al., 2019a). If regeneration potential was low, we also considered terrain slope to assess the viability of using mechanised techniques, using the same threshold of slope <12%. In these instances, we assume an average price of USD 1754 ± 991 ha^{-1}

(Antoniazzi et al., 2016; Brancalion et al., 2019a). In areas of pasture with a slope >12%, we also assumed that only seedling planting will be viable and assumed an average the price of USD 2328 ± 465 ha^{-1} for restoration (Antoniazzi et al., 2016; Brancalion et al., 2019a).

We focus on degraded pastures as potential sites for restauration, as we expect them to have a lower opportunity cost. However, to account for the opportunity cost associated with the profit that the landowner could gain from selling the land, we included the cost of land in the total restoration cost. For that, we used reference prices from the land market in the past five years within each state region (INCRA, n.d.). We used the price of pasturelands and when this was not available, we used the price for land with general use. We note however that the cost of restoration has been notoriously poorly documented and will be highly variable in time, depending on many factors, including the cost of labour, currency exchange rates, and the land market.

2.4. Calculation of CO_2 e cost efficiency

To calculate the CO_2 *e* cost efficiency (USD tCO_2 *e*) over time we used the cost of restoration (USD ha^{-1}; see *section iii*) divided by the potential carbon storage per hectare (tC ha^{-1}; see *section ii*) at the same location (municipality based) corrected by a discount rate. This was then converted to CO_2 equivalent, where one tC equals to 3.67 tCO_2 *e*, to generate a CO_2 *e* cost efficiency per municipality. To compare the CO_2 *e* cost efficiency across Brazilian ecoregions we used a Kruskal-Wallis analysis followed by a post hoc test and we then used maps to represent how these restoration opportunities costs are distributed across Brazilian municipalities. For this comparison we considered significant differences at the statistical level of $p<0.05$.

We applied a discount rate of 5% to the potential carbon storage, to account for the cost associated with the time between the investment and its return (Austin et al., 2020). To account for the financial loss associated with the delay in return, we reduced this C accumulation rate using the discount formula $(1 - r)^{n}$, where r is the discount rate of 5% (Austin et al., 2020) and *n* is years since the initial investment, in this case the beginning of the restoration. For each year, we multiplied the discount by the annual C gain, and then summed the C gain through the 100 years to get the discounted total C, which we used to calculate the $CO_2\,e$ cost. We also calculated the $CO_2\,e$ cost using a discount rate (*r*) of 3% and 10% to evaluate how sensitive the costs were to a shifting rate (Supplementary Information; Figure S3).

Restoration costs usually occur at the time of the enrolment of land in the restoration program, while we assume 95% of full potential C return occurs 100 years later, with the maximum annual return occurring at 5 (i.e. Amazonia and Atlantic Forest), 6 (i.e. Cerrado, Pantanal and Pampa) or 8 years (i.e. Caatinga) post enrolment, depending on the ecoregion. These parameters were obtained by fitting regressions against tropical forest, savannah and dry forest C accumulation data in (Cook-Patton et al., 2020) and using respective curves to fit a lognormal distribution that describes annual C sequestration rates (tC ha^{-1} yr^{-1}) ensuring cumulative C is zero at time zero and saturates over time (see Supplementary methods *i, Model Step 2*). Thus, for each municipality, we were able to derive the annual C increment (i.e., sequestration) after each hectare was restored.

2.5. Carbon sequestration from Restoration

To evaluate how the restoration planning can help Brazil reach its 2030 NDC within and across its ecoregions, we used a model to predict how restoration could occur and how this would affect the carbon sequestration potential in terms of $CO_2\,e$. Restoration involves technical, social, economic, and institutional barriers, which can delay the enrolment of land into restoration projects. In order to account for these staggered enrolments, we implemented a two-step modelling approach. The first step calculated the annual area likely to be enrolled in restoration projects (i.e., total new number of hectares restored each year) from 2023 to 2200. The annual enrolment of land for restoration is a function of the restoration cost, in USD tCO_2 e^{-1}. The land available for restoration was divided based on restoration cost into 1 USD tCO_2 e^{-1} bins. We assumed that the most cost-effective areas available for restoration will be prioritised and thus enrolled before more expensive restoration options. We calculated the area restored by defining the cumulative enrolled area as an S-shaped curve with three main restoration phases (Supplementary Methods – section *1.1*; Figure S4a) that are defined according to their rate of restoration as a function of time. In each of the three phases the restoration rate changes to simulate the different characteristics of each phase.

In the second step, we used the cumulative area restored from step 1 as the basis to estimate the cumulative CO_2 *e* sequestration. We assumed that once enrolled a restoration project will take some time to reach its maximum CO_2 *e* sequestration rate, following which sequestration rates will then decline (Figure S4b). This two-step modelling approach aims to improve on previous assumptions of instantaneous enrolment and fixed carbon sequestration rates by using more realistic restoration enrolment rates and varying rates of carbon accumulation over the lifetime of restoration projects (Figure S5). The detailed two-steps restoration modelling methods is presented in the Supplementary Information (Supplementary Methods – section *1.1*).

To understand the restoration planning and its contribution to Brazil`s NDC within each ecoregion and at a national scale, we ran the model using two different approaches. First, we considered the restoration to happen independently within each ecoregion, with a maximum rate (R_{max}) of restoration set to 622,500 ha y^{-1} for each ecoregion, a rate derived by running the model to find the maximum annual rate Brazil would need to meet their current commitment to restoring their national target of 12 Mha by 2030 (Crouzeilles et al., 2019). And second, we considered the restoration to be enrolled across the whole of Brazil, regardless ecoregion, where more CO_2 *e* cost-efficient areas would be restored first. In this stage, we used a maximum rate (R_{max}) of restoration set to 3,600,000 ha y^{-1}.

2.6. Reduced emissions from conservation

We calculated emission reductions from avoiding deforestation using a similar model as that for restoration, applying the same two step approach to first enrol hectares and then calculate emission reductions generated by those hectares over time. However, while our restoration model generates annual sequestration following a lognormal relationship over time, avoided deforestation is assumed to generate all emission reductions in the same year in which the avoidance happens (i.e., a hectare is enrolled and avoids all emissions in year 1, and is maintained/protected in every subsequent year but does not generate any emission reductions). The emission reductions potential from avoiding deforestation is also directly related to the counterfactual baseline of how much deforestation would occur without action. Moreover, although deforestation is more likely to occur close to areas with existing deforestation, urban areas or other anthropic areas, we do not include this direct effect in the model. For our analysis we used the reprocessed analyses of Austin et al. (2020) published by Roe et al. (2021) to assume a static baseline deforestation rate for the next 30 years. This equates to 4.5 Mha yr-1 of avoidable deforestation across Brazil at unlimited cost and 2.6 Mha yr-1 at a cost of < USD 100 tCO2 e-1. These estimates are also well-aligned with (Busch et al., 2019).

