



Balancing food production with climate change mitigation and biodiversity conservation in the Brazilian Amazon

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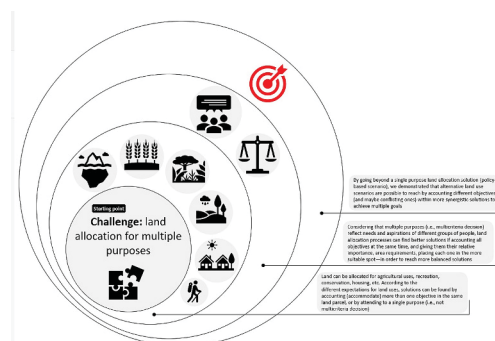
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HIGHLIGHTS

- Amazon faces great conservation deficits of natural vegetation in private lands.
- We use a multicriteria analysis to allocate land for restoration in the Amazon.
- Restoration have potential to engage landowners into new land market opportunities.
- Our food-carbon-biodiversity nexus model decreases land-use trade-offs.
- Ecosystem restoration in the Amazon has potential to create a green land market.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change mitigation and biodiversity conservation are two major environmental actions that need to be effectively performed this century, alongside ensuring food supply for a growing global human population. These three issues are highly interlinked through land management systems. Thus, major global food production regions located in biodiversity hotspots and with potential for carbon sequestration face trade-offs between these valuable land-based ecosystem services. The state of Mato Grosso in Brazil is one such region, where private lands that have been illegally used for agriculture could be restored to natural vegetation – with potential benefits for climate change mitigation and biodiversity conservation, although with potentially negative effects on food production. To address this challenge, in this study we used a multicriteria nexus modeling approach that

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considers carbon stocks, priority areas for biodiversity conservation, and the opportunity for food production, to develop scenarios of land allocation that aim to balance the benefits and drawbacks of ecosystem restoration. Results show that forcing landowners to restore their individual lands compromises the potential for a “green land market” throughout the Amazon biome in which private landowners with lower food production capacities (e.g., less connected to markets and infrastructure) would benefit from restoration programs that compensate them for the inclusion of environmental restoration among their economic activities, instead of taking large economic risks to produce more food. We additionally highlight that strategic ecosystem restoration can achieve higher gains in biodiversity and carbon with lower costs of restoration actions and with minimal impacts on agriculture. Analyses like ours demonstrate how scenarios of land allocation that simultaneously address climate mitigation and biodiversity conservation through ecosystem restoration, while also minimizing possible impacts on food production, can be sought to move the world towards a sustainable future.

1. Introduction

Land conversion from natural vegetation to agricultural production represents a major driver of greenhouse gas emissions and biodiversity loss, especially in developing countries in tropical regions [e.g., Brazil, Indonesia (Hong et al., 2022)]. In addition, human population growth, together with an increase in economic affluence and changing consumption habits (e.g., switch to animal protein diets), have led to the emergence of global food systems in which consumers are often geographically distant from food production areas (Silva et al., 2017a; Kapsar et al., 2019; Viña and Liu, 2023). Such telecoupled food systems at multiple scales (e.g., international and national) put pressure on local ecosystems in distant areas (Liu et al., 2018; Fischer et al., 2013; Silva et al., 2021). Under this premise, the linkages between food, climate, and biodiversity (Schulte et al., 2022; Borma et al., 2022) challenge current agreements to address the climate and biodiversity crises (e.g., Paris climate COP21, Montreal biodiversity COP15; Strassburg et al., 2020; IPBES, 2019), as well as the UN Sustainable Development Goals (SDGs; Liu et al., 2018). Land conversion is especially challenging as major food suppliers to global commodity chains are located in key areas for biodiversity conservation and climate change mitigation (DeFries et al., 2017; Agus et al., 2022; Leal Filho et al., 2022).

Given the significant role of land-use and land-cover (LULC) change on biodiversity loss and global climate change (Hong et al., 2022), environmental policies regulating land use and protected areas are vital for land management (Silva et al., 2017b). One such environmental policy is the Brazilian Forest Code, which requires landowners of rural properties to maintain a minimum area within their private lands under natural vegetation [named ‘legal reserve’ (Soares-Filho et al., 2014; Delaroche et al., 2022)]. However, as with many environmental policies, compliance with the rules of the Brazilian Forest Code has been incomplete and many private landowners do not retain the required legal reserve (LR hereafter) within their property boundaries (Silva et al., 2023a). This non-compliance has been attributed to the lack of surveillance and law enforcement (Silva et al., 2017b), beliefs by offenders that they will receive amnesty (Soares-Filho et al., 2014), and the burden of conserving common goods in private lands (Azevedo et al., 2017; Nascibem et al., 2023). Nevertheless, recovering the minimum areas of natural vegetation required by the Forest Code could be achieved using ecological restoration strategies that simultaneously target environmental (biodiversity and climate) and economic (agricultural production) goals, while minimizing land conflicts (Nunes et al., 2020; Adams et al., 2021; Meyfroidt et al., 2022; Lemos et al., 2023).

Although the rates of carbon uptake associated with natural vegetation and ecosystem recovery are still uncertain (Poorter et al., 2016; Doelman and Stehfest, 2020), restoration has been shown to effectively reverse the negative effects of deforestation, including the loss of soil organic matter and carbon stocks (Veldkamp et al., 2020; Nunes et al., 2020; Borma et al., 2022). For example, previous studies have shown that recovery of natural ecosystems can potentially restore up to 90 % of natural carbon stocks, with more than 50 % during the first 20 years (Poorter et al., 2016) or earlier (Adinugroho et al., 2022). Furthermore, both active (e.g., tree-planting) and passive (e.g., natural regeneration)

restoration actions have been shown to recover biodiversity at significant levels (Crouzeilles et al., 2017). However, in tropical ecosystems, the interaction of past land-uses, restoration approaches, biophysical features (e.g., precipitation) and age of restoration influence the success of biodiversity recovery (Crouzeilles et al., 2017; Romanelli et al., 2022). Furthermore, the conversion of land used for intensive agriculture to natural vegetation reduces food production and economic income while agricultural land-use still represents a major driver of deforestation (Pendrill et al., 2023). Thus, food production constitutes one of the most challenging issues currently facing climate change mitigation and biodiversity conservation actions (Meyfroidt et al., 2022). Such a challenge is being addressed using nexus approaches that examine the interactions (e.g., synergies and trade-offs) among multiple dimensions, including different disciplines (e.g., economics, ecology, biogeography, sustainability science), sectors (e.g., food, energy, water) and places, simultaneously (Liu et al., 2018).

Although synergies are often sought, the analysis of trade-offs constitutes an important tool for achieving different needs while also achieving acceptable land-use solutions (Seppelt et al., 2013; Meyfroidt et al., 2022). Strassburg et al. (2020) demonstrated that forest restoration scenarios that simultaneously consider economic, climate and biodiversity targets result in better environmental and economic outcomes. Scenario-based decision-making processes (Davenport et al., 2019) and land optimization frameworks (Thomson et al., 2009) are, therefore, key approaches enabling the identification of synergistic solutions, reducing land conflicts (e.g., food production and conservation of ecosystem services) and avoiding top-down conservation decisions which often marginalize local voices and prevent sustainable development (Seppelt et al., 2013; Tamburini et al., 2023). For instance, used in the Nature Futures Framework, scenario-based decision-making approaches (e.g., using multicriteria analysis) have provided the means for accounting for multiple dimensions across space and time, and to find balanced, alternative solutions that consider the expectations of all involved stakeholders (Polasky et al., 2008; Kalbar et al., 2012; Seppelt et al., 2013; Stewart et al., 2013; Rosa et al., 2017; Davenport et al., 2019; Strassburg et al., 2020).

