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Using policy scenarios to assess challenges and opportunities for reaching restoration targets in Brazil's Atlantic Forest

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Abstract

Brazil's Atlantic Forest is a global restoration hotspot. Most of the remaining forest areas are degraded and separated by large cities, and agricultural lands essential for national food security. Brazil's restoration agenda is defined by multiple national and global restoration targets and policies, including Brazil's Native Vegetation Protection Law (No. 12,651/2012) also known as the Forest Code, which sets minimum levels of native vegetation to be maintained or restored in rural properties. In this study we simulate the impacts of alternative restoration policies addressing targets for Brazil, and explore their impacts on selected terrestrial species and agricultural development potential in the Atlantic Forest biome. Our results show several policy options could result in different restoration amounts and spatial distributions being implemented between 2020 and 2050, but trade-offs between agriculture, biodiversity and rural livelihoods differ. Compared to the baseline scenario (implementation of the Forest Code), a scenario which focuses restoration on small farms (not mandated to undergo restoration under the current legislation) could increase forest area by 6.7 Mha across the biome (139% more than with the Forest Code), while a scenario which maximizes biodiversity gains could lead to an additional 3.9 Mha by 2050 (81% more compared to the Forest Code). We find that our restoration scenarios still allow cropland expansion and an increase in cattle herd, while pasturelands decrease. There are relatively small agricultural production losses under the alternative restoration scenarios when compared to the baseline (up to 14.4%), meaning that cattle ranching intensification is critical to enable large-scale restoration to co-exist with agricultural production. Our scenarios suggest that ambitious restoration targets in the Atlantic Forest biome (up to 15.5 Mha, consistent with existing regional initiatives) could be feasible with necessary improvements in pasture yield and a focus on scaling up support and developing restoration policies for smallholder farmers.

1. Introduction

The critical role of ecological restoration has resulted in ambitious restoration initiatives and policies gaining momentum at national and global scales (such as the Bonn Challenge (Verdone and Seidl 2017), and Brazil's Intended Nationally Determined Contribution (INDC) restoration targets (World Bank 2017)), culminating in the declaration of the UN Decade on Ecosystem Restoration (2021–2030). In Brazil, and across the tropics, native vegetation restoration initiatives are key to tackling the ecological damage caused by centuries of habitat degradation, led mainly by agricultural expansion (Kehoe *et al* 2017, Newbold 2018, Pendrill *et al* 2022). Ecosystem restoration is one example of nature-based solutions and can deliver multiple benefits including climate change mitigation, biodiversity protection by reducing species' extinction risk, provision of ecosystem services, and improved economic resilience for local communities (Suding 2011, Chazdon et al 2017, Seddon et al 2021).

The Atlantic Forest biome is one of the most biodiverse and threatened biomes on Earth (Joly et al 2014, de Lima et al 2020), providing essential ecosystem services and cultural value to millions of Brazilians (Begossi et al 2002, Brancalion et al 2014, de Carvalho et al 2014). Research suggests native forest remains in only 8%–22% of the biome (Rezende et al 2018, SOS Mata Atlântica & INPE 2019), and large-scale restoration will involve competition for land between agriculture and biodiversity in a region dominated by large-scale cattle ranching and croplands, such as sugarcane and soybean plantations (IBGE/PAM 2017). Brazil is a global leader in soy and cattle production, with agriculture representing around 7% (World Bank 2022) and beef 8.5% (Malafaia et al 2021) of the country's gross domestic product (GDP). Smallholder agriculture is also practised across the biome by diverse traditional and neo-traditional communities affected by complex and interrelated challenges from climate change (North et al 2023), land degradation, and socio-economic marginalisation (Cechin et al 2021), such as those living in quilombos (communities first formed by enslaved Africans and their descendants during Brazil's slave trade in the 19th century) (De Castro et al 2006) and agrarian reform settlements (Cechin et al 2021, Shennan-Farpón et al 2022b).

In Brazil, one of the most important legislative acts for ecosystem restoration is the Native Vegetation Protection Law (NVPL) (Law n.12.651/12), known as the Forest Code. In the Atlantic Forest this law requires that farms of medium-large sizes, larger than approx. 20 ha depending on the municipality (see Brancalion et al 2016 for details on farm classification in Brazil) protect or restore native vegetation on 20% of their land (these areas are called legal reserves (LRs), see glossary in SM1). The revision of the Forest Code in 2012 added an exemption for small properties (smaller than approx. 20 ha depending on the municipality) from restoring land within LRs, meaning approximately 3 Mha of private land on small farms, typically supporting subsistence and small-scale agriculture, are exempt from restoration requirements (da Silva et al 2023).