We used two different approaches: in Conservation Scenario 1 we forecast emission reductions from a full reduction of deforestation in Brazil (from 4.5 to 0 Mha yr^{-1} by 2030), whereas under Conservation Scenario 2 the model forecasts emission reductions from all ‘cost-effective’ deforestation using the threshold of < USD 100 $tCO_2\ e^{-1}$ (from 2.6 to 0 Mha yr^{-1} by 2030) (Figure S6). In this last case, there are still emissions from deforestation occurring where preventative action would cost > USD 100 $tCO_2\ e^{-1}$ (i.e., 1.9 Mha yr^{-1}). Finally, beyond the two scenarios of (i) unconstrained cost and (ii) cost-effective constraints (< USD 100 tCO_2 e^{-1}) we did not separate avoided deforestation potential by cost. These differences make calculating emission reductions from avoided deforestation much simpler. Also, the conservation model was only run at the national scale, with no distinction across ecoregions. The detailed two-step conservation/avoided deforestation modelling methods are presented in the Supplementary Information (Supplementary Methods – section *1.2*).

3. Results

3.1. Land available for restoration and potential carbon sequestration in Brazil

Conversion into pastures accounted for more than 18% of all land across Brazil (Table 1).Amazonia and the Cerrado contained the largest percentage (and total area) of pastureland, ~ 34% and 33%, followed by 20% in the Atlantic Forest, and 11% in the Caatinga (52.2, 51.8, 30.8, 16.8 million ha, respectively, Table 1). The Pantanal and Pampa contributed less to the total pastureland (~ 2%). However, in the Pantanal pasturelands corresponded to about 19% of the land cover (2.9 million ha).

Our first Restoration Scenario (i.e. pastures with moderate to severe degradation) included 69% (11.6 million ha), 65% (1.8 million) and 56% (28.8 million ha) of all the pastures in the Caatinga, Pantanal and Cerrado, respectively. This can be compared to 53% (16.3 million ha) and 43% (22.3 million ha), in the Atlantic Forest and Amazonia (Table 1, Figure 1a). In a more conservative scenario (Restoration Scenario 2), where we suggest restoring only severely degraded pastures, the percentage of pastureland available for restoration in each ecoregion reduced to 28, 24, 17, 13, 12 and 8% of Pantanal, Caatinga, Cerrado, Atlantic Forest, Pampa and, Amazonia, respectively (Table 1 and Figure S7a).

Table 1. Total land area available for restoration (ha) and carbon storage potential (Pg C) from restoration in each ecoregion under two scenarios. S1 = Restoration of moderate and severely degraded pastures; S2 = Restoration of severely degraded pastures only. The total area of each ecoregion and the area converted to pasture are also shown (Data from Map Biomes *collection 6.1* for 2020). The restoration and CO_2 *e* costs correspond to the average cost (± standard deviation) of the areas, which could be restored across all municipalities within each ecoregion.

IBGE regions	**Total coverage (ha)**	**Pasture areas (ha)**	***Scenario 1:*** *Restoring moderately + severely degraded pastures*		***Scenario 2:*** *Restoring only severely degraded pastures*		**Restoration Cost ($ ha^{-1})**	**CO_2*e* ($ t^{-1})**
			Area S1 (ha)	**C S1 (Pg C)**	**Area S2 (ha)**	**C S2 (Pg C)**		
Amazonia	421,202,317	52,245,003	22,337,512	1.638	4,106,747	0.287	1750 ± 769	27.6 ± 36.3
Atlantic Forest	110,655,987	30,840,841	16,260,152	0.533	4,050,785	0.115	3883 ± 1333	86.4 ± 59.9
Cerrado	198,456,604	51,852,918	28,842,297	1.297	8,955,284	0.407	3461 ± 1323	51.0 ± 24.2
Pantanal	15,094,348	2,859,081	1,855,225	0.074	796,546	0.031	2703 ± 544	40.5 ± 10.1
Caatinga	86,259,905	16,839,040	11,568,853	0.125	4,117,546	0.044	1737 ± 863	108.3 ± 74.9
Pampa	19,391,640	22,702	7,897	0.0001	2,841	0.00002	3231 ± 433	61.4 ± 28
Total	**851,060,801**	**154,659,585**	**80,871,936**	**3.668**	**22,029,749**	**0.884**	**3184 ± 1503**	**75.3 ± 59.1**

When we consider the potential C (Carbon) that could be sequestered from the restoration of pastures to native vegetation (average C from native vegetation for each municipality minus biomass of pasture), the restoration of moderate to severely degraded pastureland across Brazil (Restoration Scenario 1) translated to a potential 3.6 Pg C sequestered in above and below ground biomass stocks alone. From this total, 44.7% was in the Amazonia, 35.4% in the Cerrado, 14.5% in the Atlantic Forest, 3.4% in the Caatinga, and 2% in Pantanal (Figure 1b and Table 1). If only severely degraded pastures were restored, this resulted in potential sequestration of 0.88 Pg C, also concentrated in the Cerrado and Amazon (Table 1; Figure S7). Focusing only on tropical rainforests limited the C sequestration potential to 0.4 - 2.2 Pg C in scenarios 2 and 1, a respective decrease of 54 and 39 %, relative to considering all Brazil's ecoregions (Table 1).

