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EXPLORING DIFFERENT MODELLING APPROACHES TO ACHIEVE MULTIPLE RESTORATION GOALS IN THE ATLANTIC FOREST

Cassia Maria Gama Lemos

Doctorate Thesis of the Graduate Course in Earth System Science, guided by Drs. Ana Paula Dutra de Aguiar, and Pedro Ribeiro de Andrade Neto, approved in July 21, 2021.

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DEFESA FINAL DE TESE DE CASSIA MARIA GAMA LEMOS
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No dia 21 de julho de 2021, as 08h00min, por teleconferência, o(a) aluno(a) mencionado(a) acima defendeu seu trabalho final (apresentação oral seguida de arguição) perante uma Banca Examinadora, cujos membros estão listados abaixo. O(A) aluno(a) foi APROVADO(A) pela Banca Examinadora, por unanimidade, em cumprimento ao requisito exigido para obtenção do Título de Doutor em Ciência do Sistema Terrestre. O trabalho precisa da incorporação das correções sugeridas pela Banca Examinadora e revisão final pelo(s) orientador(es).

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“Não há problema que não possa ser solucionado pela paciência.”

"There is no problem that cannot be solved by patience."

Chico Xavier

To all who want to make the world a better place.

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My family and friends for moment of relaxation

My parents who taught me never to give up

ABSTRACT

From global to local levels, land use decisions and restoration initiatives can affect landscapes and livelihoods in heterogeneous ways. Understanding the cost-effectiveness of restoration initiatives is critical for their successful implementation. In this context, this thesis aims to contribute with one new approach to understand the relationships between potential explanatory variables and the natural regeneration process and two new approaches to estimate the cost-effectiveness of different forest landscape restoration strategies for achieving multiple restoration goals (habitat increase, carbon stock increase and reduction of soil loss) in a strategic region in the Brazilian Atlantic Forest Biome, the Paraiba Valley in São Paulo State. The first modelling approach is the use of alternative statistical models for understanding the relationships between potential explanatory variables and the natural regeneration process. The second is an allocation modelling approach that estimates the amount of natural regeneration potential (NRP), allocate forest increments based on the NRP, and estimate the cost-effectiveness at the end of the process. This second approach considers different Payments for ecosystem services (PES) programs to restrict areas and to elaborate forest restoration scenarios. The last is an optimization modelling approach that allocates the forest increment based on the maximization of three environmental benefits while minimizing the cost, this third approach considers scenarios based on the Brazilian Forest Code, and different PES mechanisms for composing the restoration cost. Each modelling approach presents advantages and limitations, the most important advantage of our statistical approach is the possibility to explore the relation between quantities of explanatory variables and quantities of regenerated forest cover, while the most limitation is the difficulty in finding the goodness of fit of our statistical models. In relation to the allocate approach, one of the strengths is the possibility to investigate which alternative statistical model better captures the natural regeneration process in the study area. This is possible through the calibration and validation steps of the percentage of simulated regenerated forest cover based on the percentage of estimated regenerated forest cover from our four alternative statistical models. Another relevant strength is the possibility to estimate the amount of area of natural regeneration potential, this possibility allows us to combine passive and active restoration methods for restoring areas inside the same planning unit. In our allocation modelling approach, the most relevant limitation is that our simulation of the regenerated forest from 2015 to 2025 is assuming the maintenance of the same conditions and relations captured by the statistical models derived for 2011. This limitation could be corroborated by our finding of only 30 km² of area that are favored to receive passive ecological restoration in 2015. Considering that allocation modelling quantifies the cost-effectiveness after the allocation of the increment restoration areas, we develop the third modelling approach of this thesis, our optimization model. The strength of the optimization approach is the possibility of allocating the restored areas based on cost-effectiveness. This possibility requires a very well architected database. The construction of this database is one of the biggest challenges for executing this approach. Independently of the modelling approach, the scenarios that presented restriction rules to allocate the forest increment (constrained scenarios) are the scenarios that present the highest cost when they compare with their scenarios without restriction rules (unconstrained scenarios). The enforced conversion from pasture to forest within restricted areas results in allocating forest in areas with lower natural regeneration potential. As a consequence, it increases the need to use an active (and more expensive) method for restoring the incremented area, which increases the restoration cost. However, in relation to the environmental benefits, the constrained scenarios present the highest carbon benefits when they are compared with their unconstrained scenarios. In relation to the biodiversity benefit, this benefit is highest in the unconstrained scenario that is based on the allocation approach. In the unconstrained scenario that is elaborated based on the allocation approach, the soil benefit is lower than in the constrained scenarios. While, in the unconstrained scenarios that are elaborated based on the optimization approach, the soil benefit is higher than in the constrained scenarios. These results indicate that restriction rules increase the restoration cost and can reduce some environmental benefits. These results reinforce the importance of investigating the cost-effectiveness of restoration initiatives before their implementation. Because our approaches present multiple strategies to investigate the cost-effectiveness of restoration actions, we consider that our three modelling approaches are an important contribution for the advances in the effective large-scale restoration planning. Considering that natural regeneration increases across time, for future studies, we suggest the adoption of a dynamic natural regeneration potential to better investigate the natural regeneration potential throughout the years. This thesis is structured in scientific articles where the two first modelling approaches are presented as the first article that is chapter 2 of this thesis, and the third modelling approach is presented as the second article that is chapter 3 of this thesis.

Keywords: Allocation model. Optimization model. Cost-effectiveness. Brazilian Forest Code. Payments for Ecosystem Services Programs

EXPLORANDO DIFERENTES ABORDAGENS DE MODELAGEM PARA ALCANÇAR MÚLTIPLOS OBJETIVOS DE RESTAURAÇÃO NA FLORESTA ATLÂNTICA

RESUMO

Do nível global ao local, as decisões de uso da terra e iniciativas de restauração podem afetar paisagens e meios de subsistência de maneiras heterogêneas. Compreender a relação custo-benefício das iniciativas de restauração é fundamental para sua implementação bem-sucedida. Neste contexto, esta tese tem como objetivo contribuir com uma nova abordagem para entender as relações entre variáveis explicativas potenciais e o processo de regeneração natural e duas novas abordagens para estimar a relação custo-benefício de diferentes estratégias de restauração de paisagem florestal para atingir múltiplos objetivos de restauração (aumento de habitat , aumento do estoque de carbono e redução da perda de solo) em uma região estratégica do Bioma Mata Atlântica, o Vale do Paraíba Paulista. A primeira abordagem de modelagem é o uso de modelos estatísticos alternativos para compreender as relações entre as variáveis explicativas potenciais e o processo de regeneração natural. O segundo é uma abordagem de modelagem de alocação que estima a quantidade de potencial de regeneração natural (PRN), aloca incrementos de floresta com base no PRN e estima a relação custo-benefício no final do processo. Esta segunda abordagem considera diferentes programas de Pagamentos por Serviços Ambientais (PSA) para restringir áreas e elaborar cenários de restauração florestal. A última é uma abordagem de modelagem de otimização que aloca o incremento florestal com base na maximização de três benefícios ambientais enquanto minimiza o custo, esta terceira abordagem considera cenários baseados no Código Florestal Brasileiro, e diferentes mecanismos de PSA para compor o custo de restauração. Cada abordagem de modelagem apresenta vantagens e limitações, a vantagem mais importante de nossa abordagem estatística é a possibilidade de explorar a relação entre quantidades de variáveis explicativas e quantidades de cobertura florestal regenerada, enquanto a maior limitação é a dificuldade em encontrar o ajuste de nosso modelos estatísticos. Em relação à abordagem de alocação, um dos pontos fortes é a possibilidade de investigar qual modelo estatístico alternativo capta melhor o processo de regeneração natural na área de estudo. Isso é possível por meio das etapas de calibração e validação da porcentagem de cobertura florestal regenerada simulada com base na porcentagem de cobertura florestal regenerada estimada de nossos quatro modelos estatísticos alternativos. Outro ponto forte relevante é a possibilidade de estimar a quantidade de área com potencial de regeneração natural, esta possibilidade nos permite combinar métodos de restauração passiva e ativa para restaurar áreas dentro de uma mesma unidade de planejamento. Em nossa abordagem de modelagem de alocação, a limitação mais relevante é que nossa simulação da floresta regenerada de 2015 a 2025 está assumindo a manutenção das mesmas condições e relações capturadas pelos modelos estatísticos derivados para 2011. Essa limitação deve ter corroborado para nossa descoberta de apenas 30 km² de área favorecida para receber restauração ecológica passiva em 2015. Considerando que a modelagem de alocação quantifica o custo-efetividade após a alocação das áreas de incremento de restauração, desenvolvemos a terceira abordagem de modelagem desta tese, nosso modelo de otimização. O ponto forte da abordagem de otimização é a possibilidade de alocar as áreas restauradas com base na relação custo-benefício. Essa possibilidade requer um banco de dados muito bem arquitetado. A construção desse banco de dados é um dos maiores desafios para a execução dessa abordagem. Independentemente da abordagem de modelagem, os cenários que apresentaram regras de restrição para alocar o incremento florestal (cenários restritos) são os cenários que apresentam o maior custo quando comparados com seus cenários sem regras de restrição (cenários irrestritos). A conversão forçada de pastagem em floresta dentro de áreas restritas resulta na alocação de floresta em áreas com menor potencial de regeneração natural. Como consequência, aumenta a necessidade de se usar um método ativo (e mais caro) para restaurar a área incrementada, o que aumenta o custo de restauração. No entanto, em relação aos benefícios ambientais, os cenários restritos apresentam os maiores benefícios de carbono quando comparados com seus cenários irrestritos. Em relação ao benefício para a biodiversidade, esse benefício é maior no cenário irrestrito que se baseia na abordagem de alocação. No cenário irrestrito elaborado com base na abordagem de alocação, o benefício do solo é menor do que nos cenários restritos. Enquanto, nos cenários irrestritos que são elaborados com base na abordagem de otimização, o benefício do solo é maior do que nos cenários restritos. Esses resultados indicam que as regras de restrição aumentam o custo de restauração e podem reduzir alguns benefícios ambientais. Esses resultados reforçam a importância de investigar a relação custo-benefício das iniciativas de restauração antes de sua implementação. Visto que nossas abordagens apresentam múltiplas estratégias para investigar o custo-benefício de ações de restauração, consideramos que nossas três abordagens de modelagem são uma contribuição importante para os avanços no planejamento eficaz da restauração em grande escala. Considerando que a regeneração natural aumenta ao longo do tempo, para estudos futuros, sugerimos a adoção de um potencial de regeneração natural dinâmico para melhor investigar o potencial de regeneração natural ao longo dos anos. Esta tese está estruturada em artigos científicos onde as duas primeiras abordagens de modelagem são apresentadas como o primeiro artigo que é o capítulo 2 desta tese, e a terceira abordagem de modelagem é apresentada como o segundo artigo que é o capítulo 3 desta tese.

Palavras-chave: Modelo de alocação. Modelo de otimização. Custo-efetividade. Código Florestal Brasileiro. Programas de Pagamentos de Serviços Ambientais

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LIST OF ACRONYMS AND ABBREVIATIONS

AIC	Akaike Information Criteria
CLUE	Conversion of Land Use and its Effects
CS	Cellular Space
Eco	Ecological
FLR	Forest Landscape Restoration
INPE	Instituto Nacional de Pesquisas Espaciais
Km	Kilometer
LCM	Land Change Models
m	Meter
MBC	Maximum Biophysical Capacity
Mha	Million Hectare
NDC	Nationally Determined Contribution
Pact	Atlantic Forest Restoration Pact
PES	Payments for Ecosystem Services
PNPSA	Política Nacional de Pagamento por Serviços Ambientais
Pot	Potencial
Reg	Regression Value
SDGs	Sustainable Development Goals
SDR	Sediment Delivery Ratio
SID	Serviço de Informação e Documentação
SPG	Serviço de Pós-Graduação
TDI	Teses e Dissertações Internas
Ton	Tonne
UM	United Nations
UNFCC	United Nations Framework Convention on Climate Change
USLE	Universal Soil Loss Equation
VPP	Vale do Paraíba Paulista

CONTENTS

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1 GENERAL INTRODUCTION

Forest landscape restoration (FLR) has the objective of reconciling conservation biodiversity, promotion of ecosystem services and human well-being with agricultural gains in degraded landscapes (CHAZDON; GUARIGUATA, 2016). FLR is crucial to reverse the impacts of historical deforestation (IPBES, 2019), while also potentially contributing to achieving different UN Sustainable Development Goals (SDGs) (UN, 2021). It can contribute with SDGs 1 and 2 through food security by enabling and improving the provision of forest goods such as wild fruits, leaves, seeds, nuts, honey, and vegetables. These forest products can in turn be commercialized, bringing economic and livelihood benefits. Other benefits of FLR corroborate with SDGs 13 and 15, bringing benefits for climate change mitigation and conservation of life on land. These benefits are achieved through implementing forest and grassland conservation to protect communities from soil erosion and sandstorm, to protect rivers against flooding and erosion, and to reduce urban heat island effects and improve air quality (SAIMA et al., 2017; LE et al., 2016).In short, FLR safeguards biodiversity, provides ecosystem services, and can enhance livelihood for local vulnerable people (CHAZDON et al., 2020; ROCKSTRÖM et al., 2017).

Due to all the benefits from FLR, restoration has gained traction in the world. There are global to local initiatives with the aim to restore biodiversity and improve ecosystem services through increasing forest cover. Globally, the Bonn Challenge and the New York Declaration are worldwide efforts to restore 150 million hectares (Mha) by 2020 and 350 Mha by 2030, respectively (LEWIS et al., 2019). Locally, the 20X20 Initiative is a Latin American work to restore 22 Mha of forest by 2030 (20X20 INITIATIVE, 2021).

In Brazil, the Aichi Targets (CBD, 2021) were fundamental to combine biodiversity in the national context with the country's development strategies. In this context, the Brazilian government has established the National Biodiversity Targets for 2020, including the plea to restore at least 15% of the degraded ecosystems (UNCN, 2011). In parallel, Brazil declares its Nationally Determined Contribution (NDC) to the United Nations Framework Convention on Climate Change (UNFCCC), voluntarily committing to restore 12 Mha of forests by 2030 for multiple uses (BRASIL, 2015).

Among the Brazilian Biomes, the Atlantic Forest Biome has undergone the higher 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 (METZGER et al., 2009). The remaining forest area is only 12% of the original forest in the biome (RIBEIRO et al., 2011). For this Biome, a leading Brazilian effort, called Atlantic Forest Restoration Pact, aims to restore 15 Mha of degraded lands by 2050 (CALMON et al., 2011). Aligned to this, several other nested restoration initiatives are taking place in both regional and local scales (ALARCON et al., 2017).

The understanding about the cost-effectiveness of restoration initiatives (CROUZEILLES et al., 2020; STRASSBURG et al., 2018) is critical for their implementation. The restoration implementation costs depend on the restoration method chosen. For example, restoration costs may range from US$ 50.03 (natural regeneration method) to US$ 2,102.83 (total planting method, as seedling planting) per hectare in the Brazilian Atlantic Forest (BRANCALION et al., 2019). The same authors suggest adopting natural regeneration - a passive and inexpensive method - whenever possible for reducing the financial barriers to scaling up restoration at a global scale. Other studies also highlight that natural regeneration needs to be combined with active restoration methods (total planting methods) in situations of low natural regeneration potential (CHAZDON et al. 2016; CROUZEILLES et al. 2019). In general, previous studies have estimated the natural regeneration potential using empirical analysis based on multiple biophysical, land use history and socioeconomic factors on Brazilian Atlantic Forest Biome (MOLIN et al., 2018; PADOVEZI et al., 2018). All these previous studies used approaches to estimate natural regeneration potential based on the chance for the area may, or not may, have natural regeneration potential (CROUZEILLES et al., 2020; MOLIN et al., 2018; PADOVEZI et al., 2018; STRASSBURG et al., 2018).

In addition to the cost-effectiveness, FLR depends on the local decision, as private rural properties are the lowest level of decision making related to the implementation of restoration projects. One way of connecting landscape and local levels are the payment instruments to convert low productivity agricultural lands into forest areas (ADAMS et al., 2016). Known as Payments for ecosystem services (PES), these initiatives promote forest cover by compensating landholders for keeping forest intact or planting new trees (JACK; JAYACHANDRAN, 2019). PES programs are already taking place in Brazil in experimental mode since the last decades. As of early 2021, these programs have been regulated by Law number 14.119/2021 (BRASIL, 2021), called National Policy for Payment for Ecosystem Services (in Portuguese, *Política Nacional de Pagamento por Serviços Ambientais* - PNPSA).

The higher interest of landholders is in the modality of conservation PES, while those who demonstrated interest in taking part in PES for restoration are the landholders that would commit only those areas whose forest cover is already required according to the Brazilian Forest Code (ALARCON et al., 2017). The low interest in the restoration through PES can be justified by its costs combined with loss of profits (i.e. opportunity costs). High opportunity costs implicate in less engagement in forest restoration actions by landholders (HISSA et al., 2020). Previous studies in the Brazilian Atlantic Forest have not included PES mechanisms in analysis about cost-effectiveness of FLR (CROUZEILLES et al., 2020; MOLIN et al., 2018; STRASSBURG et al., 2018). Crouzeilles et al. (2020) suggest that including potential compensations through PES could eventually improve the opportunity cost estimation, capturing a decrease in landowners resistance to forest restoration actions. Previous studies have also restricted their analysis to one or two benefits, in general biodiversity and carbon (CROUZEILLES et al., 2020; STRASSBURG et al., 2018, 2020).

In this context, this thesis aims at contributing to advancing modelling approaches to achieve multiple restoration goals in the atlantic forest comparing different forest landscape restoration strategies. In particular, we explore three modelling approaches. The first one is the use of alternative statistical models for understanding the relationships between potential explanatory variables and the natural regeneration process. The second is a modelling approach that estimates the amount of natural regeneration potential (NRP), then allocates new forest areas based on the NRP, and estimates the cost-effectiveness in the end of the processes. This second approach considers different Payments for ecosystem services (PES) programs to restrict areas and to elaborate forest restoration scenarios. The third one is a modelling approach that allocates the forest increment based on the maximization of three environmental benefits while minimizing the cost. This third approach considers scenarios based on the Brazilian Forest Code, and different PES mechanisms for composing the restoration cost. We focus on the Paraiba Valley in Sao Paulo State (in Portuguese, Vale do Paraiba Paulista - VPP), an interesting area for exploring cost-effectiveness analysis which combines agricultural activities and multiple PES programs.

This region has a historical occupation that is strongly based on agricultural activities. The occupation began in the centuries XVI e XVIII, but it intensified with the coffee cycle in th century XIX. The coffee activities made intense use of fire that resulted in the soil degradation of the region. The reduction of the soil productivity occured at the same period of the expansion of the coffee frontier to other areas in the interior of the São Paulo State. Currently, the most relevant agricultural activities are dairy production, eucalyptus planting, and rice cultivation (DEVIDE, 2013; ITANI, et al. 2011).

Although agricultural activities occupy almost the region, the economic return of these activities is small when it is compared with the economic return of industrial and services activities that are concentrated near Dutra highway, one of the most important highways in Brazil. The intense urbanization process in the last decades contributed to the abandonment of rural activities in the VPP, which is undergoing a forest transition process in the last decades (SILVA et al., 2016a). In recent years, Paraiba Valley has been chosen as the target of multiple restoration initiatives and PES programs (OIKOS 2015; SÃO PAULO 2019). These PES programs have the objective of restoring areas that are relevant to biodiversity conservation, mitigate climate change and water security (LEMOS et al., 2021). We present below the goals, scientific questions, and hypothesis of this thesis.

1.1 Main goal, hypothesis, specific objectives and scientific questions

1.1.1 Main goal

Considering the context of Paraiba Valley, the main goal of this thesis is:

Contribute to advancing modelling approachesto understand the relationships between potential explanatory variables and the natural regeneration process and estimate the cost-effectiveness of different forest landscape restoration strategies for achieving multiple restoration goals (habitat increase, carbon stock increase and reduction of soil loss) in the Paraiba Valley. We explore restoration strategies related to: (a) amount of natural regeneration potential to combine different ecological restoration methods ; (b) the choice of restoration areas aligning priority areas of nested Payments for ecosystem services (PES) programs; (c) alternative payment rules for the PES mechanisms, in particular in relation to the enforcement of the Brazilian Forest Code and the recent National Policy for Payment for Ecosystem Services.

1.1.2 Hypothesis

Restoration strategies which impose strict rules to the allocation of the new forest areas may increase restoration costs while not necessarily increasing the multiple environmental benefits such as habitat increase, carbon stock increase and reduction of soil loss.

This hypothesis is elaborated considering that strict restriction rules can prevent new forest in areas that have low restoration costs and high environmental benefits from being allocated.

1.1.3 Specific objectives

For achieving this main goal, the specific objectives are:

(a) estimate the natural regeneration potential in the Paraiba Valley based on alternative sets of biophysical, land cover, and socioeconomic factors.