There is growing evidence to show supporting the livelihoods of rural poor and/or marginalised communities is critical to successful landscape restoration across the tropics (Ota et al 2020). As large-scale restoration initiatives grow within the UN Decade on Ecosystem Restoration, many are focused on, and better suited to, large properties, through approaches such as payments for ecosystem services (PESs) and carbon credit schemes (Alarcon et al 2017, Corcioli et al 2022). Such schemes risk exclusion or displacement and low uptake by local and/or marginalised communities (Newton et al 2016), due to limited access to finance, a lack of logistical and/or technical capacity (Adams et al 2016, Miccolis et al 2017, Fischer et al 2021) and insecure land tenure (Shyamsundar et al 2022, Rakotonarivo et al 2023). Understanding the relationships between restoration, agriculture, and rural livelihoods is critical in developing ethical and just approaches which aim to tackle social as well as environmental challenges, such as food security, food sovereignty, and poverty alleviation (Buainain and Garcia 2018, Fleischman et al 2020). In this study we combine stakeholder-driven restoration scenarios with regional economic land-use change modelling to explore the opportunities and potential trade-offs of reaching ambitious restoration targets, adding evidence on the use of participatory scenario development (PSD) in restoration planning and target setting (Acosta et al 2018), lacking for Brazil (Durrant et al 2023), and for the Atlantic Forest biome specifically. We particularly ask: what are the implications for agricultural expansion, land-use change and biodiversity conservation of (i) increasing restoration targets within small farms; (ii) imposing restoration targets based on 'biodiversity priority areas' (BPAs); or (iii) following existing national political and economic trajectories in the Atlantic Forest biome?

2. Methods

2.1. Study site

The Atlantic Forest biome covers a vast territory along the densely populated Eastern coast of South America, and is home to 70% of Brazil's population (Guedes Pinto and Voivodic 2021). The biome is a conservation and restoration hotspot with high levels of biodiversity and species endemism (Mittermeier et al 2005, Joly et al 2014), as well as many undiscovered and undescribed species. It is also the second largest biome in Brazil in terms of agricultural land cover, and the largest producer of sugarcane (5.8 Mha, 12.5% of the biome's area) (Greschuk et al 2023). Despite high levels of agricultural and urban development, the biome provides essential ecosystem services to millions of people, including water provisioning and climate regulation (Joly et al 2014, Prist et al 2021). High levels of forest degradation and fragmentation are key drivers of species loss, with landscapes separated by large agricultural areas dominated by cattle farming, sugarcane and soybean production (Bogoni et al 2018, Chazdon et al 2020). More details on the study site can be found in SM1 and Marques et al (2021).

2.2. Model framework

To assess the impacts of different restoration policies on agricultural production and biodiversity, we project land-use changes under alternative restoration scenarios using the regional version of the global economic partial equilibrium land use model GLOBIOM (Havlik *et al* 2014), developed in the GAMS modelling language. The model simulates the competition for land to maximise welfare (measured as the sum of consumer and producer surpluses), and has been adapted to incorporate Brazil's specificities, including national policies and data (Soterroni *et al* 2018, 2019, 2023, de Andrade Junior *et al* 2019, Zilli *et al* 2020). GLOBIOM-Brazil has a double cropping system for soybean and maize (Soterroni *et al* 2019) and a semi-intensive cattle ranching production system (Cohn *et al* 2014), and assumes technological and yield changes (e.g. intensification of cattle ranching) to meet land availability and spatial constraints set by the restoration scenarios so that national and global demand can be met. In this study, the model is recursively run for 5 year time steps, 2000–2050, and optimises over seven land use classes (table S1, SM1). Although the model simulates land-use changes for the whole country, here we are focusing on the impacts of various restoration targets in the Atlantic Forest biome.

The GLOBIOM-Brazil model has been validated and calibrated for the period of 2000–2015 in several published works to ensure accuracy in its representation of changes in economic factors, land-use, emissions, forest cover, and agricultural trends (Soterroni *et al* 2018, 2019, 2023). We include further details in SM1 (supporting material).

2.3. Restoration policy scenarios

Our research questions are explored using the GLOBIOM-Brazil model to run four scenarios: a baseline and three alternative restoration policy scenarios: Restoration for Biodiversity, Restoration for Smallholders and Maximum Restoration (table 1). The characteristics of the four quantitative scenarios were defined during two PSD workshops involving key regional stakeholders conducted in October and November 2019 (see SM1 and Shennan-Farpón 2022a for details on the scenario development process). While the PSD process led to the creation of seven qualitative scenarios in total, here we focus on four quantitative policy scenarios (2020–2050) as this aids comparison, and represents contrasting restoration strategies and plausible alternatives contextualised in the country's socio-political and environmental realities. The baseline of this study (referred to as 'Forest Code scenario') is based on the *FC scenario* from Soterroni *et al* (2018) which simulates the NVPL. The baseline scenario is compared against three alternative restoration policies or approaches: (1) removal of existing small farms amnesty, which makes small farms exempt from maintaining or restoring vegetation within LRs (Soares-Filho *et al* 2014); (2) restoration actions are implemented on BPAs derived through spatial multicriteria analyses of restoration benefits for species of conservation concerns (based on Strassburg *et al* (2019)) (described in table S3, SM1); and (3) simulating a target of 15 Mha restored by 2050, set by multi-stakeholder organization the Atlantic Forest Restoration Pact (Crouzeilles *et al* 2019). We compare scenarios where restoration areas are focussed within BPAs versus scenarios where restoration actions occur wherever is economically convenient. Scenario characteristics are summarised in table 1, and below. Scenarios are identical from 2000 to 2020, and assume different trajectories after 2020. A glossary with key terms and definitions is included in SM1.