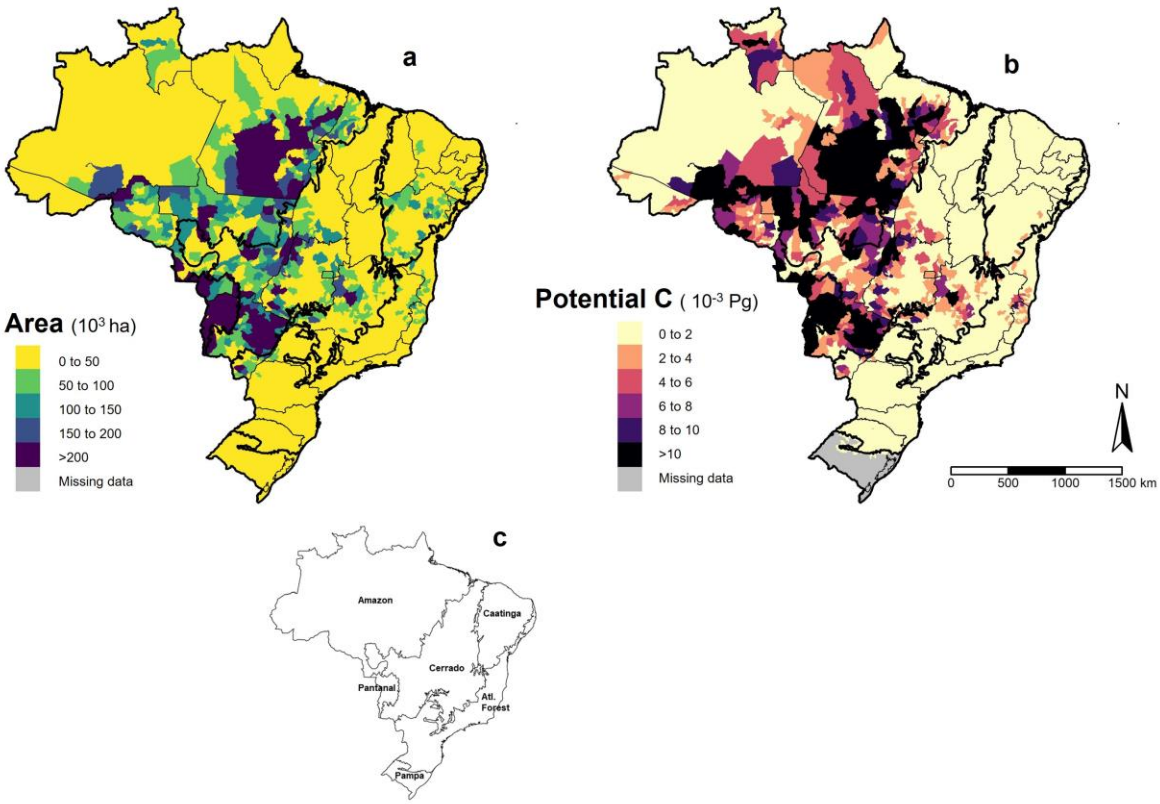

Figure 1. Area to be restored and potential C uptake with restoration in Scenario 1 (S1). **(a)** Area of pasture per municipality (10^3 ha) available for restoration considering moderate to severely degraded pasture (Scenario 1). (**b)** The C sequestration potential (10^{-3} Pg) from above and below ground biomass within each municipality if areas in **a** are fully restored (see Methods). Data in grey represents areas with no data of pasture degradation or biomass. (**c**) The physical limits of the six ecoregions (Amazonia, Atlantic Forest, Cerrado, Caatinga, Pantanal and Pampa) defined by the Brazilian Institute of Geography and Statistics (IBGE).

3.2. Carbon cost-efficiency

Restoration costs varied greatly across all ecoregions from USD 1.67 -340 tCO_2 e^{-1} (Figure 2b). From a carbon perspective, the most cost-effective places to undertake restoration are inAmazonia, followed by the Pantanal and Cerrado ($p<0.001$; Figure 2d), where the average cost to capture a tonne of CO_2 (tCO_2 *e*) over the lifetime of a restoration project (100 years) was USD 27.6 ± 36.3, USD 40.5 ± 10.1 and USD 51.0 ± 24.2 tCO_2 e^{-1} respectively (Table 1 and Figure 2d).

Considering a voluntary carbon market price of up to USD 50 tCO_2 e^{-1}, we estimated that 45.4 million ha could be restored across Brazil (43.9% in Amazonia, 39.6% in Cerrado, 11.7% in Atlantic Forest, 3.7% in Pantanal and 1% in Caatinga) (Figure 3). This generated 10.1 Pg CO_2 *e*, with 56.25% from Amazonia, 31.6% from the Cerrado, 9.32% from the Atlantic Forest, 2.41% from the Pantanal and 0.37% from the Caatinga. However, a price of USD145 tCO_2 e^{-1} generated 71.8 million ha for restoration across Brazil (30.5 in Amazonia, 39.7 in Cerrado, 18.5% in Atlantic Forest, 8.76% in Caatinga and 2.56% in Pantanal). This equated to 12.9 Pg CO_2 *e*, with 45.5% from Amazonia, 35.8% from the Cerrado and 13.8%, 2.85% and 2.05%, from Atlantic Rainforest, Caatinga and Pantanal, respectively.