To contribute to an understanding of the trade-offs among different dimensions, this study focuses on the development of a nexus model to evaluate some scenarios that balance different combinations of costs and benefits among biodiversity conservation, carbon sequestration, food production, and restoration costs. Based on a multicriteria approach, the developed nexus model was used to examine possible alternative scenarios of natural vegetation recovery in the Brazilian state of Mato Grosso, Brazil. Mato Grosso is a major agricultural producer that also provides climate and biodiversity services that have been considerably reduced through the non-compliance of current environmental policy (Silva et al., 2023a). Mato Grosso's agricultural production area spans a large geographic region within the Amazon, Cerrado, and Pantanal biomes (Souza et al., 2020). Forming a tropical deforestation frontier (Silva et al., 2021), many rural private properties in the state do not comply with the Brazilian Forest Code, thus contributing to a statewide LR deficit (Azevedo et al., 2017; Delaroche et al., 2022). Using Brazil's *Rural Environmental Cadastre* (CAR) data to evaluate the deficit of LR in

rural private properties, we developed a series of allocation scenarios that consider different combinations of criteria to prioritize areas for land restoration.

2. Study area

Mato Grosso state is the largest producer of soybean, corn, cotton, and beef in Brazil. The dynamic and active agricultural sector has been responsible for the state's large deforestation rates observed during the last decades (Silva et al., 2023b), with a total of 8.6 Mha of natural vegetation converted to agriculture from 2000 to 2021, according to the MapBiomas platform (<https://mapbiomas.org/>). The state lies within the Brazilian mid-west, and occupies a territory of 90.3 Mha, equivalent to 2.5 times the size of Germany. Given its large territory, Mato Grosso stands between two climate zones—*Tropical Central Brazil* and *Equatorial*—with average annual precipitation of 1700 mm, but ranging from 1200 mm to 2000 mm (Cordeiro et al., 2020). Mato Grosso comprises three Brazilian biomes: Pantanal, Cerrado and Amazon. With a total population of 3,567,234 inhabitants in 2021 (IBGE, 2021), the state ranked 16th in Brazil, in terms of population. Mato Grosso's gross domestic product (GDP) contributed with 2.3 % of the national GDP in 2020, 25 % of which came from the agricultural sector (IBGE, 2020).

3. Methods

Our multicriteria-based nexus model searches for the best land allocation scenarios for the restoration of natural vegetation by considering potential carbon sequestration and conservation of priority areas for biodiversity, while accounting for food production opportunity. In the state of Mato Grosso, the Brazilian Forest Code requires rural private properties to have a minimum of 80 %, 35 % and 20 % of natural vegetation cover as LR, in the Amazon, Cerrado, and Pantanal biomes, respectively. To develop a scenario-based decision support system for natural vegetation restoration, our model relies on four data sources (i.e., criteria): (a) the Brazilian map of carbon stocks; (b) the priority areas for biodiversity conservation; (c) the food production opportunity; (d) and the spatial restoration opportunity. Model scenarios were designed at the biome level and with an additional scenario designed at the rural property level (i.e., the base line scenario), for comparison purposes. In this study scenarios are designed to target two major global

environmental issues, the climate change and biodiversity loss. Therefore, given the 'opportunity' for ecosystems restoration enforced by the Brazilian Forest Code, those targets can be better attained if spatially explicit models account for both processes while minimizing the impacts on food production (as restoration will take place over current food production lands). From this perspective, the resulting scenarios constitute potential tools to lever informed policy design and implementation towards sustainable production landscapes. In Fig. 1 we present the major steps of our nexus model.

3.1. Datasets

3.1.1. Rural private property data

Our vegetation recovery analyses only considered rural private properties in the state of Mato Grosso. Data on rural private properties were retrieved on April 2021 from the CAR dataset, with is freely available through the National CAR System (SICAR). Through the SICAR, landowners declare their rural properties as polygons using the ESRI shapefile format. These polygons represent the properties' boundaries (Silva et al., 2019). In addition to the LR, the Forest Code also demands Permanent Preservation Areas (APP) to protect specific features such as water springs and riverbanks (Soares-Filho et al., 2014). Because APP represent a set of specific land features within the private properties, they were not considered in our analysis. In addition, we only used polygons representing rural private properties (IRU).

3.1.2. Land-use and land-cover data

Data on land-use and land-cover (LULC) for 2008 and 2020 were obtained from the MapBiomas dataset v.6 (<https://mapbiomas.org/>). These LULC data are derived from the classification of Landsat imagery at 30-meter spatial resolution, with a 90 % accuracy. From the original LULC classes of MapBiomas, we reclassified 'Forest formation', 'Savanna formation', and 'Grassland' into the 'Natural vegetation cover' class. 'Forest plantation', 'Sugar cane', 'Mosaic Agriculture and Pasture', 'Soybean', and 'Other temporary crops' were reclassified as 'Cropland'. Other LULC classes, such as 'Pastureland' remained the same (Fig. 2a).

3.1.3. Carbon sequestration potential

The potential of a specific landscape to sequester carbon is associated with the status of its natural vegetation. Thus, the restoration of natural

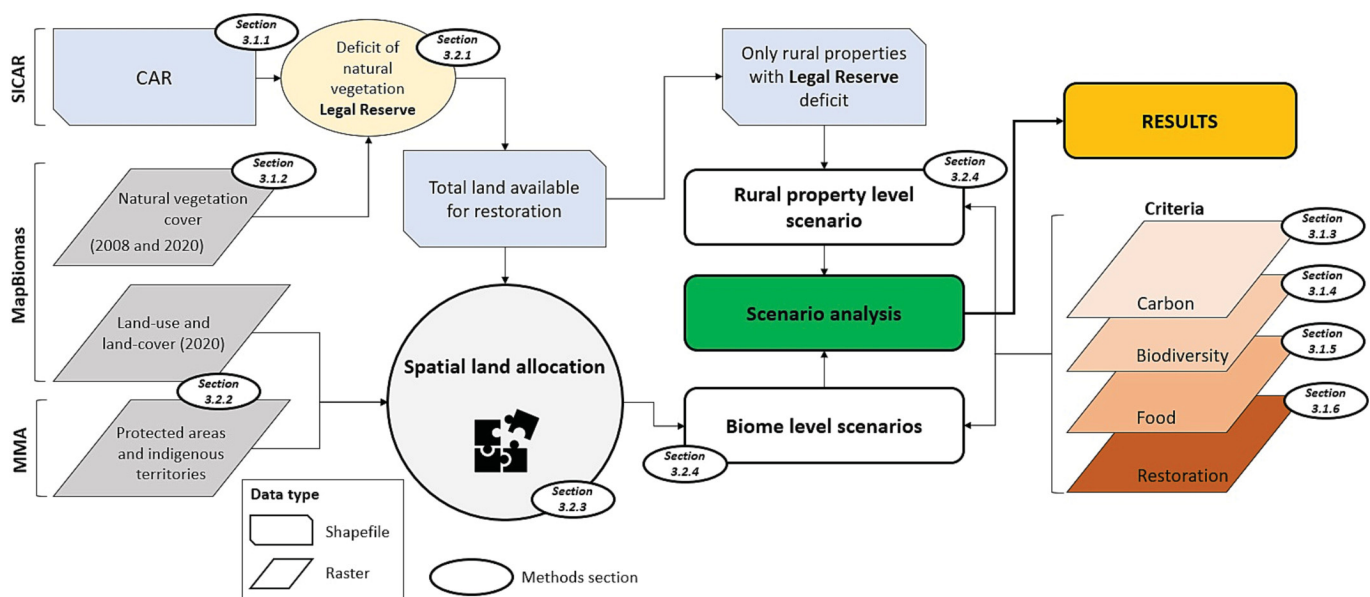


Fig. 1. Flowchart showing the steps of the nexus model. In the Figure, SICAR is the national system to store and access the Rural Environment Cadastre (CAR), while MMA is the Brazilian Ministry of Environment.