- Forest Code (baseline scenario): Baseline scenario based on Soterroni *et al* (2018) which assumes the full implementation of the Forest Code, including the protection and restoration of LRs and areas of permanent preservation (APPs) (areas within rural properties that must protect water springs, steep slopes, riparian zones and other sensitive ecosystems), the mechanism for compensating illegally deforested LRs called environmental reserve quotas (CRA), and the amnesty of illegally deforested LRs granted to small farms.
- Restoration for biodiversity: Restoration targets for 2050 combine the requirements of the Forest Code with additional restoration within BPAs in the Atlantic Forest Biome.
- Restoration for smallholders: Restoration targets for 2050 include the requirements of the Forest Code, with the removal of the restoration amnesty for small farms. In the Atlantic Forest biome, small farms are defined as those smaller than 4 'fiscal modules', varying from 20 to 1100 ha depending on municipality (see de Oliveira *et al* 2020). This scenario is simulating a reality in which restoration could be performed in small farms through support programmes, such as agroforestry and PES.
- Maximum restoration: Restoration targets for 2050 are maximised by combining the requirements of the Forest Code, with the removal of the restoration amnesty for small farms, and restoration within BPAs in the Atlantic Forest Biome. This is the most ambitious scenario, the only one which reaches the Atlantic Forest Restoration Pact target of restoring 15 Mha across the biome by 2050 (Crouzeilles *et al* 2019).

We use information from Brazil's rural environmental registry (CAR) (Brazil's property georeferencing system to promote monitoring and compliance with the Forest Code, see Guidotti *et al* 2017) to calculate the extent and location of areas with restoration requirements, with and without the LR exemptions. Although lack of enforcement and compliance remain an issue across the country (Azevedo *et al* 2017, Chiavari *et al* 2021), the Forest Code scenario remains the most suitable baseline for our

Table 1. Summary of modelled restoration policy scenarios and key variables. The last two columns show total forest area restoration targets in 2050, and percentage change compared to the FC baseline in brackets.

Scenario	Variables				Restored forest area target 2050	
	Restoration of LRs[a]	Restoration of APPs	Restoration of LRs in small farms	Restoration in BPAs	Atlantic Forest biome	Brazil
Forest code	✔	✔	×	×	4.8 Mha	12.5 Mha
Restoration for smallholders	✔	✔	✔	×	8.7 Mha (+81%)	16.4 Mha (+31%)
Restoration for biodiversity	✔	✔	×	✔	11.5 Mha (+140%)	30.6 Mha (+145%)
Maximum restoration	✔	✔	✔	✔	15.5 Mha (+222%)	34.6 Mha (+177%)

[a] Restoration of LRs following the current Forest Code legislation (which includes an amnesty for small farms, meaning restoration in LRs is forced only in medium-large farms), after compensations through the Environmental Reserve Quotas (CRA) mechanism (Soterroni *et al* 2018).

research questions since modelling a less ambitious representation of the regulation would be counter-productive to advancing knowledge on the restoration agenda. We follow a 'middle-of-the-road' Shared Socioeconomic Pathway scenario (SSP2) (Riahi *et al* 2017) to define exogenous demand drivers such as population and GDP growth, dietary patterns, and meat consumption (SSP2 assumes livestock consumption will increase by 60%–98% by 2050 globally, Valin *et al* 2014). We assume continued protection within conservation areas and no deforestation between 2020 and 2050, representing full compliance with the Atlantic Forest Law in all scenarios. The Atlantic Forest Law (Num. 11.428, 2006) allows deforestation only if authorised in case of public or social need, and must be compensated. Although not a 'zero deforestation' law, data shows it plays a critical role in reducing deforestation in this biome beyond what is required under the NVPL (Guedes Pinto *et al* 2023). Additionally, forest cover loss data shows reductions compared to historic trends, with approx. 260 000 ha of native forest loss over a ten-year period (2005–2015) (Rosa *et al* 2021), and more recent data showing 13 053 ha of loss between 2019 and 2020 (SOS Mata Atlântica 2023), although estimates vary (Andreacci and Marenzi 2020). These estimates of forest loss represent relatively small amounts compared to the model's pixel size, approx. 306 000 ha at the Equator, supporting inclusion of the Atlantic Forest Law in modelled scenarios. Rosa *et al* (2021) also found native forest cover to be relatively stable in the biome (1989–2018), although we acknowledge variations in habitat quality and connectivity.