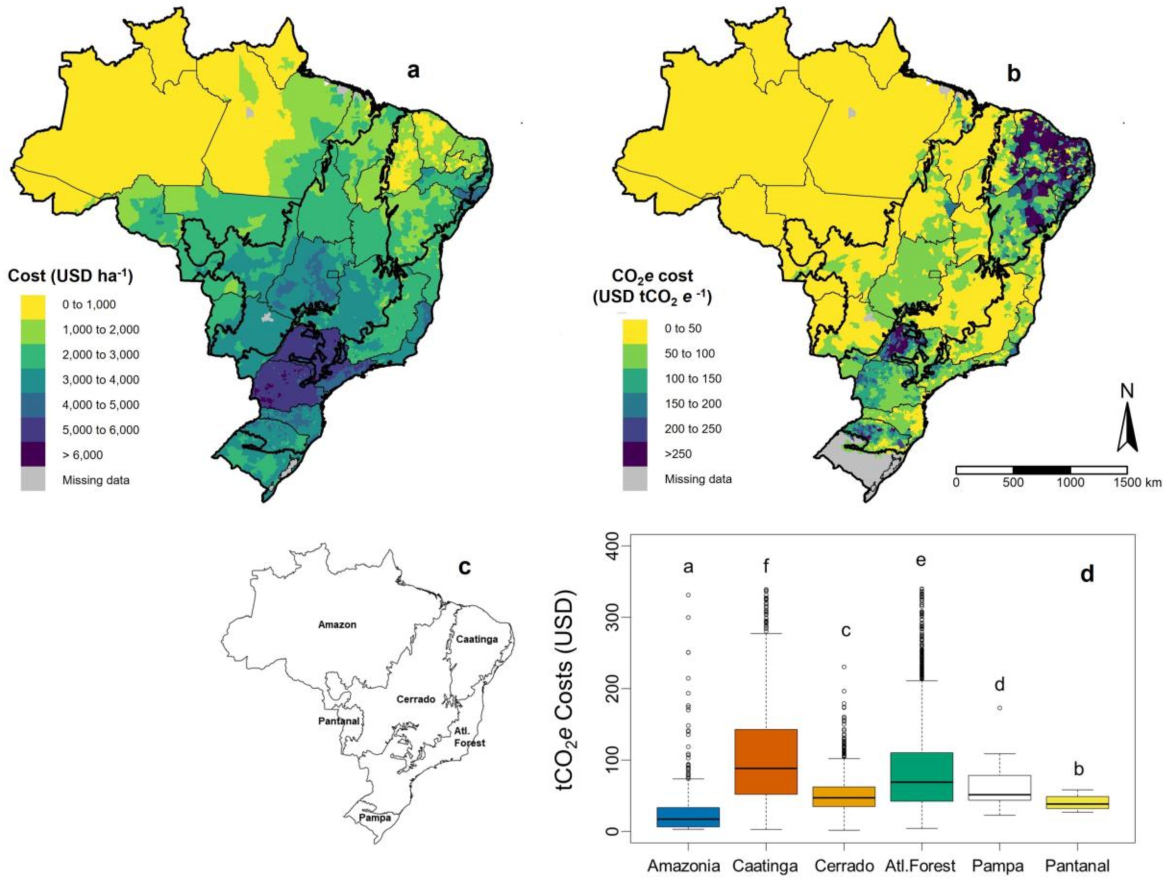

Figure 2. Spatial distribution of restoration costs and carbon price in Brazil. (**a**) The cost of restoration (USD) per hectare in each municipality. (**b**) Spatial distribution of CO_2 *e* price (USD per tCO_2 *e*) across municipalities within Amazon, Cerrado, Atlantic Forest, Caatinga, Pantanal and Pampa. Missing data (grey) represents areas with no data to calculate costs or biomass, or no C uptake potential. (**c**) The physical limits of the six ecoregions (Amazonia, Atlantic Forest, Cerrado, Caatinga, Pantanal and Pampa) defined by the Brazilian Institute of Geography and Statistics (IBGE). **(d)** Distribution of restoration costs for each ecoregion. Each sample unit corresponds to one municipality within each region. The box limits represent the first and third quartiles, with the middle line representing the median. The whiskers represent the minimum and maximum values, excluding the outliers, represented by the empty circles. Different letters represent significantly different values across Brazilian ecoregions ($p<0.05$).

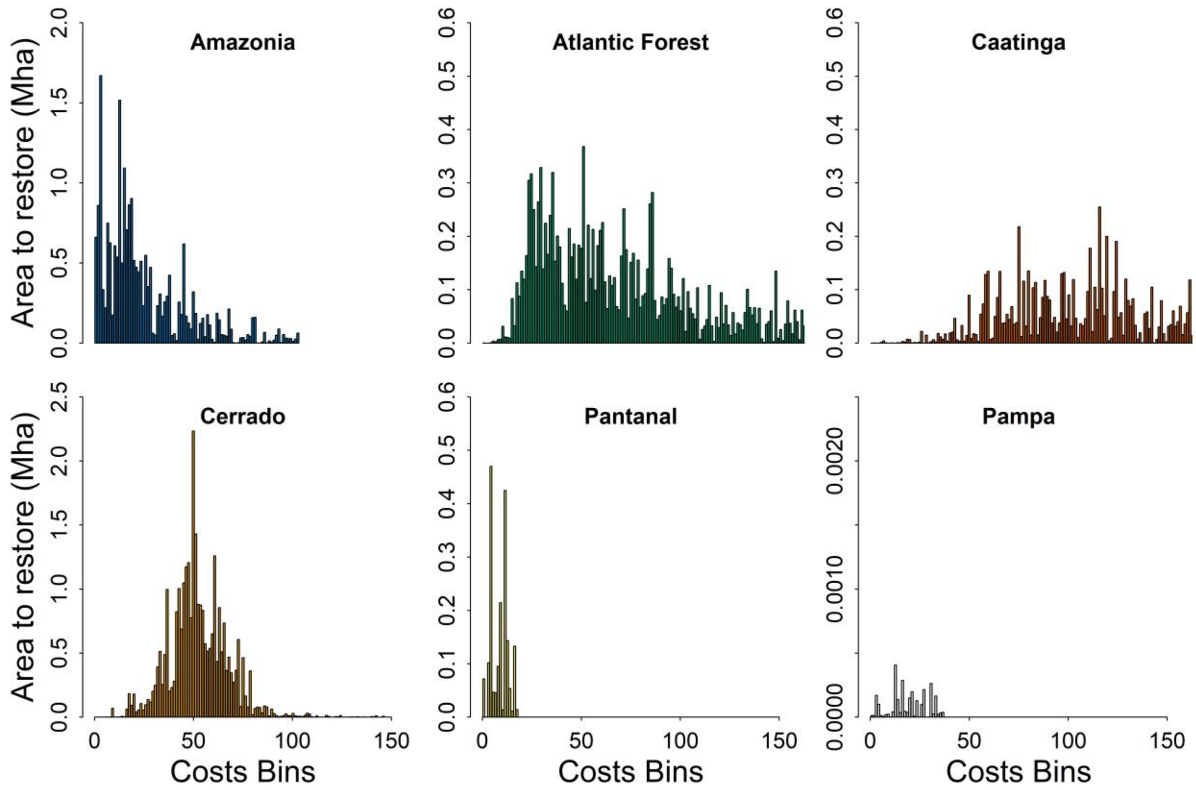

Figure 3. The total area (millions of ha) within each USD1 tCO_2e^{-1} cost bin which could be restored from S1 within each ecoregion. The costs bins are ordered from the lowest (0-1 USD tCO_2e^{-1}) to the highest price (144-145 USD tCO_2e^{-1}).

3.3. Restoration and conservation contribution to Carbon sequestration

When restoration was planned independently within each ecoregion (i.e. enabling equal rates of restoration in each ecoregion, irrespective of whether restoration costs are more expensive in one region than another), 7.6 million ha could be cost effectively restored in Brazil by 2030 (Figure 4a-b). If these areas were successfully enrolled for restoration, together they would sequester 0.13 of Pg CO_2 *e*, of which 45.8% would be from Amazonia, 20.1% from Atlantic Forest, 18% from Cerrado, 12% from Pantanal and 3.4% from Caatinga (Figure 4c). However, if restoration was enrolled all over Brazil focusing on prioritising the lowest cost restoration solutions, irrespective of ecoregion, 8.82 Mha could be enrolled for restoration (Figure 5a), but with lower potential for CO_2 *e* sequestration of 0.08 Pg by 2030 (Figure 5b). By 2050, 47.7 to 67.4 could be restored and 3.9 to 4.0 Pg CO_2 e^{-1} could be sequestered if restoration programs are maintained and succeed (Figure 4 and 5).

These results showed restoration alone cannot be used as a solution to climate mitigation in the short term, as it would contribute from 6% (0.08 Pg CO_2 *e*) to 10% (0.13 Pg CO_2 *e* of Brazil's NDC target by 2030 (~ 1.28 Pg CO_2 *e*) (Figure 4d, 5b). However, conservation strategies, across our two conservation scenarios (see methods), would avoid the emission of 4.3 or 1.5 Pg of CO_2*e* for scenario 1 and 2 respectively, between 2022 and 2030. This amount of CO_2*e* is greater than the NDC for 2030 (i.e., 1.28 Pg CO_2*e*) (Figure 6).