(b) explore forest restoration scenarios for the Paraiba Valley to estimate the cost-benefit (habitat increase, carbon stock increase, and/or reduction of soil loss) of alternative restoration strategies considering different ecological restoration methods and restriction rules for limiting the restoration to the priority areas of the existing PES Programs.

(c) explore forest restoration scenarios for the Paraiba Valley to optimize the cost-benefit of achieving multiple goals (habitat increase, carbon stock increase, and/or reduction of soil loss) at the rural property level, considering as restoration strategies: combining different ecological restoration methods; restriction rules related to the Brazilian Forest Code, and alternative payment rules to rural private properties related to National Policy for Payment for Ecosystem Services.

1.1.4 Scientific questions

The specific objectives contribute for answering the scientific questions and to investigating the hypothesis of this thesis, that are:

1- What are the relevant biophysical, land use history, and socioeconomic factors to natural regeneration?

2- What is the amount of natural regeneration potential within the Paraiba Valley?

3- What are the restoration implementation cost, habitat increase, carbon stock increase, reduction of soil loss, and spatial patterns of restoration of the scenarios that consider the priority areas of the PES Programs in the Paraiba Valley?

4- How much does the restoration of legal deficits according to the Brazilian Forest Code influence the costs, benefits, and spatial patterns of restoration in the Paraiba Valley?

5- How much do alternative PES mechanisms in legal deficits according to the Brazilian Forest Code influence the costs, benefits, and spatial patterns of restoration in the Paraiba Valley?

1.2 Structure of the thesis

This thesis is structured in scientific articles, where:

- Chapter 1 is this general introduction.

- Chapter 2 is our first scientific article. This article was published recently as an original article with open access in the Regional Environmental Change by the DOI: https://doi.org/10.1007/s10113-021-01792-0. This chapter contemplates the specific objectives (a) and (b), and answers the Scientific questions 1, 2, and 3. In Chapter 2, we develop a multivariate statistical approach to estimate the amount of natural regeneration potential of the study area, and develop allocation scenarios using the spatially explicit LuccME modeling framework (AGUIAR et al., 2016). Scenarios are aligned with the spatial partitions of the Hydric PSA Program and the Protection PSA Program. We quantify the restoration costs and three environmental indicator benefits resulting from alternative restoration scenarios.

- Chapter 3 is our second scientific article. This chapter covers the specific objective (c), and contributes to answering part of the Scientific questions 4 and 5. We apply a multicriteria optimization approach (BEYER et al., 2016), using scenarios aligned with different levels of the Brazilian Forest Code enforcement and mechanisms of payment for Environmental Service. The objective is to find, for each policy scenario, the best solution in relation to environmental and economic indicators at the rural property level. We adopt the same environmental indicators developed in Chapter 2, allowing for comparison in Chapter 4.

- Chapter 4 extends the discussions presented in Chapters 2 and 3. This on deepening the discussion of the modelling approaches that are developed in this thesis, addressing elements that can be analyzed and compared in an integrated way.

- Chapter 5 brings the general conclusions of this thesis, revisiting the scientific questions presented in Chapter 1.

- The Appendices supplement details for the understanding of the modelling approaches of this thesis.

2 COMBINING REGIONAL TO LOCAL RESTORATION GOALS IN THE BRAZILIAN ATLANTIC FOREST[1]

2.1 Introduction

Forest restoration is crucial to reverse the impacts of historical deforestation, safeguarding b[1]iodiversity and an adequate provision of ecosystem services, including climate change mitigation and adaptation (IPBES, 2019). Given its importance, there are multiple ongoing restoration efforts at several scales. Taken together, countries have committed to restore a global area equivalent to the size of China (SEWELL et al., 2020). Examples of restoration commitments are the Bonn Challenge and the New York Declaration that are worldwide efforts to restore 150 million hectares (Mha) of degraded and deforested lands by 2020 and 350 Mha by 2030, respectively (LEWIS et al., 2019). Brazil voluntarily committed to restore 12 Mha of forests by 2030 for multiple uses, as part of its Nationally Determined Contribution (NDC) to the United Nations Framework Convention on Climate Change (UNFCCC) as well as it is one of the goals of the Brazil's National Plan for Native Vegetation Recovery (BRANCALION et al., 2019). Moreover, the Atlantic Forest Restoration Pact, a multi-stakeholder coalition, aims to restore 15 Mha of degraded lands in the Brazilian Atlantic Forest Biome by 2050 (Calmon et al. 2011). The Pact pledged to contribute with 1 Mha to the 2020 Bonn Challenge. From those, around 700,000 ha has been achieved from 2011 to 2015 (CROUZEILLES et al., 2019).

Planning the necessary change in land systems to accommodate restoration projects is always complex and challenging due to the varied interests of decision-makers acting on the landscape (BOILLAT et al., 2017). Previous studies emphasize the relevance of adopting a multiscale approach to achieve effective large-scale restoration planning (ADAMS et al., 2016). Frequently, reaching tropical forest landscape restoration goals is proposed through passive ecological restoration as it is a cheaper strategy, easier to be implemented (CROUZEILLES et al., 2020). In situations of historical anthropogenic degradation, passive ecological restoration methods need to be combined with active ones to achieve better outcomes (RODRIGUES et al., 2011), considerably increasing the cost of the restoration. For

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example, restoration costs may range from US$ 50.03 to US$ 2,102.83 per hectare in the Brazilian Atlantic Forest depending on the ecological restoration method adopted (BRANCALION et al., 2019).

Assessing the potential for employing passive restoration methods in a given area is therefore essential for planning such large-scale ecological forest restoration commitments (BRANCALION et al., 2019). The potential is dependent on natural ecological succession processes. It relies on favourable biophysical conditions for native seedling establishment and growth, the spontaneous arrival of new species over time, and presence of species with differing and complementary ecological behaviours (RODRIGUES et al., 2011). For example, shrubs and herbaceous plant species in parts of the Loess Plateau in China present different potentially suitable habitats, but both need to be considered as the pioneer plants of revegetation in future revegetation plans (ZHENG et al., 2021). In general, one challenge for employing passive restoration methods is the difficulty to reliably predict the future species composition (VICKERS et al., 2011). In the Brazilian Atlantic Forest, previous studies have estimated the natural regeneration potential using empirical analysis based on multiple biophysical, land use history and socioeconomic factors (CARVALHO RIBEIRO et al., 2020; MOLIN et al., 2018; SILVA et al., 2016a; STRASSBURG et al., 2018;), without differentiating, in most cases, the factors influencing the ecological regeneration process from the socioeconomic context.

In this work, we build upon these previous studies to propose a novel spatially-explicit scenario approach to explore how and where, within a given region, multiple restoration commitments could: (a) be implemented through natural regeneration, (b) be combined to achieve cost-effectiveness outcomes in order to gain scale. Our goal is to facilitate the elaboration of forest restoration plans at the regional level, taking into consideration the costs for active and passive restoration methods. The approach includes: (1) a statistical analysis to estimate the natural regeneration potential for a given area based on alternative sets of biophysical, land cover and socioeconomic factors; (2) the use of a land change allocation model to explore the cost-effectiveness of combining multiple restoration commitment through alternative scenarios representing different restoration commitments in our study area. We test our approach in a strategic region in the Brazilian Atlantic Forest Biome, the Paraiba Valley in São Paulo State.

This region is an old occupation area undergoing a forest transition process, and it is one of the strategic regions to the Brazilian economic development (SILVA et al., 2016b). For this reason, it has been chosen as a target area for different programs for Payments for Environmental Services (PSA), such as the Protection PSA Program (SÃO PAULO, 2017; 2019) and Hydric PSA Program (OIKOS, 2015). The Protection PSA is a State level program with the objective of financing remnant forest protection and restoration actions in rural private properties located in key areas for water and biodiversity conservation. The Hydric PSA Program is a local level program implemented with the objective of restoring areas that are relevant to water security in the Paraiba Valley in São Paulo. Moreover, our study area, as an example of a degraded pasture area undergoing a forest transition process (SILVA et al., 2016b) inside the Atlantic Forest biome, is also relevant for a large-scale national level restoration commitment, the Atlantic Forest Restoration Pact. In this way, the Protection PSA Program, the Hydric PSA Program and the Atlantic Forest Restoration Pact are three restoration commitments that we consider in this study. The three scenarios that we explore correspond to the alignment of these three commitments.

The goal of our scenarios is to analyze the cost-effectiveness of combining the Atlantic Forest Restoration Pact to other programs targeting our study area. Using the allocation model of land use change, we compare the costs of restoration (combining passive and active methods) and gains (in biodiversity, carbon and soil) of the alternative allocation scenarios aligned with the different restoration commitments. The scenarios explore the cost-effectiveness of maintaining a high rate of conversion from pasture to regenerated forest (60 km²/year), according to the priority areas defined by different restoration programs in the region. We calibrate our models with empirical evidence of regeneration from 1985 to 2011, validate the model until 2015 and build alternative scenarios until 2025, as follows.

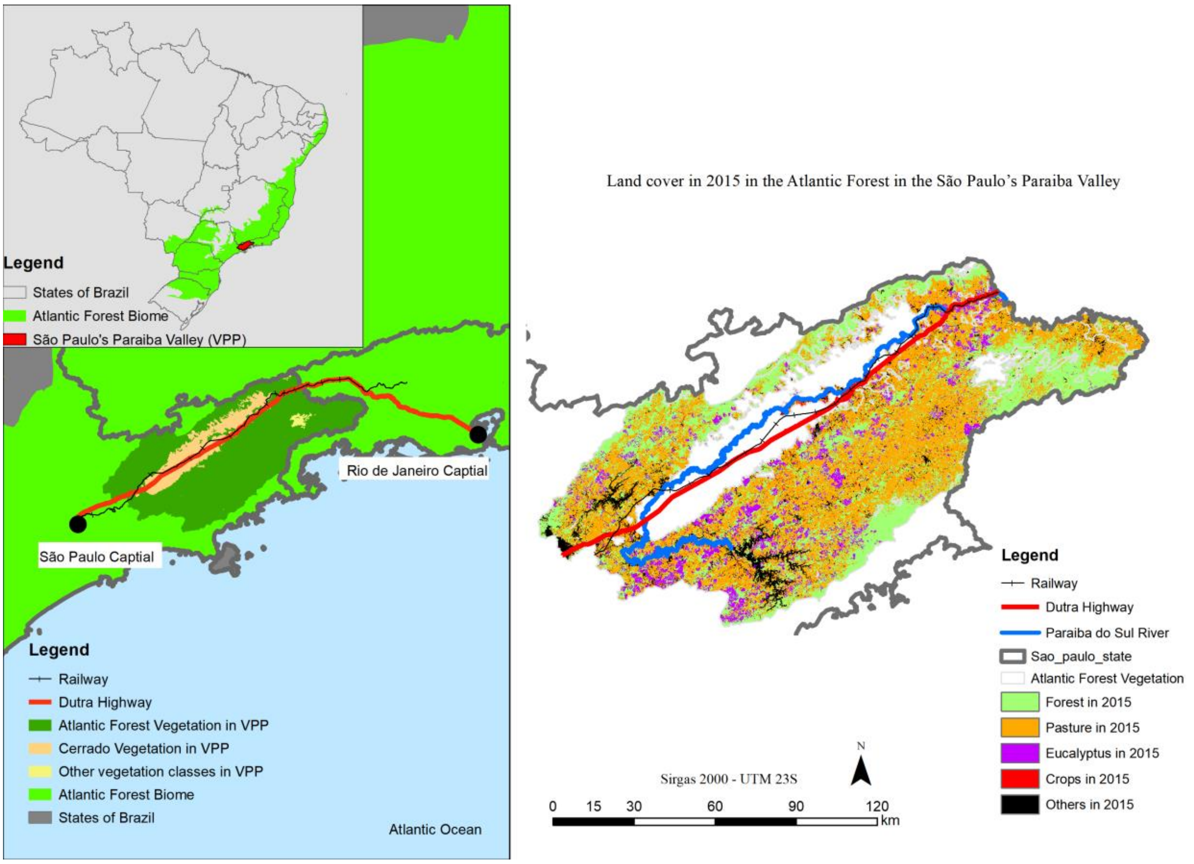
2.2 Material and methods

2.2.1 Study area

Our study area is the of the Paraiba Valley located in São Paulo State (in Portuguese, *Vale do Paraíba Paulista* - VPP) in the Southeast of Brazil (Figure 2.1). This region occupies, approximately, 1.4 Mha, encompassing 34 administrative municipal units. Economically it is one of the most developed regions in the country, with a flourishing industrial park along a major highway connecting São Paulo to Rio de Janeiro. Although the area is located in the

Atlantic forest biome, it contains some patches of Cerrado and special vegetation classes, such as rock outcrop vegetation (IBGE, 2012) (Figure 2.1). By reason of the different adaptation for biophysical conditions of each vegetation class (MENDES et al., 2019; ROSSATO et al., 2009; SCARANO, 2007), and considering that Atlantic Forest vegetation is the most representative vegetation class in the study area, covering approximately 80% of the region, we focus our analysis solely on the area that has been originally occupied by Atlantic Forest vegetation.

Figure 2.1 - Location of the study area.



Source: Lemos et al. (2021).

2.2.2 Land change process and data

The study area has undergone historical different cycles of agricultural production since the 19th century, and lost most of its original forest areas in this process (SILVA et al., 2017). However, from 1985 to 2015, the areas covered by forest increased from 21% to 37%, mostly converted from pasture, that dropped from 69% to 47% (RONQUIM et al., 2016; SILVA et al., 2016b). Although there was some active ecological restoration, the forest cover increase is dominated by natural regeneration (SILVA et al., 2017). *Therefore, here we adopt the assumption that forest cover increase in the study area is 100% related to natural regeneration.* We base our analysis on a land cover map series covering the 1985 to 2015 period (available for 1985, 1995, 2005, 2011, 2015), derived from Remote Sensing images by (RONQUIM et al., 2016; SILVA et al., 2016b). From a temporal analysis of these maps, we extract *regenerated forest cover maps for 2011 and 2015*, the calibration/validation period of our model, as discussed in Section 2.6. When a forest area has been identified as non-forest by the land cover maps (RONQUIM et al., 2016; SILVA et al., 2016b) as non-forest in the previous years of the analysis, this area is reclassified as a *regenerated forest.* A similar approach of forest cover reclassification is applied in other studies (CROUZEILLES et al, 2020; SCHULZ; SCHRODER, 2017;). When the forest area is classified as forest for all years of analysis, this area is reclassified as a *remnant forest*. Our main focus of interest in this work is the conversion from pasture cover to regenerated forest cover, as this is the dominant process in the region (PADOVEZI et al., 2018). Pasture areas in the study area usually have low productivity, and thus reduced land competition for more profitable uses, which might favor natural regeneration (STRASSBURG et al., 2018). Table 2.1 summarizes the land cover change in the study area from 1985 to 2015 (Figures 2.1 and A.1 illustrates them).

Table 2.1 - Summary of land cover in the study area from 1985 to 2015.

Land cover	Area (km2) and %				
	1985	1995	2005	2011	2015
Remnant Forest	2432	1959	1829	1771	1687
%	*21%*	*17%*	*16%*	*15%*	*14%*
Regenerated Forest	n.a.	1465	1978	2442	2639
%	-	*13%*	*17%*	*21%*	*23%*
Pasture	8083	7232	6856	6031	5453
%	*69%*	*62%*	*58%*	*52%*	*47%*
Other land covers	1136	995	988	1407	1872
%	*10%*	*8%*	*9%*	*12%*	*16%*
Total	11651	11651	11651	11651	11651
%	*100%*	*100%*	*100%*	*100%*	*100%*

Source: Lemos et al. (2021).

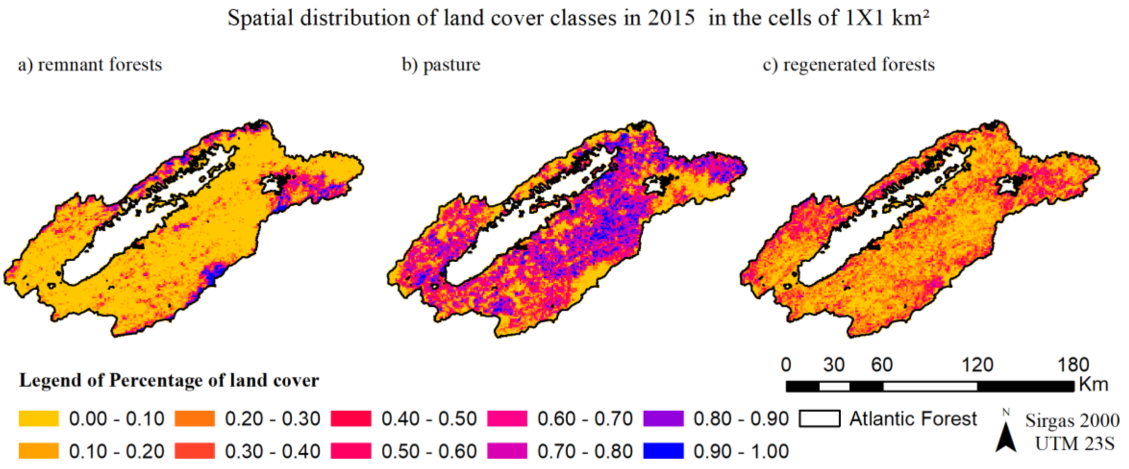
2.2.3 Celular database organization

In this work, we apply an empirical analysis to capture which biophysical and socioeconomic factors (Section 2.4) relate to the regenerated forest cover in 2011. This empirical analysis is used to identify the relevant factors as well as their quantitative relationships with land cover changes. The first step in this analysis is to organize the multiple data sets in a comparable spatial and temporal resolution. In particular, considering the disparity of resolutions between the land cover data sources (30 m x 30 m) and socioeconomic data derived from census data (in our case study, we have 34 municipalities in the area, with an average size of 410 km² - Table A.1), we perform a preliminary analysis to verify which spatial resolution better aggregates the multiple data sources, capturing the general trends and relationships between land cover and the socioeconomic and biophysical factors. It is known from the literature that coarser resolutions tend to improve the capture of general patterns (AGUIAR et al., 2007; VERBURG et al., 1999).

In order not to lose information derived from the finer scale data sets, we use continuous variables to represent our land cover and biophysical variables, following the works of Aguiar et al. (2007) and Verburg et al. (1999). We characterize the land cover by the relative extent of each land cover class in each grid cell, e.g. a grid cell can contain 30% remnant forest, 40% pasture and 30% regenerated forest. Based on this preliminary analysis, we organize our data as continuous variables in regular cells of 1km x 1km, using the TerraView/TerraME/LuccME environment (CARNEIRO et al., 2013). A regular grid of 1km² used in Schulz and Schroder (2017) that has a study area with similar extension of our study.

The Figure 2.2 illustrates the spatial distribution of percentage of remnant forest, regenerated forest and pasture in the 1 km x 1 km cells (in 2015). The histogram in Figure A.3 illustrate that cells have, in average, 20% of regenerated forests.

Figure 2.2 - Spatial distribution of land cover classes in 2015, aggregated as a percentage of 1 km x 1 km cells: a) remnant forests; b) pasture; c) regenerated forests.



Source: Lemos et al. (2021).

2.2.4 Explanatory factors related to natural regeneration spatial patterns

Previous studies investigate different combinations of historical land use, multiple socioeconomic and biophysical drivers to explain the natural regeneration in different countries, and the Atlantic Forest and VPP. Table 2.2 summarizes their findings, spatial and temporal scale, and methods used.

Table 2.2 - Summary of previous studies.

Author	**Approach to identify the natural regeneration potential**	**Scale** Extension/ Resolution/ Temporal	**Most important drivers/results**
Schulz and Schroder (2017)	Multiple logistic regression models	Central Chile/ 1000m and / 26 years	The most importants drivers are elevation, slope, precipitation in the coldest quarter, temperature seasonality, and distance to primary road, Regeneration potential occurs more clearly on the higher mountain ranges, and only small areas show slightly higher probabilities.

(to be continued)

Table 2.2 – Continuation.

Author	**Approach to identify the natural regeneration potential**	**Scale** Extension/ Resolution/ Temporal	**Most important drivers/results**
Vergarechea et al. (2019)	Maximization of a likelihood	Northern Plateau of Spain/ 2ha/ 15 years	The results also point to the existence of climate-mediated annual regeneration occurrence, reflecting the complex interaction which exists between environmental factors and the optimum conditions for natural regeneration.
Strassburg et al. (2018)	Ecological uncertainty of forest restoration success for plant biodiversity	Atlantic Forest Biome/ 1 Km/ -	The study identifies areas where natural regeneration and active restoration methods are most likely to foster plant biodiversity recovery to similar levels found in reference systems.
Crouzeilles et al. (2020)	Random Forest regression models	Atlantic Forest Biome/ Municipality and 30m/ 20 years	Predictive model based on 10 variables related to landscape conditions, soil properties, climate, topographic relief, and past disturbance intensity related to pasture and sugarcane production explain 80.2% of the natural regeneration at municipality resolution. The most important predictor of the occurrence of natural regeneration is the proximity to forest at the pixel-based resolution.
Carvalho Ribeiro et al. (2020)	Favourability-to-natural-regeneration model	Rio Doce basin/ 30m / -	The study takes into account the 1) landscape context (land use and legal compliance), 2) physiographic attributes related to local resilience (as concave terrain), and 3) land use intensity.