2.4. Analysis of indicators to compare restoration scenarios

The analysis and comparison of scenario outcomes for agricultural development, land-use change and ecological indicators had two stages. First, we acquired and processed a range of spatial datasets that provided spatial and policy constraints to the scenarios run using the GLOBIOM-Brazil model framework. We then compared indicators of change over time (2020–2050) and change relative to the Forest Code baseline in 2050 for the three alternative scenarios:

- *Changes in land use*: Changes in cropland area, pastureland, and restored native vegetation in each scenario.
- *Agricultural indicators*: From the 18 available crops in the GLOBIOM-Brazil model (see Soterroni *et al* 2018 for details), we focused on the change in area and production of the two crops most relevant to the study region: sugarcane (occupying around 6% of the biome, with up to 200% expansion in some areas over the past 10 years) and soybean (occupying around 8% of the biome) (IBGE/PAM 2017). In the livestock sector, we focus on the evolution of cattle herd and pastureland.
- *Ecological indicators*: Building on the amount of restored area in 2050, we calculated the change in area of habitat (AOH) (2020–2050) for 1621 terrestrial species resident in the Atlantic Forest biome (413 amphibians, 809 birds, 283 mammals, 116 reptiles) between scenarios and compared to the Forest Code scenario (baseline), replicating methods described in Visconti *et al* (2016) and Leclère *et al* (2020). AOH was calculated for each species, year and scenario (using the IUCN Red List Database; IUCN 2019), matching habitat preferences from the IUCN habitat classification scheme with GLOBIOM-Brazil land-use classes in 2050 (SM2). We calculate the number of species which see an increase in AOH above 50%, to represent improved ecosystem structure and reduction in extinction risk, consistent with literature on 'ecological thresholds' in the tropics (e.g. conserving

50% of species' area reduces extinction probability by over 70%, Hannah *et al* 2020, Shennan-Farpón *et al* 2021), especially for forest specialists (Banks-Leite *et al* 2014).

All data processing and analysis was done in Excel and R Studio version 4.0.3 (R Core Team 2019) and ArcGIS version 10.6. We used the Atlantic Forest biome boundary from Global Forest Watch Open Data Portal (Global Forest Watch 2019) and considered only results for pixels which overlap >50% with the biome boundary. For data analysed and reported at the national scale, we used the administrative borders shapefile from GADM (version 2.8).

3. Results

3.1. Model validation

Model validation of results for major commodities show differences between GLOBIOM-Brazil model projections and official statistics from Brazil's annual agrarian surveys (IBGE/PAM; IBGE/PPM) are within a 16% range. Model validation for the projected cattle herd showed strong similarity: IBGE/PPM data for Brazil in 2015 are 1.6% lower than the GLOBIOM-Brazil model projections. Comparisons with other well established macro-economic models in the agriculture and land-use change sectors show model projections to have similar accuracy (Frank *et al* 2017). Further validation details are given in the supporting material, SM1.

3.2. Change in forest cover and distribution

The four scenarios have different spatial distribution of restoration across the Atlantic Forest biome by 2050 (figure 1). Scenarios which prioritise restoration within BPAs (Restoration for Biodiversity and Maximum Restoration) create higher forest restoration in coastal areas by 2050 (figures 1(b) and (d)), compared to the Restoration for Smallholders scenario, which prioritises restoration on LRs, resulting in a more even distribution of forest restoration across the biome (figure 1(c)).

3.3. Change in indicators of agricultural development under alternative restoration scenarios

According to the baseline Forest Code scenario, between 2020 and 2050, agriculture will expand in the Atlantic Forest biome as follows: total cropland increases by 16.2%; soybean area increases 11.7%, and sugarcane area 39.2% (table S4, SM1). Conversely, total pastureland is 15%–25% lower in 2050 compared to 2020 regardless of the modelled scenarios (table S6, SM1), including the baseline (−14.8%). Although the model projects a decrease in pasturelands, an increase in total cattle herd is observed in all scenarios over time (2020–2050) (6%–11%; table S6, SM1). These results indicate that cattle ranching intensification is necessary in any scenario that involves large-scale native vegetation restoration in the Atlantic Forest biome.

Under alternative scenarios, by 2050, pasturelands within the Atlantic Forest biome are between 5.7 and 12.1% lower than the area projected by the Forest Code (or baseline). Meanwhile, cattle herd sizes remain relatively stable, fluctuating by approximately ±2% compared to the baseline (figure 2). By 2050, total cropland is also projected to decrease under alternative scenarios compared to the baseline: a 2.6% reduction under the Restoration for Biodiversity, 10.1% under Restoration for Smallholders, and 12.6% under Maximum Restoration scenarios (figure 2).

Regarding soy and sugarcane, the crops with the largest cultivated areas within the biome, scenarios that prioritise restoration within smallholder farms (i.e. scenarios which model the removal of the smallholder amnesty) have negative impacts on expansion and production by 2050, compared to the baseline. Soy experiences a more significant reduction in cultivated area (up to 15% decrease) than sugarcane (up to 8% decrease) (figure 2). Under the Restoration for Biodiversity scenario, both soy and sugarcane are similarly affected, with a relative decrease of less than 2.1% compared to the baseline. These losses in crop production would be more pronounced without the exogenous yield increase intensification performed by the model. By 2050, soybean and sugarcane yields are, respectively, 0.4%–4% and 0%–4.6% higher compared to the baseline (figure 2). The greatest increases are projected for the stocking rates (number of cattle heads per ha), expected to be 4%–13.5% higher under the alternative restoration scenarios (figure 2).