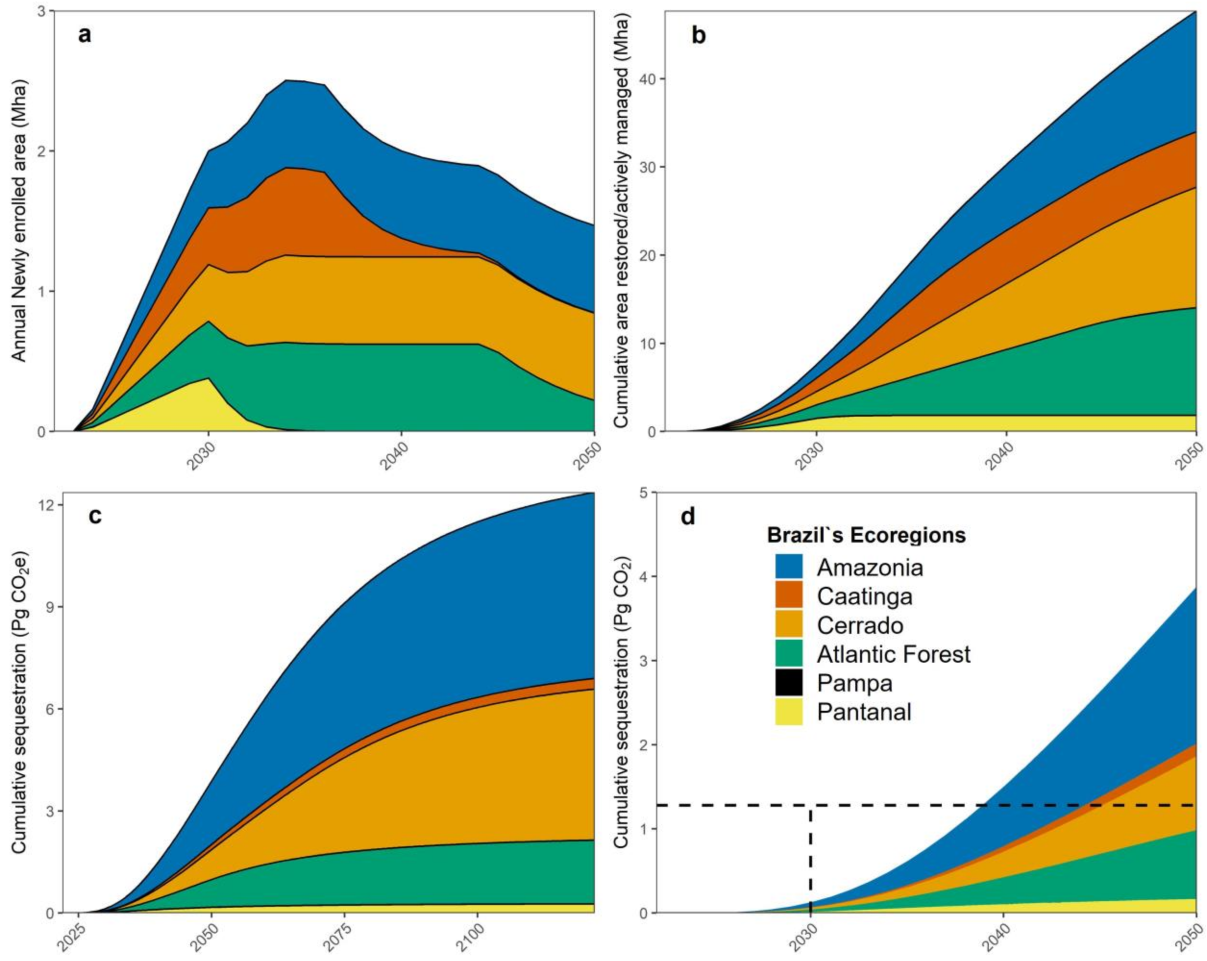

Figure 4. Projected restoration outcomes from each ecoregion being restored independently. **(a)** The modelled annual newly enrolled area (Mha) into restoration projects from 2023-2050 to reach the cumulative C sequestration presented in **d** and the cumulative area restored from 2023-2050 showed in **b**. The cumulative carbon sequestration (Pg CO_2 *e*) over time is presented in **c** and **d**. (**c**) The full timeline 2023-2122 for restoring all the moderately and severely degraded pastures and (**d**) a timeline from 2023-2050 with dashed lines showing the carbon sequestration needed to meet the 2030 NDC target. Colours indicate the contribution of each of the ecoregions.

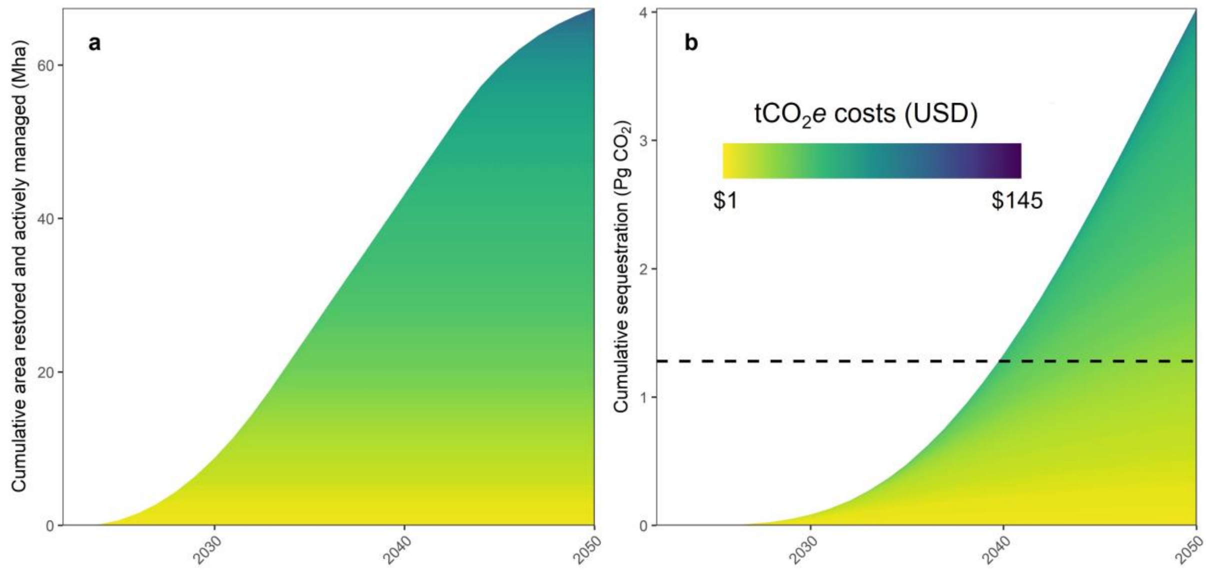

Figure 5. Projected restoration outcomes for the whole of Brazil, irrespective of ecoregion. **(a)** The cumulative area restored from 2023-2050 and **(b)** the cumulative carbon sequestration (Pg CO_2 *e*) from 2023-2050 with dashed lines showing the carbon sequestration needed to meet the 2030 NDC targets. Colours indicate the contribution of each one of cost bins.