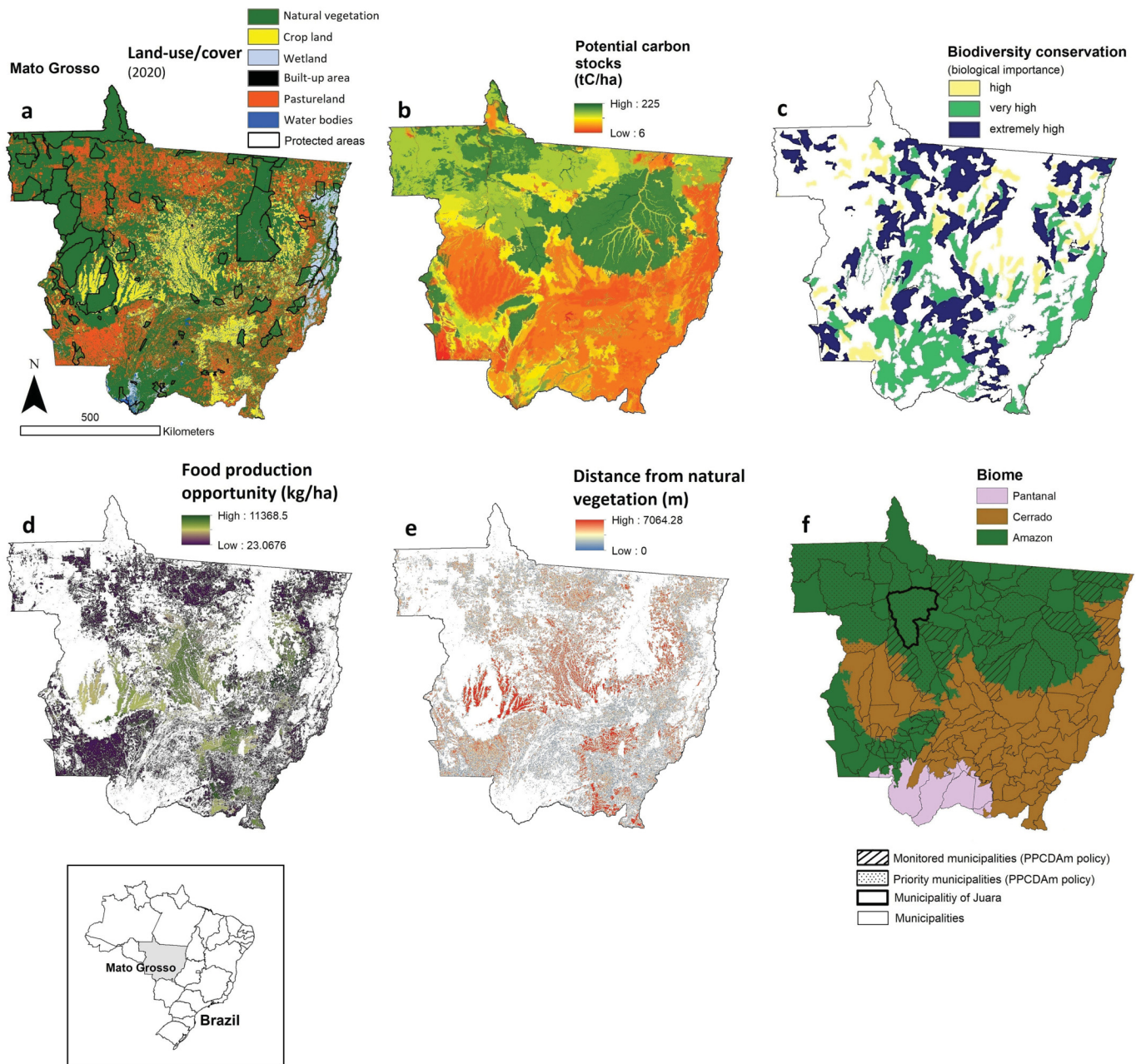


Fig. 2. Maps of the state of Mato Grosso showing the range of values and spatial distribution of key features for the multicriteria-based nexus model. a) LULC map of 2020 with protected areas overlaid; b) Map of the potential carbon stocks associated to each vegetation type and biome; c) Priority areas for biodiversity conservation; d) Food production opportunity based on crop-livestock production in 2020; e) Distance from natural vegetation; f) Distribution of biomes with the boundaries of municipalities overlaid.

vegetation increases the potential for carbon sequestration (Boisvenue et al., 2022). To assess carbon sequestration potential, we used the Brazilian map of potential carbon stocks (Silva et al., 2023a). This product associates carbon values (tC/ha) with each vegetation type and biome, to represent the total carbon stock (i.e., including above- and below-ground, litter, and dead wood), Fig. 2b.

3.1.4. Priority areas for biodiversity conservation

To evaluate potential effects of the recovery of natural vegetation cover on biodiversity, we used the *Priority Areas for Biodiversity Conservation* (PABC) dataset (second version, 2018), developed by the Brazilian Ministry of Environment (Brock et al., 2021). The PABC were developed through the participation of different groups of stakeholders (e.g., NGOs, Universities, Public servants, private sector) and led by the

Ministry of Environment. PABC data values (Fig. 2c) are ranked according to the biological importance of a given region (MMA, 2021).

3.1.5. Food production opportunity

Based on the LULC dataset from 2020 derived from MapBiomas we identified lands without natural vegetation cover that could be restored. To evaluate the effects of different restoration scenarios on food production, the 'food production opportunity' variable considers the current land value associated with agricultural production, and for the year of 2020. Pasturelands were assigned values to represent the potential amount of beef according to the stocking rate (n^0 of cattle/ha) at the municipality level. The cattle data at municipality level were obtained from the Brazilian Institute of Geography and Statistics [IBGE (<https://sidra.ibge.gov.br/tabela/3939>)]. Considering the average beef

production in Mato Grosso (state level) of 85.8 kg/ha, and with an average stocking rate of 1.57 (Zen et al., 2018), the stocking rate of each municipality was converted to kilograms by multiplying per 54.6 kg—i.e., the State's average weight per hectare. The lower the beef production, the higher the suitability for restoration, given that the impact on food production will be lower. Cropland land was evaluated following five major food crops produced in Mato Grosso: soybean, maize, rice, beans, and cassava. Average yields (kg/ha) per crop at the municipality level were combined into a single crop yield average which was assigned to each 30-m pixel to the respective municipality, to assess its potential crop production. The crop yield data were obtained from the IBGE (<https://sidra.ibge.gov.br/tabela/1612>). From these calculations we generated two map layers (*i* – layer with the pixels representing ‘Pastureland’ class with the respective values of meat production, and *ii* – layer with pixels representing ‘Cropland’ class with the respective values representing the crop production), which on the aggregate represent the ‘food production opportunity’ (measured in kg/ha). This ‘food production opportunity’ represents how much agricultural output (beef or crop) each pixel potentially produces actual production in 2020 (Fig. 2d).

3.1.6. Distance from natural vegetation & spatial restoration opportunity

Proximity to existing natural vegetation is known to be a key factor to foster passive restoration through natural secondary succession (Chazdon, 2003; Uriarte et al., 2011; Robinson et al., 2015; Viña et al., 2016; Crouzeilles et al., 2017; Silva et al., 2023b). It also constitutes an important spatial landscape pattern as it constitutes a proxy for estimating the reduction of restoration costs (Strassburg et al., 2019). This factor has been utilized to evaluate restoration in several previous studies (Dorrough et al., 2007; Evans et al., 2015; Brancalion et al., 2016; Strassburg et al., 2019). Based on the LULC dataset of MapBiomass for 2020, in this study we created a variable representing the distance from existing natural vegetation areas. This metric was created using the Euclidean distance (using ArcGIS Desktop 10.8), in meters (Fig. 2e)—with the assumption that the closer to existing natural vegetation the higher the likelihood of natural vegetation recovery. Considering the importance of the restoration opportunity cost, we additionally created a buffer of 180 m from existing natural vegetation for post-analysis purposes, to measure scenario results for ‘spatial restoration opportunity’ (i.e., we calculated the hectares of priority areas within the buffer for performing comparisons among scenarios).