In the scenarios that prioritise biodiversity (restoration within BPAs), land conversion from pasture to restored forests are predominant (under the Restoration for Biodiversity scenario, 65% of restored area in 2050 occurs on previous pasture lands, and 50% under a Maximum Restoration scenario) (table S7, SM1), while the Restoration for smallholders scenario has similar transitions from both pasture and croplands (42% of the restoration areas come from croplands and 40% from pasturelands) (table S7, SM1).

3.4. Change in ecological indicators under alternative restoration scenarios

The total increase in AOH for measured species (2020–2050) ($n = 1621$) is proportional to the total restoration amount reached in 2050 under each scenario, as expected, while mean percentage change is similar between the Restoration for Biodiversity and the Restoration for Smallholders scenarios (14.3% and 18.3% respectively) and highest under a Maximum Restoration scenario (24.9%) (table 2, figure 3). Our results show some increase

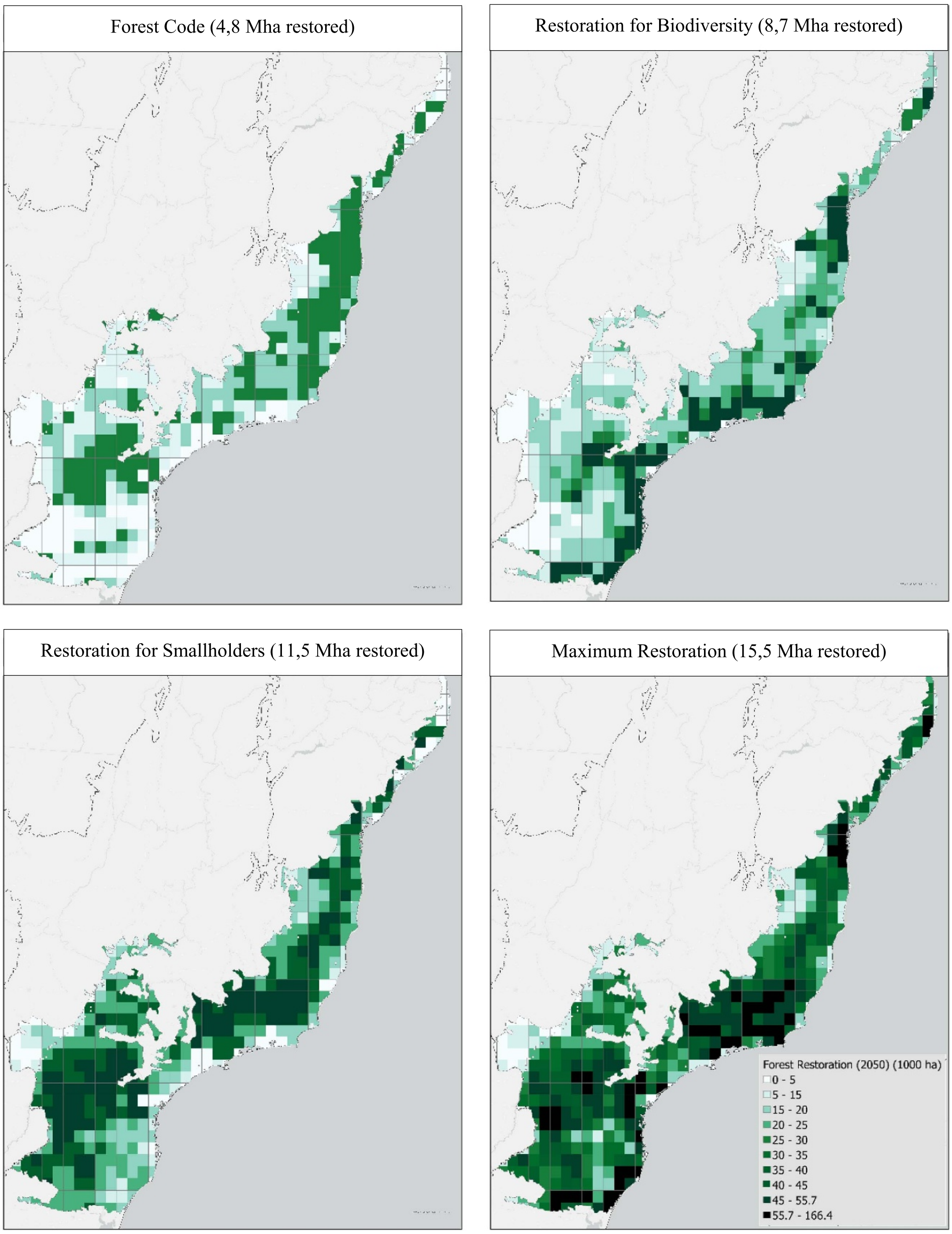

Figure 1. Spatial distribution of projected final restored areas in 2050 across the Atlantic Forest biome under (a) forest code scenario, (b) restoration for biodiversity scenario, (c) restoration for smallholders scenario and (d) maximum restoration scenario. Gradient green colours show the number of hectares restored per pixel (50 × 50 km). Final restored areas reached across the biome in 2050 per scenario are shown in figure headings.

