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Multicriteria optimization to develop cost-effective pes-schemes to restore multiple environmental benefits in the Brazilian Atlantic forest

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ABSTRACT

Understanding the cost-effectiveness of restoration initiatives is critical for their successful implementation. In this context, this study presents a new approach to investigating the cost-effectiveness of different forest landscape restoration strategies for achieving multiple restoration goals. The approach is based on an optimization model that allocates forest restoration to maximize three environmental benefits (biodiversity conservation, carbon stock increase, and soil loss reduction) while minimizing the cost. We explore scenarios based on the Brazilian Forest Code and the National Policy for Payment for Ecosystem Services. Our optimization approach simultaneously achieves high levels of multiple environmental benefits - more than 90% of the maximum possible biodiversity, carbon, and soil in a cost-effective manner for all scenarios. Variation among the scenarios in the absolute performance concerning the three objectives was small (within 2.5%) compared to variation in costs (up to 19.4%). These results reinforce the importance of quantifying trade-offs among objectives to a better understanding of the cost-effectiveness of restoration initiatives before their implementation.

1. Introduction

Forest landscape restoration aims to reconcile the conservation of biodiversity, promotion of ecosystem services, and human well-being with agricultural production in degraded landscapes (Chazdon et al., 2020). It is crucial to reverse the impacts of historical deforestation (IPBES, 2019), while also achieving UN Sustainable Development Goals (SDGs) (UN, 2021) including “Zero Hunger”, “Climate Actions”, and “Life of land”. In brief, forest landscape restoration safeguards biodiversity, provides ecosystem services, and can enhance livelihood for vulnerable local people. Due to all these benefits, restoration initiatives have gained worldwide relevance (Mansourian et al., 2021).

From global to local scales, land use decisions and policy instruments can affect landscapes and livelihoods in heterogeneous ways (Adams et al., 2016). Payments for ecosystem services (PES) are an economic instrument that can promote the conversion of low productivity agricultural lands into forest areas by compensating landholders for leaving forest intact or planting trees (Jack and Jayachandran, 2019). Some PES programs finance restoration actions within private lands, promoting well-balanced regional solutions with environmental and socio-economic benefits (Le et al., 2014; Wunder, 2015).

In Brazil, the Native Vegetation Protection Law, also known as the Brazilian Forest Code, establishes that forest cover deficits in Permanent Preservation Areas (in Portuguese, *Área de Preservação Permanente* - APP) and Legal Reserve (LR) must be restored (Alarcon et al., 2017). Financing restoration through PES programs could be an excellent opportunity for landowners, where finance is usually a barrier to meeting legal requirements. PES programs on municipality and state levels currently pay for different restoration actions over legally required deficit areas. However, at the national level, the National Policy for Payment for Ecosystem Services (in Portuguese, *Política Nacional de Pagamento por Serviços Ambientais* - PNPSA, Law 14.119/2021 (BRASIL, 2021) restricts payments using public resources in some situations, leading to discrepancies among payment mechanisms at the municipality, state, and national levels. It reinforces the need to investigate the impacts of alternative PES mechanisms on the cost-effectiveness of

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multiple environmental benefits and restoration costs (Crouzeilles et al., 2020; Wunder et al., 2020).

The Atlantic Forest domain has experienced high rates of forest loss (Ribeiro et al., 2009). After five centuries of human expansion, current landscapes are mosaics of agricultural and urban land uses with small forest fragments (Joly et al., 2014). In this biome, a leading Brazilian effort, called the Atlantic Forest Restoration Pact, aims to restore 15 Mha of degraded lands by 2050 (Calmon et al., 2011; Mansourian et al., 2021). In parallel, other restoration initiatives are taking place at regional and local scales, including different PES programs within the Paraiba Valley in south-eastern Brazil. This region is crucial for Brazilian economic development and water and biodiversity conservation in the Atlantic Forest (Lemos et al., 2021).

Previous studies for the Paraiba valley investigated the combined objectives of biodiversity conservation, carbon sequestration, and sediment loss (as a proxy for water quality) by exploring the cost-effectiveness of different scenarios to allocate restoration areas (Strassburg et al., 2016; Padovezi et al., 2018; Lemos et al., 2021). At Atlantic Forest and global scales, Strassburg et al. (2018; Strassburg et al., 2020) have employed linear programming to identify the optimal distribution of restoration benefits to biodiversity conservation and carbon sequestration, the two most relevant environmental benefits discussed in different restoration commitments such as the Bonn Challenge (Lewis et al., 2019).

Here, we develop a policy-relevant framework to identify opportunities to simultaneously achieve biodiversity, carbon stock, and soil conservation benefits (Fig. 1). We maximize three environmental benefits: biodiversity conservation, carbon stock increase, and soil loss reduction. We apply this method to *private rural properties (henceforth parcels)* as *planning units,* which is the scale at which land management decisions take place (Adams et al., 2016). We build alternative scenarios to explore the cost-effectiveness of enforcing the Brazilian Forest Code (BFC) and the recent PNPSA for Paraiba Valley. The scenarios aim to answer the following questions: (1) How will restoration of BFC legal deficit areas alter the provision of ecosystem services in the Paraiba Valley, and at what cost? (2) To what extent can PES mechanisms improve the provision of ecosystem services and reduce costs to landholders? To achieve these goals, we explore how the financial costs and environmental gains of restoration scenarios, reflecting different public policies in the Paraiba Valley.

2. Material and methods

2.1. Study area

Paraíba Valley in São Paulo State (in Portuguese, *Vale do Paraíba Paulista* - VPP) encompasses 34 municipalities with heterogeneous socioeconomic characteristics, supporting a population of over 2 million inhabitants (Fig. 2). It is a long-occupied region that has undergone historical agricultural production cycles since the 19th century. The region contains some patches of *Cerrado* that do not belong to the Atlantic Forest domain. Atlantic Forest vegetation classes cover approximately 80 % (12,000 km^2) of VPP. In this study, we focus our analysis solely on the area occupied originally by Atlantic Forest vegetation (Lemos et al., 2021).

Natural forest regeneration occurred over 2,639 km^2 from 1985 to 2015, mainly converted from pasture areas. There remains a large amount of pasture in the region (5,453 km^2) (Lemos et al., 2021) that typically has low productivity (Silva et al., 2016a; Silva et al., 2016b). Milk production activity is responsible for around 73 % of the agriculture revenue (IBGE, 2021a).

Considering that the region has low agricultural productivity and is important for biodiversity conservation (Silva et al., 2016a), VPP has been chosen as the target area for several PES programs for forest landscape restoration. One such program is Protection PSA, a governmental initiative that targets biodiversity conservation, climate change mitigation, and water resources conservation. It allocates financial resources to private rural properties for implementing local restoration actions. Restoration can take place in legal deficit areas as well as outside deficit areas (SÃO PAULO, 2019).