3.2. Land allocation

To assess land allocation for natural vegetation recovery we used *Zonation* (v.4). This software was designed for land optimization analysis in support of land use planning (Moilanen, 2007; Thomson et al., 2009; Moilanen et al., 2011; Lehtomäki et al., 2015; Montemayor et al., 2022; Tamburini et al., 2023). *Zonation* works with raster data and is capable of dealing with numerous criteria (socioeconomic and environmental features) to identify spatial solutions for optimal allocation scenarios for conservation—i.e., balancing alternative land uses (Moilanen et al., 2011). The ‘Carbon stocks’, ‘Biodiversity conservation’, ‘Food production opportunity’, and ‘Distance from natural vegetation’ raster datasets obtained at 30-m per pixel (Fig. 2b, c, d, e) were resampled to 90-m per pixel (given computational limitations), using the nearest neighbor resampling approach. These resampled raster datasets were treated as criteria in *Zonation*, and the resampling strategy kept total land area for original classes at 99.9 %.

3.2.1. Parameter setting: amount of land for allocation scenarios

The minimum area of land required to be maintained as natural vegetation (the LR) varies by private property size and the biome in which it is located. Although the Forest Code has a long-standing requirement for the LR, the last review of the Code (in 2012) introduced the concept of Fiscal Modules (FM), which vary among

municipalities from 1 ha to 110 ha (Silva et al., 2023a). Defined by the Agrarian Reform Law (Law 8629/1993), these FM constitutes the minimum area of land considered necessary for a rural family to produce and make the farm economically viable. A threshold of four FM was then created to divide rural properties into two groups, one group below the threshold corresponds to small rural properties [also called the ‘tolerant’ regime (Soares-Filho et al., 2014)] and the other above the threshold corresponds to medium-to-large properties. For the medium-to-large properties, we calculated the LR deficit in 2020 according to Article 12 of the Forest Code, i.e., using the 80 %, 35 % and 20 % schemes in the Amazon, Cerrado and Pantanal biomes, respectively. Properties that have less (more) natural vegetation cover (measured in ha) than expected by this scheme, are then considered in deficit (surplus). Calculation of LR deficit in the ‘tolerant’ regime group needs to be different given that small landowners in this group were waived (“amnestied”) from the obligation to recover deficits of LR (Soares-Filho et al., 2014). Thus, for the ‘tolerant’ regime, we first calculated the natural vegetation cover in 2008. If this cover was above the minimum required by the forest code, we applied the rule for medium-to-large properties in 2020. However, if the rural property had less than the minimum, the amount of natural vegetation cover in 2008 was set as the LR for that property. Hence, for small properties, we calculated the change between natural vegetation cover in 2008 and 2020 to evaluate loss (gain) and thus evaluate if the property was considered to be in deficit (surplus). We then aggregated all property deficit/surplus values to the biome level to assess if there was a net biome-level surplus or deficit. If a net deficit was found, then the biome (Fig. 2f) was analyzed to find the location and extent of the best areas for natural vegetation cover restoration. These eligibility criteria are based on the current Forest Code, which allows landowners with LR deficits in their properties to compensate through the natural vegetation cover surplus of other properties within the same biome. Alternatively, in the case of a net biome-level LR deficit, a restoration will be required to achieve full compliance with the Forest Code. Our data showed that although LR deficits of 2.2 Mha and 63 kha were observed in the Cerrado and Pantanal biomes, respectively, the LR surpluses of 4.9 Mha and 2.7 Mha observed in the Cerrado and Pantanal biomes were larger. Thus, we only examined the Amazon biome (i.e., total deficit of 10 Mha, surplus of 1.8 Mha, and a net LR deficit of 8.2).

3.2.2. Parameter setting: constraints for land allocation scenarios

Areas excluded (masked) using the *Zonation* software were considered as constraints. For allocation scenarios of natural vegetation cover restoration, built-up areas, wetlands and water bodies (e.g., lakes, rivers) in 2020 are constrained by the model as the return of those areas to natural vegetation cover is unrealistic and not economically viable. In addition, indigenous territories and public protected areas of integral protection were also included in the model as constraints (Fig. 2a). Furthermore, areas under natural vegetation cover in 2020 were also considered a constraint, since the algorithm searches for areas suitable for restoration.

3.2.3. Parameter setting: modeling with zonation

In our modeling approach, for *Zonation*'s removal rule, which determines the lower marginal loss in carbon stocks or biodiversity conservation value, we used the *additive benefit function* (ABF). The ABF considers the feature (weighted) proportion of all criteria in a given pixel instead of the highest parameter of one of the criteria set (Moilanen, 2007), following Eq. (1):

$$\delta i = \frac{1}{c_i} w_j \sum_j \Delta V_j = \frac{1}{c_i} w_j \sum_j [V_j(q_j - i)] \quad (1)$$

The δi value of the cell corresponds to the sum over feature-specific declines in value

following the loss of cell *i*. The *qj* represents the feature *j* in the remaining set of sites while *qj-i* indicates the set of remaining cells minus

cell i . The weights of the feature j in the equation are represented by w_j while c_i is the cost (i.e., the food production opportunity) of planning unit i . Hence, the cell with the smallest δ_i value is removed.

To allow scenarios with solutions considering more connected areas for restoration, we used the *distribution smoothing* aggregation method (Montemayor et al., 2022). For this parameter we set the α value as 0.011 to represent areas of 3.24 ha (i.e., four 90-m pixels). This constitutes a minimum area solution to allow more aggregation among pixels for restoration considering the raster resolution used in the study. The α value is found by dividing 2 per the ‘use of landscape’ in the same pixel unit (Moilanen et al., 2014) (i.e., 180 m in this study). The *warp factor* (WF), which defines the number of pixels removed in each iteration, was set to represent around 1 % of the total pixels available (WF = 100,000 for the Amazon biome). The *boundary length penalty* is another aggregation method applied to induce more compacted network solutions at the landscape level—i.e., it reduces the ratio between the edge and the area of the remaining areas during the removal process (Moilanen and Wintle, 2007). We set this parameter to 0.01, corresponding to a minimum penalty solution—the higher the parameter value, the higher the spatial clumping. We also applied the *edge removal* function, part of the Zonation algorithm, used to speed-up the removal process while allowing pixels to be removed only from the edge of the remaining study area (Moilanen et al., 2014). In scenarios for natural vegetation cover restoration that aim to mitigate climate change and increase biodiversity conservation with minimum impact on food production, the ‘Food production opportunity’ criteria are weighted with a negative value. Hence, the allocation process assigns the lowest values in the priority ranking (spatial solution) to the pixels of low carbon/conservation values and with high food production, and vice versa (Moilanen et al., 2011). In Zonation, the ranking of priority areas ranges from 0 to 1 where 1 represents the maximum conservation value (higher priority). ‘Carbon stocks’, ‘Biodiversity conservation’, and ‘Distance from natural vegetation’ criteria were weighted at 1, while ‘Food production opportunity’ at -1 .