(to be continued)

Table 2.2 – Conclusion.

Author	Approach to identify the natural regeneration potential	Scale Extension/ Resolution/ Temporal	Most important drivers/results
Molin et al. (2018)	Transition matrices and weight of evidence coefficients	Piracicaba River basin/ 30m / 10 years	The authors evaluate 12 variables used to model the spatial probability of natural regeneration (Biophysical variables: soil type, hydrographic network, forest type, rainfall, slope, and altitude. Socioeconomic variables: population density, rural population density, municipal GDP, road network, urban spots, and predominant land uses). Among the 12 variables used, the six socioeconomic variables show negligible weights of evidence. Slope, distance to watercourses, and distance to forest remnants are the main biophysical drivers of forest regeneration in the basin.
Padovezi et al. (2018)	Logistic regression model	Paraiba Valley/ 30m/ -	The authors evaluate five biophysical variables (Distance to remnant forest, elevation, slope, aspect, and curvature) that are relevant ecological processes. Among the variables, the most relevant is the distance to remnant forest.
Silva et al. (2016a)	Multi-layer Perception by Neural Net-work	Paraiba Valley/ Municipality/ 26 years	The authors evaluate 17 variables for three periods (1985–1995; 1995–2005; and 2005–2011), the proximity of forest plays a major role in the increase of forest cover in all periods. The first period of the analysis reveals that biophysical drivers (aspect and slope) are the most relevant drivers. For the next periods of change, a different set of socioeconomic variables (Proximity of eucalyptus, rural farms, Credit farms, and concentrate of industries and commercial establishments) are more relevant for the forest increase.

Source: Lemos et al. (2021).

Based on these previous studies summarized in Table 2.2, we compile an initial set of twenty-four **candidate** variables that could potentially explain the natural forest regeneration process that took place in our study area from 1985 to 2011. These candidate variables are also organized into the cellular space (CS) of 1 km x 1 km. The CS allows us to homogenize different data sources and easily explore the statistical relationship with land change variables (Section 2.2). The candidate variables correspond to the following broad categories (see details in Tables A.2 and A.3):

- **Biophysical factors**: We select a group of nine candidate variables which could capture the main drivers of the ecological processes underlying natural regeneration. In relation to terrain characteristics, we consider *aspect*, *surface curvature*, *slope.* Each factor is categorized into a small number of classes and included in our database as percentage of each class (e.g., *percentage of steep slope)*. Each cell also has a variable representing the average *elevation*. We include categories related to *soil type* and *agricultural suitability,* following Padovezi et al. (2018) and Rossi et al. (2017), respectively. We have climate related factors, including *temperature* and *precipitation,* included as averages in the cells. Finally, related to water availability, we include the variable *distance to the waterbody*.
- **Land cover factors:** We include candidate variables related to *proximity/percentage of forest, proximity/percentage of eucalyptus* and *percentage of degraded pasture*. Forest cover is chosen because several studies (Table 2) concluded that proximity to forest areas is one of the main drivers for natural regeneration. Silva et al. (2016a) identify a trend of forest cover increase near eucalyptus plantations in the VPP. Finally, degraded pasture is chosen because it is the land use class that has contributed over 70% to the new forest cover areas on VPP (SILVA et al., 2016a). These historical land use variables are important to represent the dynamics of land change conversion that contribute to forest cover increase in VPP.
- **Socioeconomic factors:** We include variables broadly related to accessibility, relevant socioeconomic activities in the area and rural/urban relations. Accessibility factors include *Distance to Dutra Highway* (one of the most important highways in Brazil, with a large concentration of industries and population) and *distance to urban centers*. Previous studies use these variables (CROUZEILLES et al., 2020; SILVA et al., 2016a) to represent accessibility and to identify marginal lands, more likely to be

set aside for natural regeneration (MOLIN et al., 2018). We select three indicators representing the main rural activities developed in pasturelands of our study area, namely *stocking rate, milk productivity, and milk revenue.* Besides, similar to Silva et al. (2016b), we include indicators of *Rural Population, Farm jobs, Farm revenue, Farm profit, and Farm Credit*. These socioeconomics variables are important to represent the rural conditions in relation to the total socioeconomic conditions in the municipalities (SILVA et al., 2016a).

2.2.5 Exploratory analysis and selection of alternative statistical models

Considering we use continuous values for characterizing our land cover classes, linear regression is the appropriate technique for the analysis of the relevant factors as well as their quantitative relationships with each land cover (LESSCHEN et al., 2005). We apply a statistical analysis using the statistical software RStudio (RSTUDIO, 2021). An initial exploratory statistical analysis shows that some of the relationships between potential explanatory variables and the regenerated forest cover in 2011 are not linear. We apply a logarithmic transformation to the land-use variables and to some explanatory variables. We also perform a correlation analysis between the variables in our dataset to prevent those factors with a correlation coefficient to be used in the same regression (Table A.4). Following the process adopted in Aguiar et al. (2007), after removing the explanatory variables that are strongly correlated (> 0.80) (HILL et al., 1999), alternative linear models are constructed for finding the regression model with the significant variables ($p < 0.05$), the highest coefficient of multiple determination (R^2), and the lowest Akaike information criteria (AIC). These parameters indicate the model with the best goodness of fit (ANSELIN et al., 2006). The regression coefficients (beta) are then standardized for determining the relative importance between the variables in the model (AGUIAR et al., 2007). An automatic linear forward stepwise regression is applied to refine the models and discard non-significant variables.

To better understand the multiple factors underlying the natural regeneration process in the region, we build and compare four alternative linear regression models considering: (a) only biophysical factors (**B Model)**; (b) biophysical and forest cover (**Eco Model**); (c) biophysical, forest and other land covers (**BH Model)**; (d) biophysical, forest and other land covers, and socioeconomic factors (**BHS Model)**.

2.2.6 LuccME modelling approach

LuccME is an open-source framework for the development of dynamic spatially explicit land change models (LCM) representing the evolution of land use and cover spatial patterns over time. The LuccME framework organizes the models in three components, following the generic structure found in land use and cover change models (VERBURG et al., 2006). A *Demand Component* defines the amount of change that will be allocated by the model at each time step. A *Potential Component*, usually based on empirical methods, calculates the potential for each land cover in each cell, according to a set of explanatory variables. The *Allocation component* is the core computational mechanism that distributes, at each time step, the changes as defined by the demand according to the potential of each cell. LuccME framework provides multiple components which can be chosen according to the study area and land change process needs.

In this work, we use the LuccME components based on the Conversion of Land Use and its Effects (CLUE) model for continuous land-use variables (VELDKAMP AND FRESCO, 1996; VERBURG et al., 1999) to generate our natural regeneration alternative scenarios for 2025. The CLUE model projects near future land use changes based upon current and past land use conditions, and has been applied to many different countries and scales to understand the evolution of land use and cover spatial patterns over time for continuous land-use variables (AGUIAR et al., 2016).

In our work, the dynamic land cover variables are the *percentage of regenerated forest* and *percentage of pasture* in each cell of 1 km x 1 km. As our core interest is the conversion from pasture to forest, we adopt the simplifying assumption that the other land use classes remain static during the calibration and scenarios phase. We also assume that the remnant forests will not be disturbed. We calibrate our potential component using the alternative linear regression models described in Section 2.5. In this case, the potential for each dynamic class in each cell is computed at each time step using the coefficients of the linear regression models estimated for each class. The potential is the difference between the current land cover percentage and the estimated percentage according to the linear regression models (VERBURG et al. 1999). At each time step, we estimate a natural regeneration potential for each cell (and a pasture potential). We then run the allocation simulation until 2015, validating the results against the observed 2015 information (also derived from Ronquim et al. 2016 and Silva et al. 2016a).

We use a multiscale validation metric (VAN VLIET et al., 2016) to support the choice/analysis of alternative models capturing the change from 2011 to 2015. Finally, we run scenarios from 2015 to 2025, as described in Section 2.7.

2.2.7 Scenarios: alternative assumptions about the scale restoration commitments

We explore three alternative scenarios related to different restoration commitments targeting our study area, comparing their cost-effectiveness (see Section 2.2.8 for a description of the cost, soil, biodiversity and carbon indicators considered), according to the following assumptions. During the previous decade (2005-2015), the rate of increase of the natural regeneration cover has been, in average, 60 km²/year (Table 2.1). We assume this rate will be maintained in the next decade (2015-2025), as the contribution of the region to the Atlantic Forest Restoration Pact (that is an additional 600km² in 10 years). We also assume the maintenance of the same conditions and relations captured by the statistical models derived for 2011. Applying the empirically derived relationships relating patterns of land cover to explanatory factors is acceptable for such time frame (VERBURG et al., 2004). For regenerated forest, we opt for using the **Eco Model** to run the scenarios. This model better aligns with our overall goal of favouring passive ecological restoration, minimizing costs related to the active method. For pasture, we use a model combining biophysical, land cover and socioeconomic variables (**BHS model)**.

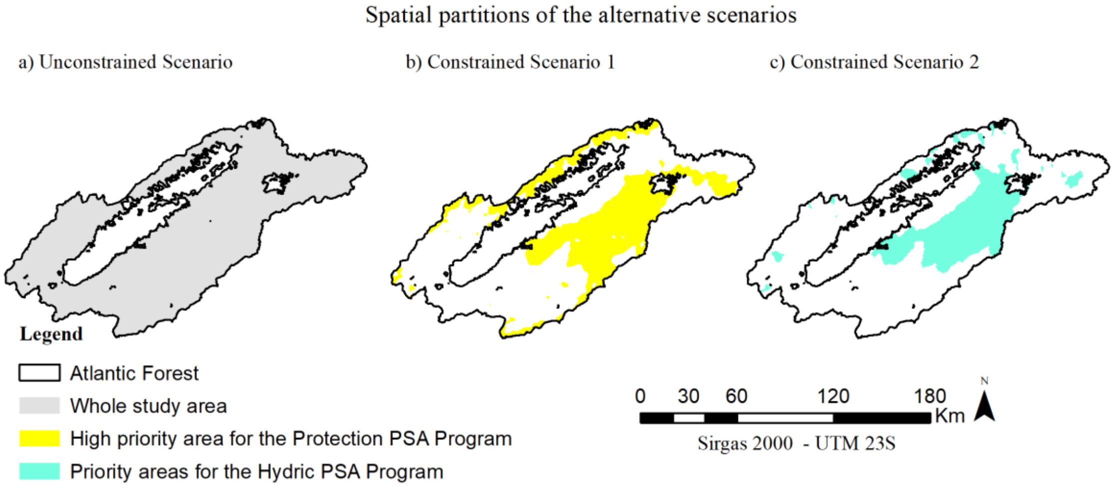
The three scenarios vary in relation to the priority area defined by the different commitments:

- **Unconstrained Scenario (Atlantic Forest Restoration Pact):** Allocation is possible in the pasture area of the whole study area.
- **Constrained Scenario 1 (Protection PSA Program):** Allocation restricted to areas of high priority for the Protection PSA Program, that is, areas for high gain in biodiversity conservation, climate change, and water supply.
- **Constrained Scenario 2 (Hydric PSA Program):** Allocation restricted to 34 watersheds inside our study area, which are relevant for the Hydric PSA Program, that focus on water supply.

Therefore, in each scenario, we work with alternative spatial partitions which might not constrain the possible area of conversion from pasture to regenerated forest (Figure 2.3). The first scenario allows converting pasture into regenerated forest in the whole study area, without constraints or alignment to the state-level programs. This scenario aligns to the Atlantic Forest Restoration Pact (Pact) that aims to restore 15 Mha of degraded lands in the Brazilian Atlantic Forest Biome by 2050 (CALMON et al., 2011), where our study area is located. The second scenario only allows allocating regenerated forest in the pasture area in areas of high priority for gains in biodiversity conservation, climate change, and water supply according to the Protection PSA Program (Figure 2.3.b) (SÃO PAULO, 2017; 2019). The last scenario constrains the allocation of regenerated forest in the remaining pasture area of the 34 watersheds considered as a priority study area for gains in water supply as defined by the Hydric PSA Program (OIKOS, 2015) (Figure 2.3.c).

The spatial partitions considered in the different scenarios contain 5453 km², 1650 km², and 1688 km² of available pasture land, respectively, as illustrated in Figure 2.3. Although with some small differences, the Hydric PSA Program (OIKOS, 2015) is nested to the Protection PSA Program area (SÃO PAULO, 2019). Both of them are nested to the area of the Unconstrained scenario.

Figure 2.3 - Spatial partitions considered in: (A) Unconstrained Scenario; (B) Constrained Scenario 1: high priority areas for the Protection PSA Program; (C) Constrained Scenario 2: Priority areas for the Hydric PSA Program.



Source: Lemos et al. (2021).

2.2.8 Indicators for comparing the scenarios: cost, carbon, biodiversity and soil

The indicators used to compare each scenario are computed as follows (see details in Supplementary Material):

- **Cost of restoration (US$):** For each scenario, we compare the costs of restoration, that is a sum of costs of allocating passive and active restoration across cells. We use the values presented by Brancallion et al. (2019) to assign per hectare costs for natural and active restoration methods. Next, we use the regenerated forest percentage estimated in the **Eco Model** as the *maximum biophysical capacity* (MBC) to forest regrowth. The MBC is used to identify a per cell threshold that will define if the amount of natural restoration a cell can support. We assume that any additional restoration that surpasses this cap value will require an active restoration method (Figure A.4). The total *cost of restoration* is the sum of the cost of restoration of each cell.
- **Biodiversity benefit (Average number of benefited groups or species/ha):** For each scenario, this indicator is the average number of benefited groups or species by restoration actions in the regenerated forest area from 2015-2025. The number of benefited groups or species by restoration actions is derived from the score of priority areas for biodiversity restoration proposed by Joly et al. (2010) (Figure A.6) that ranges from 0 (no priority) to 8 (high priority). For each cell, the number of benefited groups or species by restoration actions is the majority score. The majority score of the cell is multiplied by the regenerated forest incremented area from 2015-2025 of the cell. The majority score of the scenario is the sum of this multiplication of each cell. The *biodiversity gain* is the division of the majority score of the scenario by the total forest incremented area from 2015-2025.
- **Carbon benefit (Ton)**: For each scenario, the indicator represents the total carbon stock increase from the conversion from pasture to regenerated forest area from 2015-2025. For each cell, we quantify the mean carbon stock increase (Ton/ha) based on the carbon stock adopted in the Third Brazilian Inventory of greenhouse gas emissions to the UNFCCC (MCTI, 2015). The mean carbon stock increase is multiplied by the regenerated forest incremented area from 2015-2025 of the cell. The *carbon gain* is the sum of this multiplication of each cell.
- **Soil benefit (Ton):** For each scenario, the indicator represents the total *reduction of soil loss* with the conversion from pasture to regenerated forest area from 2015-2025. For each cell, we quantify the mean reduction of soil loss [ton/ha/year] through the Universal Soil Loss Equation (USLE) based on Padovezi et al. (2018). The mean *reduction of soil loss [ton/ha/year]* is multiplied by the restored forest incremented

area from 2015-2025 of the cell. The *soil gain* is the sum of this multiplication of each cell.

2.3 Results

2.3.1 Statistical analysis results

In this section we present the results of alternative linear regression models relating the regenerated forest cover in 2011 to alternative sets of candidate explanatory variables. The models are built by adding new groups of explanatory variables (Section 2.4). Some variables in these groups are found to be significant ($p<0.05$) in some of the models and non-significant in others. Table 2.3 summarizes the final set of variables, and in which model they were included.

Table 2.3 - Final set of variables considered in the analysis for alternative statistical models. We use standardized beta coefficients to compare the relative order of importance (#) of the factors in explaining the variation of the dependent variable.

Linear regression models to natural regeneration cover from in 2011								
Dependent variable: Percentage of Regenerated forest cover at 2011 (Log)								
Explanatory variables	Biophysical (B) Model		Ecological (Eco) Model		Biophysical, History of land use (BH) Model		Biophysical, History of land use, Socioeconomic (BHS) Model	
	$R^2 = 0.37$		$R^2 = 0.63$		$R^2 = 0.70$		$R^2 = 0.71$	
	AIC = 21900		AIC = 15901		AIC= 12382		AIC= 12005	
	Beta	#	Beta	#	Beta	#	beta	#
% of Southeast orientation (Log)	0.096	5	-	-	-		-	-
% of surface with flat curvature (Log)	0.266	2	0.157	2	0.038	7	0.050	9

(to be continued)

Table 2.3 – Continuation.

Linear regression models to natural regeneration cover from in 2011								
Dependent variable: Percentage of Regenerated forest cover at 2011 (Log)								
Explanatory variables	Biophysical (B) Model		Ecological (Eco) Model		Biophysical, History of land use (BH) Model		Biophysical, History of land use, Socioeconomic (BHS) Model	
	$R^2 = 0.37$ AIC = 21900		$R^2 = 0.63$ AIC = 15901		$R^2 = 0.70$ AIC= 12382		$R^2 = 0.71$ AIC= 12005	
	Beta	#	Beta	#	Beta	#	beta	#
% of slope between 20º and 45º	-	-	-	-	0.018	8	0.017	13
% of slope between 20º and 45º (Log)	0.401	1	0.096	3	-		-	-
% of Humic Cambisol (Log)	-0.021	7	-0.053	6	-		0.016	14
% of high agricultural suitability (Log)	-0.078	6	-0.027	8	-0.043	6	-0.041	10
Average of Elevation	0.132	3	-0.032	7	-		-	-
Average of Precipitation	0.128	4	0.076	4	0.069	4	0.089	5
Average of Temperature (Log)	-0.100	5	-0.074	5	-0.068	5	-0.084	6
% of forests (remnant and regenerated) in 2005 (Log)	-	-	0.704	1	0.736	1	0.715	1
Distance to Eucalyptus in 2005 (Log)	-	-	-	-	-0.109	3	-0.113	4

(to be continued)

Table 2.3 – Conclusion.

Linear regression models to natural regeneration cover from in 2011								
Dependent variable: Percentage of Regenerated forest cover at 2011 (Log)								
Explanatory variables	Biophysical (B) Model		Ecological (Eco) Model		Biophysical, History of land use (BH) Model		Biophysical, History of land use, Socioeconomic (BHS) Model	
	R² = 0.37 AIC = 21900		R² = 0.63 AIC = 15901		R² = 0.70 AIC= 12382		R² = 0.71 AIC= 12005	
	beta	#	beta	#	Beta	#	beta	#
% of Degraded pasture in 2005 (log)	-	-	-	-	0.321	2	0.312	2
Distance to City center (Log)	-	-	-	-	-	-	0.012	16
Distance to Dutra/Railway (Log)	-	-	-	-	-	-	0.081	7
% of Protected areas (Log)	-	-	-	-	-	-	-0.034	12
Average Farm jobs/Total jobs in 2011	-	-	-	-	-	-	-0.124	3
Average Farm revenue/Total revenue in2011 (Log)	-	-	-	-	-	-	0.038	11
Average Stocking rate (@/ha) in 2011 (Log)	-	-	-	-	-	-	-0.067	8
Milk productivity (l/ha) at 2011 (Log)	-	-	-	-	-	-	0.014	15

Source: Lemos et al. (2021).

The **B Model** (biophysical variables only) explains 37% of the variation of natural regeneration in the study according to R^2. The most important factors in this model relate the higher percentage of natural regeneration to the steep slopes with a flat curvature, in elevated areas with higher precipitation (see Table 2.2). Terrain characteristics, climate and agricultural suitability are significant factors in all models. However, adding the percentage of forests (remnant and regenerated) improves to 63% the explanatory power of the model (we name this combination of biophysical factors and percentage of forests as **Eco Model**).

Including additional land cover factors (**BHS Model**) increases the R^2 considerably ($R^2 = 0.70$, AIC = 12382). The significant factors included in the model relate to the percentage of degraded pasture in the cells in the previous years. It also relates distance from planted forests to natural regeneration. These factors remain as the most important ones when socioeconomic factors are included (**BHS Model**).