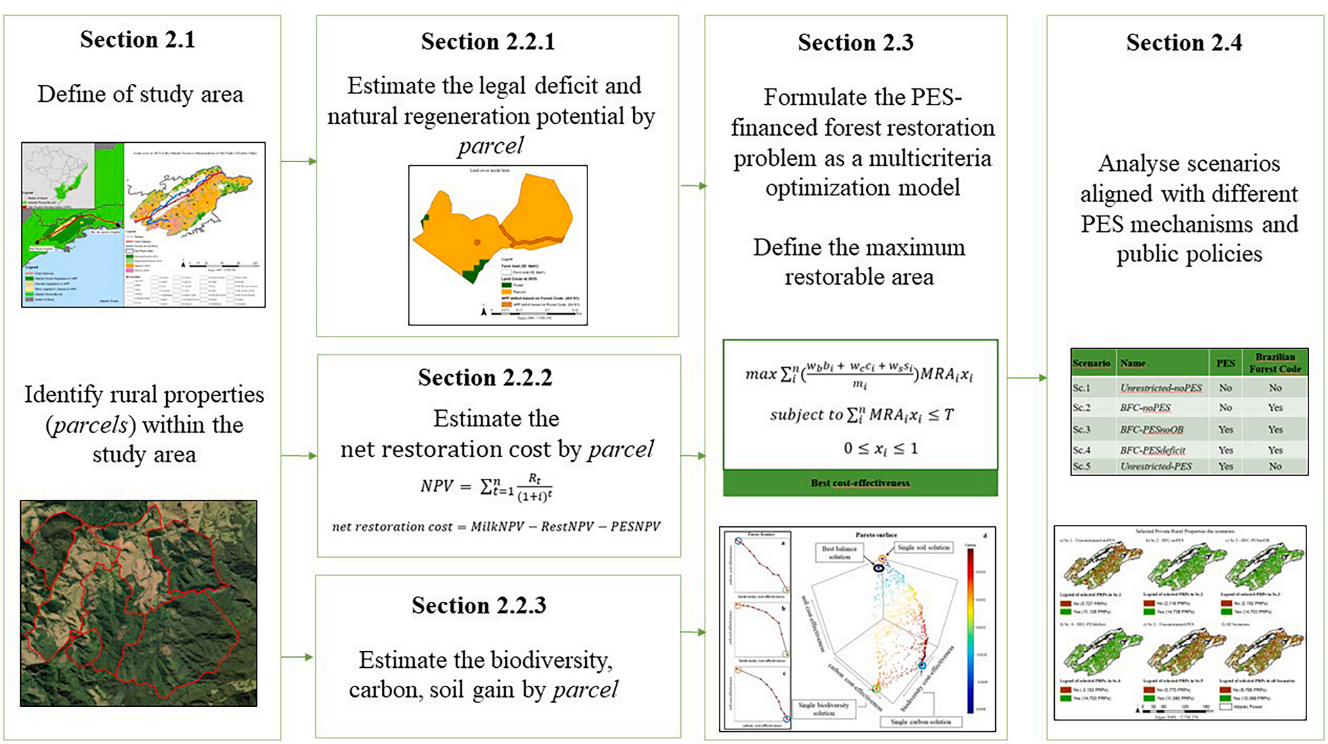

Fig. 1. Flowchart of our methodology.

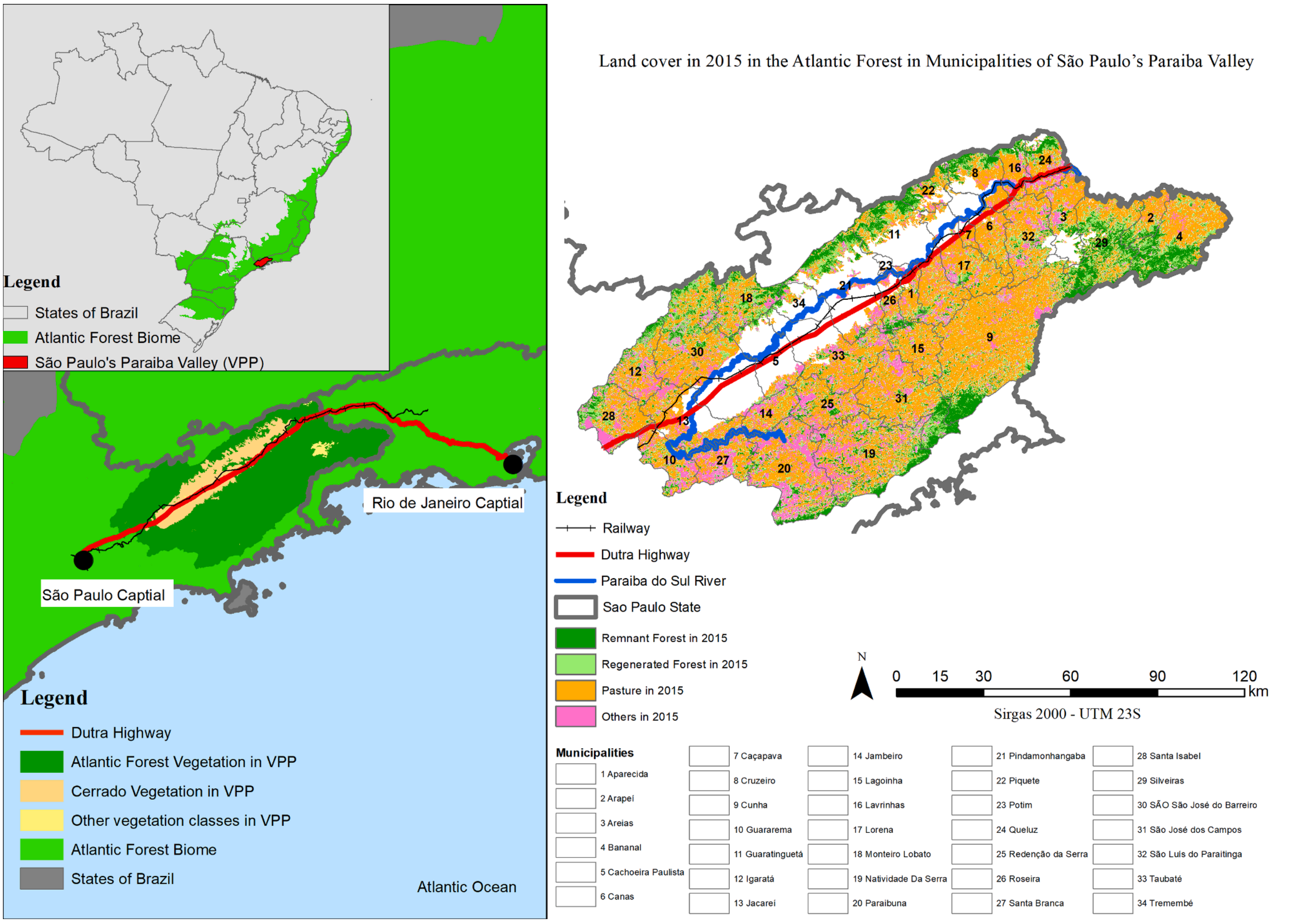

Fig. 2. Location of the study area (Paraiba Valley): Location in Brazil; Location in São Paulo State, and Land cover in 2015 by municipality of São Paulo's Paraiba Valley.

2.2. Database organization

For each private rural property (*parcel*; N = 16,855), we estimate: (1) the legal forest deficit, remaining pasture area, regenerated forest area, and natural regeneration potential in 2015 (Section 2.2.1); (2) economic indicators for each *parcel*, considering different forest restoration actions, agricultural activities and PES (Section 2.2.2); and (3) three environmental indicators for each *parcel* (biodiversity, carbon, and soil benefits) (Section 2.2.3). See Supplementary Materials for details. Table SM.1 presents each *parcel*'s the complete list of attributes, detailed in the following subsections.

2.2.1. Legal deficit and natural regeneration potential

The land tenure in our study area is composed of public, private, and undesignated lands (Freitas et al., 2017; Hissa et al., 2019). Concerning private lands, there are two public sources of information: SIGEF (INCRA, 2021) and SICAR (SICAR, 2020). Although both provide private property boundaries, only SICAR has information about springs, watercourses, and the location of APP within *parcels*. For this reason, here we use the rural cadastral information (in Portuguese, *Cadastro Ambiental Rural* - CAR) data, available within SICAR. We select only *parcels* entirely within the Atlantic Forest in the Paraiba Valley. They occupy 6,461 km^2, around 58 % of our study area.