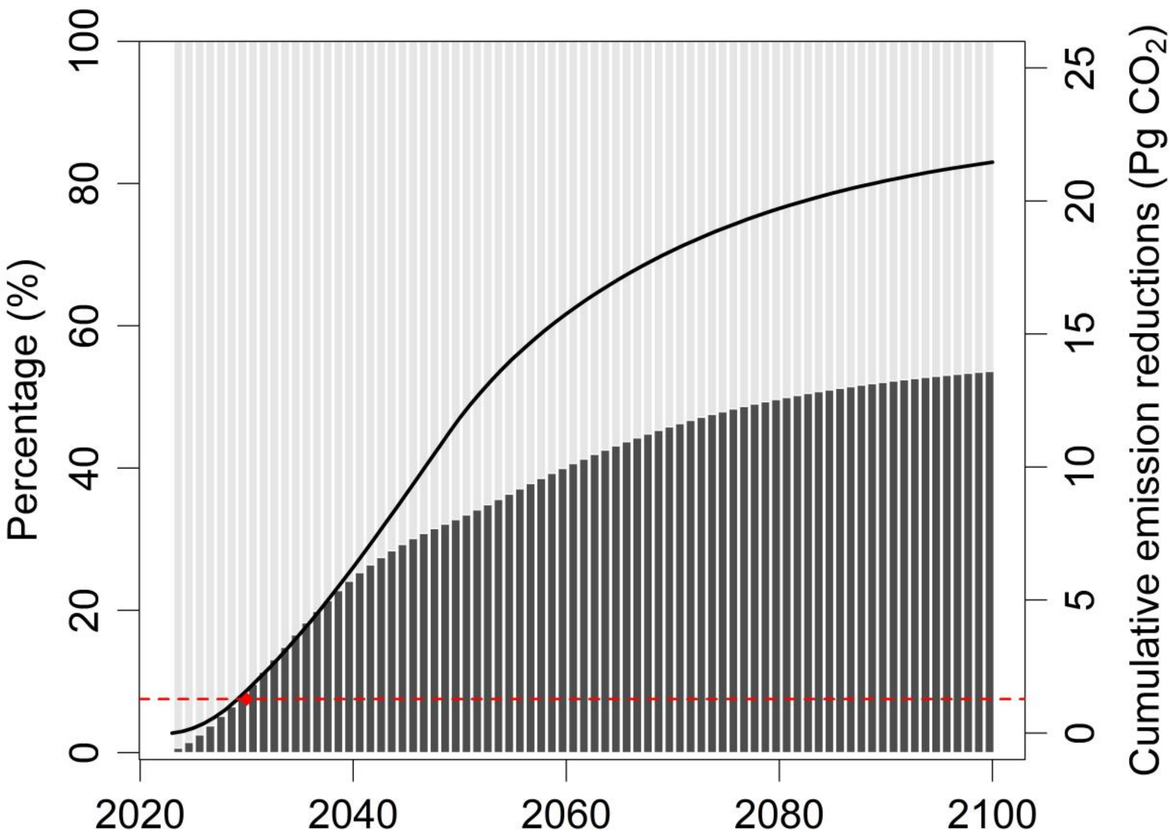

Figure 6. Comparison of the restoration and conservation contributions to emissions reductions (ER) in Brazil when balancing the land restoration across ecoregions (data from Figure 5). The black line (right axis) represents the cumulative ER (Pg CO_2e) from the combination of modelled restoration and avoided deforestation until the end of the century; and the bars (Percentage %; left axis) represent the relative contribution of each, restoration, or conservation to the total cumulative ER of each year until 2100. Dark grey represents the percentage of the emission reductions from restoration and the light grey from conservation. The dashed red line represents the National Determined Contribution (NDC) target for Brazil for 2030 and the red diamond symbol represents the combination conservation and restoration to the 2030 NDC. For these data we used the Conservation Scenario 2 (i.e. the cost-effective one), where we consider only the areas with costs lower than USD 100 $tCO_2\,e^{-1}$.

4. Discussion

Our results highlight the importance of restoring degraded pastures to native vegetation as a long-term climate solution in Brazil. Restoration across all biomes in Brazil could sequester between 3.9 and 9.8 Pg of CO_2e from the atmosphere by 2050 and 2080. Currently, pastures accounts for a high percentage of land cover in Brazil and more than 50% of pastures in Brazil have medium to severe levels of degradation, with the greatest concentration of these, 60%, in Amazonia and the Cerrado. This level of degradation means they are largely unproductive for raising cattle (Lapig, n.d.), which may be associated with the high percentage (~ 70%) of underutilized pastures (i.e., with the carrying capacity being two or more times larger than the current number of animals per hectare) (Arantes et al., 2018; Strassburg et al., 2014). Here, we assume restoring these areas has minimal opportunity cost in terms of losses of food production, and we used this land as potential area for restoration projects. In doing this, we demonstrate restoration can be C cost-effective across almost all of Brazil's biomes, although certain areas such as Amazonia, Pantanal and Cerrado were more cost-effective to restore from a carbon only perspective. However, restoration alone is unlikely to generate enough C sequestration in the short term to significantly contribute to Brazil's 2030 NDC target, thus necessitating a strong focus on conservation to meet these short-term targets.

4.1. Cost-efficient $CO_2\,e$ sequestration through restoration

For restoration activities enabled through C market mechanisms to be viable for climate mitigation, their cost must not exceed the market value of carbon, making the carbon price (USD $tCO_2\,e^{-1}$) an essential metric for determining restoration viability (Philipson et al., 2020). However, the carbon price can be highly volatile. Between 2009 and 2019, the carbon price on the European Union's Emissions Trading System (EU ETS), the most established market for trading carbon, was consistently below USD 20 $tCO_2\,e^{-1}$, but it reached over USD 50 $tCO_2\,e^{-1}$

in 2021 and briefly over USD 100 $tCO_2\,e^{-1}$ in early 2022. Moreover, if we consider the social value associated with the damages which would be prevented by reducing emissions, the carbon costs could be even greater (~ USD 185 $tCO_2\,e^{-1}$; Rennert et al., 2022), which would increase the potential area which could be restored even further. Similar trends have been seen on the voluntary carbon market and the carbon price is expected to rise significantly in the next decade due to increased demand associated with the challenge of achieving global climate ambitions. Indeed, some studies suggest the carbon price needs to reach USD 145 $tCO_2\,e^{-1}$ by 2030 to keep global warming below 1.5 ℃ (UN Environmental Programme Finance Initiative UNEPFI, 2021). At this price our analysis suggests a total of 71.8 Mha pastures to be restored, with a sequestration potential of 12.9 P $CO_2\,e$. This area is considerably greater than the 19.4 Mha which must be restored to meet Brazil's environmental protection law (Guidotti et al., 2017).