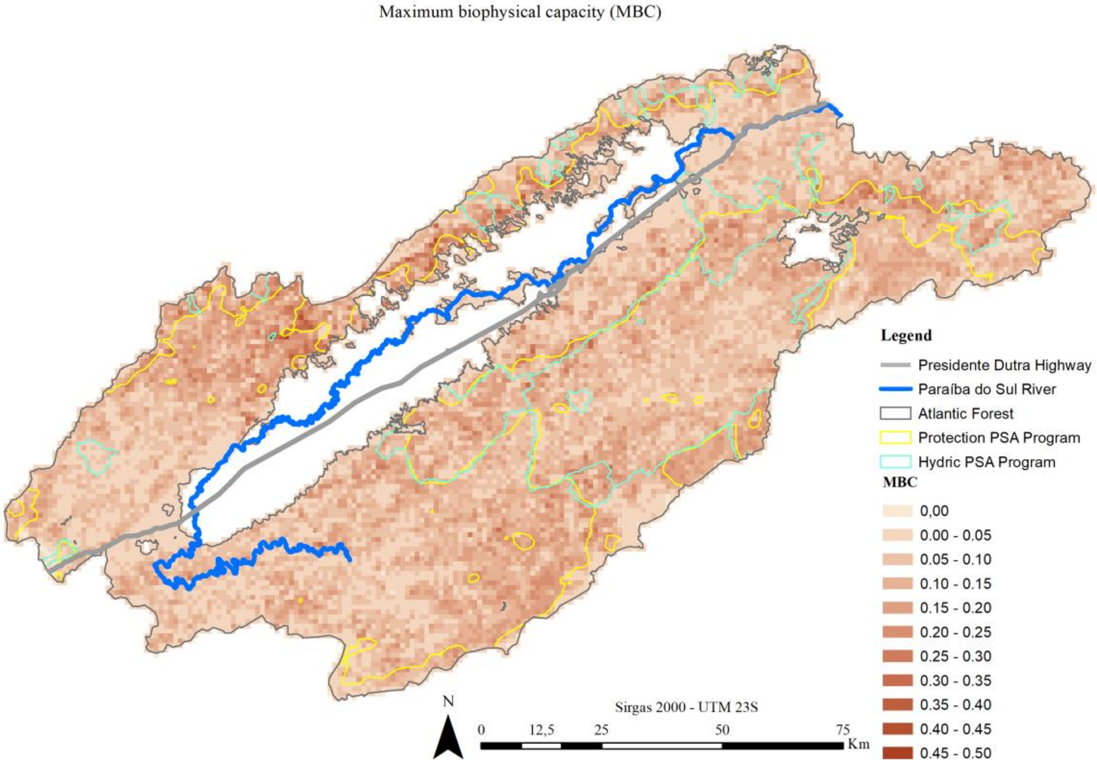
Although adding several socioeconomic potential explanatory factors does not increase the explanatory power of the regression ($R^2 = 0.71$, AIC = 12005), some relevant understanding can be derived from this model. First, the percentage of jobs in rural areas in relation to the total number of jobs in the municipalities becomes the third more important variable in the model. It presents a negative signal, meaning that less jobs in the rural areas in a given municipality implies more natural regeneration in the cells in such municipalities. Aligned to that, the furthest to the main highway (parallel and close to the railway, where most of the large cities and industries are located), the higher the percentage of natural regeneration. Also interestingly, higher stocking rates implies small percentages of natural regeneration within the cell. On the other hand, milk productivity presented a positive signal.

2.3.2 Maximum biophysical capacity

Using the **Eco Model** (Table 2.2), we estimate the spatial distribution of the *Maximum biophysical capacity (MBC)*, illustrated in Figure 2.4. The MBC values are used to compute the cost of restoration in each scenario (Atlantic Forest Restoration Pact, Protection PSA Program and Hydric PSA Program). And the cost of restoration in each scenario is used to compare the cost of all scenarios.

As Figure 2.4 illustrates, the MBC varies from 0 to 0.50 in the study area. MBC values indicate the proportion of the cell area that can support natural regeneration, the allocation of restoration above this biophysical threshold would require active restoration methods, e.g. for cells with 0.3 MBC for which the allocation of regeneration in a given scenario equals to a proportion of 0.4 of the cell area, 0.3 would be allocated as natural restoration and the remainder 0.1 as active restoration. The MBC average is close to 0.1 (see the histogram in Figure A.4), and around 60% of the cells in the region have less than 10% of maximum biophysical capacity for natural regeneration. This impacts the costs of our scenarios, as discussed in the next section.

Figure 2.4 - Spatial distribution of the Maximum biophysical capacity (MBC) estimated using the Eco Model (Linear regression).

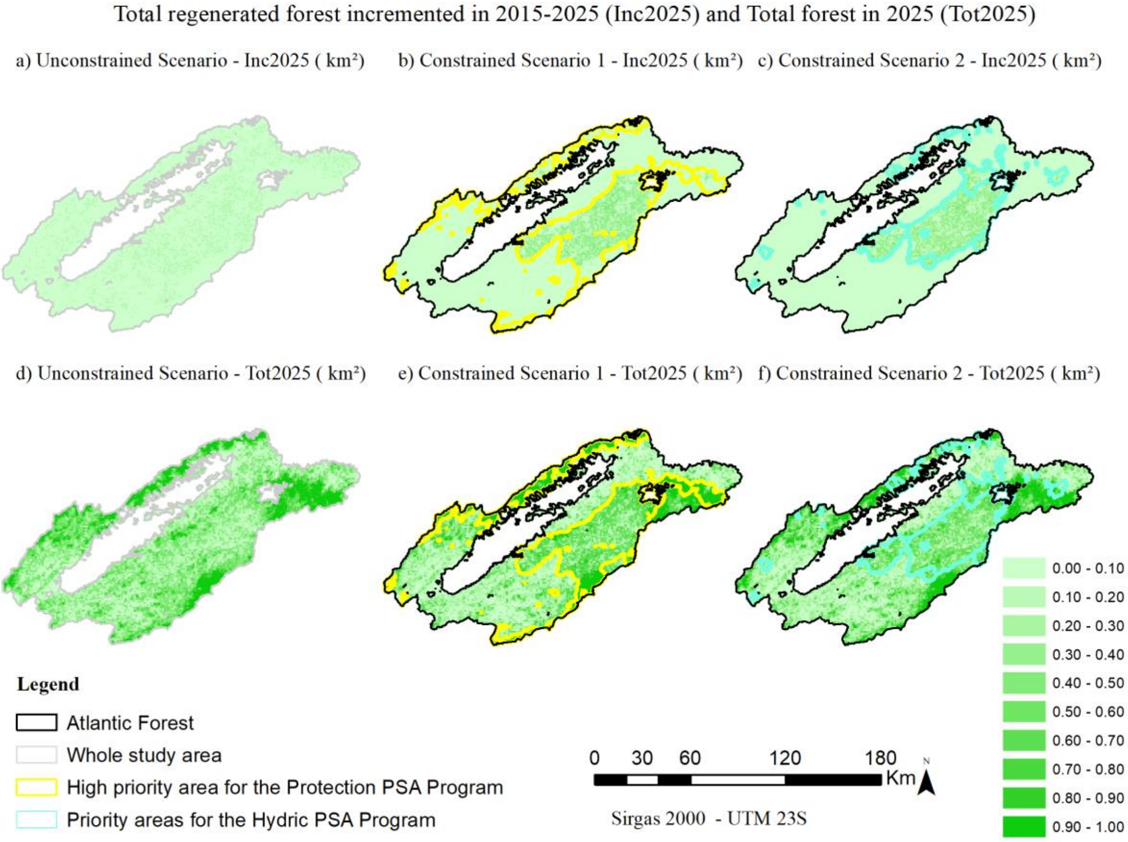


Source: Lemos et al. (2021).

2.3.3 Alternative allocation scenarios

Based on the results of the statistical analysis phase (Section 3.1), in this section we present the LuccME modeling and scenario results. We parameterize, calibrate and validate LuccME (from 2011-2015) with the alternative linear regression models for regenerated forest, as Table A.9 summarizes. Interestingly, this model combination (Ecological for Regeneration and BHS for Pasture) provides slightly better results in the LuccME multiscale validation process from 2011-2015 (Table A.10). Combining the two models allows the LuccME allocation component to explore the competition in each cell between the multiple factors underlying the pasture economic activity and the ecological processes allowing for regeneration.

Figure 2.5 - Scenario results - where the 600 km² of regenerated forest were allocated under the scenarios.



Source: Lemos et al. (2021).

Figure 2.5 illustrates the alternative spatial patterns of change in forest cover from 2015-2025 under the assumptions of the three alternative scenarios (Section 2.7). Given the smaller target-area in the two programs (Figure 2.5.b and 2.5.c), the percentage of change in each cell is comparatively higher than in the unconstrained scenario (Figure 2.5.a). The final forest cover considering existing and newly allocated areas are shown in Figure 2.5.d, 2.5.e, and 2.5.f. Table 2.4 compares the results of the three scenarios considering the indicators of cost, biodiversity, soil and carbon.

Table 2.4 - Scenario comparison: cost-effectiveness (2015-2025) of converting 600 km^2 from pasture to regenerated forest (Eco Model).

Constrained scenarios			
Indicator	**Unconstrained Scenario (Whole area)**	**High Priority Areas - PSA Protection**	**Priority Areas - PSA Hydric**
Cost of restoration (Million US$)	130.65	134.41	133.61
Carbon Gain (M TonC)	4.45	4.50	4.51
Soil Gain (M Ton)	1.82	2.20	2.03
Biodiversity Gain (Average number of taxonomic group/ha)	3.01	2.96	2.78

Source: Lemos et al. (2021).

Table 2.4 shows the comparison of the carbon, biodiversity and soil indicators across the scenarios. Each scenario has positive and negative aspects in relation to each other. Although the Protected PSA and Hydric PSA Scenarios outperforme the unconstrained scenario in relation to the soil and carbon indicators, they present relatively worse biodiversity gain indicators, with a slight decrease in the average number of benefited groups or species. However, all scenarios have a similar number of benefited groups or species, close to three, the dominant category in the study area. On the other hand, the Protection PSA presents a 10% improvement in the soil indicators when compared to the Hydric PSA scenario. The results for carbon are similar.

We observe the enforcement of conversion from pasture to forest within cells with lower natural regeneration potential in the constrained scenarios (Protection PSA Program and

Hydric PSA Program) in comparison to the natural regeneration potential of the unconstrained scenario. This conversion within cells with lower natural regeneration potential results from the prohibition to allocate new forest areas outside the spatial partition of the constrained scenarios - excluding cells that could potentially have higher natural regeneration potential. The enforced conversion from pasture to forest within cells with lower potential increases the total cost in both scenarios (Figure 2.4). In cells with lower potential, it is necessary to use an active (and more expensive) method for restoring the incremented area, which increases the restoration cost. Besides, as we observe in Figure 2.4, given the smaller target-areas in the two programs, the percentage of change in the available cells is comparatively higher to allocate the 600 km² of forest. Changes in the unconstrained scenario are, as expected, more spread, i.e., less concentrated in each cell.

2.4 Discussion

2.4.1 Relevant factors to the natural regeneration process

Independently of the spatial and temporal scales, and methods used, previous studies identify the importance of combining multiple drivers for understanding the natural regeneration potential (Table 2.2). Our work builds on the previous studies that analyzed the underlying factors related to natural regeneration by building models that combine biophysical, land use history, and socioeconomic data in alternative ways.

As Schulz and Schroder (2017) concluded in Central Chile, the main significant biophysical factors explaining forest regeneration in this work are local terrain characteristics. Local terrain characteristics remain significant even when other land cover and socioeconomic variables are added. Carvalho Ribeiro et al. (2020) presupposes that concave areas have local terrain characteristics that favor natural regeneration because they accumulate soil and water. However, our model identified that flat areas are more relevant for natural regeneration. Flat areas are more stable environments, resulting in less movement of soil and water in relation to concave areas. This stability promotes the establishment of propagules during the natural regeneration processes (SANTOS et al., 2016).

South facing terrain is another relevant factor for forest growth as they receive less solar radiation (SILVA et al., 2016a). One possible explanation is that Atlantic Forest species are adapted for shading and prevail in low light conditions (MENDES et al., 2019). Interestingly, the south facing factor is not significant when the forest cover is included (**Eco Model**).

Adding the forest cover variable greatly improves the explanatory power of the statistical model when compared to the biophysical factors only. The results of the **Eco Model** corroborate the findings of Carvalho Ribeiro et al. (2020), that forest fragments are important sources of seeds for nearby areas in natural regeneration processes. Our approach for estimating costs was solely based on the biophysical capacity for undergoing ecological regeneration at the cell level, which provides a straightforward indicator for the necessity of applying active restoration methods, as opposed to previous work (CROUZEILLES et al., 2020) that included socioeconomic drivers when calculating the suitability for natural regeneration and assigning associated costs.

Our statistical analysis also explores the relative importance of other land cover and socioeconomic factors. A key land cover factor in the model is the percentage of degraded pasture, as replacing them by forests that previously occupied the area is a well known process in the region (CHAZDON et al., 2020). In fact, our land cover change data source shows that 74% of the new forest areas between 1985 and 2011 take place over degraded pasture in Paraiba Valley (SILVA et al., 2016a).

We also explore how different categories of socioeconomic factors could improve the statistical models. Although presenting a marginal increase in the explanatory power, the BHS model sheds light on how the socioeconomic heterogeneity of the region relates to the natural regeneration spatial patterns, corroborating previous results that indicate socioeconomic drivers play an important role in forest recovery (SILVA et al., 2016a). The percentage of jobs in rural areas and the distance to the major highway, where the large cities and industries are located (Figure 2.1), are particularly important. In the borders of Paraiba Valley, there is an interesting combination of adequate biophysical and socioeconomic conditions for regeneration, as they are far away from the most economically active areas in the region. Interestingly, the percentage of regenerated forest in the cells also presents a positive relation to both Farm revenue and cattle stocking rate in the BHS model. These results need to be further explored, as they might provide links to the land sparing debate (LOCONTO et al., 2020). These results might also imply that multiple pathways of forest transition (RUDEL et al., 2005; RUDEL et al., 2020) are taking place in the region, driven by the abandonment of degraded pastures in some cases, but potentially by agricultural intensification in others.

2.4.2 Planning the implementation of restoration commitments

The results of our analysis also indicate that there is no “better” solution among the scenarios we explore. Nesting local to large-scale commitments (like in Scenario 2) might provide a compromised solution. Our results reinforce the importance of the simultaneous planning of large-scale and local restoration commitments, and the relevance of multiscale approaches (ADAMS et al., 2016).

Paraiba Valley accumulates 2639 km² of natural regeneration forests from 1985 to 2015 (Table 2.1), mainly converted from pasture areas. Although there is still a large amount of pasture in the region (5453 km²), our results suggest that such areas have low ecological potential for natural regeneration. Using the available data for 2011, calibrated for 2015, our models indicate that the natural regeneration potential of the region is actually very low, as the estimated MBC *(maximum biophysical capacity)* varies from 0 to 0.50 in the study area. This incurs in high restoration costs across scenarios, reinforcing the need to further investigate the feasibility of large-scale forest restoration goals based on the natural regeneration potential (LEWIS et al., 2019). This is particularly true in areas in which the historical anthropogenic degradation can impact ecosystem structure and functioning (ROCHA et al., 2015).

2.4.3 Limitations and suggestions for future studies

One missing aspect in the ecological model is possibly the inclusion of an indicator of soil degradation/loss as a potential candidate to explain the low natural regeneration potential (or MBC) we estimated in our study. Soil degradation/loss reflects the land use history and inadequate agricultural practices (MEDEIROS et al., 2016), which are very common in this region that have undergone different cycles of agricultural production since the 19th century (SILVA et al., 2017). Although other studies have also identified a low regeneration potential for the Paraiba Valley (PADOVEZI et al., 2018), we suggest that future studies could evaluate our estimated MBC by comparing it with field data. Vergarechea et al. (2019) and Zheng et al. (2021) use the observed data for calibrating models that are looking for estimating the regeneration potential.

Furthermore, in future studies, we envision some possible improvements. For example, scenarios could include land restrictions such as forcing new regeneration areas to be evenly distributed across the 34 basins in the Hydric scenario. Such restrictions could also address especifities of the legal environmental framework in Brazil, in particular theForest Code (SPAROVEK et al., 2019). Another aspect not considered in our analysis is the transaction costs, for example the cost of negotiating with farmers and monitoring the implementation of a PSA program. It could possibly be higher in the unconstrained scenario, reflecting the less concentrated effort. Another possible improvement is the use of fine resolution data for estimating the biodiversity and the gains.

The current version of LuccME Model does not account for the competition for pasture land with other uses, such as eucalyptus. Finally, and importantly, the explanatory variables in our model are currently not dynamic. This is particularly relevant for distance to forest areas, especially, because remnant forests are decreasing over time (Table 2.1). Future works could consider dynamically updating such variables, in particular the changes in forest areas produced by the model itself. This might increase the *maximum biophysical capacity (MBC)* of the landscape to forest growth, and consequently the local need for active methods.

2.5 Conclusion

The implementation of large-scale restoration commitments is a key challenge of our times. Our study builds upon the extensive literature about forest restoration and proposes a novel approach to support the planning of multiple restoration goals and programs targeting the same area. We combine statistical analysis and spatially-explicit dynamic modeling to assess the cost-effectiveness of alternative allocation models. The LuccME allocation mechanism distributes the necessary change through the scenario target-area proportionally to their potential for natural regeneration. We believe our approach can positively contribute to improving forest restoration commitments. Programs for Payment for ecosystem services, for example, could use our results for selecting the farms that are most indicated for receiving payment for passive restoration. We also believe our approach can be used to support large-scale decision making about the overall design of alternative plans and combined to other approaches for more refined analysis (e.g., optimization models).

3 MAXIMIZING MULTIPLE ENVIRONMENTAL BENEFITS IN BRAZILIAN ATLANTIC FOREST: COMBINING RESTORATION COST AND PAYMENTS FOR ECOSYSTEM SERVICES

3.1 Introduction

From global to local levels, land use decisions and policy instruments can affect landscapes and livelihoods in heterogeneous ways (ADAMS, et al., 2016). Payments for ecosystem services (PES) are one type of instrument that can promote the conversion of low productivity agricultural lands into forest areas (KAWASAKI et al., 2020), compensating landholders for leaving forest intact or for planting new trees (JACK; JAYACHANDRAN, 2019). Some PES programs grant cash through financing restoration actions within private lands, and can foster a well-balanced regional solution between environmental and socio-economic outcomes, such as rural jobs and food-security (LE et al., 2014).

In Brazil, financing restoration through PES programs could potentially be a good opportunity for landowners that are legally required to restore their forest cover deficits in areas called Legal Reserve (LR) and Permanent Preservation Areas (in Portuguese, *Área de Preservação Permanente* - APP), as established by the Brazilian Forest Code (BFC) (SPAROVECK et al., 2015). Currently, PES programs on municipality and state levels pay for restoration actions over legally required deficit areas, but at the national level, new regulations might prohibit such payments with public resources in some situations. Brazilian Congress enacted Law number 14.119/2021 (BRASIL, 2021), called National Policy for Payment for Ecosystem Services (in Portuguese, *Política Nacional de Pagamento por Serviços Ambientais* - PNPSA). This law establishes that only legal deficit areas with high priority for water supply or biodiversity conservation are allowed to be restored using public resources via national-level PES programs. This can then lead to discrepancies among payment mechanisms in place at municipality, state, and national levels - with some PES programs paying for restoring the legal deficits, while others do not (ALARCON et al., 2017).

The impacts of these alternative PES mechanisms on the cost-effectiveness of multiple environmental benefits and restoration costs need to be further investigated. Previous studies have employed linear programming to explore the optimal distribution of restoration, considering two environmental benefits (STRASSBURG et al., 2018; 2020). In both studies, the authors adopt decision variables to represent the proportion of natural vegetation that can be restored within regular cells (e.g., 25x 25 km²) and elabore an objective function that maximizes restoration benefits while reducing restoration and opportunity costs. Such studies explore the restoration benefits to Biodiversity Conservation and Carbon Sink, which are the two most relevant environmental benefits discussed in different restoration commitments such as the Bonn Challenge (LEWIS et al., 2019).

In this work, we build upon both previous studies to propose a novel optimization approach to model how and where multiple PES mechanisms might change the cost-effectiveness of three environmental benefits in forest landscape restoration initiatives. We maximize three environmental benefits related to biodiversity conservation, carbon stock increase and reduction of soil loss, while previous studies maximize only the first two environmental benefits. Our work *adopts private rural properties (PRPs) as planning units*, which is the lowest level of decision making (ADAMS et al., 2016). Using detailed information about each PRP available in the rural cadastral database (CAR) and multiple PES mechanisms, we build alternative scenarios to explore the cost-effectiveness in the enforcement of the BFC as well as the recent PNPSA. The goal of our scenarios is to support information for answering the questions: (1) How much do the restoration of the legal deficits according to the Brazilian Forest Code influence the costs, benefits, and spatial patterns of restoration in the Paraiba Valley? (2) How much do alternative PES mechanisms in legal deficits according to the Brazilian Forest Code influence the costs, benefits, and spatial patterns of restoration in the Paraiba Valley? To achieve this goal, we explore restoration costs (combining implementation restoration costs with opportunity cost and PES) and environmental gains (biodiversity, carbon, and soil) of restoration scenarios, aligned with different public policies in the Paraiba Valley in São Paulo State (in Portuguese, Vale do Paraíba Paulista - VPP).