Parcels were classified as *small*, *medium*, and *large*, following the farm-size categorization based on the official fiscal module unit that ranges from 5 to 110 ha. It is calculated based on the economic returns from the predominant agricultural activities in each municipality, being used by the Brazilian Government for taxation and land governance purposes (Freitas et al., 2017; INCRA, 2020). This classification is necessary to estimate *legal deficits* according to the BFC, whose articles 12, 15, 61-A, and 67 establish the rules to restore APP and LR within *parcels*. APPs include areas that protect riverside forest buffers, hilltops, high elevations, and steep slopes, being explicitly defined and fixed, while LRs can be defined by the landowner (Soares-Filho et al., 2014). Although the latest revisions to the BFC granted amnesty to some areas that were illegally deforested prior to 2008 (Soares-Filho et al., 2014), here we consider those areas are available for restoration.

To quantify the total pasture area within *parcels*, we intersect the *parcels* described above with the land cover map generated by Ronquim et al. (2016). We separate the pasture of each *parcel* into two classes: *pasture areas considered legal deficit* (both APP and LR) and *pasture areas in Private no Obligations* (*noOB*) lands. This distinction is necessary to explore BFC scenarios.

To estimate the *natural regeneration potential* in each *parcel*, we use the *maximum biophysical capacity* (MBC) proposed by Lemos et al. (2021). The authors estimated the MBC through a linear regression model that *indicates the amount of natural restoration that can be expected in each local area*. The difference between regenerated forest cover and MBC allows us to identify the actual *natural regeneration potential* (*NRP*) for the remaining pasture areas. When the NRP is equal to or less than zero for a given *parcel*, we consider that it does not have natural regeneration potential. In this case, the remaining *pasture areas* in the *parcel* must be restored using an active restoration method. When the NRP exceeds the remaining pasture area, natural regeneration (passive method) is enough to restore the whole pasture area. On the other hand, if the NRP is greater than zero but smaller than the remaining pasture area, only *a fraction of the pasture area* could be restored using natural regeneration, calling for a combination of passive and active restoration methods.

2.2.2. Economic indicator

We explore three activities: restoration actions, milk production, and PES. To estimate the financial viability of different activities, we standardize their economic costs using Net Present Value (NPV), a method that allows us to compare the financial viability of different projects (Runting et al., 2019; López-Cubillos et al., 2022). We make three assumptions to estimate the NPV of economic activities. First, forest restoration is possible in every *parcel*. Second, all values are expressed in 2015 price level as this was the year of the land cover data. Third, because of the predominance of milk production compared to other agricultural activities (IBGE, 2021a; IBGE, 2021b), we assume that milk production is a suitable measure of opportunity costs.

The NPV for a given *parcel* is described as follows:

$$NPV = \sum\nolimits_{t=1}^{n} \frac{R_t}{(1+i)^t} \tag{1}$$

where: NPV is the Net Present Value; R_t is the net cash inflow-outflow during a period *t*; *i* is the discount rate or return that could be earned in alternative investments; *n* is the number of time periods considered.

For all calculations, we apply a discount rate of 10 % per year based on Prata and Rodriguez (2014). Using this equation, we estimate the NPV for each economic activity (US$/ha). We convert all values from BRL to USD, applying the conversion rate of US$ 1 equals R$ 3.95, as proposed by Strassburg et al. (2016). They are:

- **NPV of restoration actions (RestNPV)**: Required restoration actions are determined by the natural regeneration potential of the remaining pasture areas. Considering this potential, we combine active and passive restoration methods and their costs. We estimate the restoration cost using US$ 2,102.83/ha for active restoration (seedling planting) and US$ 50.03/ha for passive restoration (natural regeneration without fences), as proposed by Brancalion et al. (2019). This cost is split into implementation costs (at the beginning of the project) and maintenance costs during the project, to better estimate the net cash inflow-outflow during the restoration project. We assume a project duration of three years with seven maintenance activities (two in the first year, **three** in the second year, and two in the third year), based on Collard and Bastos (2019). The revenue associated with restoration is assumed to be zero (Padovezi et al., 2018).
- **NPV of milk production activity (MilkNPV)**: We estimate the mean revenue of milk production in each municipality by dividing the total revenue of milk production (IBGE, 2021a) by the total pasture area (Ronquim et al., 2016). Each *parcel* uses the mean revenue of the municipality it belongs. We estimate the mean milk production cost using the average Revenue/Cost indicator for milk for 2014, 2016 and 2017 for *Guaratinguetá*, which is equal to R$0.98/ha (CONAB, 2010), a representative municipality in our study area. Using the mean revenue [US$/ha] and mean cost [US$/ha], we estimate the net cash inflow-outflow of milk activity over 27-years.
- **NPV of PES (PESNPV)**: We consider that private landholders receive R$432.98/ha/year (US$109.62/ha/year) related to the Protection PSA program, from 2017 to 2021. We assume that there is no cost to participate in the program. Only payments are used to compose the net cash inflow-outflow during the Protection PSA program.

We then combine these three NPVs to estimate the *net restoration cost* of each *parcel* as follows:

$$netrestorationcost = MilkNPV - RestNPV - PESNPV \tag{2}$$

In this equation, the signs are selected to produce the net restoration cost from the landowner's perspective. Therefore, MilkNPV has a positive sign because the landowner lost the milk activity remuneration due to the conversion from pasture to forest (opportunity cost). The RestNPV has a negative sign because the values provided for RestNPV are always negative, ultimately giving a positive value. PESNPV has a negative sign because the landowner receives PES as remuneration in the presence of a PES program that helps to reduce resources expense with restoration actions. The mean restoration cost [US$/ha] is our economic indicator.

2.2.3. Environmental indicators

We use three indicators to represent the environmental contribution of restoration:

- **Biodiversity (Number of benefited taxonomic groups or species):** Forest restoration provides habitat benefits to many species (Crouzeilles et al., 2020). Here, this is quantified based on Joly et al. (2010) who scored priority areas for restoration actions according **to** their benefit to seven taxonomic groups (such as mammals and birds) and landscape parameters (such as larger fragments and higher connectivity). This score ranges from zero (no priority) to eight (high priority). Although Biodiversity Conservation is not a specific ecosystem service, it is a relevant key role at all levels of ecosystem services (Mace et al., 2012).
- **Carbon (Carbon stock increase**): We estimate the carbon stock increase based on the Third Brazilian **Inventory** of greenhouse gas emissions recommendations to the United Nations Framework Convention on Climate Change - UNFCCC (MCTI, 2015; Lemos et al., 2021). We estimate the difference between the mean carbon stock in a regenerated forest for each vegetation type (44 % of the carbon stock of pristine forests) and the mean carbon stock of pasture cover. Using an area-weighted average of this difference for each *parcel*, we estimate our carbon indicator [tonne/ha] for converting from pasture to forest in the respective *parcel*.
- **Soil (Soil loss reduction**): We estimate the reduction of soil loss following the restoration of pasture lands (Tonne/ha/year) **based** on simulations using the Universal Soil Loss Equation (Padovezi et al., 2018).

2.3. Modelling approach

We formulate the PES-financed forest restoration problem as a multicriteria optimization model that is solved using linear programming to identify exact, optimal solutions for each alternative restoration scenario. The objective function is:

$$max\sum\nolimits_{i}^{n} \left(\frac{w_b b_i + w_c c_i + w_s s_i}{m_i}\right) MRA_i x_i \tag{3}$$

$$subjectto \sum\nolimits_{i}^{n} MRA_i x_i \leq T \tag{4}$$

$$0 \leq x_i \leq 1 \tag{5}$$

where: N is the number of *parcels*; MRA_i is the maximum restorable area of the i^{th} *parcel*, measured in hectares (ha) and MRA_i has 50 % of the pasture area of the i^{th} *parcel* to facilitate continued milk production; x_i is the decision variable, ranging from zero to one, that represents the proportion of the MRA in the i^{th} *parcel*; b_i, c_i, and s_i are the biodiversity, carbon, and soil gains for the i^{th} *parcel*, measured as the number of benefited groups or species, Tonne/ha, and Tonne/ha/year, respectively; w_b, w_c, and w_s are weights, ranging from zero to one, that determines the relative contribution of the biodiversity, carbon, and soil benefits to the objective function, respectively, whereby $w_b + w_c + w_s = 1$; m_i is the *net restoration cost* of i^{th} *parcel* measured as US$/ha; *T* is the total area to be restored, implemented as a constraint, measured as ha. We describe trade-offs among the three benefits by varying the weights to describe the Pareto surface (Beyer et al, 2016; Liang and Mahadeven,

2017) (see Supplementary Materials for a detailed description).