3.2.4. Restoration scenarios

Considering alternative scenarios is important to evaluate impacts of different land allocation results where some key variables (criteria) are neglected during the land optimization process (Moilanen et al., 2011; Strassburg et al., 2020). Hence, first we used the net LR deficit to define the biomes eligible for land allocation scenarios. Second, the amount (ha) of natural vegetation cover in deficit represents the total land area that must be restored in the biome to reach full compliance with the Forest Code. Thus, all agricultural lands within private properties were considered eligible regardless of their respective LR deficit (or surplus). In this case, for biome level restoration scenarios, we searched for the best areas (i.e., pixels) within rural private properties to target at the highest priority. Second, the Forest Code allows landowners with LR deficit in their private properties to compensate through (i.e., restore natural vegetation in) other private lands within the same biome (Article 66 of the Forest Code). This creates a potential market for landowners willing to restore natural vegetation cover within their properties to be financially compensated, to trade carbon emissions, or to participate into payment for ecosystem services programs (Bernasconi et al., 2016; Adams et al., 2021). Third, for a comprehensive trade-off analysis we considered five different scenarios based on different combinations of our criteria of interest, and confront the results obtained in these scenarios with a baseline scenario developed at the private property level (named hereafter *command-and-control*). These scenarios are as follows:

Scenario 1 (Command-and-Control) was established at the private property level and represents our baseline scenario. Based on the LR deficit of each rural property we examined the impacts on food production, potential carbon sequestration, and natural vegetation cover increase within priority areas for biodiversity conservation, if restoration was enforced in all private properties according to their

respective deficit allowance (i.e., not considering any potential impacts on food production, biodiversity conservation or climate change mitigation). In this case, the LR deficits of a particular property would not be allowed to be compensated through restoration in other properties but exclusively within the respective property where the deficit was found. Considering the Amazon net LR deficit of 8.2 Mha, we created a random sample corresponding to 83 % of the private rural properties (44,578 properties) with LR deficit for scenario analysis (this sample size was enough to reach the 8.2 Mha of deficit). Using the vector shapefile with sampled private property boundaries, for properties with LR deficit (ha) we extracted the values for ‘carbon stocks’ and ‘food production opportunity’ using the ‘majority’ zonal statistic (Hyndman and Fan, 1996). We then multiplied the extracted value for each criterion by the natural vegetation cover deficit of each individual rural property. For the ‘biodiversity conservation’ and ‘spatial restoration opportunity’ we tallied the hectares of both criteria within the rural property and calculated how much of those hectares could be restored considering the respective LR deficit. With the random sample of private rural properties, a hotspot analysis by the Getis-Ord G_i^* method (Getis and Ord, 1992) was applied to evaluate spatial dependence and clustering patterns of LR deficits—this spatial analysis was performed using *ArcGIS Desktop 10.8*.

Scenario 2 (Carbon-Biodiversity-Food) searches for the best solution to allocate areas for natural vegetation cover restoration considering all three factors: potential carbon sequestration, biodiversity and food production.

Scenario 3 (Carbon-Biodiversity) considers only potential for carbon sequestration and biodiversity priority areas, without considering food production opportunity.

Scenario 4 (Carbon-Food) allocates land for restoration considering the potential impacts for carbon sequestration while minimizing impacts for food production, without considering the impacts for the restoration of priority areas for biodiversity conservation.

Scenario 5 (Biodiversity-Food) considers as priority for land restoration only areas with greatest value for biodiversity conservation and the impacts on food production.

Scenario 6 (Carbon-Biodiversity-Food-Restoration) uses the same variables of Scenario 2 but also includes the ‘distance from natural vegetation’ in 2020 (Fig. 2e). This additional scenario is important for balancing the solution obtained from the model considering all major criteria under a “cost-opportunity” evaluation scenario, while also utilizing the proximity layer as a proxy of restoration costs. Under this scenario, areas that are nearest to natural vegetation have lower restoration costs, given the higher vegetation recovery observed in areas closer to existing natural vegetation areas. In our analysis, areas near existing natural vegetation exhibit lower costs, which then increase as the distance increases.

4. Results: land allocation scenarios

Our analysis of the natural vegetation cover within private properties in Mato Grosso shows that a net LR deficit occurred only in the Amazon biome. Based on a total of 103,138 private properties within the Amazon biome in Mato Grosso, the difference between the total deficit of 10 Mha and the surplus of 1.8 Mha, led to a net deficit of 8.2 Mha across all private properties within this biome. Medium-to-large properties represented 16 % of the properties with LR deficit but accounted for 96 % of the deficit in area. Based on LULC data for 2020, we found that the potential area for natural vegetation cover restoration in the Amazon biome portion of Mato Grosso (i.e., all current areas used for agricultural production) is 19 Mha. Of this, around 45 % (8.2 Mha) should be restored to ensure a full compliance (i.e., eliminating the net LR deficit) scenario with the Forest Code (Fig. 3a–f).

The multiple scenarios examined led to the formulation of varying

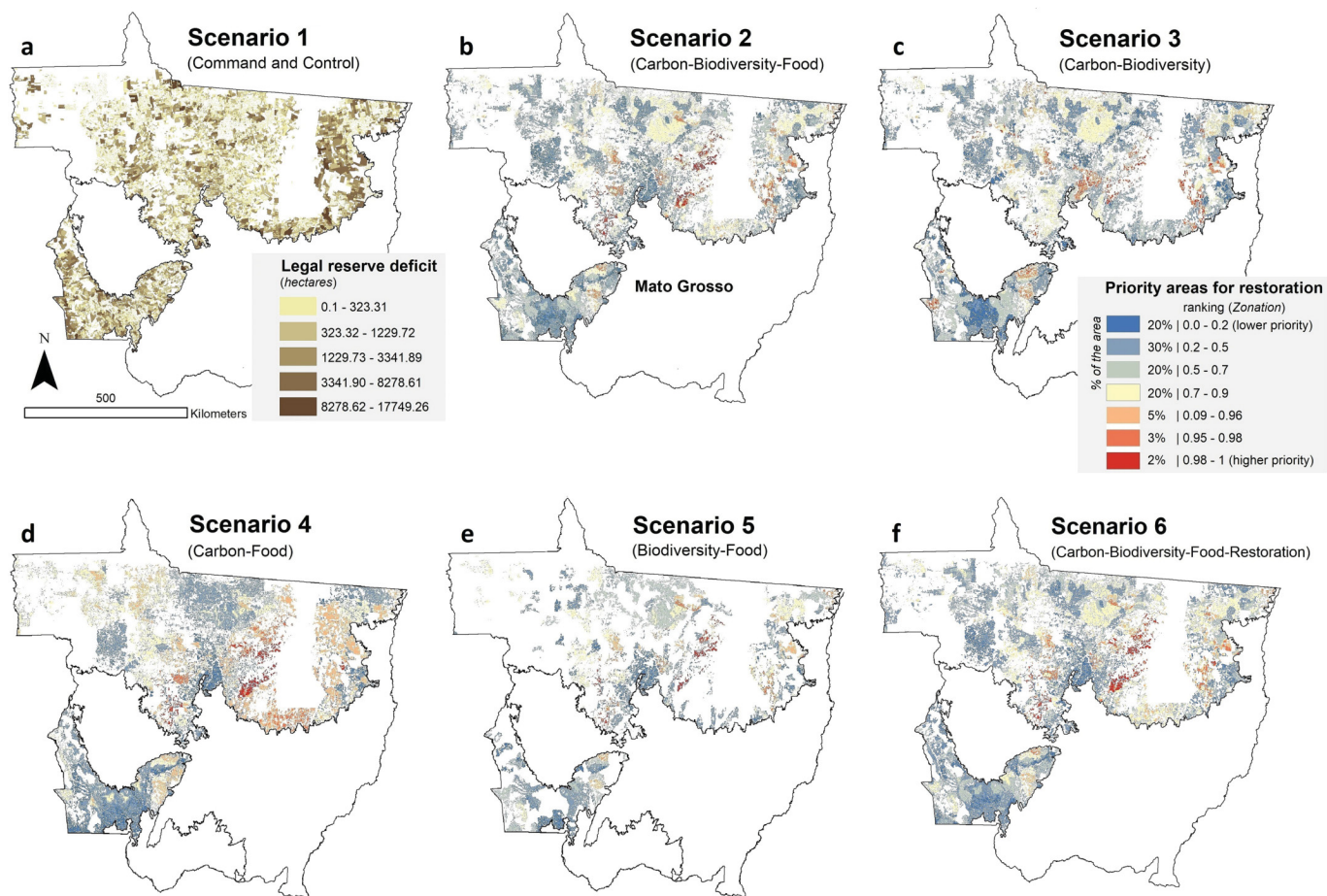


Fig. 3. a) The Command-and-Control scenario. b, c, d, e and f) Restoration scenarios based on different combinations of criteria.