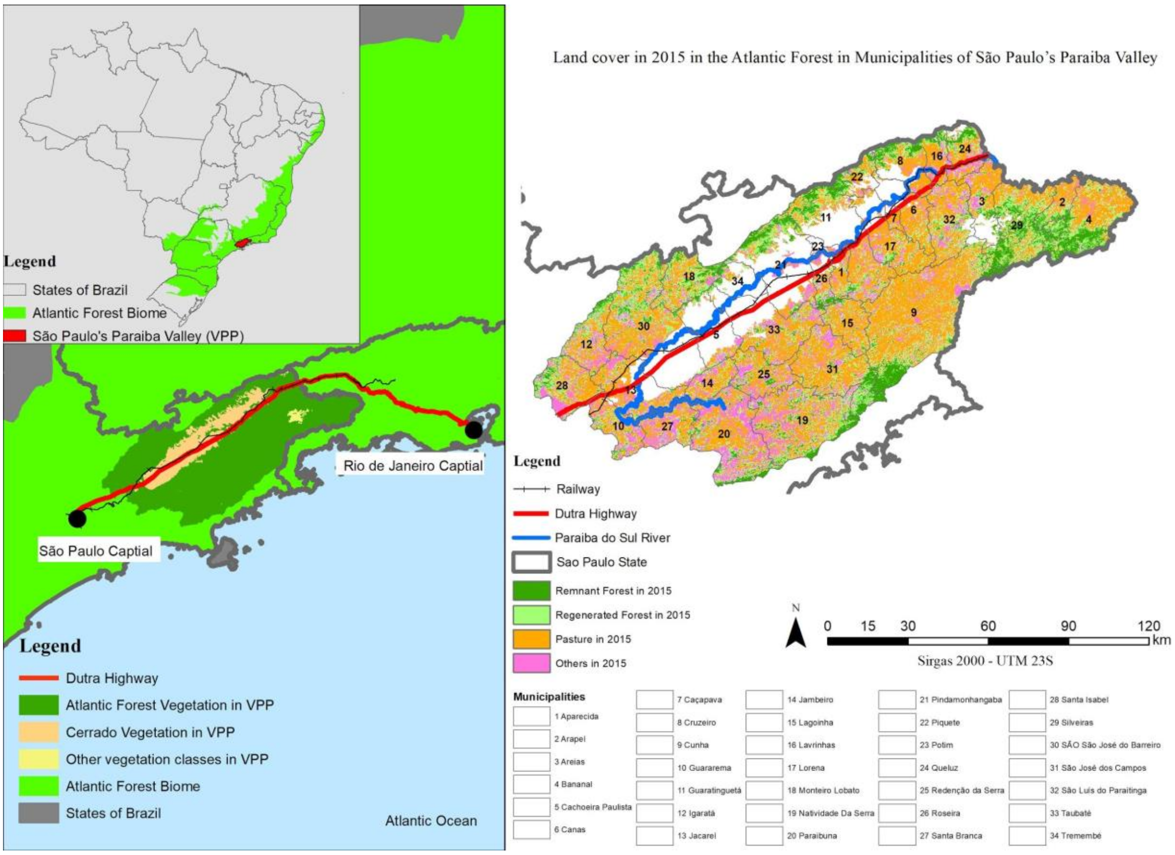
This paper is structured as follows. Section 3.2 describes the study area and the methods for assessing cost-effectiveness of five **forest landscape restoration strategies**, including the database organization, our modeling approach and scenarios. Section 3.3 presents the results, including the characterization of the PRP and the cost-benefit analysis results. Section 3.4 discusses the results in relation to previous analyses, in particular how the PRPs could contribute to achieving the restoration goals while also complying with the BFC and recent PNPSA. Section 5 concludes this paper.

3.2 Material and methods

3.2.1 Study area

Paraíba Valley in São Paulo State encompasses 34 municipalities with heterogeneous socioeconomic characteristics, supporting a population of over 2 million inhabitants. It is an old occupation region that has undergone historically different cycles of agricultural production since the 19th century. Pasture areas within the study area usually have low productivity, with reduced land competition for more profitable uses (SILVA et al., 2016a,b). Milk production activity is responsible for around 73% of the agriculture revenue, while the overall agricultural revenue represents less than 1% of the revenue of agricultural production in São Paulo State in 2015 (IBGE, 2021a,b).

Figure 3.1- Location of the study area (Paraiba Valley).



Source: Author's production.

Approximately 80% (12,000 km²) of VPP is covered by Atlantic Forest vegetation classes. Because of the large extension of Atlantic Forest vegetation in VPP, we focus our analysis solely on the area that has been originally occupied by Atlantic Forest vegetation. The region accumulated 2,639 km² of natural regeneration of Atlantic Forests from 1985 to 2015, mainly converted from pasture areas (Figure 3.1). Although there is still a large amount of pasture in the region (5,453 km²) (Chapter 2).

Considering that the region has very low agricultural productivity and is very important for biodiversity conservation (SILVA et al., 2016a), VPP has been chosen as the target area for different programs for PES of forest landscape restoration, such as the Protection PSA Program. This program is a governmental initiative that aims at biodiversity conservation, climate change mitigation, and water resources conservation. It allocates financial resources for restoration actions on private rural properties (PRPs). Private landholders receive around payment for implementing restoration actions on their PRP. Restoration can take place on legal deficit areas as well as outside deficit areas, henceforth called Private no Obligations (noOB) lands (SÃO PAULO, 2019).

3.2.2 Database organization

The first step of our modeling approach consists of creating a database organized per private rural property (PRP), as follows: (1) compile the PRPs database, and quantify legal deficit, remaining pasture area, regenerated forest and natural regeneration potential inside them in 2015 (Section 3.2.2.1); (2) estimate economic indicator for each PRP, considering different forest restoration actions, agricultural activities and PES (Section 3.2.2.2); (3) compile information about three environmental indicators for each PRP (biodiversity, carbon, and soil benefits) (Section 3.2.2.3). Table 3.1 presents the complete list of attributes for each PRP, detailed in the following subsections. Appendix B contains a complete description of the process to prepare the data.

Table 3.1 - Attributes compiled for each PRP.

Category	**PRP atribute**
Area	Total area of the PRP [ha]
Size Class	Small, Medium, or Large
Deficits	APP deficit [ha]
	LR deficit [ha]
	Total deficit [ha]
Pasture	Total Pasture [ha]
	Pasture as APP deficit [ha]
	Pasture as LR deficit [ha]
	Pasture outside APP/LR deficit (noOB) [ha]
Forest Regeneration	Regenerated forest [ha]
	Maximum biophysical capacity [ha]
	Natural regeneration potential [ha]
Restoration method	Pasture area for active restoration [ha]
	Pasture area for passive restoration [ha]
Economic Parameters	NPV of restoration actions [US$/ha]
	NPV of milk production activity [US$/ha]
	NPV of payment in program for payment for ecosystem services [US$/ha]
Economic Indicator	Cost - Sum of up to three NPV values [US$/ha] (depending on the scenario)
Environmental Indicators	Biodiversity - [Mode of number of benefited groups or species]
	Carbon - Mean Stock Carbon Increase [Ton/ha]
	Soil - Mean Soil Loss Reduction [Ton/ha/year]
Maximum Restorable Area	Available Pasture Area to be restored [ha] (depending on the scenario)

Source: Author's production.

3.2.2.1 Legal deficit and natural regeneration potential

The land tenure structure 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: the SIGEF (INCRA, 2021) and the SICAR (SICAR, 2020). Although both contain information about private property boundaries, only SICAR has information about springs, watercourses, and location of different classes of APP within PRPs. For this reason, here we use the rural cadastral information (in portuguese, *Cadastro Ambiental Rural* - CAR) data. The original CAR data presents a substantial number of overlaps among the PRPs, and between PRPs and public lands. Appendix B details the necessary steps to prepare the CAR data. By selecting only the PRPs that are fully within theAtlantic Forest in the Paraiba Valley, there are *16,855 units* out of the 23,274 original CAR properties for the VPP, occupying 6,461 km², around 58% of our study area.

As a next step, we classify the PRPs as *small, medium*, and *large* properties, considering the official fiscal module size (INCRA, 2020). This classification is used by the Brazilian State for taxation and land governance purposes, being necessary to calculate *legal deficits*. For this purpose, we adopt the rules of the BFC, in particular articles 12,15, 61-A, and 67. These articles present the rules to restore native vegetation of the APP (61-A) and LR (12, 15, and 67) within PRPs. Although the latest BFC granted amnesty to most irregular deforestation prior to 2008 (SOARES-FILHO et al., 2014), in this work, we do not consider the year of deforestation to decide whether a given deforested area is irregular.

To quantify the *total pasture area* within PRPs, we intersect the PRPs described above with the land cover map generated by Ronquim et al. (2016). We separate the pasture of each PRP in two classes: p*asture areas considered legal deficit (both APP and LR)* and *noOB lands*, which are outside APP and LR. This distinction of pasture classes is relevant for exploring scenarios related to the BFC.

To estimate the *natural regeneration potential* in each PRP, we use the difference between *regenerated forest cover* and *maximum biophysical capacity* (MBC) as proposed by Lemos et al. (2021) (Chapter 2). The MBC is elaborated using a linear regression model that *better aligns with our overall goal of favoring passive ecological restoration, and it indicates the amount of natural restoration that can support.* The difference between these attributes allows us to discount the regenerated forest that happened in the past, identifying the actual natural *regeneration potential* (NRP) for the remaining pasture areas.

Based on this value, we estimate the proportion of the remaining total pasture area in the PRP which would have to be restored by **active and passive restoration methods,** as follows. When the NRP is equal to or less than zero, we consider that PRP does not have natural regeneration potential. In this case, the remaining pasture areas in the PRP would have to be restored using an active restoration method. When the NRP is equal to or greater than the remaining *pasture area*, we consider that only natural regeneration (passive method) would be enough to restore the whole pasture cover of the PRP. On the other hand, if the NRP is greater than zero but smaller than the remaining pasture area in the PRP, only *a share of the pasture area* could be restored using natural regeneration, calling for a combination of passive and active restoration methods. The difference between the pasture area and natural regeneration potential is the amount of pasture area that needs to be restored by an active method, while the remaining pasture areas can be restored with natural regeneration.

3.2.2.2 Economic indicator

We explore three economic activities: restoration actions, milk production, and PES. To estimate the financial viability of different activities, it is necessary to standardize their economic costs. We adopt the Net Present Value (NPV), a financial analysis tool for comparing the financial viability of different projects (RUNTTING et al., 2019).

We make four assumptions to estimate the NPV of the economic activities. First, each PRP is able to develop a restoration project. Second, we assume 2015 as the first period of our analysis because it is the same year of the land cover data used in our analysis. Third, because of the high representativity of milk production compared to other agricultural activities (IBGE 2021a,b), we focus on milk to estimate the opportunity costs. Fourth, we use the financial values of PES from the Protection PSA Program, which takes place in our study area (SÃO PAULO, 2019).

To estimate the NPV, the net cash inflow-outflow is the difference between the revenue and cost of a given economic activity, as follows:

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} \tag{3.1}$$

Where Rt is the net cash inflow-outflow during a single period t, *i* is the *discount rate or return* that could be earned in alternative investments, and *n* is *the total number of time periods.* Using this equation, we estimate the NPV for each economic activity, measured as US$/ha[2]. They are:

- **NPV of restoration actions (RestNPV):** Restoration actions rely on 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 for each PRP 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 splitted into implementation costs (at the beginning of the project) and maintenance costs (during the project), necessary to better estimate the net cash inflow-outflows during a single period of 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 Haddad and Bastos (2019). The revenue of the restoration actions is always zero, because we use ecological forest restoration methods that do not have revenue (PADOVEZI et al., 2018). We use a discount rate of 10% by year, based on Prata and Rodriguez (2014).

- **NPV of milk production activity (MilkNPV)**: We use municipality data to compute the mean revenue of milk production. It results from dividing the total revenue of milk production activity in each municipality for 2015 (IBGE,

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[2] We convert all values from BRL to USD, applying the conversion rate of US$ 1 equals to R$ 3.95, as proposed by Strassburg et al. (2016).

2021a) by the total pasture area in each municipality (RONQUIM et al., 2016). Each PRP uses the mean revenue of the municipality it belongs to. We estimate the mean milk production cost [R$/ha] using the average cost/revenue indicator for milk between 2014 and 2017[3] for Guaratinguetá, a very representative municipality in our study area (CONAB, 2010). Using the mean revenue [US$/ha] and mean cost [US$/ha], we estimate the net cash inflow-outflows of the milk activity. Concerning the milk activity duration, we use the maximum number of time periods for the milk activity to have positive economic viability, which is 27 years. We apply a discount rate of 10% by year, which is the rate for milk activity in Brazil (PERES et al., 2009).

- **NPV of PES (PESNPV)**: We consider that private landholders receive payments of 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. Therefore, only payments are used to compose the net cash inflow-outflow during the Protection PSA program. We apply a discount rate of 10% by year, which is the discount rate for forest activity in Brazil, based on Prata and Rodriguez (2014).

We combine these three NPVs to estimate the mean restoration cost of each PRP, as follows:

$$mean\ restoration\ cost = MilkNPV - RestNPV - PESNPV \tag{3.2}$$

In this equation, the used signals are because we formulate the mean restoration cost from the landowner perspective. MilkNPV has a positive signal because the landowner lost the milk activity remuneration due to conversion from pasture to forest. The RestNPV has a negative signal because the restoration action only presents a cost. PESNPV has negative sign because the landowner receives PES as remuneration in the presence of a PES program that helps to reduce the expense of resources with restoration actions. The mean restoration cost [US$/ha] is our economic indicator.

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[3] This indicator is negative for 2015 because it was an atypical year for milk activity (CONAB, 2010), therefore we exclude this value.

3.2.2.3 Environmental indicators

The restoration objective of our optimization model combines benefits of biodiversity conservation as well as environmental services of carbon stock and soil conservation. As an input for the model, we use three indicators to represent the environmental contribution of restoring each PRPs. These indicators are:

- **Biodiversity**: The habitat increase is relevant for biodiversity conservation, since it benefits different species and landscape structural parameters (such as forest fragmentation) (CROUZEILLES et al., 2020). Considering the judgement of eight teams of experts on increasing the habitat that can benefit the conservation of seven taxonomic groups (such as mammals and birds) and landscape parameters (such as larger fragments and higher connectivity), Joly et al. (2010) proposed a score of priority areas for receiving restoration actions. This score is based on the experts' judgment of whether conservation of a specific taxonomic group benefits or not of habitat restoration actions in that area. Each expert team (that is, one team specializes in mammals, another specializes in birds, and so on) considers if the restoration actions contribute or not to conservation of each specific taxonomic group, and the score is the number of times the area has been judged by experts as relevant for the conservation. This score ranges from zero (no priority) to eight (high priority), indicating the priority for the area to receive restoration actions. For example, score three means that a restoration action can benefit three taxonomic groups, or two taxonomic groups and a landscape structure. We use this score to elaborate our biodiversity indicator. This indicator is the mode of score identified for pasture areas of the respective PRP that means the number of benefited groups or species by the restoration action of the respective PRP.

- **Carbon:** We estimate the carbon stock increase based on the recommendations of the Third Brazilian Inventory of greenhouse gas emissions to the United Nations Framework Convention on Climate Change - UNFCCC (MCTI, 2015; LEMOS et al., 2021). First, we identify the vegetation types present in our study area, then we estimate the difference between the mean carbon stock in regenerated forest for each vegetation type (44% of the carbon stock of pristine forest) and the mean carbon stock of pasture cover. This difference indicates the mean carbon stock removal with conversion from pasture to regenerated forest (ton/ha) that represents the mean carbon stock increase by vegetation type (Ton/ha). Using the area-weighted average of this difference for each PRP, we estimate our carbon indicator as the mean carbon stock increase [ton/ha] by converting from pasture to forest in the respective PRP.

- **Soil:** We estimate the reduction of soil loss [Ton/ha/year] based on Padovezi et al. (2018) that estimates the soil loss for the VPP through the Universal Soil Loss Equation (USLE). For simulating soil loss before restoration, we use the three same input data of Precipitation, Soil and Elevation adopted by Padovezi et al. (2018), and the land cover data for 2015 from Ronquim et al. (2016) as our input data of land cover. For simulating the soil loss after the restoration, we reclassify all pasture areas as forest cover to quantify the soil loss. The difference of soil reduction among these two simulations is the reduction of soil loss [Ton/ha/year] provided by the restoration. Using the average of this reduction for each PRP, we estimate our soil indicator for each PRP as the mean reduction of soil loss [Ton/ha/year] with the conversion from pasture to forest.

3.2.2.4 Maximum restorable area

In this work, we assume each PRP has a *maximum restorable area* (MRA) of 50% of its pasture area [ha]. This is a strategy for keeping part of the pasture areas to continue the milk production, which is the main agricultural activity. The environmental benefits as well as the total benefit from restoring a given PRP will be related to its MRA.

3.2.3 Modelling approach

Linear programming (LP) is an approach that transforms a complex problem into a mathematical model to find out the best solution among a range of possibilities. It uses an objective function represented as a mathematical equation to describe the relationship between actions and outcomes. A set of restrictions that limit the search space are also described as mathematical equations. The objective function is then solved by a computational algorithm that finds out a maximum or minimum result for the equation, guaranteeing that all restrictions are satisfied (BEYER et al., 2016).

In this work, we use LP to maximize environmental gain through restoration of pasture areas of PRPs within the Paraiba Valley. We develop a multicriteria optimization model to investigate alternative restoration scenarios. The objective function is described as follows:

$$\max \sum_{i}^{N} \left(\frac{w_b b_i + w_c c_i + w_s s_i}{m_i} \right) MRA_i x_i \tag{3.3}$$

$$\text{subject to} \sum_{i}^{N} MRA_i \, x_i \leq T \tag{3.4}$$

where:

- N is the amount of PRPs;
- MRA_i is the maximum restorable area of i^th^ PRP;
- x_i is the decision variable, ranging from zero to one, that represents the *proportion of the MRA* in the *i*th PRP;
- b_i , c_i , and s_i are the biodiversity, carbon, and soil gains for ith PRP, respectively;
- w_b, w_c, and w_s are weights, ranging from zero to one, for biodiversity, carbon, and soil, respectively, with $w_b + w_c + w_s = 1$;
- m_i is the mean restoration cost of ith PRP;
- *T* is the total area to be restored.

The total area (*T*) for restoration in each scenario is implemented as a constraint, ensuring approximately the same total restored area in all scenarios. Based on this constraint and on the decision variable (proportion of the MRA in each PRP), the model seeks the best solution to attain our restoration objectives.

Considering that our restoration objectives have different units (biodiversity (b_i): [number of benefited groups or species], carbon (c_i): [Ton/ha] and soil (s_i):

[Ton/ha/year]), we investigate how to combine them as part of the optimization process. We include our three objectives in a unique single objective function, using weights (w_b, w_c, and w_s) associated to each environmental benefit, with the relative contribution of the biodiversity, carbon, and soil components, respectively. Given a set of weights, a simulation of the LP model finds out the optimal allocation of restoration areas that maximises the environmental benefits according to their weights. It is important to note that each of these weights will have the same value for each PRP in a single run of the LP model.

As the weights are parameters of the LP model, we apply two steps to find out the best solution to our model:

1. Run LP model three times, each with a given weight set as one. These simulations will find the maximum benefit of soil (using soil as the only relevant environmental benefit, that is, $w_s = 1$, $w_c = 0$, $w_b = 0$), carbon ($w_s = 0$, $w_c = 1$, $w_b = 0$), and biodiversity ($w_s = 0$, $w_c = 0$, $w_b = 1$) individually. Together, these three cost-effective solutions describe the Pareto frontier (BEYER et al., 2016), which is the maximum (possibly not attainable) solution that can be found by any possible combination of w_s, w_c, and w_b.
2. Look for a solution in the search space $0 \leq w_s \leq 1$, $0 \leq w_c \leq 1$, $0 \leq w_b \leq 1$, that maximizes the proportion of each of the three environmental benefits proportionally to the maximum benefits found in (1). The results for these combinations of parameters is a 3D surface describing the tradeoffs among the three objectives, called *Pareto surface*. We perform an exhaustive search to find out the solution that has the minimum sum of the three proportions between the benefits found and the maximum benefits. Note that this strategy now considers that they are equally important.