2.4. Scenarios

Using the restoration area of 600 km^2 proposed by Lemos et al. (2021), we evaluate five restoration scenarios that combine different strategies related to the law enforcement commitment and payment rules for PES programs. In these scenarios, we explore the cost-effectiveness of two public policies: BFC and PNPSA. Table 1 summarizes the five scenarios.

Scenario ***Sc.1*** **(*Unrestricted-noPES*)** optimizes the conversion of 600 km^2 of pasture to forest in any location within *parcels*. Scenario ***Sc.2*** **(*BFC-noPES*)** optimizes the conversion from pasture to forest only in areas without legal deficit (noOB) after restoring all legal deficit areas. In other words, ***Sc.1*** is not committed to BFC, while ***Sc.2*** is, but both do not consider PES. The difference between both scenarios answers the following question: (1) How will restoration of BFC legal deficit areas alter the provision of ecosystem services in the Paraiba Valley, and at what cost?

Contrary to ***Sc.1*** and ***Sc.2***, ***Sc.3*** (***BFC-PESnoOB***) and ***Sc.4*** (***BFC-PESdeficit***) consider PES. They restore legal deficits and optimize the conversion from pasture to forest only in noOB areas. In ***Sc.3***, Landholders receive PES only when restoring noOB areas, while in ***Sc.4*** they receive PES for restoring any area. Differently from ***Sc.3*** and ***Sc.4***, ***Sc.5*** (***Unrestricted-PES***) optimizes the conversion of 600 km^2 of pasture to forest without considering if the pasture area is within APP or RL areas. In this case, landholders receive PES for any restored area. In other words, ***Sc.5*** is not - committed to BFC, but it presents a mechanism widely adopted by PES programs on municipality and state levels. The differences among ***Sc.2***, ***Sc.3***, ***Sc.4***, and ***Sc.5*** answer question (2) To what extent can PES mechanisms improve the provision of ecosystem services and reduce costs to landholders?

3. Results

3.1. Characterization of parcels

Small *parcels* represent 91 % of all *parcels* in the Paraiba Valley, being homogeneously distributed across the study area. Medium and large *parcels* are mostly closer to the major highway (Dutra Highway) (Fig. 3). There are 306 km^2 of legal deficit areas in the Paraiba Valley with a total pasture area of 3,543 km^2. There are 766 *parcels* without any pasture area. The Supplementary Material details the characteristics of the *parcels* according to size and legal deficit parameters in our study area.

Table 1
Summary of the explored scenarios.

Scenario	*Brazilian Forest Code application*	PES mechanisms
Sc.1-Unrestricted-noPES	Optimize 600 km^2 of pasture areas within *parcels*	No PES to restore pasture areas within *parcels*
Sc.2 - BFC-noPES	Restore 100 % of the legal deficits then optimize restoration in noOB pasture areas up to a total of 600 km^2	No PES to restore noOB pasture areas and deficit areas
Sc.3 - BFC-PESnoOB	Restore 100 % of the legal deficits then optimize restoration in noOB pasture areas up to a total of 600 km^2	PES to restore noOB pasture areas
Sc.4 - BFC-PESdeficit	Restore 100 % of the legal deficits then optimize restoration in noOB pasture areas up to a total of 600 km^2	PES to restore noOB pasture areas and deficit areas
Sc.5 -Unrestricted-PES	Optimize 600 km^2 of pasture areas within *parcels*	PES to restore pasture areas within *parcels*

Unrestricted in the scenario's name means that the scenario does not prescribe areas to be restored. BFC in the scenario's name means that the scenario restores 100% of pasture *areas considered legal deficit* based on the Brazilian Forest Code. PES in the scenario's name indicates that the PES mechanism is applied. *Parcels* are the private rural properties boundaries that are the irregular planning units of our study. noOB pasture refers *pasture areas in Private no Obligations* (*noOB*) lands.

Restoration actions (RestNPV) are always negative as they represent a cost to landholders. RestNPV ranges from US$ −2,017/ha (54 % of *parcels*), corresponding to areas that require complete active restoration, to US$ −48/ha (less than1% of *parcels*), representing areas where restoration can occur through natural regeneration. The remaining 7,723 *parcels* (45 %) require a combination of active and passive methods. MilkNPV is generally low (from US$ 2.37/ha to US$ 63.32/ha), indicating a small profit. The Ecosystem Services Payments (PESNPV) is always equal to US$377/ha, as landholders receive fixed payments. Considering that the net restoration cost for a given *parcel* is the sum of up to these three NPV indicators (Equation (2)), the net restoration cost ranges from US$ 50/ha to US$ 2,080/ha in the absence of PES, while ranging from US$ − 325/ha to US$ 1,702/ha in the presence of PES (Fig. 4a, b).

Concerning the biodiversity indicator, the median score of 3 occurs in 6,385 *parcels* (39 % of our *parcels*; Fig. 4c). The restoration action can benefit three taxonomic groups (mammals, birds, and others) or two taxonomic groups and a landscape structure (such as large fragments and high connectivity). The maximum estimated carbon stock increase (70.6 Tonne/ha) is widespread in 91 % of our *parcels* (Fig. 4d). For the soil benefit, almost all *parcels* (greater than99 %) present less than 1 Tonne/ha/year as mean reduction of soil loss with the conversion from pasture to forest (Fig. 4e).

3.2. Cost-effectiveness analysis

Although each objective has different units, they can be combined in a single objective function, using additional parameters to control the relative weighting among the objectives. The set of every best compromise solution in the sense that every point of this set is optimal according to a specified set of preferences (relative weights) among the objectives, and it plots the trade-off result. The trade-offs among objectives are analyzed based on the line curvature that links them, where straight indicates that objectives present a strong relation, and exponential curvature indicates a weak one. Non-defined curvature indicates modest relation.

In our study, these weighted parameters are the relative contribution of the biodiversity (w_b), carbon (w_c) and soil (w_s) benefits. The trade-offs among pairs of benefits are analyzed by varying weights describe their Pareto Frontiers (2D) (Fig. 5a-c). Trade-offs between the three benefits describe the Pareto Surface (3D) (Fig. 5d). There is a substantial trade-off between carbon and biodiversity benefits (Fig. 5a), a less severe trade-off between biodiversity and soil objectives (Fig. 5b), and a modest trade-off between carbon and soil objectives (Fig. 5c). The "best" compromise solution (Fig. 5d) was defined as the solution that minimizes the least squared difference between each objective and the maximum attainable value for that objective (standardized by expressing the difference as a proportion).

Further, we combine more than one public policy into a unique modelling approach that allows exploring environmental gains and economic costs before implementation. Our study converts public policy rules into equations and constraints to incorporate two important Brazilian public policies, the Brazilian Forest Code (BFC) and the National Policy for Payment for Ecosystem Services (in Portuguese, *Política Nacional de Pagamento por Serviços Ambientais* - PNPSA).

Fig. 5 depicts the solutions associated with the ***Sc.1*** (***Unrestricted-noPES***) scenario, though it representative of the other scenarios (see Supplementary Materials). The best-balanced solution achieves 90 % of the maximum potential biodiversity benefit, 99 % of the carbon benefit and 98 % of the soil benefit (Table 2).