prioritizations of areas to allocate land for natural vegetation cover restoration (Fig. 3b–f). However, we see advantages and disadvantages inherent to each scenario. For example, in Scenario 4 (Carbon-Food—Fig. 3d) the carbon stock was the most benefitted in the allocation process, however yielding the lower outcome for biodiversity conservation (which was a variable excluded for the allocation process). Scenario 1 (command-and-control), which does not consider any of the criteria for optimization of land allocation scenarios but rather enforces the restoration of natural vegetation cover in each private rural property according to their own individual deficit (Fig. 3a), resulted in the most disadvantageous outcome for food production (reducing the food production of 2020 by 60 %—i.e., 20 Mtons) while not improving carbon or biodiversity compared to alternative scenarios (Fig. 4a). Still, the command-and-control scenario provides the best outcome for ‘spatial restoration opportunity’—i.e., it is the scenario with the highest trade-off (Fig. 4b). In this case, the restoration opportunity would be higher in the command-and-control scenario because a greater number of areas would be restored nearby existing natural vegetation—i.e., facilitating restoration through secondary succession, which lower the financial costs of restoration. Considering all scenarios, Scenarios 5 (Biodiversity-Food—Fig. 3e) provides the most balanced solution (lowest trade-offs, Fig. 4b) in which potential carbon sequestration and biodiversity conservation are favored while minimizing the impacts on food production, and also achieving a favorable outcome for restoration opportunity cost compared to scenarios 2, 3, 4, and 6. According to the total food production of 2020 found in the Amazonian portion of Mato Grosso at 33 million tons (based on the food production opportunity criteria, Fig. 2d), restoration following Scenario 5 would lead to a food production loss of 39 % if net LR deficit eliminated. Among scenarios we highlight that

scenario 6, by accounting a criterion to allocate restoration closer to the existing natural vegetation areas, improved the result of scenario 2 for ‘spatial restoration opportunity’ but also lowering trade-offs on carbon, biodiversity, and food (Fig. 4b).

From the private rural properties with LR deficit data (Fig. 3a), it was created a hotspot analysis map to show the spatial pattern of clustering for deficits (Fig. 5). It was observed that from 75 municipalities with over 50 % of its territory within the Amazon biome (accounting for 97 % of the total LR deficit), twenty (Fig. 5) concentrated 50 % of the LR deficit. If considering priority Scenario 2 as an example, ten out the twenty municipalities would be enough to fill 30 % of the net LR deficit and seventeen to reach 50 %. Additionally, Scenario 2 reveals that the remaining seven municipalities with large areas indicated as high restoration priority do not constitute large contributors to the current LR deficit in the Amazon biome within Mato Grosso state.

5. Discussion

The United Nations Decade of Ecosystem Restoration (2020–2030) is a key time for decision-makers and managers to foster the recovery of degraded areas worldwide. In many places, conflicts between policy, institutions, economic development, and beliefs of local stakeholders will need to be negotiated, considering human diversity and interests among different decision-making arenas (Morrison et al., 2019; Dunning, 2022). In such institutional policy-governance contexts, previous studies have shown that more decentralized systems tend to act more efficiently in governing the “commons” (Dorsch and Flachslund, 2017; Dunning, 2022). This is because decentralized systems create more innovative responses and take into consideration the views and

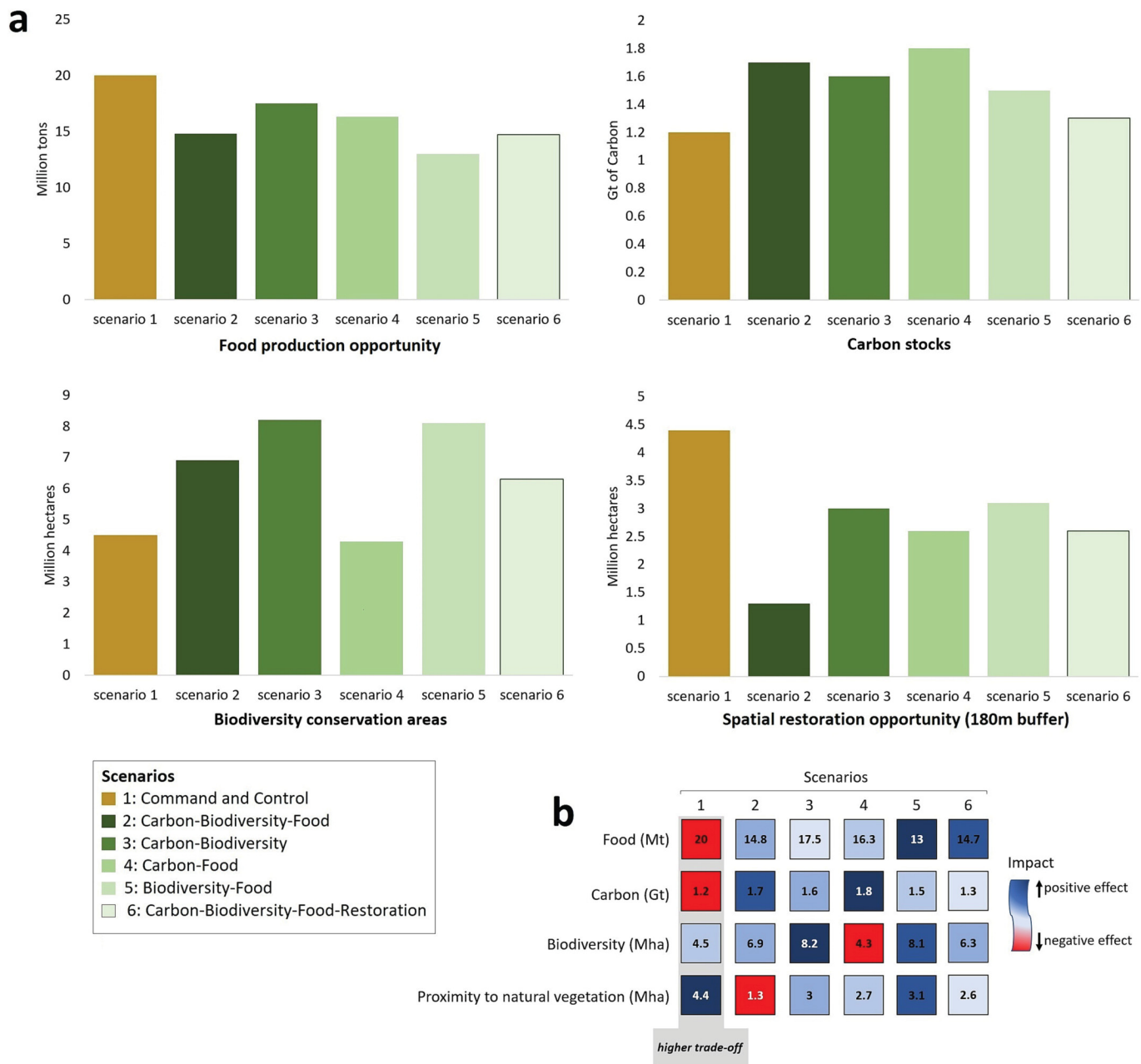


Fig. 4. a) Impacts of multicriteria scenarios to carbon sequestration, biodiversity conservation areas, and food production in the Amazon biome of Mato Grosso state, Brazil. b) Trade-off analysis highlighting the benefits of each scenario.

perspectives from different stakeholders (Dunning, 2022). In this vein, we argue that scenario-based decision approaches – like those we have pursued here – will have the capacity to enlighten and improve the debate regarding environmental policy implementation, by empowering different stakeholders with key information about potential trade-offs related to specific decisions. This is particularly important when considering compliance with the Forest Code on private rural properties in Brazil. Landowners have the right to make profits from their private lands, but compliance with legislation has been failing, with the consequence of rising LR deficits (Azevedo et al., 2017; Silva et al., 2023a). Market mechanisms that compensate landowners willing to restore natural vegetation cover within their properties, whether in the mold of carbon emissions trading or payments for ecosystem services (Bernasconi et al., 2016; Adams et al., 2021), could be a way to reverse this failure, and our results highlight scenarios and locations where this may be best targeted within a key tropical food production region.