in AOH for 84%–86% of assessed species (table S8, SM1), but only 3% of species see an increase of over 50% in their AOH (2020–2050) in the baseline Forest Code scenario, compared to 28% and 49% of species in the Restoration for Smallholders and Maximum Restoration scenarios, respectively (table 2). Looking at median change in AOH, our results suggest the Restoration for Smallholders scenario—despite requiring an additional 2.8 Mha restored native forest by 2050—and Restoration for Biodiversity scenarios would increase AOH by a similar amount (30.2% and 31.5% respectively), but when comparing against the Forest Code baseline in 2050, AOH would increase by 9.8% and 6.1%, respectively.

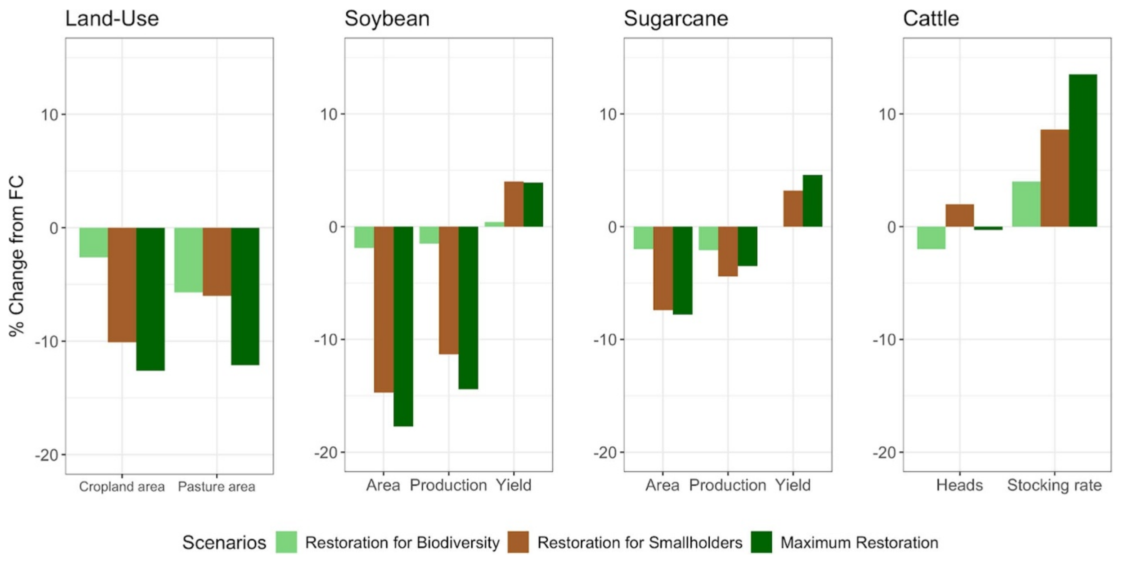

Figure 2. Change in key agricultural indicators under alternative scenarios compared to the baseline Forest Code scenario, measured in 2050. Bars indicate positive change (increase) and negative change (decrease) in 2050 compared to the baseline (baseline values included in SM1). Cattle are measured using TLU (tropical livestock unit) with 1 cattle head equal to 0.7 TLU. Cattle stocking rate (TLU per ha) represents cattle farming yield. Indicator groups are described above data bars.

Table 2. Projected change in AOH ($N = 1621$) between 2020 and 2050 under different forest restoration scenarios, and compared against the baseline Forest Code scenario. All percentages indicate increase.

Scenario	Median change in AOH (2020–2050)	Mean change in AOH (2020–2050)	Species with >50% increase in AOH (2020–2050)
Forest code (baseline)	14.4%	7.8%	3.0%
Restoration for biodiversity	31.5%	14.3%	13%
Restoration for smallholders	30.2%	18.3%	28.0%
Maximum restoration	47.8%	24.9%	49.0%