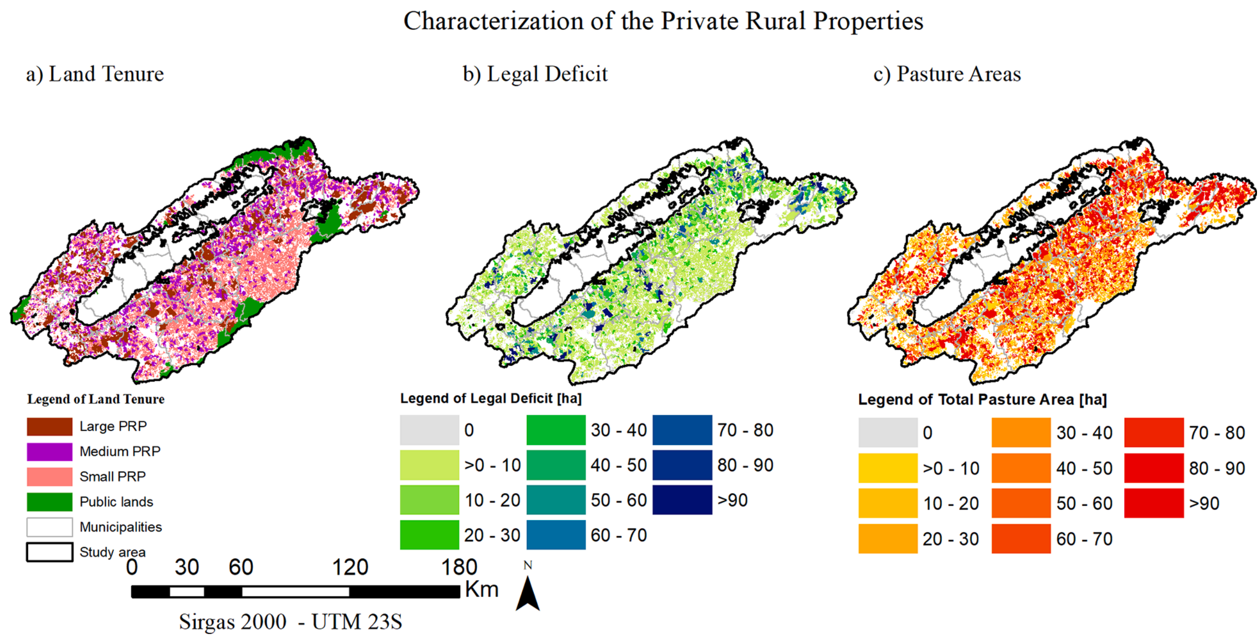

Fig. 3. Spatial distribution of Private Rural Properties (*parcels*): a) Land tenure based on the farm-size categorization using the official fiscal module unit that ranges from 5 to 110 ha (INCRA, 2020), b) Legal deficit refers to the pasture area that must be restored under the Brazilian Forest Code (Freitas et al., 2017), and c) Pasture areas in 2015 based on Ronquim et al. (2016).

3.3. Comparison of the cost-effectiveness scenarios

Our optimization approach simultaneously achieves high levels of multiple environmental benefits - more than 90 % of the maximum possible biodiversity, carbon, and soil in a cost-effective manner for all scenarios. Variation among the scenarios in the absolute performance concerning the three objectives was small (within 2.5 %; Table 3) compared to variation in costs (up to 19.4 %). All scenarios restore 600 km^2 of pasture area under different assumptions relate to the legal deficits and payment for ecosystem services (Table 1). Table 3 summarizes the total values of the economic and environmental indicators for the best solution for the five scenarios. Fig. 6 illustrates the *parcel* distribution with restoration in each scenario.

Comparing first the two scenarios without PES, ***Sc.1*** (***Unrestricted-noPES***) and ***Sc.2*** (***BFC-noPES***), the results indicate that ***Unrestricted-noPES*** benefits a more significant number of taxonomic groups and landscape structural parameters than ***BFC-noPES***. Similar to biodiversity, the carbon benefit of ***Unrestricted-noPES*** is higher than ***BFC-noPES***. On the other hand, the soil benefit and the cost of ***Unrestricted-noPES*** are smaller than ***BFC-noPES***. These environmental and economic differences reflect that different *parcels* are restored in different scenarios to maximize the multiple indicators due to the obligation to restore the deficit areas. While 11,128 *parcels* (66 % of our *parcels*) are restored in ***Unrestricted-noPES***, 14,736 *parcels* (87 % of our *parcels*) are restored in ***BFC-noPES***. As expected, more *parcels* are selected for restoration in the BFC scenario once restoring their legal deficits is mandatory (Fig. 6).

Comparing the scenarios with PES, ***Sc.3*** (***BFC-PESnoOB***) and ***Sc.4*** (***BFC-PESdeficit***) have two different assumptions. Although the deficit areas must be restored in both scenarios, landowners only receive PES for restoring noOB pasture areas in ***BFC-PESnoOB***, while they receive PES for restoring both noOB and deficit areas in ***BFC-PESdeficit***. Despite these differences, the environmental benefits, cost, and the selected *parcels* for being restored are the same in both scenarios (Table 3). The same 14,703 *parcels* (87 % of our *parcels*) are restored in ***BFC-PESnoOB*** and ***BFC-PESdeficit***. Presumably, the payment did not affect selected areas in the study area. Finally, ***Sc.5*** (***Unrestricted-PES***) results in 11,080 *parcels* (65 % of our *parcels*) being restored. It explores the third PES mechanism where landowners receive PES for restoring the pasture areas inside *parcels*, regardless of the forest code enforcement. The biodiversity and carbon benefits of ***Unrestricted-PES*** are higher than BFC-PESnoOB and ***BFC-PESdeficit***. In contrast, while the soil benefit and the cost of ***Unrestricted-PES*** are smaller than ***BFC-PESnoOB*** and ***BFC-PESdeficit***. ***Unrestricted-PES*** is the scenario that presents the smallest cost among all the scenarios, as it is the only scenario with PES that optimizes 600 km^2.

4. Discussion

4.1. Policy-relevant scenarios

A key finding of this study is that the PES program can make forest restoration more profitable than the continued use of land for marginal agricultural production. The BFC alone is explored by different studies (Freitas et al., 2017; Sparovek et al., 2019), but PNPSA was enacted at the beginning of 2021, with no modelling studies so far. Our approach revealed PES's role in reducing landholders' costs while still supplying the same level of environmental benefits. Among the 42 *parcels* that have a negative cost in the presence of PES, and so the landowners could have a profit with the PES, only eight *parcels* were selected in ***Sc.3 (BFC-PESnoOB)***, ***Sc.4 (BFC-PESdeficit)***, while no one is selected in the scenario ***Sc.5 (Unrestricted-PES)***. These eight *parcels* are selected because they present a legal deficit, and not because they contribute with a significant increase in the environmental benefits. The similar environmental benefits found across scenarios are likely related to the spatial scale of the environmental indicators. For example, to estimate carbon gain, we use a vegetation-type map with a scale of 1:5,000,000 (MCTI, 2015). Higher resolution spatial data on the distribution of biodiversity, carbon, and soil loss may alter the optimal spatial arrangement restoration actions and ultimately the environmental benefits delivered. Other limitations are that we assume the restoration time and environmental gains are the same for pasture areas with different degradation levels due to the need for fine-scale data on land degradation. Other studies use a similar approach (e.g., Strassburg et al., 2016), and accounting for varying times to achieve restoration remains an important area for future research.