Similar to other studies, our scenarios show that solutions achieving more than one goal simultaneously can be identified using analysis frameworks that consider multiple societal needs and aspirations. However, our study goes beyond previous studies (e.g., Moilanen et al., 2011; Lehtomäki et al., 2015; Montemayor et al., 2022; Tamburini et al., 2023) by specifically targeting private rural properties into land allocation solutions while also confronting multicriteria scenarios with a policy baseline, rather than searching potential conservation areas at regional/national scales. Thus, our approach provides more policy-oriented scenarios that are capable of finding better solutions that address multiple purposes rather than those envisioned by command-and-control policies (Fig. 4), which usually consider large and complex ecosystems as simple land units and without considering their inherent variance with regard to natural features and potentials. For example, Scenario 5 (Biodiversity-Food) resulted in 35 % lower impact on food production than the command-and-control Scenario 1

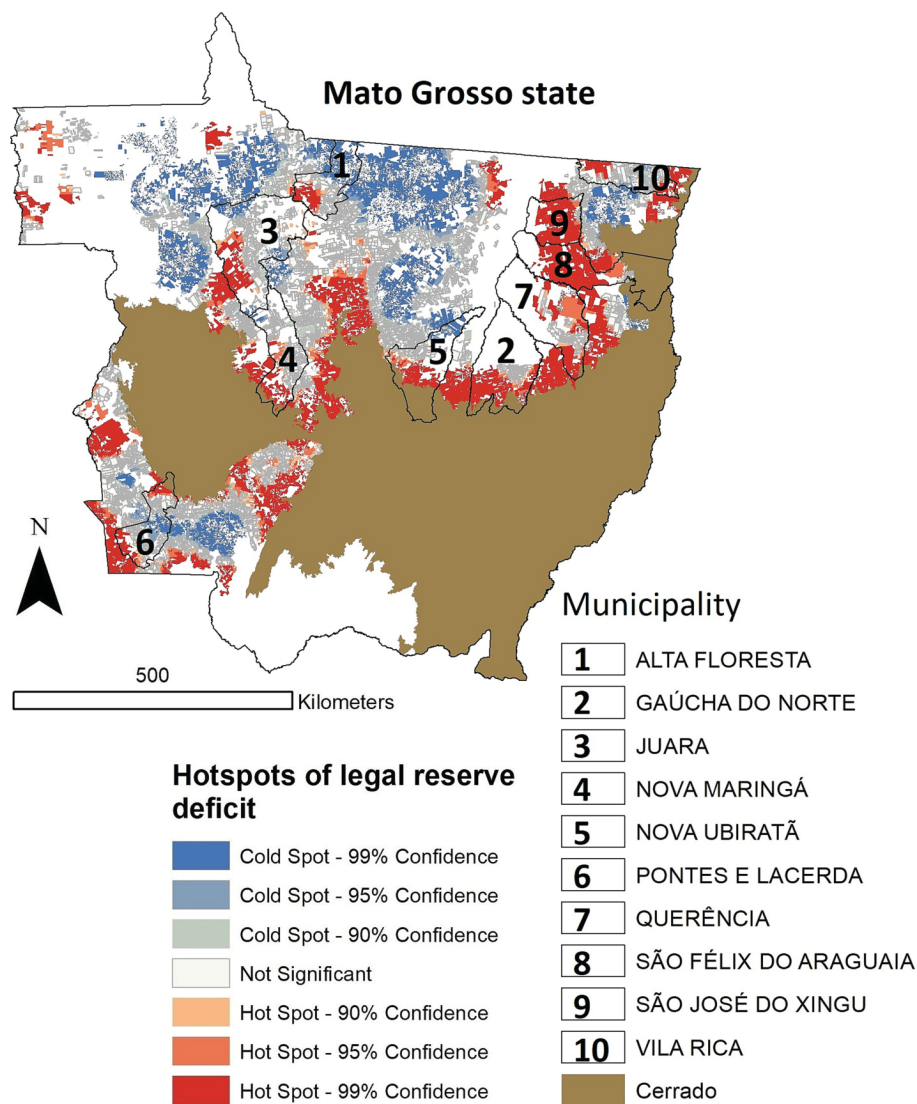


Fig. 5. Spatial distribution of hotspots of private rural properties according to their amount of legal reserve deficit (ha) in the Amazon biome within Mato Grosso State, Brazil. The municipality list indicates the ten municipalities with more areas considered to be priority areas for restoration, according to the Scenario 2—i.e., enough to restore 30 % the state's net LR deficit in the Amazon.

(baseline), which aimed solely to force private properties to restore their individual LR deficits (Fig. 4b). Furthermore, our results show that forcing landowners to restore their own lands individually instead of searching for opportunities to compensate deficits across the broader region would compromise the potential for a “green land market” in the Amazon biome. In this market, private landowners with lower food production (e.g., less connected to markets and infrastructure) would benefit from restoration programs to diversify agri-forestry-livestock activities, instead of taking large economic risks to produce more food (Silva et al., 2020). Although it is not realistic to expect a total elimination of net LR deficits as described in baseline Scenario 1 at some point in the future, our scenarios do prove useful to plan and allocate land for future restoration programs aiming to find solutions with the lowest impacts on food production and providing favorable solutions for lowering restoration costs. In addition, previous studies have indicated that the Forest Code alone will be insufficient to protect biodiversity (Vieira et al., 2018; Silva et al., 2023a), so complementary actions are required; which also aligns with our finding about the benefits of adopting a multi-objective strategy. Hence, we argue that our nexus multicriteria model brings relevant contributions to policy implementation and development in Brazil, as the Forest Code, after 10-years

of its last modification, which created the CAR instrument, still has only 1 % of the CAR registries implemented (with 3.8 % at Mato Grosso State level) and approved by governmental authorities (CAR, 2023). This is a necessary first step to allow compensations (“green land market”) such as landowners searching other private rural properties to restore natural vegetation in the form of LR. In this case, our study reinforces the Forest Code's vision presented in Article 66—that institutes the possibility for landowners to compensate LR deficits in other private lands (as long as they are in the same biome) to avoid replacing consolidated agricultural areas into ecosystem restoration.

By accounting for distance from existing natural vegetation areas in our Scenario 6, we obtained a better outcome for the ‘spatial restoration opportunity’ (proxy for restoration costs) but lowering other benefits (Fig. 4b—comparison between Scenario 2 and 6). However, more positive results for ‘spatial restoration opportunity’ were found in alternative scenarios, such as Scenario 5 (which did not include the ‘distance from natural vegetation’ criterion). This result highlights the importance of trade-off analysis under alternative scenarios that consider multiple influencing factors. Such an analysis reveals the complexity inherent to land-allocation problems and the need for comprehensive methods based on multicriteria approaches. This study also corroborates

previous findings (e.g., [Strassburg et al., 2019](#)) that strategic ecosystems restoration can achieve higher gains in biodiversity and carbon sequestration while providing lower costs for restoration actions and with minimal impacts on food production.