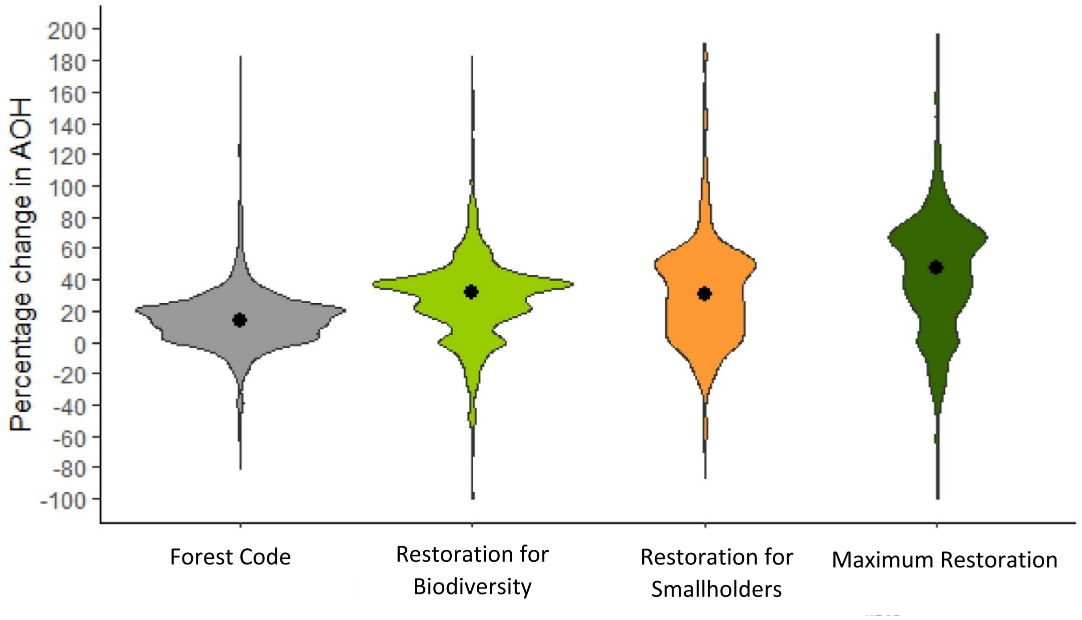

Figure 3. Distribution of data showing percentage change in AOH for all measured species ($N = 1621$) in each scenario, between 2020 and 2050. Black circles indicate median percentage change in area of habitat between 2020 and 2050 in each scenario.

4. Discussion

4.1. Trade-offs in meeting restoration targets

We found that under all four scenarios, various spatial distributions and targets for large-scale native vegetation restoration within the Atlantic Forest biome can be met without hindering the increase in agricultural production between 2020 and 2050. However, in general, the larger the restoration target, the greater the reduction in agricultural outputs compared to the baseline. According to the model projections, the restoration within the biome occurs over pastures and croplands, requiring different levels of agricultural intensification, especially regarding cattle ranching. Overall, regardless of the scenario, cattle herd sizes increase between 2020 and 2050. Compared to the baseline, cattle herds by 2050 fluctuate by around 2% under the alternative scenarios, while pasturelands always decrease. It is worth noting that in the scenarios prioritising restoration for biodiversity (Restoration for Biodiversity) and for smallholder farms (Restoration for Smallholders), the reduction in pasturelands by 2050 is approximately 6%, despite their different restoration targets of 3.9 Mha and 6.7 Mha, respectively. The level of cattle ranching intensification is defined by the combination of both cattle herd increase and pasture decrease over time. Our results confirm that cattle ranching intensification needs to increase with the size of the restoration target (figure 2). This intensification helps to mitigate agricultural production losses within the Atlantic Forest biome and meet Brazil's meat demand consistent with the 'Middle of the Road' SSP2 scenario at national level.

Our results suggest that prioritising restoration on small farms could cause greater reduction in cropland area than focusing restoration within BPAs. By 2050, while total cropland area in the Atlantic Forest is reduced under the alternative scenarios relative to the baseline (between 8% and 13%), the relative differences outside the biome are virtually zero (figure S2(a), SM1); for soy and sugarcane areas, relative differences are smaller than 2% (figures S2(b) and (c), SM1). This highlights that, according to our scenarios, the Atlantic Forest biome is likely to accommodate most of the decrease in crop area, including soy and sugarcane, without significant displacement (or leakage) of crop farming outside the biome. Regarding pastures, the relative differences between the alternative scenarios and the baseline outside the Atlantic Forest are small (less than 4%) (figure S2(d), SM1). The changes in stocking rates under the alternative scenarios compared to the baseline are virtually zero outside the biome (figure S2(f), SM1). These results suggest a small displacement or leakage in cattle ranching outside the Atlantic Forest due to the implementation of large-scale restoration within the biome. This points to the need for financial mechanisms and incentives to support the farmers inside the Atlantic Forest. It is worth mentioning that without cattle ranching intensification, the implementation of restoration targets could have further negative impacts on reducing cropland expansion.

4.2. Enabling factors and limitations

4.2.1. Yields and intensification

The Atlantic Forest biome faces huge pressure and competition for land, holding around 27% of Brazil's agricultural lands (SOS Mata Atlântica & INPE 2019). Or results show that more ambitious restoration scenarios can only co-exist with demand for cattle products and the replacement of pasturelands by croplands and forests if intensification and technological improvements are met, as highlighted by other studies (Strassburg *et al* 2014, Silveira *et al* 2022, de Oliveira Silva *et al* 2017). These results support evidence from Feltran-Barbieri and Féres (2021) who show efficient selection of degraded pasturelands and targeted restoration initiatives would allow Brazil to comply fully with the Forest Code, while increasing the cattle herd. Targeted investment within Brazil's agricultural plan (Plano Safra) to support policies of low emissions and sustainable production urgently needs to be scaled up (Stussi and Souza 2023), as well as investment to improve persistent low productivity across Brazil's pasturelands (Strassburg *et al* 2014).