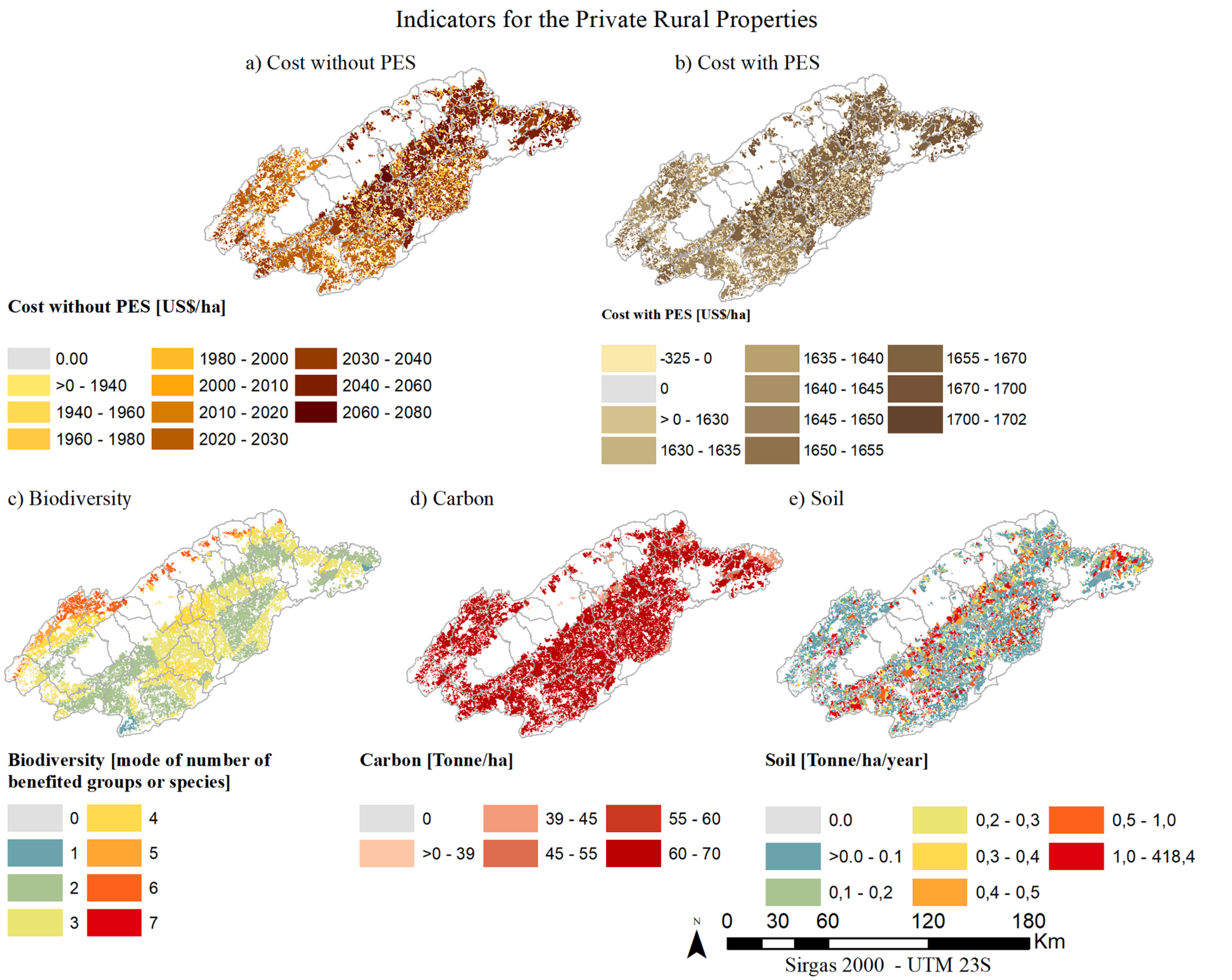

Fig. 4. Spatial distribution of economic indicators and environmental indicators within Private Rural Properties (*parcels*): a) Cost without PES is the net restoration cost estimates based on the consideration that the landowner does not receive PES as remuneration, b) Cost with PES is the net restoration cost estimates based on the consideration that the landowner receives PES as remuneration, c) Mode of number of benefited groups or species indicates the number of groups or species that are benefited with the restoration action based on Joly et al. (2010), d) Mean carbon stock increase following conversion from pasture to forest in each planning unit, e) The soil loss reduction following conversion from pasture to forest in each planning unit.

The comparison of ***Sc.1*** (***Unrestricted-noPES***) and ***Sc.2*** (***BFC-noPES***) reveals how the restoration of Brazilian Forest Code legal deficit areas alters the provision of ecosystem services, cost, and spatial patterns of restoration in the Paraiba Valley. Based on our analysis, BFC compliance increases less than 1 % of the cost and soil benefit and reduce less than 1 % of the biodiversity and carbon benefits. Given the minor differences, our results reinforce the importance of aligning restoration initiatives to BFC (Crouzeilles et al., 2019), as this provides a more equitable distribution of the restored area over the landscape. Ignoring the BFC focuses restoration on specific locations of higher potential, which may place an unfair burden on some landholders.

We also compare scenarios ***Sc.2 (BFC-noPES)***, ***Sc.3 (BFC-PES-noOB)***, ***Sc.4 (BFC-PESdeficit)***, and ***Sc.5 (Unrestricted-PES)***, which are scenarios with and without PES. This comparison reveals the potential of alternative PES mechanisms to improve the provision of ecosystem services cost-effectively. Here, PES reduced the cost to the landowners by 19 % while maintaining the level of environmental benefits. We use the average annual profit in our NPV equation for milk production to calculate the economic costs. Alternatively, suppose grazing pressure and pasture growth are simulated over time. In the case, we can include inter-annual variability in the profit from milk production (Crouzeilles et al., 2020), and it could improve the services cost-effective of our scenarios.

4.2. *Restoration costs*

Active restoration is a significant component of high costs across all scenarios (Brancalion et al., 2016, 2019). Our approach to combining active and passive restoration methods within each parcel is crucial for improving cost-effectiveness. For example, the restoration cost is around US$ 2,103 per hectare in the Brazilian Atlantic Forest when only active restoration is adopted (Brancalion et al., 2019), while our approach reduces the cost to US$ 1,996 (average of ***Sc.1*** and ***Sc.2***) per hectare when active and passive restoration is combined. Considering that Atlantic Forest Restoration Pact aims to restore 15 Mha of degraded lands in the Brazilian Atlantic Forest by 2050 (Calmon et al., 2011), this reduction (US$ 107 per hectare) could contribute to saving around US$ 1,605 million to achieving this restoration commitment.

These mixed restoration methods are relevant to 7,753 parcels (46 % of all parcels). With adequate planning and implementation support, landowners could adopt natural regeneration in part of their restoration projects to reduce costs while still delivering key environmental benefits