The most cost-effective places to undertake restoration are in Amazonia, the Pantanal and the Cerrado, however all ecoregions showed potential areas for restoration under current and predicted voluntary C market prices (Figure 2 and 3). Natural regeneration potentials were greater in Amazonia and the Pantanal (Ministerio do Meio Ambiente, 2017), making cheaper passive restoration techniques more viable. In Amazonia, the high carbon storage potential per unit area also considerably reduces the cost per $tCO_2\,e$. The costs in Cerrado and Atlantic Forest are driven by the need for more expensive, active restoration techniques (e.g. soil preparation, seedling planting or direct seeding (Brancalion et al., 2019a; Schmidt et al., 2019), due to high levels of soil degradation, steep slopes (Hunke et al., 2015; Soares da Silva et al., 2019), and the capacity of invasive grasses to outcompete native vegetation (Cava et al., 2018; Coutinho et al., 2019). Moreover, the higher land costs in the Atlantic Forest, which is surrounded by the most populated and wealthiest regions of Brazil (i.e., south and southeast) reduces the C cost effectiveness of restoration. In the Caatinga the high average $CO_2\,e$ costs were mostly a consequence of comparatively lower biomass stocks within this ecoregion. Although these last ecoregions are less cost-effective, they should not be ignored, as some cost-effective restoration can still be undertaken and the additional benefits, such as biodiversity, from a multi-region approach will certainly be of greater value than a focus in only a few ecoregions.

Our analysis of restoration potential is deliberately carbon centric, as no other universal market for selling restoration projects currently exists. However, we emphasise that other ecosystem services like biodiversity, poverty alleviation and water security are amongst some of the other key priorities that should considered (Brancalion et al., 2019c; Fleischman et al., 2022; Strassburg et al., 2020). Comprehensive cost benefit analyses of restoration potential, including non-carbon ecosystem service benefits, principally biodiversity, have been assessed elsewhere in studies focused on prioritising global areas for forest restoration (Brancalion et al., 2019b; Strassburg et al., 2020). These studies are important for determining where to prioritise restoration which can be funded outside of a carbon market, which we acknowledge may be in some of the more costly areas we model in Figure 2b. However, value is starting to be given to other important ecosystem services, such as water security at a local scale (Durigan et al., 2022). Creating and accounting for markets in alternative ecosystem services could drastically change where the most cost-effective places to restore across Brazil are, most likely further emphasising the benefits of restoring across all ecoregions simultaneously to maximise things like biodiversity benefits.

We opt to focus on moderate to severely degraded pastures in our restoration scenarios, as at least, initially, we believe these areas are associated with lower opportunity costs and they would maximise cost efficiency of restoration. Evidence suggests there is no need to expand pasture areas if we invest in developing techniques to improve productivity, even accounting for population increases (Arantes et al., 2018; Strassburg et al., 2014). Restoring productive pastures and agricultural areas is often more challenging and has a large opportunity cost associated, as they are profitable and intensively managed (Hunke et al., 2015). These potentially high opportunity costs are complex to calculate (Brancalion et al., 2012) and are variable over time, making using them for long-term restoration planning difficult.

Degraded or underutilised pastures may also have hidden future opportunity costs. For instance, many landowners may keep degraded pastures speculating that land prices will rise or that the cost of reforming them to be more productive arable or pasture areas will fall in the future. A small percentage (mean 2.76 %) of the pastures in this study which would have been categorised as severely degraded (MapBiomas, 2020) were replaced by soy across Brazil's municipalities over the past 20 years. However, in some ecoregions, such as Amazonia and Cerrado the annual conversion rate from pasture to soy across pasturelands (severely degraded) is higher than the others, reaching an average annual conversion of 7.87 ± 1.1 % and 6.13 ± 0.8 % over the past 20 years, respectively (Figure S8). Accounting for such changes over time is highly complex, as the economic controls on such markets are highly unpredictable, however understanding how land and commodity prices could alter the availability of land for restoration is vital to improving our ability to model restoration rates.

Although our model prioritizes CO_2e cost-effective restoration, it is important to consider the social impact of restoration (Fleischman et al., 2022). Recent studies have demonstrated the high social costs of CO_2 where they monetize the values of the damage of emissions to society (Rennert et al., 2022). In this sense, restoration should be allocated at a higher CO_2 cost, as it could reduce the impacts of climate change on most vulnerable communities, which also usually associated to greater poverty. Moreover, restoration with a higher CO_2 cost should also be considered in challenging places to restore, where the costs to overcome multiple barriers could reduce the cost effectiveness of restoration. These are some examples of where focusing only on CO_2e cost-effectiveness may be the wrong approach, as it could serve to increase social inequality. In our model, we could not model social inequality, due to a lack of consistent data at sufficient scales, however, addressing these issues are vital to restoration decision making and collecting the data to address such issues should be a research priority.

4.2. Modelling temporal trends in C sequestration from restoration across Brazil

Instantaneous restoration of all this land is an unrealistic basis for restoration modelling. Our model attempts to project how this restoration could occur across all Brazilian`s ecoregions, where there is a preferential enrolment of lower cost restoration opportunities. Our model starts restoration in 2023, so the total carbon sequestration is initially constrained while restoration activities ramp up. Using this approach our results show restoration cannot be used as a solution to climate mitigation on short timescales. Considering the current restoration rate in our model, based on Brazil' s the existing target to restore 12 Mha across all ecoregions (Crouzeilles et al., 2019) by 2030, Brazil would achieve 50% and 100% of the 2030 NDC target, through restoration alone, only 5 and 10 years later. For this, it would require approximately 20 to 27 Mha respectively, to be enrolled in restoration across all Brazil's ecoregions by 2035 and 2040. To restore this amount of land and meet the 2030 NDC target, it would require increasing our model's maximum enrolment rate by more than 10 times (i.e., 6.2 Mha yr^{-1} per ecoregion), significantly above current restoration rates. However, on timescales beyond 2030 (Figure 6), we demonstrate a huge capacity to sequester CO_2 already emitted to the atmosphere by restoring degraded and underutilised land within Brazil, if restoration programs are maintained and succeed. Within these scenarios the largest contributions to climate mitigation would come from the biggest ecoregions (Amazonia and the Cerrado) (Figure 4). However, for this to happen, restoration needs to be implemented at large scales in the next few years, across biomes. This requires restoration to be ramped up across all biomes, but with an urgent need to invest in building capacity to restore non-forested ecosystems, which are generally marginalised (Dudley et al., 2020; Silveira et al., 2021). The cost of continuing to ignore restoration opportunities outside of Brazil's rain forests is an additional 37 Mha, which could be cost-effectively restored (< USD 145 tCO_2 e^{-1}), beyond the 35.1Mha, which exist in rainforest regions. This translates to an increase of the 100-year carbon sequestration potential from 7.6 Pg CO_2 *e* in rainforests to 12.9 Pg CO_2 *e* across all Brazilian biomes.