As shown by our spatial hotspot analysis, we found that greater LR deficits were present in regions more likely to be located bordering the Cerrado biome ([Fig. 5](#)). This result reflects the tendency of increasing agricultural production in areas of the Amazon biome in Mato Grosso that are geographically closer to the Cerrado, following a pattern of contagious (path-dependent) agricultural expansion ([Millington et al., 2021; Silva et al., 2021](#)). Additionally, at the municipality level, we found few municipalities (twenty) accounting for half of the net LR deficit, while Scenario 2 reached a land allocation solution where ten out these twenty would be enough to restore 30 % of the deficit, and seventeen to reach 50 %. Here we argue that policy actions could target greater non-compliant municipalities, which would lead to positive outcomes for carbon and biodiversity with low impacts on food production, while managing and monitoring a few set of hotspot-municipalities for restoration.

In 2022, Brazil introduced the Federal law for Payment of Environmental Services (PES, Law n^o 14,119), an innovative governance tool, which could take advantage of the spatial knowledge generated by our approach to define areas for restoration that prioritize biodiversity conservation (essential for *provisioning services* such as freshwater supply and *supporting services* such as habitat for species) and carbon stocks (i.e., regulating services of ecosystems). Channeling PES efforts in the Amazon towards more focused application of funds that at the same time minimizes impacts on food production (and other externalities) might be achieved by stimulating producers in key hotspots for restoration (e.g., municipality list in [Fig. 5](#)) to trade their lands with non-compliant landowners from regions with lower suitability for restoration (such as municipalities with high LR deficits but not included in the list of municipalities in [Fig. 5](#)). This creates more engagement in a “green” market of LR deficit compensations. As an example, if we consider the Juara municipality (northwest Mato Grosso, [Fig. 2f](#)), which appears to be highly impacted by land changes for restoration based on Scenario 2 (398 thousand ha to eliminate net LR deficit—76 million tC), the carbon market could potentially generate around \$1 billion dollars over the next 30 to 40 years [values considering carbon future prices for one ton at \$20 dollars over the next few decades ([Turner et al., 2021](#))]. This value was obtained considering that about four decades are required to reach over two-thirds of the reference carbon values of tropical forests ([Poorter et al., 2016](#)). The use of scientific evidence like this may help strengthening the effectiveness of environmental policies by creating more confidence in policy outcomes among users ([European Commission, 2022](#)). It and may also support policies such as the *Reducing Emissions from Deforestation and Forest Degradation* (REDD+) program and other initiatives (e.g., *Amazon Fund, Green Climate Fund*).

5.1. Caveats and limitations

Further refinements could also improve our multicriteria approach. For example, our study used a broad concept of biodiversity (biological importance), but by adopting functional-groups or species-specific data, crucial results could be produced. Furthermore, here we set the same weights for all criteria, but a weighting process considering empirical, cultural and/or economic reasoning need also to be considered. In addition, for a more concise economic evaluation of restoration costs vs. benefits in agricultural production areas, more complex metrics of agricultural economic value (e.g., basic prices for agricultural outputs, net profit) may be used instead of the food production opportunity used here. Previous literature on ecosystem restoration have mainly focused on the effects of different scenarios addressing (i) restoration costs or (ii) or agricultural revenue, or other social aspects ([Aillery et al., 2001; Carvalho et al., 2011; Robbins and Daniels, 2011; Dorrough et al., 2007; Evans et al., 2015; Brancalion et al., 2016; Strassburg et al., 2020](#)).

However, in this study we focused on the direct impacts on food production if current croplands are converted into restored ecosystems. This constitutes a new approach where restoration scenarios are evaluated under the lens of the land-use food-carbon-biodiversity nexus. Agricultural systems in Mato Grosso are highly associated with diverse amounts of carbon stocks, having systems such as ‘managed pastures’ achieving higher carbon stocks than ‘cropland’ ([Carauta et al., 2021](#)). However, here we do not consider those stocks as the focus is on the replacement of agricultural systems to natural vegetation cover, a necessary action towards eliminating net LR deficit and achieving higher levels of compliance with the Brazilian Forest Code. Finally, in our study we did not consider the Cerrado and Pantanal biomes since the surpluses of LR in these biomes were larger than the deficits (net surplus of LR at the biome level). Hence, landowners with LR deficits in the Cerrado and Pantanal may compensate by negotiating LR “quotas” with landowners with surpluses ([Amaral et al., 2017](#)), which will not impact current food production. Such behavior excludes the need for a multicriteria analysis, since no situations of conflicting land uses emerge. Nevertheless, the Cerrado and Pantanal biomes are hotspots of biodiversity and as such, they need to be protected, especially if stringent Amazon conservation policies restrict land-use within the Amazon, and force rural producers to search opportunities in neighboring biomes, leading to increases in deforestation trends [what has been reported as a negative spillover effect ([Dou et al., 2018](#))]. In this case our results can be alarming as there are considerable amounts of natural vegetation still eligible to be legally deforested according to the Forest Code in the Cerrado and Pantanal biomes. Hence, we advocate for a more restrictive policy and the development of market instruments that avoid further deforestation in the Cerrado and Pantanal biomes.

5.2. Implications for management

If put into practice, the scenarios presented here, namely those favoring a “green-land market”, would demand a change in the way landowners interact and manage LRs, seeing them as assets of the property's economic activities and not only seeing them as fallow land where neither value or product is generated. In addition to the legal instruments mentioned before, namely the Brazilian Forest Code of 2012 and the PES law, which have their own regulations and requirements for managing LRs, the Brazilian Congress is currently analyzing a law to establish a formal national market on carbon credits. Requirements on the land management related to carbon credits originated from LRs and other farming practices should be publicized soon. However, it is reasonable to assume such land management would demand tending these tracts of land by avoiding fires, the leakage of pesticides, and biological invasions [e.g., of wild pigs ([Hegel et al., 2022](#))], among other actions. Getting the right dose of trade-offs between benefits for conservation and requirements on land management is therefore key to engaging landowners and guaranteeing the success of policies on this regard. On a larger scale, the type of scenarios shown here provide a promising opportunity for policy makers to refine, in spatial terms, the so called ecological-economic zoning (ZEE), managing agricultural landscapes in an optimized way—this is of course dependent on a concerted involvement of landowners, which, again, can be promoted with proper benefits/trade-offs.

6. Conclusions

Our findings contribute with useful insights for science and policy in three important ways. First, there is still a large deficit in fulfilling the Forest Code in the Amazon biome, whereas in the Cerrado and Pantanal biomes there are still some surpluses. Hence, despite the progress in controlling deforestation over the last decade, more actions are needed in the Amazon biome. However, the surpluses in the Cerrado and Pantanal biomes also suggest that the current requirement may need to be raised to a higher level to be effective. Second, the spatial allocation of

the areas for restoration of alternative environmental targets can lead to different outcomes (e.g., varying between 20MT to 13MT in food production loss). Thus, multicriteria-based nexus modeling approaches such as the one implemented here, are crucial for finding optimal regions for environmental restoration that simultaneously target multiple sectors (e.g., food production, carbon sequestration, biodiversity conservation). And third, while many studies have developed different approaches for prioritizing different regions for environmental restoration, such approaches have used large geographic areas as units of analysis, which implicitly ignore the spatial variability across such large areas. While aggregated to evaluate biome-level priority areas, our approach is more comprehensive since it used private properties as units of analysis. Such approach allows evaluating not only the effects of deforestation and restoration programs at multiple scales, but also allows for a more holistic analysis of the effectiveness of environmental policies. Since such analysis requires knowledge of the extent and distribution of individual private properties, we, therefore, conclude with a plea for the development of procedures that allow obtaining the necessary data for such property-oriented analyses throughout the world.

CRedit authorship contribution statement

R.F.B.S. led the manuscript conceptualization, methodology, data-gathering, software, investigation, formal analysis, and the writing – original draft, writing – review & editing. E.F.M., J.L., A.V., Y.D., M.B., D. M.L., and J.D.A.M. contributed to the investigation and conceptual framework of analysis, commented on the manuscript, writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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