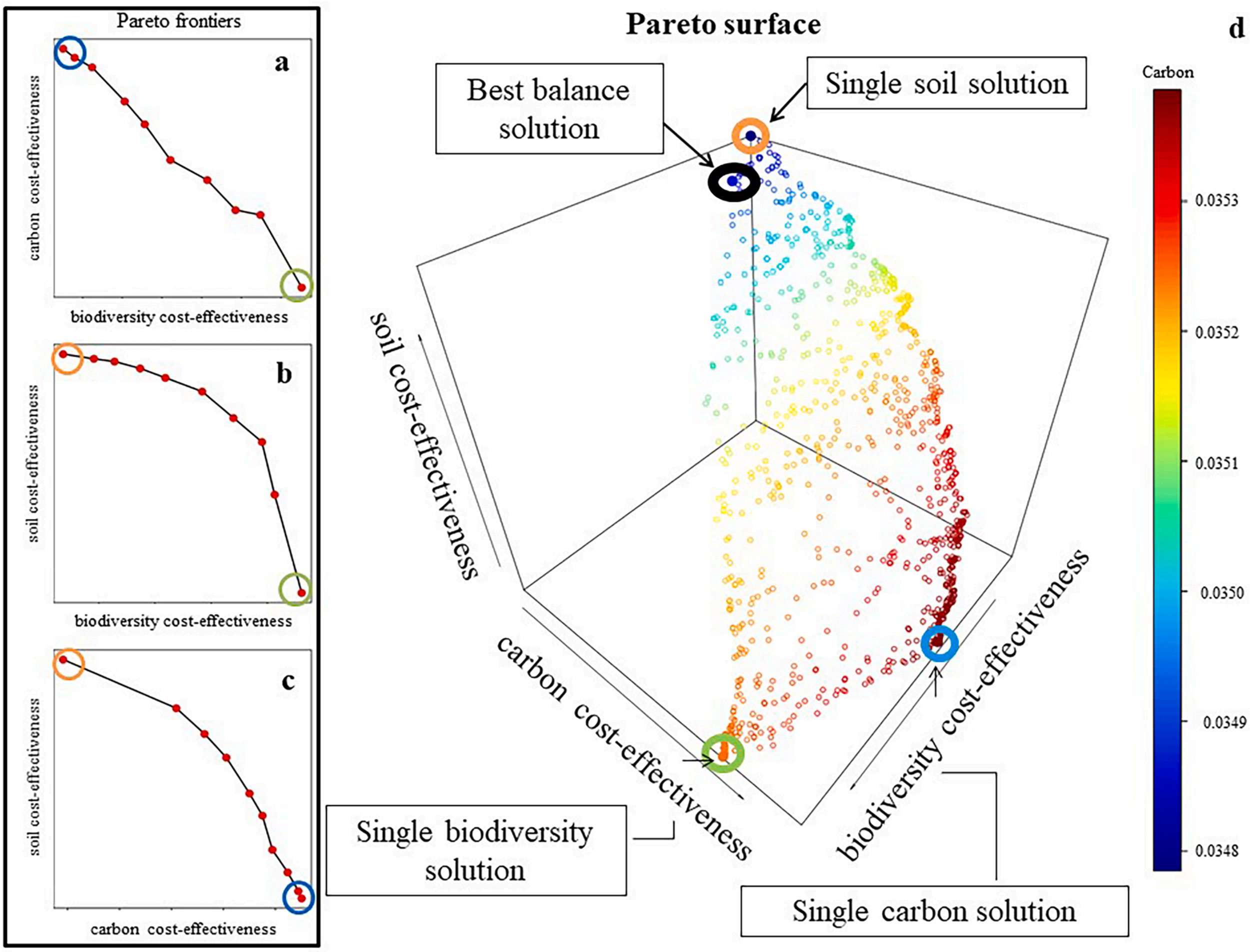

Fig. 5. A) pareto frontier for carbon sequestration and biodiversity conservation benefit, b) pareto frontier for soil erosion reduction and biodiversity conservation benefit, c) pareto frontier for soil erosion reduction and carbon sequestration, d) pareto surface for all three ecosystem service benefits in scenario ***Sc.1***. The maximum carbon sequestration benefit is highlighted by a blue circle, the maximum biodiversity conservation benefit by a green circle, and maximum soil erosion reduction by an orange circle. The three Pareto frontiers that connect each pair of these extremes are trade-offs between the respective objectives, composing the borders of our Pareto surface. The best balance compromise is highlighted by a black circle. The axis scales for a-c can be found in the supplementary materials (Fig. SM.5). Carbon gain means the total carbon stock increase from pasture to forest in the respective scenario. Biodiversity gain means the sum of mode of number of benefited groups or species with the restoration action based on Joly et al. (2010). Soil gain means the total soil loss reduction from pasture to forest in the respective scenario. Cost means the total cost of the respective scenario.

Table 2
Benefit gain and cost for the best balance solution and the three single-objective solutions.

Sc. 1 Solution	**Absolute benefit gain Biodiversity [sum of mode number of benefited groups or species]**	**Carbon [M Tonne]**	**Soil [M Tonne]**	**Mean of the sum of the three proportions of the three benefits**	**Cost [Million US $]**
Biodiversity single-objective (step 1)	193,636 (100 %)	4.19 (99.7 %)	0.041 (38.7 %)	79.47 %	118.77
Carbon single-objective (step 1)	179,375 (92.6 %)	4.20 (100 %)	0.044 (41.5 %)	78.03 %	118.78
Soil single-objective (step 1)	169,677 (87.6 %)	4.16 (99.2 %)	0.106 (100 %)	95.60 %	119.64
Best balance (step 3)	*174,886 (90.3 %)*	*4.16 (99.2 %)*	*0.104 (98.1 %)*	*95.87 %*	*119.46*

Biodiversity single-objective is the solution that maximum biodiversity gain. Carbon single-objective is the solution that maximum carbon gain. Soil single-objective is the solution that maximum soil gain. *Best balance* is the solution that maximum, simultaneously, biodiversity, carbon, and soil gains. Sum of mode of number of benefited groups or species indicates the sum of number of groups or species that are benefited with the restoration action based on Joly et al. (2010). Carbon means the total carbon stock increase from pasture to forest in the respective solution. Soil means the total soil loss reduction from pasture to forest in the respective solution. Cost means the total cost of the respective solution.

(Díaz-García et al., 2020). Our approach allowed allocating both active and passive restoration within individual *parcels*, which adds considerable complexity compared to prior studies, such as Padovezi et al. (2016), Molin et al. (2018), and Crouzeilles et al. (2020), which consider only natural regeneration potential (NRP). These previous studies used statistical analysis to identify the chance of having NRP in a planning

Table 3
Results of each scenario.

Scenario	Environmental benefit Biodiversity [sum of mode number of benefited groups or species]	Carbon [M Tonne]	Soil [M Tonne]	Cost [Million US$]
Sc.1 -Unrestricted-noPES	174,886	4.1645	0.10366	119.46
Sc.2- BFC-noPES	173,559	4.1427	0.10621	120.06
Sc.3- BFC-PESnoOB	173,623	4.143	0.10616	97.41
Sc.4- BFC-PESdeficit	173,623	4.143	0.10616	97.41
Sc.5 -Unrestricted-PES	174,893	4.1646	0.10367	96.80

Unrestricted in the scenario's name means that the scenario does not use rules to allocate areas to be restored. BFC in the scenario's name means that the scenario restores 100% of pasture *areas considered legal deficit* based on the Brazilian Forest Code. PES in the scenario's name indicates the PES mechanism was applied. noOB pasture means *pasture areas in Private no Obligations* (*noOB*) lands. Sum of mode of number of benefited groups or species indicates the sum of number of groups or species that are benefited with the restoration action based on Joly et al. (2010). Carbon means the total carbon stock increase from pasture to forest in the respective scenario. Soil means the total soil loss reduction from pasture to forest in the respective scenario. Cost means the total cost of the respective scenario.