For example, suppose that the first step found that the maximum benefit of soil is 1 MTon, the maximum benefit of carbon is 4 MTon, and the maximum benefit of biodiversity is 100,000 as the sum of mode number of benefited groups or species. The second step will then search for solutions that maximize the proportional percentage to these three values. Now suppose that during the exhaustive search it has found two solutions: (1) 0.95 Mton for soil, 3.6 Mton for carbon, and 98,000 as the sum of mode number of benefited groups or species for biodiversity, and (2) 0.97 Mton for soil, 3.6 Mton for carbon, and 95,000 as the sum of mode number of benefited groups or species for biodiversity. The first solution has a percentage (95%; 90%; 98%) of the best solution, while the second one has (97%; 90%; 95%), which indicates that the first solution is better as it is closer to the maximum benefit of soil, carbon and biodiversity.

3.2.4 Scenarios

Lemos et al. (2021) (Chapter 2) explore restoration scenarios aligned with different restoration commitments: Hydric PSA Program and Protection PSA Program. The Hydric PSA Program is a local initiative that aims to restore forest inside 34 watersheds that are priority areas for water resources conservation in VPP; these areas are defined based on soil erosion and their relevance to the human water supply (OIKOS 2015). The Protection PSA Program is a state initiative, and it is one of the PSA programs of the Atlantic Forest Connection Project (in Portuguese, Projeto Conexão Mata Atlântica) present in VPP; these program aims to protect and manage of remaining and regenerating forest fragments that are relevant for biodiversity conservation, increase the carbon stock, reduction the soil erosion, and human water supply (SÃO PAULO 2019). In short, these PES programs have the objective of restoring areas that are relevant to biodiversity conservation, carbon stock increase and reduction of soil loss. The authors assume the same increase of the forest (600km²) that has occurred during the previous decade (2005–2015) as the contribution of the region for the next decade (2015-2025).

Using the same 600km², we elaborate five restoration scenarios that combine different strategies related to the level of law enforcement and to the payment rules for PES programs. In these scenarios, we explore the cost-effectiveness of two public policies: BFC and PNPSA. Table 3.2 summarizes the five scenarios assumptions.

Table 3.2 - Summary of the explored scenarios.

Scenario	***Brazilian Forest Code application***	**PES mechanisms**
Sc.1- *Unconstrained-noPES*	Restore 600 km² of pasture areas within PRPs using the optimisation framework	No PES to restore pasture areas within PRPs
Sc.2 - BFC-noPES	Restore 100% of the legal deficit and optimize the restoration of the difference to 600 km² on noOB pasture areas	No PES to restore noOB pasture areas and deficit areas
Sc.3 - BFC-PESnoOB	Restore 100% of the legal deficit and optimize the restoration of the difference to 600 km² on noOB pasture areas	PES to restorenoOB pasture areas
Sc.4 - BFC-PESdeficit	Restore 100% of the legal deficit and optimize the restoration of the difference to 600 km² on noOB pasture areas	PES to restore noOB pasture areas and deficit areas.
Sc.5 -Unconstrained-PES	Restore the 600 km² of pasture areas within PRPs using the optimisation framework	PES to restore pasture areas within PRPs.

Source: Author's production.

Scenario **Sc.1** (**Unconstrained-noPES**) optimizes the conversion of 600km² of pasture to forest in the whole PRP, while scenario **Sc.2** (**BFC-noPES**) optimizes the conversion from pasture to forest only in areas without legal deficit, that is, on noOB pasture areas, converting pasture into restored forest in 100% of the legal deficit. To quantify the environmental benefit and cost of the conversion from pasture areas within the legal deficit to restored forest, it is not necessary to run an objective function, as they can be quantified straightforwardly. In other words, **Sc.1** is not aligned to BFC (BRASIL, 2012; FREITAS et al., 2017), while **Sc.2** is, enforcing the obligation of restoring legal deficits. The difference between these scenarios provide support information to answer the following question: (1) How much do the restoration of the legal deficits according to the Brazilian Forest Code influence the costs, benefits, and spatial patterns of restoration in the Paraiba Valley?

Sc.3 (**BFC-PESnoOB**) and **Sc.4** (**BFC-PESdeficit**) optimize the conversion from pasture to forest only *in areas outside legal deficit*, that is, noOB pasture areas, quantifying the environmental benefits and costs of converting from pasture areas within legal deficit. **Sc.3** and **Sc.4** are aligned with the BFC as it requires restoring legal deficits, considering different PES mechanisms based on *Article 9* of PNPSA (BRASIL, 2021). Landholders receive PES for restoring noOB pasture areas only in **Sc.3,** while in **Sc.4** they receive PES for restoring noOB pasture areas as well as deficit areas. Differently from **Sc.3/Sc.4**, **Sc.5** (**Unconstrained-PES)** optimizes the conversion of 600km² of pasture to forest in the whole PRP. **Sc.5** optimizes the conversion from pasture to forest without considering if the pasture area is within APP or RL areas. In this case, landholders receive PES for restoring pasture areas. In other words, **Sc.5** is not aligned to BFC, presenting a third mechanism of payment by the Program for Ecosystem Service, a mechanism widely adopted by PES programs on municipality and state levels. The difference between **Sc.2**, **Sc.3 and Sc.4** provides support information for answering the question (2) How much do alternative PES mechanisms in legal deficits according to the Brazilian Forest Code influence the costs, benefits, and spatial patterns of restoration in the Paraiba Valley?

3.3 Results

3.3.1 Characterization of the Private Rural Properties (PRP)

In this section we present an overview of the PRP attributes (including land cover, legal deficit, environmental and economic indicators) resulting from the database organization process described in Section 3.2.2 (Table 3.1). There are the parameters which will later be used to run the restoration scenarios (Section 3.3.1 and 3.3.2). Small PRPs are predominant in number in the Paraiba Valley, representing 91% of all PRPs. The total pasture area within PRPs is equal to 3,543 km², with 306 km² of pasture areas in legal deficit. There are 766 PRPs without any pasture area. Table 3.3 characterizes the PRPs according to size and legal deficit parameters in our study area.

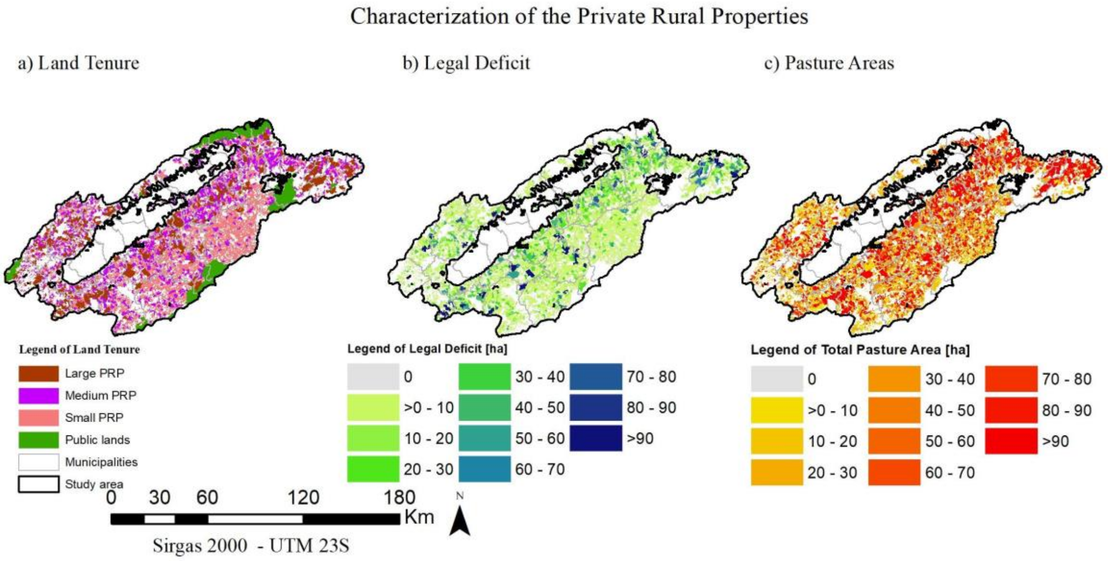
Table 3.3 - Composition of Private Rural Properties (PRP).

PRP	Small	Medium	Large	APP deficit	LR deficit	Total deficit	Total Pasture	Pasture as deficit	Pasture in noOB
16,855 [number]	15,335	1,276	244	11,794	269	11,808	16,089	11,194	16,061
100% [number]	91%	8%	1%	70%	2%	70%	95%	66%	95%
6,461 [area in km^2]	3,173	1,908	1,380	354	20	374	3,543	306	3,237
100% [area in km^2]	49%	30%	21%	5.5%	0.3%	5.8%	55%	5%	50%

Source: Author's production.

Considering the class size, legal deficit, and pasture area characteristics, the small PRPs are distributed across the study area, while medium and large PRPs are more definite close to the major highway (Dutra Highway) (Figure 3.1). Figure 3.2 shows the spatial distribution of each of these characteristics.

Figure 3.2 - Spatial distribution of Private Rural Properties: a) Land tenure, b) Legal deficit, and c) Pasture areas.



Source: Author's production.

Table 3.4 summarizes the economic indicators of the PRPs. RestNPV (restoration actions NPV) signal is negative as it only represents a cost. The PRPs with minimum RestNPV (US$ -2,017/ha) correspond to areas where active restoration will be necessary (seedling planting). The maximum RestNPV (US$ -48/ha) represents areas where natural regeneration is enough for restoring 100% of the pasture of the PRPs. For the remaining 7723 PRPs (45% of our PRPs), it will be necessary to combine active and passive methods. In relation to MilkNPV, a positive signal means that the revenue is higher than the cost of the milk activity. However, the MilkNPV is generally low because the Revenue/Cost is equal to 0.98 (CONAB, 2010), indicating that its profit is very small. Finally, the mean Net Present Value of Ecosystem Services Payments (PESNPV) is always equal to 377 US$/ha, based on the PSA Protection payment values (SÃO PAULO, 2019).

Table 3.4 - Economic parameters of PRPs.

	Characterization of Economic parameters								
PRPs	**Value [US$/ha]**	**Nº of PRP [%]**	**Local**	**Value [US$/ha]**	**Nº of PRP [%]**	**Local**	**Value [US$/ha]**	**Nº of PRP[%]**	**Local**
	NPV of Restoration actions			*NPV of Milk production activity*			*NPV of PES*		
Min.	-2,017	54	All	2	3	Monteiro Lobato	377	95	All
Max.	-48	<1	Some	63	<1	Cachoeira Paulista			

Source: Author's production.

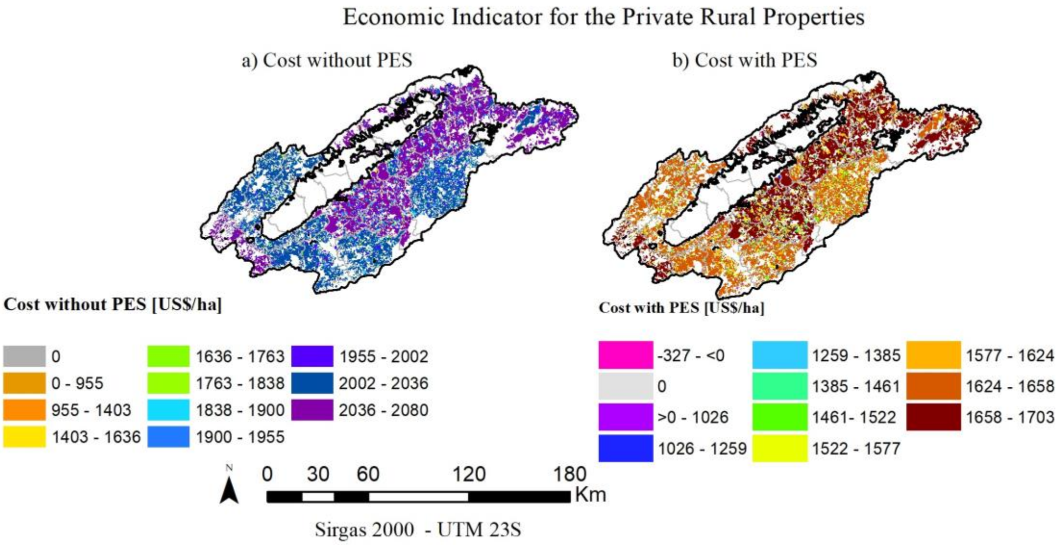
The sum of up to three of these NPV indicators is the mean restoration cost for a given PRP. Table 3.5 shows the mean restoration cost [US$/ha] in the absence of PES (Figure 3.3a) and in the presence of PES (Figure 3.3b). There are 42 PRPs with a negative cost in the presence of PES, which means that the landowners have a profit only when PES is considered. These 42 PRPs belong to different municipalities of the VPP.

Table 3.5 - Economic indicators of PRPs.

	Characterization of Economic parameters					
PRPs	**Value [US$/ha]**	**Nº of PRP [%]**	**Local**	**Value [US$/ha]**	**Nº of PRP [%]**	**Local**
	Cost without PES			*Cost with PES*		
Min.	50	<1	Monteiro Lobato	-327	<1	Monteiro Lobato
Max.	2080	<1	Cachoeira Paulista	1703	<1	Cachoeira Paulista

Source: Author's production.

Figure 3.3 - Spatial distribution of economic indicators within PRPs.



Source: Author's production.

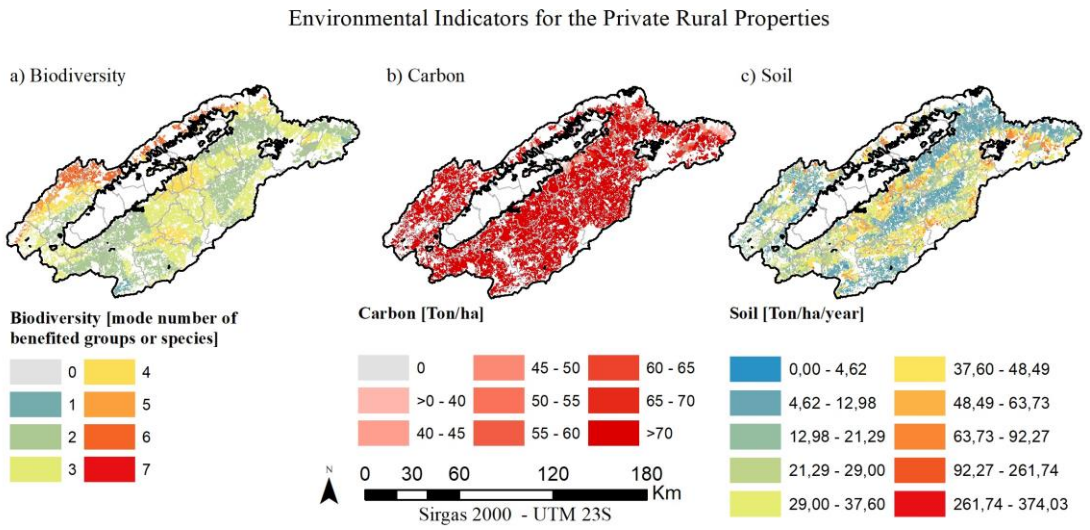
The minimum and maximum values for the biodiversity indicator totalize less than 2% of the PRPs, as shown in Table 3.6. The predominant score in the study area is 3, which means that the restoration action can benefit 3 taxonomic groups (as mammals, birds, and others groups) or 2 taxonomic groups and a landscape structure (such as large fragments and high connectivity). The score 3 is identified in 6,385 PRPs (39% of the our PRPs), distributed across a large number of municipalities (Figure 3.4). Concerning the carbon indicator, the maximum value of mean carbon stock increase is predominant in our study area, being distributed in all municipalities. For the soil benefit, only one PRP presented the maximum value, which is localized in Paraibuna.

Table 3.6 - Environmental indicators of PRPs.

	Characterization of Environmental indicators								
PRPs	**Value [US$/ha]**	**Nº of PRP [%]**	**Local**	**Value [US$/ha]**	**Nº of PRP [%]**	**Local**	**Value [US$/ha]**	**Nº of PRP[%]**	**Local**
	Biodiversity conservation			*Carbon stock increase*			*Reduction of soil loss*		
Min.	1	<1	Paraibuna, Bananal	39	<1	Cunha	0	<1	Many
Max.	7	<1	Cruzeiro, Monteiro Lobato, Tremembé, Pindamonhangaba	71	91	All	374	1	Pindamonhangaba

Source: Author's production.

Figure 3.4 - Spatial distribution of environmental indicators within PRPs.



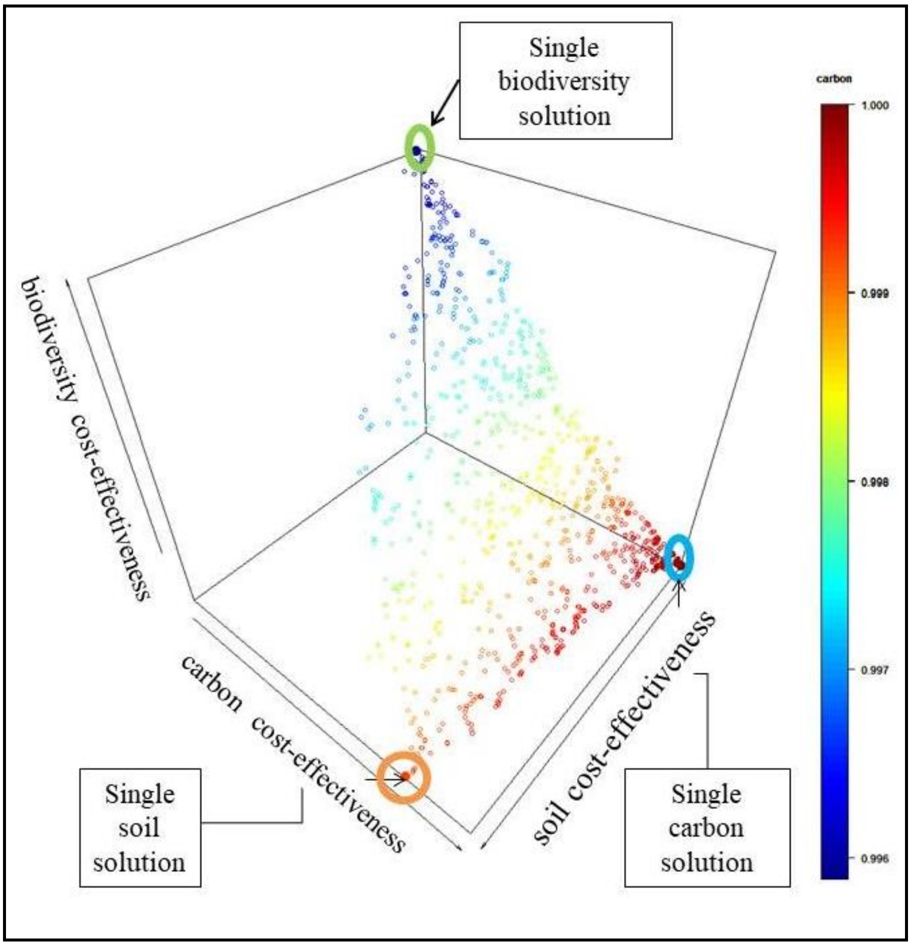
Legend: a) Biodiversity - mode of number of benefited groups or species, b) Mean carbon stock increase, c) Mean reduction of soil loss

Source: Author's production.

3.3.2 Detailing the cost-effectiveness analysis

In this section, we show only the results of **Sc.1** (**Unconstrained-noPES**), but the other scenarios present the same pattern (Appendix B). We can visualise the Pareto surface as a 3D plot in Figure 3.5. The solutions that define the Pareto frontier are the three single-objective extremes, which are the vertices of a spherical triangle. The best compromise solution is a point on the surface of the triangle. The maximum biodiversity is highlighted by a green circle, the maximum carbon by a blue circle, and maximum soil by an orange circle. The three curves that connect each pair of these extremes are trade-offs between the respective objectives, composing the borders of our Pareto surface..

Figure 3.5 - Pareto surface for carbon in Sc.1.



Source: Author's production.

In Figure 3.5, each point represents one optimal solution for a given set of weights for carbon, soil, and biodiversity. The color of each point indicates the carbon benefit for the respective solution. We can see that the maximum carbon benefit is achieved in the single carbon solution (ws = 0, wc = 1, wb = 0), and it is represented by the dark red color in the legend color range. The single soil solution (ws = 1, wc = 0, wb = 0) has an intermediate value of carbon benefit, and it is represented by the orange color in the legend color range. The lowest carbon benefit is related to the single biodiversity solution (ws = 0, wc = 0, wb = 1), and it is represented by the dark blue color in the legend color range. The best balance solution (ws = 1, wc = 0, wb = 0) presents the same carbon benefit of the single soil solution because their weights are the same.

Considering the absolute benefit gain for the three single-objective solutions and for the best balance solution (Table 3.7), it is possible to identify that the best balance solution present 92.6% of the biodiversity benefit gain identified in the biodiversity single-objective solution, 99.9% of the carbon benefit gain identified in the carbon single-objective solution, and 100% of the soil benefit gain identified in the soil single-objective solution. These percentages indicate that the best solution is close to achieving all three single objectives simultaneously through optimisation.

Table 3.7 - Absolute benefit gain for the best balance solution and the three single-objective solutions, and percentage gain for the best balance solution in relation to the three single-objective solutions for scenario 1.