We find higher restoration targets would reduce available cropland and pastureland by 2050 compared to the baseline Forest Code scenario, with related trade, socio-political and economic consequences. At the national scale, modelled scenarios require soybean yields to increase 3.7%–5.5% compared to current average yields for Brazil (USDA 2023a), while sugarcane yields would need to increase by up to 8.6% in 2050 (USDA 2023b) (table S5, SM1). This is within the potential for growth in both soybean and sugarcane yield according to the literature (Bordonal *et al* 2018), with Greschuk *et al* (2023) estimating 46% and 38% of Brazil's municipalities could improve yields for soybean and sugarcane respectively, through better management practices. Further investigation of socio-economic trade-offs is needed to develop successful restoration policy sensitive to territorial and agricultural realities.

4.2.2. Socio-political context

Competition for land between forest restoration and food production is a global challenge (Fleischman *et al* 2022, Jung *et al* 2023) and in the densely populated and degraded Atlantic Forest biome, large-scale landscape restoration is closely linked to issues of local food security, food sovereignty, and wellbeing (Moraes 2016, Erbaugh *et al* 2020). Under the existing Forest Code, our results show 6.7 Mha of private land will be exempt from restoration requirements within the Atlantic Forest biome in 2050, mainly due to the amnesty of environmental debts granted to small farms when the legislation was revised (Soares-Filho *et al* 2014). However, removing this amnesty carries significant social, ethical, and economic risks (Pinto 2020, Fleischman *et al* 2022, Rakotonarivo *et al* 2023). Our results, focused on global commodity crops, show the potential for continued agricultural development, with growth within or beyond current trends, at the same time as modelled increases in protection of key biodiversity areas and maintenance of the Small Farms Amnesty for restoration and NVPL compliance. Nonetheless, focusing restoration on BPAs only, without removal of the Small Farms Amnesty, would not be enough to reach the restoration target of 15 Mha set by the Atlantic Forest Restoration Pact (Crouzeilles *et al* 2019). We highlight the need for smallholder-specific incentives and restoration initiatives which can better capture the interaction between food production (mainly fruit and vegetables for national consumption), food sovereignty, local biodiversity, and restoration targets on Brazil's small farms. These could include continuations or modifications of existing and past initiatives, such as: the National Supply Company (CONAB)'s PAA (Food Acquisition Programme), a federal government grant which distributed funds at municipal levels to support smallholder farmer produce being used for social welfare programmes (e.g. food banks); and the PNAE (National School Feeding Programme), which used a structured demand approach to incentivise small farmers to produce food crops, mostly organic, to supply school meals (IPC-IG, International Policy Centre for Inclusive Growth, United Nations Development Programme 2013, Martínez *et al* 2023). The PAA programme, designed to support smallholders in gaining market access, was dismantled in 2018 (Sabourin *et al* 2020).

4.2.3. Consumption patterns and the global food system

Progress towards sustainable and equitable land use and management approaches should be supported by a reduction in consumption and production of livestock products (especially beef) if we are to achieve multiple goals of conserving biodiversity while feeding the global population (Visconti *et al* 2015, Godfray *et al* 2018, Shceimeier 2019, Kozicka *et al* 2023). The Food and Agricultural Organization (FAO) projects a 15% increase in meat protein consumption by 2030 (Happer and Wellesley 2019, FAO 2017, 2021). In the Brazilian context (where 75% of beef is destined for the national market), consumer awareness of the relationship between beef farming, consumption, and the environment remains low (Hötzel and Vandresen 2022). The livestock consumption parameters used in our scenarios, following SSP2, are conservative, but further engagement from the conservation science community in debates around livestock-derived protein consumption is needed, in Brazil and more widely (Sheeran and Webb 2016, Balmford *et al* 2017).

4.2.4. Treatment of uncertainty and model limitations

Models and scenarios remain approximate and simplified representations of reality, in support of decision-making. It is important to recognize limitations in results and the social and ethical implications of their application. Key limitations are summarised as follows. Climate change impacts on agricultural yields are not accounted for in our scenarios, and will likely exacerbate existing challenges to improving yields, for example reduced beef and milk production due to cattle heat stress (North *et al* 2023), and drought-induced crop failures. Our scenarios also rely on the assumptions and uncertainty of GDP and population dynamics represented in SSP2. Lastly, implementing restoration action in large vs small farms will have different impacts on biodiversity, food security, and livelihoods (Mansourian *et al* 2024, Fleischman *et al* 2022, Strassburg *et al* 2022), but these relationships could not be further explored since modelling diverse agroecological systems (such as agroforestry) and their interaction with restoration is not well represented within the GLOBIOM-Brazil model framework, nor similar models. Integrated crop-livestock-forestry systems and Agriculture 5.0 (Ragazou *et al* 2022) are also not currently available. Finally, we highlight that there remains uncertainty around the implementation and level of enforcement of the existing Forest Code law (NVPL) (Chiavari *et al* 2021, da Cruz *et al* 2020), our baseline scenario.

Data availability statement

The data supporting this article is openly available from the King's College London research data repository, KORDS, at https://doi.org/10.18742/26165926.

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Conflict of interest

The authors declare no conflict of interest.

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