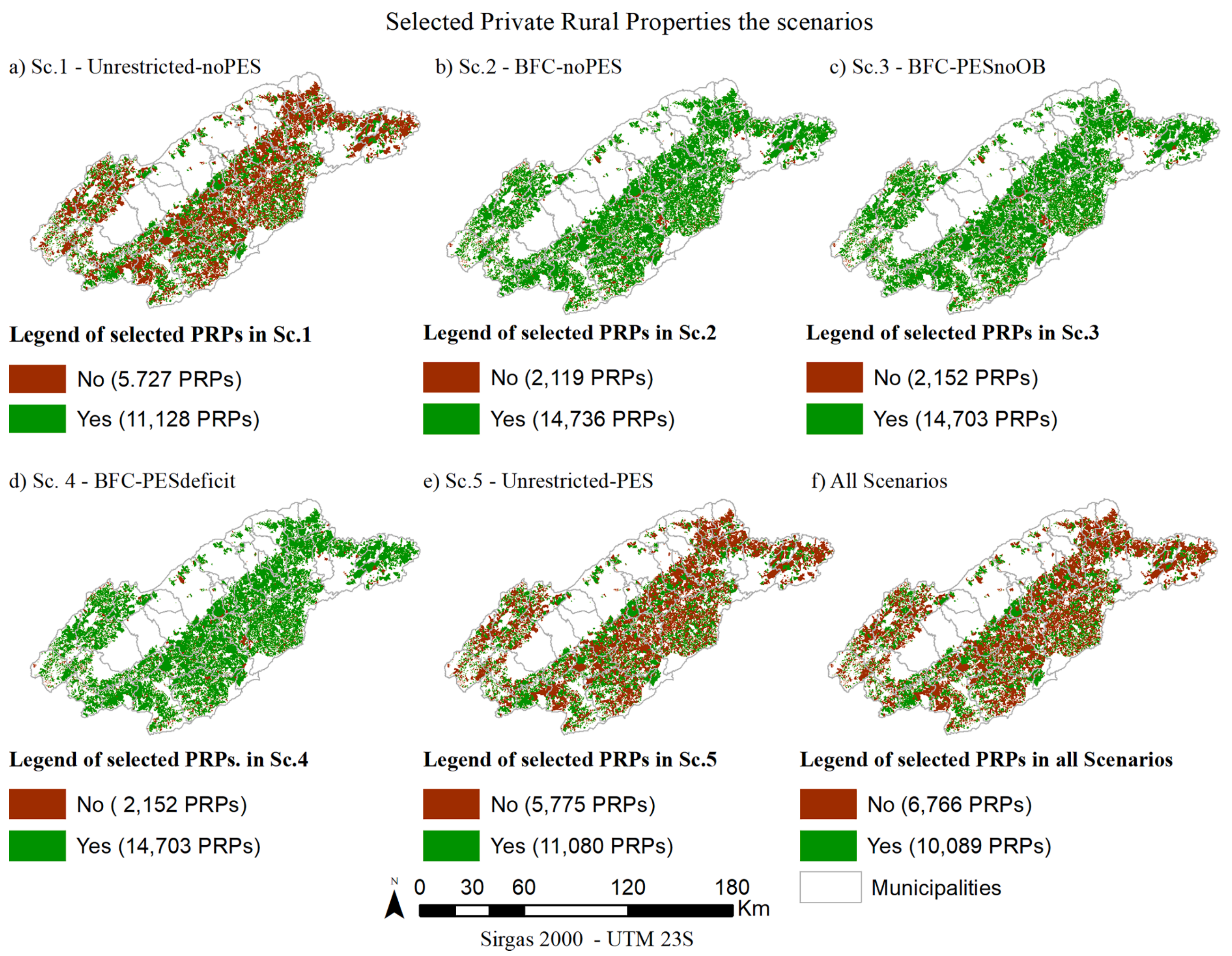

Fig. 6. Selected Private Rural Properties (*parcels*) in: a) Sc.1 (Unrestricted-noPES), b) Sc.2 (BFC-noPES), c) Sc.3 (BFC-PESnoOB), d) Sc.4 (BFC-PESdeficit), e) Sc.5 (Unrestricted-PES), f) Every scenario. Unrestricted in the scenario's name means that the scenario does not use rules to allocate areas to be restored. BFC in the scenario's name means that the scenario restores 100% of pasture *areas considered legal deficit* based on the Brazilian Forest Code. PES in the scenario's name indicates the PES mechanism was applied. Private rural properties boundaries (*parcels*) are the irregular planning units of our study. noOB pasture means *pasture areas in Private no Obligations* (*noOB*) lands.

unit, whereas we estimate the amount of NRP area within *parcels*. In doing so, we indicate whether the area could be restored by natural regeneration or if it requires an active method, which allows combining both methods in the same *parcel*.

4.3. Modelling advances and limitations

Specifically, our calculations of natural regeneration could be improved by accounting for dynamic variables. To estimate the quantity of natural regeneration potential (NRP) present within each *parcel*, we use the data developed by Lemos et al. (2021), which uses static explanatory variables for 1 km^2 cells. This approach may indicate relatively small quantities of NRP inside the cells, as natural regeneration usually starts to take hold in areas smaller than 1 km^2 on the edge of pre-existing forest fragments. However, natural restoration is a dynamic process, iteratively expanding into new areas with each passing year

(Chazdon et al., 2021). We recommend that future simulations of NRP are estimated using dynamic variables, particularly percentage of forest cover in the previous year. Using this method is likely to indicate a more significant area available for natural regeneration, which may reduce the amount of active restoration and, therefore, the costs of each scenario.

This study considers only ecological restoration methods, presenting the costs of restoration solely, with no potential for restoration revenue. However, it is also possible to use restoration methods that create income, reducing the overall restoration cost. For example, different agroforestry systems provide commodity and non-commodity benefits such as ecosystem services, resulting in positive cash inflow-outflow (Padovezi et al. 2018; Shapiro-Garza, 2013), improving food, nutrition, and income security (Seghieri et al., 2021). This strategy is aligned with the current context of VPP, where an increasing number of restoration areas are based on agroforestry systems (Devide et al., 2014, Devide, 2019). Alternatively, Enrichment Planting, which uses fewer seedlings than typical active restoration, may reduce restoration costs (Brancalion et al., 2019). Our approach could be adjusted to consider other ecological restoration methods, including those that provide revenue or reduce costs.

Further, we use the financial values of PES in our economic cost calculations, and consider more than one PES value. This is possible because the PES value is one component of our Net Present Value equation that allows adding other PES values as new components. The inclusion of PES as potential landowner compensation is suggested by Crouzeilles et al. (2020) as one way to improve the opportunity cost estimation and encourage uptake by landholders. These modelling advances allow for more detailed identification of priority areas for restoration, especially by including realistic (irregular) planning units and more than one type of restoration. Optimizing for multiple environmental indicators also allows a balanced solution to be found, even where these objectives may be competing. Such an approach can be extended to other contexts. For example, the prioritization of watersheds could consider a broad set of relevant parameters, such as quality and amount of water, or even water uses, such as human supply or agricultural production (Cook and Bakker, 2012).

5. Conclusions

Using economics methods such as multi-objective optimization methods and Net Present Value accounting, we explore the potential for mixtures of environmental policy to foster cost-effective forest restoration. Although there are trade-offs among objectives, we identify an excellent opportunity to achieve multiple benefits simultaneously with the balanced solution achieving more than 90 % of the maximum possible biodiversity conservation, carbon stock increase, and soil loss reduction among all scenarios. Brazilian Forest Code (BFC) compliance results increase the cost and soil benefit by less than 1 %, reducing less than 1 % of the biodiversity and carbon benefits. Our analysis shows that supplementary PES mechanisms improve the provision of ecosystem services cost-effectively because they reduce the cost to the landowners by 19 % while maintaining the level of environmental benefits.

Our modelling approach provides five key innovations: (1) we explore policy-relevant scenarios, such as BFC and the National Policy for Payment for Ecosystem Services; (2) we develop an optimization based on linear programming that maximizes three environmental benefits of forest restoration; (3) we explore three economic activities: restoration actions, milk production, and PES; (4) we incorporate the potential for both passive and active restoration within the same *planning unit;* (5) we use irregular planning units (*private rural property* boundaries, *henceforth parcels*). If available, our flexible modelling approach can easily accommodate improved data on environmental benefits and costs data. It is built on the recent optimization modelling approaches that maximize only two environmental benefits for forest restoration and consider uniform-shaped planning units (Strassburg et al., 2018; 2020).

Our flexible approach can also be adapted to different contexts, such as supporting large-scale decision-making considering alternative PES mechanisms and policies in Brazil and broad. PES mechanisms promote rural jobs, market access, food security, and good forest growth performance (Le et al., 2014). Therefore, well-designed and efficient strategies help to achieve UN Sustainable Development Goals (SDGs), particularly "Zero Hunger", "Climate Actions", and "Life of land" (UN, 2021). The potential of our modelling approach to simulate many different PES mechanisms in complex environments helps ensure that the enacted policy will ultimately deliver on this promise.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2023.101515.

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