Sc. 1	**Absolute benefit gain**			
Solution	**Biodiversity** **[sum of mode number of benefited groups or species]**	**Carbon [M Ton]**	**Soil** **[M Ton]**	**Cost** **[Million US$]**
Best balance	179345 (92.6%)	4.200 (99.9%)	2.12 (100%)	122.170
Biodiversity single-objective	193696 (100%)	4.186	1.59	122.166
Carbon single-objective	179256	4.203 (100%)	1.58	122.158
Soil single-objective	179345	4.2000	2.12 (100%)	122.170

Source: Author's production.

3.3.3 Comparison of the scenarios cost-effectiveness

All scenarios aim to restore 600km² of pasture area under different assumptions in relation to the legal deficits and payment for ecosystem services (Table 3.2). **Sc.1** (**Unconstrained-noPES**) optimizes the restoration of 600km² of pasture areas inside PRPs, where the maximum area that can be restored is equal to 50% of the total pasture inside PRPs (1,771 km², according to our estimates on Section 3.1). **Sc.2** (**BFC-noPES**), **Sc.3** (**BFC-PESnoOB**) and **Sc.4** (**BFC-PESdeficit**) restore the legal deficit (306 km²), and optimize 294 km² of the 50% of the pasture area localized in noOB lands (1,619 km²). **Sc.5** (**Unconstrained-PES**) optimizes the same pastura area of **Sc.1**, that is, 600km² of pasture areas inside PRPs, where the maximum area that can be restored is equal to 50% of the total pasture inside the PRPs (1,771 km²). Table 3.8 summarizes the total values of the economic and biodiversity indicators for the best solution for the five scenarios. Figure 3.6 illustrates the distribution of the PRP with restoration in each scenario.

Table 3.8 - Results of each scenario.

Scenario	**Environmental benefit**			
	Biodiversity **[sum of mode number of benefited groups or species]**	**Carbon [M Ton]**	**Soil [M Ton]**	**Cost [Million US$]**
Sc.1 -*Unconstrained-noPES*	179345	4.20	2.121	122.17
Sc.2- BFC-noPES	178813	4.15	1.898	122.21
Sc.3- BFC-PESnoOB	178762	4.15	1.899	111.11
Sc.4- BFC-PESdeficit	178762	4.15	1.899	99.56
Sc.5 -*Unconstrained-PES*	179388	4.20	2.122	99.50

Source: Author's production.

Comparing first the two scenarios without PES, **Sc.1** (**Unconstrained-noPES**) and **Sc.2** (**BFC-noPES**), the results indicate that the unconstrained scenario **Sc.1** benefits a larger number of taxonomic groups (as mammals, birds, and others groups) and landscape structural parameters (such as large fragments and/or high connectivity) than **Sc.2**. Similar to biodiversity, the carbon and soil benefits of **Sc.1** are higher than **Sc.2**. On the other hand, the cost of **Sc.1** is lower than **Sc.2**. These environmental and economic differences reflect the fact that different PRPs end up being restored in the different scenarios to maximize the multiple indicators due to the obligation to restore the deficit areas. While 12,095 PRPs (72% of the our PRPs) are restored in **Sc.1**, 15,252 PRPs (90% of the our PRPs) are restored in **Sc.2.** As expected, more PRPs are selected for restoration in the BFC scenarios as restoring their legal deficits is mandatory (Figure 3.6).

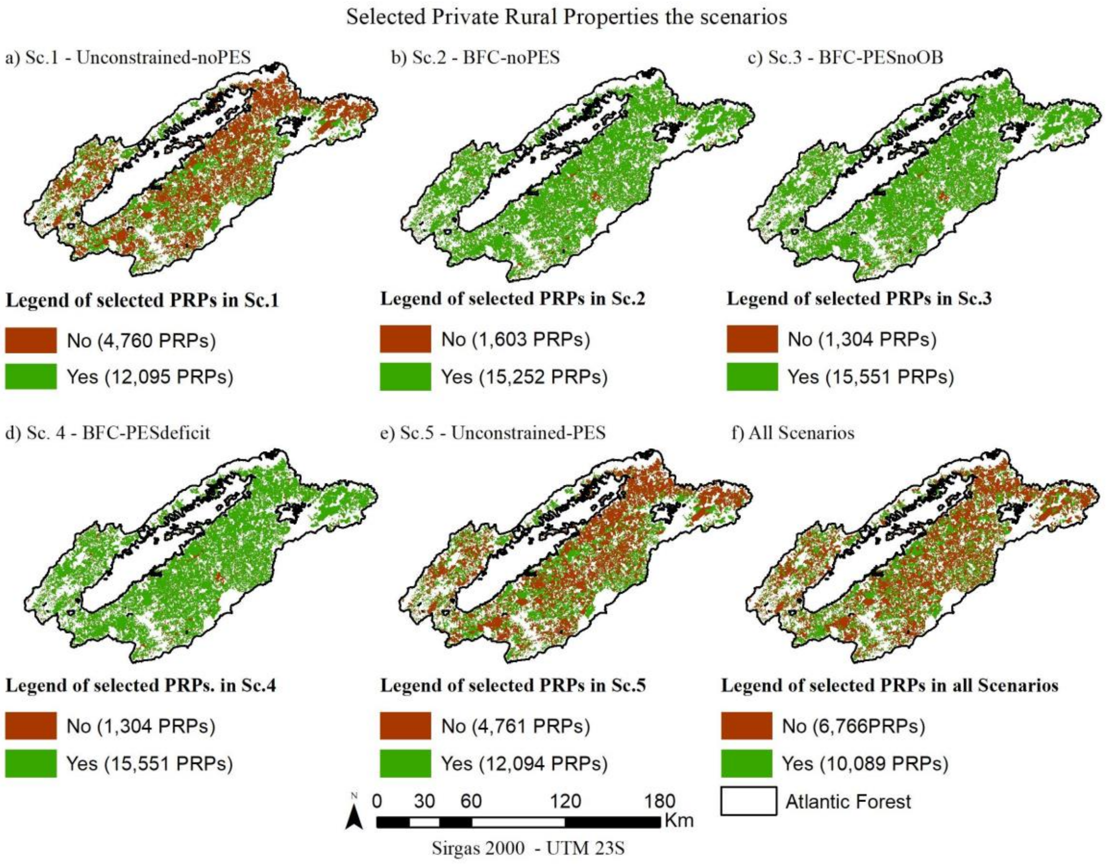
The difference between **Sc.1** and **Sc.2** scenarios provide support information to answer the following question: *How much do the restoration of the legal deficits according to the Brazilian Forest Code influence the costs, benefits, and spatial patterns of restoration in the Paraiba Valley?* As expected, more PRPs are selected for restoration in the BFC scenarios as restoring their legal deficits is mandatory (Figure 3.6). Even with the small differences in the cost-effectiveness between the scenarios, our results reinforce the importance of aligning restoration initiatives to the BFC compliance because compliance contributes for that the restoration actions occurring across the study area instead of concentrated in specific spots areas of higher potential. This points out the need to include connectivity analysis in future studies, as we discuss later.

Comparing first the three scenarios with PES, **Sc.3** (**BFC-PESnoOB**) and **Sc.4** (**BFC-PESdeficit**) have two different assumptions in relation to PES. Although in both scenarios the deficit areas have to be restored, in **Sc.3**, landowners only receive PES for restoring noOB pasture areas (outside the deficit area), while in **Sc.4** landowners receive PES for restoring noOB pasture areas and the deficit areas. Despite these differences, the three environmental benefits and the selected PRPs for being restored are the same in both scenarios, while the cost of Sc.4 is lower than Sc.3 (Table 3.8). The same 15,551 PRPs (92% of our PRPs) are restored in **Sc.3** and **Sc.4**. Presumably, in the study area, the payment had no effect on the selected areas. The difference among **Sc.2**, **Sc.3** and **Sc.4** provide support information to answer the following question: *How much do alternative PES mechanisms in legal deficits according to the Brazilian Forest Code influence the costs, benefits, and spatial patterns of restoration in the Paraiba Valley?*

In the presence of the PES mechanism (**Sc.3** and **Sc.4**), the landowners could reduce around 15% of the cost for the situation where they do not receive PES (**Sc.2**), while the environmental benefits are almost similar. The same PRPs are selected in the **Sc.3** and **Sc.4**, and almost all of them are selected in **Sc.2** too. This last result suggests that the payment has no effect on the selected areas in the study area.

Finally, **Sc.5** (**Unconstrained-PES**) results in 12,094 PRPs (72% of our PRPs) having restoration. It explores the third PES mechanism where landowners receive PES for restoring the pasture areas inside PRPs, regardless of the forest code enforcement (legal deficits restored). The three environmental benefits of **Sc.5** are higher than **Sc.3** and **Sc.4**, while the cost of **Sc.5** is lower than **Sc.3** and **Sc.4**. **Sc.5** is the scenario that presents the smallest cost among all the scenarios.

Figure 3.6 - Selected PRP in each scenario (for restoration).



Source: Author's production.

Among the 42 PRPs that have a negative cost in the presence of PES, and so the landowners could have a profit with the PES, all PRPs are seletect in the **Sc.3** and **Sc.4**, while only 32 are selected in the scenario **Sc.5.**

3.4 Discussion

We structure the discussion around some specific topics. Section 3.4.1 highlights our modelling advances. Section 3.4.2 discusses modelling results, in particular, our results related to public policies. Section 3.4.3 discusses the opportunity cost. Section 3.4.4 discusses CAR data manipulation. Section 3.4.5 discusses the limitations of the modeling approach and suggestions for future studies.

3.4.1 Modelling advances

The innovation in our study is an optimization modelling approach based on linear programming that maximizes three environmental benefits of forest restoration, and considers irregular areas (the boundaries of private rural properties) as planning units. Our approach builds on the recents optimization modelling approaches that maximize only two environmental benefits for forest restoration and consider regular planning units (STRASSBURG et al., 2018; 2020). In our objective function, simple adjustments allow more than three environmental benefits (that is environmental indicators) to be maximized simultaneously. This is possible because the approach considers the relative contribution of each environmental indicator as different components of the objective function in our multicriteria optimization model, and allows the addition of a new indicator component with easy (BEYER et al., 2016).

Another innovation is the use of financial values of PES as part of the restoration cost in our study. The inclusion of PES value is readily executable in our approach, as is the consideration of more than one PES value. This is possible because the PES value is one component in the economic indicator that allows easy addition of other PES values as new components in the economic indicator. The inclusion of PES, as a potential landowner compensation, is suggested by Crouzeilles et al. (2020) as one way of eventually improving the opportunity cost estimation.

The last innovation is in relation to the restoration implementation cost. We use natural regeneration potential (NRP) to identify the ideal restoration method for a specific area as Molin et al. (2018), Padovezi et al. (2016), and Crouzeilles et al. (2020). However, these previous authors use statistical analysis to identify the chance of having NRP, while we estimate the amount of NRP present inside the PRP. Our approach indicates whether the area could be restored by natural regeneration or needs to be restored by an active method. Our approach opens a new path for identifying the NRP, which contributes to choice combinations between two methods for restoration actions inside the same PRP.

Considering a greater spectrum of utilities, the advances of irregular areas as planning units and the possibility of using a range of indicators open an opportunity for improving the selection of prioritization areas to receive conservation action. For example, the choice of prioritization watersheds could consider a broad set of parameters that are relevant to water resources conservation, such as quality and amount of water characteristics or water uses (such as human supply, agricultural production or food security) (COOK; BAKKER, 2012). The possibility of using a range of water parameters could be useful for improving PES programs since the Hydric PSA Program (OIKOS, 2015) that is, a local initiative that prioritizes 34 watersheds as the relevant area to receive action for water resources conservation in VPP. This program identifies the priority watersheds using a set of different water parameters (such as amount of water and soil erosion) that are analyzed in each step. Our approach could collaborate with this program with an integrated analysis, as it allows multiple criterias analysis simultaneously. All these improvements could collaborate as an integrative approach to water management (COOK; BAKKER, 2012; BEYER et al., 2016).

3.4.2 Complying to the Brazilian Forest Code and National Policy for Payment for Ecosystem Services

Our scenarios suggest how to combine more than one public policy into a unique approach, which makes it easy to investigate environmental gains, economic costs and different public policies in an integrated way. Our study shows how expressing restrictions policies rules as math rules in the scenarios. Our approach combines restriction rules of two important Brazilian public policies, that is, Brazilian Forest

Code (BFC) and National Policy for Payment for Ecosystem Services (in Portuguese, Política Nacional de Pagamento por Serviços Ambientais - PNPSA). The BFC is exhaustively discussed in different studies (FREITAS et al., 2017; SPAROVEK et al., 2019). This public policy is present in our scenarios as restriction rules for allocating forest restoration actions. The PNPSA is a recent public policy that was enacted at the beginning of this year (2021), and it is explored as different possibilities of PSA mechanisms in our scenarios.

In general, all scenarios result in similar environmental gains. This result is probably justified by the spatial scale of the environmental indicators of our study. For example, to estimate the carbon gain, we use the vegetation type map with a scale of 1: 5.000.000 (IBGE, 2004) that is the same map used in the Third Brazilian Inventory of greenhouse gas emissions (MCTI, 2015). Despite the fact that there are similar environmental gains in the scenarios, which is probably justified by input data in our database, simple adjustments in the restriction rules of our scenarios could allow an integrative investigation of BFC, PNPSA and PES programs. For example, the BFC constraints rules could be combined with the constraints rules of the scenarios presented in Lemos et al (2021), and thus the new forest allocation could be restricted to legal deficit inside areas of interest for PES programs, such as Hydric PSA Program (OIKOS, 2015) and Protection PSA Program (SÃO PAULO, 2019). These possibilities allow for advancing strategic planning to bring cost-effective benefits in addition to legal adjustments in PES programs.

3.4.3 Opportunity costs

Our scenario analysis results indicate that costs are quite high across all scenarios and comparable in magnitude to the ones in Lemos et al. (2021) (Chapter 2). High costs can be explained by the adoption of active ecological regeneration methods in many cases. Our results indicate that active and passive ecological restoration methods could be combined in the conversion from pasture area to restored forest areas of 7,753 PRPs (46% of our PRPs). This result could be used as an example that passive restoration is a promising method for restoring some PRP, and so convince landowners to adopt the natural regeneration in their restoration projects (BRANCALION et al., 2016). It is essential to reduce cost, due to limited restoration funds, to increase the adherence of restoration projects based on passive restoration (BRANCALION et al., 2019).

Although our approach considers only two ecological restoration methods, we believe that it could be adjusted to consider ecological restoration methods with low and high seedling density (such as Enrichment Planting) as one restoration strategy. This strategy could reduce the restoration implementation cost (BRANCALION, et al. 2019), which could be interesting because forest restoration is also generally perceived as a cost by landholders, proportional to the envisioned profits that could be obtained with agricultural activities (i.e., opportunity costs) (HISSA et al., 2020). Enrichment Planting uses a smaller number of seedlings than the seedling planting method, that is important information, specially because the it would take 69 years to restore the legal deficit of VPP using only seedling planting, based on seedling production of the seven nurseries presented in VPP (ALUVEI; LEMOS; ANDRADE, 2020).

This study considers only ecological restoration methods, and these methods present only costs and no revenue. To reduce restoration implementation cost, another strategy could be the adoption of restoration methods that present revenue for the landholders. For example, different agroforestry systems could be adopted as forest restoration methods because they provide commodity as well non-commodity benefits such as ecosystem services, and these range benefits result in positive cash inflow-outflow (PADOVEZI et al. 2018; SHAPIRO-GARZA, 2013) and enhance food, nutrition and income security (SEGHIER et al., 2021). This strategy is aligned with the recent context of VPP where an increase of forest restoration is observed based on agroforestry systems and strengthening the network of agroforestry professionals (DEVIDE; 2013, 2019).

3.4.4 About the CAR data manipulation

Our results are coherent with the distribution of rural proprietes present by Lemos et al. (2018) and Padovezi et al. (2018) that used the land tenure disponilized by IMAFLORA (SPAROVEK et al., 2019), the three studies indicate the predominance of 90% in Paraiba Valley. Using the springs, watercourses, and localization of different classes of the APP inside the private rural properties (PRPs) from the CAR database (SICAR, 2020), our methodology quantify around half of the legal deficit that was quantified by Lemos et al. (2018) and Padovezi et al. (2018). Our methodology quantifies around 374 km² of legal deficit while the other two studies find more than 750 km² legal deficits of native vegetation in legal reserves (LRs) and permanent preservation areas (APPs). This difference can be justified because the CAR database presents fewer watercourse vectors in relation to the number of watercourse vectors used by IMAFLORA, and this difference between the watercourse representation could be reflected in a reduction of the extension of the APP, that could be impact in the reduction of the quantification of APP with legal deficit.

We exclude the overlap among the PRPs randomically and manually, one of the first improvements could be used an automatic approach for cleaning the overlaps (FREITAS et al., 2017). In our study, we generalize that irregular deforestation is any irregular deforestation that happens before or after 2008, the second improvement could be the separe the deforestation that happens before or after 2008, and only use the deforestation that happen after to 2008 for the legal deficit calculation that is rule of the BFC (HISSA et al., 2019). We use the vectoral data elaborated from Landsat-8 data as our land cover data (RONQUIM et al., 2016), the use of this data is interesting because we can intersect the APP layer with a vector data that is better than raster data because the APP layer can be a buffer with only 5 meter. On the other hand, the Landsat-8 data has 30m resolution, so another improvement could be to adopt land cover map that is elaborate though the use of satellite images with finer resolution as RapidEye imagens that have the 5m resolution (CHEN et al., 2016).

3.4.5 Limitations of the modeling approach and suggestions for future studies

To estimate the quantity of NRP present inside the PRP, we use the NRP that is developed in Lemos et al (2021)(Chapter 2). For cells of 1km of resolution, Lemos et al. (2021) use static explanatory variables for estimating the NRP. The use of cells with 1km of resolution and static explanatory variables could indicate small quantities of NRP inside the cells. The small quantities of NRP could be explained by natural regeneration that takes place in areas smaller than 1 km² on the edge of pre-existing forest fragments, and the fact that NRP is a dynamic process that increases with each passing year (BRANCALION et al., 2016). As Lemos et al. (2021), we recommend that a new NRP could be estimated by using dynamic explanatory variables, in particular, the explanatory variables that represent the percentage of forest cover in the cell in the previous year.

We adopt some strategies during the building of the economic indicators, the first of them is considering the same profit for milk activity for all years. We adopt this strategy because we do not know the total pasture for next year, so the use of dynamic profits could be another improvement for our financial analysis (CROUZEILLES et al., 2020). The second one is considering that cost is always equal to zero during the PES program, however, financial costs of enrollment (e.g., purchasing seedlings) can limit who participates in a PES program (JACK; JAYACHANDRAN, 2019), so we suggest that futures works considering the costs of enrollment for improving the financial analysis.

Three of our scenarios direct part of the restoration forest in the legal deficit areas, the most part of the deficit areas in our study area are riparian areas. These important zones that link forest and rivers (GREGORY et al., 1991) present heterogeneous tree biomass, density and richness in communities undergoing restoration (SUGANUMA et al., 2016), and the recovery of infiltration varied depending on restoration age (LOZANO-BAEZ et al., 2019). These heterogeneities could be implemented in future studies that could reflect different environmental gains among the scenarios, while our results identified similar environmental gains among our five scenarios.

For our study area that present the predominance of small PRPs, we decide to work only with deterministically restoration of the legal deficit because small PRPs do not have LR deficit due to the absence to obligation of restoring the LR (article 67 of BFC) (FREITAS et al., 2017). For regions with large LR deficits, we suggest the optimization of the restoration of the LR deficit. The optimization of the legal deficit is explored in previous studies (STRASSBURG et al., 2018; HISSA et al., 2020).

3.5 Conclusions

In the enforcement of the BFC as well as presence of different PES mechanisms, environmental gains are similar among our scenarios where the best compromise solution captures around 93.4%, 99.8%, and 99.9% of the maximum possible biodiversity, carbon and soil cost-effectiveness, respectively, for all the scenarios. These percentages indicate good potential to achieve all three objectives simultaneously through optimisation. We believe that our optimization modelling approach could contribute to understand financing mechanisms and benefit distribution outcomes because one of the interesting strategies of using linear programing is the speed and flexibility of adjusting the weights and contranited rules based on the decision maker that allow to explore the contribution of different for conditions to solving complex problems in a few minutes (BEYER, et al. 2016).

The differential of our study in relation to other previous studies to explore the optimal distribution of restoration, considering multiple environmental benefits and linear programming (STRASSBURG et al., 2018; 2020) are: (1) use irregular planning units (PRP boundaries); (2) calculate the legal deficit considering the springs, watercourses, and localization of different classes of the APP from CAR database (a recent Brazilian database with detailed information about PRP); (3) use of linear regression model for calculating the implementation restoration cost; (4) insert the PES in the cost calculate; (5) consider three environmental objectives while the other studied consider only two environmental objectives; and (6) explore the National Policy for Payment for Ecosystem Services.