Our projections will have many of limitations and uncertainties. For example, due to a paucity of data our below-ground biomass are estimated from relatively limited data used to create ABG:BGB relationships and the AGB itself was extracted from AGB products (Figure S9), which we know is likely to have embedded bias and uncertainties (Lewis et al., 2023). Moreover, due to very high uncertainties in both the magnitude and direction of change (Figure S2) driven by very limited data availability, we were unable to include SOC storage in our analyses. However, we know in certain biomes, like the Cerrado, the total amount of carbon sequestered by restoration is likely to be significantly increased due to SOC storage (Bustamante et al., 2006). Although many uncertainties like these remain in our estimates and these certainly will be able to be improved as increasing amounts of data are available, our study represents the first attempt to integrate different types of data to project restoration CO_2*e* effective costs across all Brazil biomes. This is critical as we show there is an urgent need for stakeholders and policy makers to start to plan to undertake restoration both within and beyond forested biomes in Brazil.

Additionally, within our analysis we only consider the potential carbon which could be gained from restoration, and it is important to acknowledge this may differ substantially from the actual C gain from restoration. Firstly, the likelihood of long-term restoration success across the different ecoregions in Brazil could be highly variable. We assume all the restored areas will reach at least 95% of its full potential carbon sequestration, considering the reference of native vegetation. However, many processes contribute to successful restoration (Benini and Adeodato, 2017; Bustamante et al., 2019b) including biological factors, such as the proximity of exotic invaders (Antonio and Meyerson, 2002), or the combination of species used for restoration (Schmidt et al., 2019), alongside sociological factors, such as the degree to which communities are engaged in restoration and benefit from it (Benini and Adeodato, 2017). Limited data exists to quantify the likelihood of restoration success at large scales, particularly within regions like Cerrado, Pantanal and Caatinga where fewer restoration projects exist (Guerra et al., 2020) and many of the existing data has shown restoration sometimes fail to achieve its goals (Coleman et al., 2021; Fagan et al., 2022). Fires, drought, and climate change are other important factors that may change the stability of carbon sequestration over time. For example, the recent impacts of extreme drought and fire events in rainforests in Brazil (Armenteras et al., 2021; Phillips et al., 2010). Assessing the permanence of carbon storage under likely future climate scenarios is, therefore, also vital in order to adjust our estimates of carbon sequestration to account for potential carbon losses due to climate impacts. Given a certain proportion of restoration projects are likely to fail or not reach their target carbon gain, the realised carbon storage from restoration is likely to be lower than we project here. However, this is further justification to increase the investment in developing effective restoration techniques and the rate at which restoration occurs.

4.3. The role of Conservation versus restoration in meeting Brazil's climate targets

Our results show conservation is likely to be the most effective strategy for climate mitigation in the short-term (Figure 6). Our modelling approach simulates the enrolment (i.e., conservation) of existing native areas at threat from deforestation and calculates the annual emission reductions from those activities, as it has been done by other studies (Griscom et al., 2017; Roe et al., 2021). We aimed to avoid all deforestation/land conversion assuming the baseline deforestation in the future is the amount of annual deforestation occurring today.

However, if Brazil is to meet its target using conservation alone, several optimistic assumptions must be met. First, it must be assumed that the 2022-2030 baseline annual emissions from deforestation is consistent with annual emissions today and deforestation must reduce by at least 2.6 Mha yr^{-1} by 2030 (e.g. annual deforestation rate between 2020/2021 in Amazonia represents 50% of this value) (INPE, n.d.). Secondly, it does not consider the climate change impact on the carbon storage of these native ecosystems, which is contrary to recent evidence (Hubau et al., 2020). Furthermore, focusing climate mitigation on conservation, whilst excluding restoration, will favour the most intact region, Amazonia, potentially leaving other ecoregions under a much greater threat to continued degradation, with severe biodiversity, social-economic and climate mitigation costs (Pennington et al., 2018; Schneider et al., 2021; Strassburg et al., 2017b). Thus, in view of the continued high deforestation rates within Brazil (Schneider et al., 2021; Silva Junior et al., 2021) and the urgent need to sequester carbon from the atmosphere, the imperative to increase the rate of restoration in tropical biomes will remain. Moreover, it is important to highlight that relying on Nature Based Solutions, such as restoration and conservation, for climate mitigation are only effective if aligned with rapid reductions in fossil fuels emissions, which will provide the greatest total potential for, alongside the most rapid way, to reduce atmospheric emissions(Seddon, 2022).

5. Conclusion

Within this study we have undertaken the first assessment of cost-effective restoration and conservation potential for climate mitigation across all biomes in Brazil. We demonstrate that cost-effective climate solutions using conservation and restoration could be traded within a carbon market across all biomes within Brazil. This would provide both short-term and longer-term mechanisms through which Brazil can meet climate, targets and reduce greenhouse gas emissions. However, particularly for restoration, we demonstrate that to achieve maximum potential emissions reductions more attention must be placed on dry biomes, as these can substantially increase the total C storage potential for Brazil, beyond that which can be achieved through focusing more narrowly on rainforest biomes alone.

Acknowledgments. L.R., R.S.O., and R.T.P. acknowledge funding from a joint UK NERCFAPESP grant no. 19/07773-1 & NE/S000011/1. F.V.B., G.G.M., and D.L.M acknowledge the post doctorate funding from this same NERC-FAPESP grant (NERC, and FAPESP 2019/18145-1, 2019/18176-4, respectively). K.L. acknowledges a Shell funded PhD studentship. L.R. acknowledges a UK NERC independent fellowship grant no. NE/N014022/1. RSO received a CNPq productivity scholarship. ADR is employed by Shell International Exploration and Production Inc. (USA) at the time of publishing.We also acknowledge the help of Christian Davies in the paper and Rebecca Mitchell for providing advice regarding the methods.

Author contributions. FVB and LR conceived the idea of this work; FVB, KL, ADR, TH and CM worked on the data processing and analysis; FVB, LR and RTP worked on the text structure and writing; and all the authors helped improving the ideas, additional discussions, and text editions.

Competing interests. There is no competing interest to declare.

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