We also believe our approach can be used to support large-scale decision making about the overall design that include alternative PES mechanisms. The efficient PES mechanisms could be an excellent way to contribute to the achievement of the UN Sustainable Development Goals (SDGs), particularly towards SDG 1, 2, 5, 6, 13 and 15 (UN, 2021), in particular because PES mechanisms could provide rural jobs, market access, food-security, and good forest growth performance (LE et al., 2014). During this study, we pointed out easy ways to improve our methodological framework, and so collaborate on advances for good strategic restoration planning.

4 GENERAL DISCUSSION

Chapter 4 complements the “Discussion” sections from Chapters 2 and 3. Section 4.1 deepens the discussion of the modelling approaches developed in this thesis (Table 4.1). In this section, we discuss the differences and implications of our three new modelling approaches on our results, highlighting their strengths and limitations. In Section 4.2, focusing on elements that can be analyzed in an integrated way, we compare and discuss the eight scenarios to achieve multiple restoration goals built in Chapter 2 and 3 (Table 4.2).

Table 4.1 - Modelling approaches and scenarios of this thesis.

Model/ Approach/ Framework	Scenario	Planning unit	Performance analysis	Strengths	Limitations
Statistical model/ Linear regression/ RStudio	-	Cell of 1km×1km	Significant variables/ Coefficient of multiple determination (R^2) / Akaike information criteria (AIC)	Explore the relation among quantities of explanatory variables and quantities of regenerated forest cover in each cell	Difficulty in finding the goodness of fit of the model
Allocation Model/ Conversion of Land Use and its Effects (CLUE) /LuccME	Unconstrained whole area Protection PSA Hydric PSA	Cell of 1km×1km	Multiscale validation metric	Allow the validation of the statistical model results	Cost-effectiveness is quantified after the allocation of the restoration areas
Optimization model/ Linear programming /Gurobi R interface	Unconstrained noPES BFC-noPES BFC-PESnoOB BFC-PESdeficit Unconstrained PES	Boundaries of private rural properties	Pareto frontier	Cost-effectiveness is considered for allocating the restoration areas	Complexity in creating the database.

Source: Author's production.

Although the two sets of scenarios were built using different modeling approaches and different spatial units, the adoption of comparable economic and environmental indicators allows integrated analysis. Besides, all scenarios aim at converting 600 km² from pasture to forest in the study area. However, our aim is not to compare the exact value of the indicators, but the overall patterns found across the scenarios.

4.1 Modelling approaches for advancing in the large-scale restoration planning

In this thesis, we combine three modeling approaches: statistical modelling, allocation modelling and optimization modelling. Together, these approaches aim to contribute to the advancement of large-scale restoration planning.

4.1.1 Statistical modelling

For the statistical models, we use a grid of 12647 regular cells (also called Cellular Space) of 1km of resolution for representing the VPP in a fine scale, and we use continuous variables to explore the relationships between potential explanatory variables and the natural regeneration process. The use of Cellular Space and continuous variables is adopted to explore the distribution of land covers (VERBURG et al., 1999). For example, the deforestation on Amazon (AGUIAR et al., 2007) and the expansion of sugarcane in São Paulo State (MEDEIROS, et al. 2016).

Due to the use of continuous variables, it is possible to identify the quantity (percentage of the cell) of different land cover in the i^{th} cell, this percentage could range from 0% to 100% (CARNEIRO et al., 2013) while the discrete variables classify the cell in 100% of the major class of land cover present in the cell. For example, in our study, considering a continue data, it is possible to identify 69% of regenerated forest, 24% of pasture and 7% of other covers in a i^{th} cell; or 5% of regenerated forest, 70% of pasture and 25% of other covers in a i^{th} cell. As discrete data, the i^{th} cell with 69% of regenerated forest, 24% of pasture and 7% of other covers is classified as regenerated forest cell because the regenerated forest is the major land cover class in this cell, while the i^{th} cell with 5% of regenerated forest, 70% of pasture and 25% of other covers is classified as a pasture cell because the pasture cover is the major land cover class in this cell.

Considering that we use continuous values for characterizing our land cover classes, linear regression is the appropriate statistical model for the analysis of the relevant factors as well as their quantitative relationships with each land cover (LESSCHEN et al., 2005). To better understand the multiple factors underlying the natural regeneration process in the region, we build and compare four alternative linear regression models considering (a) only biophysical factors (B model); (b) biophysical and forest cover (Eco model); (c) biophysical, forest and other land covers (BH model); (d) biophysical, forest and other land covers; and socioeconomic factors (BHS model) where *we adopt the assumption that regenerated forest cover in the study area is 100% related to natural regeneration.*

The alternative linear models are constructed for finding the regression model with the significant variables ($p < 0.05$), the highest coefficient of multiple determination (R^2), and the lowest Akaike information criteria (AIC). These parameters indicate the model with the best goodness of fit (ANSELIN et al., 2006).

Based on our linear regression model results (Table 2.3 in Chapter 2), there are multiple explanatory variables for explaining the natural regeneration process for each alternative model (**B model**, **Eco model**, **BH model**, and **BHS model)**. For example, percentage of forests (remnant and regenerated) in 2005 (1), percentage of surface with flat curvature (2), percentage of slope between 20º and 45º (3), Average of Precipitation (4), Average of Temperature (5), percentage of Humic Cambisol (6), Average of Elevation (7) and percentage of high agricultural suitability (8) are the multiple (eight) explanatory variables for explaining the natural regeneration process in the Eco model for 2011. The equation 4.1 is a simple representation of the percentage of estimated regenerated forest cover in the ith cell by a multiple linear regression model.

$$Y_i=\beta_0+\beta_1X_{i1} + \beta_2X_{i2} +\ldots+ \beta_pX_{ip} + \varepsilon_i \tag{4.1}$$

Where:

- Y_i is it is the value of the response variable in the i^{th} cell
- $\beta_0 \ldots \beta_p$ are parameters
- $X_{i1} \ldots X_{ip}$ are predictor variable values in the ith cell

- ε_i is a random error term

  For the **Eco model**, the Y_i is the *percentage of estimated regenerated forest cover* in 2011 in the i^{th} cell, while $X_{i1}...X_{ip}$ are the *percentage of forests (remnant and regenerated) in 2005, percentage of surface with flat curvature, percentage of slope between 20º and 45º, Average of Precipitation, Average of Temperature, percentage of Humic Cambisol, Average of Elevation* and *percentage of high agricultural suitability* in the i^{th} cell.

Considering that we represent the VPP as a grid of 12647 cells, the percentage of estimated regenerated forest cover in the set of all cells of our grid represents our regression surface, also called regression cover in Verburg et al. (1999). The regression cover is used in the allocation modelling for estimating the natural regeneration potential for each cell, and in the optimization molling for estimating the natural regeneration potential for each private rural property (PRP).

There are two advantages of using statistical models based on continuous data. The first one is the possibility to explore the relation between quantities of explanatory variables and quantities of regenerated forest cover in each cell. This type of exploration refines statistical analysis because it makes it possible to understand the relation of explanatory variables with a low amount of regenerated forest cover in a specific cell as well as the relation of explanatory variables with a high amount of regenerated forest cover in another cell. The second one is the possibility of creating a regression cover, where the regression cover allows the natural regeneration potential to be estimated considering the whole universe of cells rather than considering a set of samples of the universe of cells. Considering only a set of samples of the universe of cells is the common strategy in statistical models based on discrete data (MOLIN et al., 2018; CROUZEILLES et al., 2020). The limitation of our statistical approach is the difficulty in finding the goodness of fit of our statistical models because it is necessary to find a goodness of fit for a universe of cells that present a range from 0% to 100% of regenerated forest cover. The identification of multiple linear regression that is good to represent, simultaneously, the small and high quantity of regenerated forest cover is one of the challenges of this thesis.

4.1.2 Allocation modelling

In this work, to explore the allocation models, we use the LuccME modeling framework, in particular the components based on the Conversion of Land Use and its Effects (CLUE) model for continuous land use variables (VELDKAMP AND FRESCO, 1996; VERBURG et al. 1999; AGUIAR et al., 2016). In our allocation models, the dynamic land cover variables are the percentage of regenerated forest and percentage of pasture in each cell of 1 km x 1 km, and the LuccME modeling framework is used in two goals, one being to investigate the allocation of regenerated forest cover from 2011 to 2015. This investigation is important for confirming what is the alternative statistical model that better captures the natural regeneration process in the study area, and then could be used for estimating the natural regeneration potential of the VPP in 2015. The second goal is to simulate the allocation of regenerated forest from 2015 to 2025, this simulation allows the allocation of the increment of regenerated forest until 2025.

To investigate which alternative statistical model better captures the natural regeneration process in the study area, we calibrate and to validate the percentage of simulated regenerated forest cover for 2015 based on the percentage of estimated regenerated forest cover from our four alternative statistical models described in the previous section (B model, Eco model, BH model, and BHS model). This step can be executed because we can compare the model results for 2015 against the observed 2015 information (also derived from Ronquim et al. 2016 and Silva et al. 2016a). To compare the simulated and observed percentage of estimated regenerated forest cover in 2015, we use a multiscale validation metric (VAN VLIET et al., 2016) to support the choice/analysis of alternative models capturing the change from 2011 to 2015. Based on the results of the multiscale validation metric (Table A.10 in APPENDIX A), all the alternative statistical models (B model, Eco model, BH model, and BHS model) present similar results. The Eco model presents results slightly better than the other model. Eco model presents 55% of hit percentage in the scale of 1 x 1 cell and 69% of hit percentage in the scale of 10 x 10 cells with 0% of accepted error while B model, BH model, and BHS model present 46, 54, 53% of hit percentage in the scale of 1 x 1 cell, and 65, 68, 68% of hit percentage in the scale of 10 x 10 cells, respectively, using the same parameters of validation that take into account only the areas that have undergone some change process.

Because the Eco model presents validation results slightly better than the other models, this linear regression model better aligns with our overall goal of favoring passive ecological restoration, and the regression cover resulting from the Eco model indicates the amount of natural restoration that can support. We call this regression cover as the maximum biophysical capacity (MBC) for favoring the natural regeneration processes in Paraiba Valley. The MBC varies from 0 to 0.50 in the study area. The MBC average is close to 0.1, and around 60% of the cells in the region have less than 10% of maximum biophysical capacity for natural regeneration.

Considering that the MBC is the regression cover that is most indicated for estimating the amount of natural restoration that can support, we used the MBC for estimating the natural regeneration potential in the Potential Component of LuccME. Because we work with continuous data, potential is the difference between the current land cover percentage and the estimated percentage according to the linear regression models (VERBURG et al. 1999). Then, in our study, the natural regeneration potential in 2011 is the difference between the percentage of regenerated forest cover in 2011 and the MBC (our estimated percentage according to the ECO MODEL). The natural regeneration potential in 2012 is the difference between the percentage of regenerated forest cover in 2012 and the MBC, and so on until the year 2015. Using the MBC, the natural regeneration potential in 2015 varies from 0 to 0.17 in the study area. In the region, 87% of the cells present no positive values, which means that 87% of the cells are not favorable to receive passive ecological restoration, and 13% of the cells present natural regeneration potential even at the most equal to 0.17. This 13% of cells totalize almost 30 km² of area that are favored to receive passive ecological restoration.

Using this natural regeneration potential estimated for 2015, we simulate the allocation of regenerated forest from 2015 to 2025, this simulation allows the allocation of the increment of regenerated forest until 2025. At this moment, we simulate the increment of regenerated forest until 2025 for the three scenarios: One Unconstrained Scenario that the allocation is possible in the pasture area of the whole study area; and two Constrained Scenarios that the allocation are restricted to relevant areas for two PES programs present in the VPP. In the end of the simulation, it is possible to estimate the regenerated forest incremented area from 2015 to 2025 of the cell based on the natural regeneration potential. This area is multiplied by the biodiversity, carbon, and soil benefit indicators that results in the environmental gain for the three scenarios. To estimate the cost, for each cell, the increment area is compared with the natural regeneration potential. We assume that natural regeneration potential is used to identify a per cell threshold that will define the amount of natural restoration a cell can support, and any additional restoration that surpasses this cap value will require an active restoration method. The total cost of restoration is the sum of the cost of restoration of each cell. The scenarios are more detailed in Section 4.2.

Our allocation models with continuous land use variables makes it possible to estimate the amount of area of natural regeneration potential rather than the chance the area may, or may not, have of natural regeneration potential as in the previous studies that explore natural regeneration potential (CROUZEILLES et al., 2020; MOLIN et al., 2018; PADOVEZI et al., 2018; STRASSBURG et al., 2018). The possibility of estimating the amount of area of natural regeneration potential allows us to combine passive and active restoration methods for restoring areas inside the same cell. This possibility is one of the strengths of our approach. Another strength is that the LuccME is an open-source framework for the development of land change models, and presents a friendly interface that simplifies model building and new implementation.

In our allocation modelling approach, the most relevant limitations of our simulation of the regenerated forest from 2015 to 2025 is assuming the maintenance of the same conditions and relations captured by the statistical models derived for 2011. This limitation could be corroborated by our finding of only 30 km² of area that are favored to receive passive ecological restoration in 2015. Considering that natural regeneration increases across time (BRANCALION et al, 2016), we suggest the adoption of a dynamic natural regeneration potential to better investigate the natural regeneration potential throughout the years. One way to explore dynamic natural regeneration potential is actualization of the percentage of forests (remnant and regenerated) in 2005 by the percentage of forests (remnant and regenerated) in the following years. This is an interesting solution because the percentage of forests (remnant and regenerated) in

2005 is the most relevant explanatory variable that explains around 70% of the for the natural regeneration processes in the VPP.

Other limitations of our allocation modelling approach are that we simplify the assumption that the other land use classes remain static during the calibration and scenarios phase, and we also assume that the remnant forests will not be disturbed. We adopt these limitations because our core interest is the conversion from pasture to forest. The last limitation of our allocation modelling is that the approach quantifies the cost-effectiveness after the allocation of the increment restoration areas. As a solution for the last limitation, we develop the third modelling approach of this thesis, our optimization model.

4.1.3 Optimization modelling

To develop our optimization model, we use the Linear Programming (LP) approach. In this work, we develop a multicriteria optimization algorithm that allocates the forest increment based on the maximization of three environmental benefits while minimizing the cost. The boundaries of private rural properties (PRP) are the planning units in this model.

This optimization approach estimates the cost and environmental gains of the forest restoration in each PRP. These costs and gains are combined with a decision variable (maximum restorable area - MRA) and weights in an objective function. This objective function is subject to constraint of the total area for restoration in the scenario, ensuring approximately the same total restored area in all scenarios (600km²). Based on this constraint and on the decision variable (proportion of the MRA in each PRP), the model seeks the best solution to attain our restoration objectives, that is, to maximize environmental gain while minimizing the cost. The solution that maximizes environmental gain while minimizing the cost is also called the best cost-effective solution. To find this solution the Pareto frontier is performanced (BEYER et al., 2016). The temporal resolution is unnecessary for this modeling.

With this approach, we explore the cost-effectiveness in the enforcement of the BFC as well as the recent PNPSA. We consider the BFC during the definition of the MRA of each PRP. The MRA is 50% of the pasture areas of the PRPs for the scenarios that do not enforce the BFC. These scenarios are called Unconstrained Scenarios, and they are our scenarios Sc.1 and Sc.5. The MRA is 50% of the pasture outside APP/LR deficit (noOB) of the PRPs for the scenarios that enforce the BFC. These scenarios are called Constrained Scenarios, and they are our scenarios Sc.2, Sc.3 and Sc.4. This difference in the MRA definition is because we can optimization the restoration actions to restore 600km² in pasture areas in the Unconstrained Scenarios, while we enforce the restoration of the APP/LR deficit and only optimized the difference between the 600km² and the deficit, that is the pasture restrict to the outside APP/LR deficit areas.

We explore the PNPSA through three PES mechanisms, these mechanisms pay the landholders for restoration action in their PRP. The first is when landholders receive PES for only restoring noOB pasture areas (our Sc.3), this mechanism is aligned with the Article 9 of PNPSA for the situation that the PES program only can pay for restoration outside APP/LR deficit areas. The second one is when landholders receive PES for restoring noOB pasture areas as well as deficit areas (our Sc.4), this mechanism is aligned with the Article 9 of PNPSA for the situation that the PES program can pay for restoration outside APP/LR deficit areas or APP/LR deficit areas. And the last mechanism is when landholders receive PES for pasture areas (our Sc.5), this mechanism is not aligned with the Article 9 of PNPSA, and it the a mechanism widely adopted by PES programs on municipality and state levels.

The evaluation of these mechanisms happens through an analysis of the restoration cost. We insert the financial values of PES as part of the restoration cost in our study, we use the PES values of the Protection PSA Program (SÃO PAULO, 2019) that is a PES program present in VPP. Considering the PES values could be one way to eventually improve the opportunity cost estimation (CROUZEILLES et al., 2020), we insert the cash inflow-outflow of the milk activity as opportunity cost in our study. We select the milk activity because it represents around 73% of the agriculture revenue in VPP (IBGE, 2021a,b).

In addition to the PES values and cash inflow-outflow of milk activity, we add the restoration implementation cost. To estimate the restoration implementation cost, we split the pasture area that could be restored by an active restoration and a passive restoration. Pasture areas need to be restored by an active method when the pasture area is higher than natural regeneration potential inside the PRP. On the other hand, other pasture areas could be restored by a passive restoration. Considering that pasture area and regenerated area is known by each PRP, we can estimate the amount of natural regeneration potential in each PRP. To this end, we consider that the potential is the difference between the current land cover percentage and the estimated percentage according to the linear regression models when we work with continuous data (VERBURG et al. 1999). In our case, the current land cover percentage is the regenerated forest cover in 2015, and we use the maximum biophysical capacity (MBC) as estimated percentage according to the linear regression model. The maximum biophysical capacity (MBC) is elaborated through our statistical model, and validated with our allocation model.

The strength of the optimization approach is the possibility of allocating the restored areas based on cost-effectiveness. This possibility requires a very well architected database, the construction of this database is one of the biggest challenges for executing this approach. For example, it is necessary to use the same land cover data for estimating the pasture area and the legal deficit in each planning unit. This is necessary for avoiding a legal deficit in a planning unit that only has forest cover.

4.2 What can we learn from all the scenarios?

In Chapter 2, we explore three alternative restoration scenarios aligned with the different restoration commitments: Protection PSA Program and Hydric PSA Program, and allocate 600 km² of conversion from pasture to restore forest inside cells of 1km X 1km. The first scenario (**Unconstrained scenario - whole area**) allows converting pasture into regenerated forest in the whole study area, without constraints or alignment to the PES programs. The second scenario (**Protection PSA**) only allows allocating regenerated forest in the pasture area in areas of high priority for gains in biodiversity conservation, climate change, and water supply according to the Protection PSA Program. The third scenario (**Hydric PSA**) constrains the allocation of regenerated forest in the remaining pasture area of the 34 watersheds considered a priority study area for gains in water supply as defined by the Hydric PSA Program.

In Chapter 3, we explore the other five alternative restoration scenarios that are aligned with the different public policies (BFC and PNPSA) and allocate 600 km² of conversion from pasture to restore forest inside the private rural properties (PRPs). For these five scenarios, we use the multicriteria optimization approach (BEYER et al., 2016) to identify the cost-effective solutions that maximize all three environmental objectives for each scenario. The five optimization scenarios vary in relation to the law enforcement and mechanism of Payment for Environmental Service, and they are elaborate from the landholder perspective. This first scenario (**Unconstrained-noPES**) is without alignment to the BFC, while the second scenario (**BFC-noPES**) is aligned to the BFC due to the obligation of restoring the legal deficit**.** The third scenario (**BFC-PESnoOB**) and fourth scenario (**BFC-PESdeficit**) are aligned to the BFC due to the obligation of restoring the legal deficit**,** but consider different PES mechanisms, where the landholder only receives the PES for restoring noOB pasture areas in the third scenario**,** while the landholder receives the PES for restoring noOB pasture areas or deficit areas in the fourth scenario. The fifth scenario (**Unconstrained-PES)** is without alignment to the BFC, and presents the third mechanism of payment by the Program for Ecosystem Service that is the landholder receives the PES for restoring pasture areas in their rural property.

4.2.1 Analysis of the economic indicator results

In Chapter 2, the economic results for the three scenarios only capture the total restoration cost in the area, summing the cost estimated in each cell based on the natural regeneration potential. However, in Chapter 3, the economic results are more complex, measured through the Net Present Value (NPV) for the last five scenarios. The measurement as NPV is adopted because the restoration cost is combined with opportunity cost (milk production activity) and PES payment for each PRP. To compare the economic results of all scenarios, we estimate the restoration cost using NPV for the three first scenarios (Table 4.2), using the same process adopted in Chapter 3 (see details in Appendix C). Based on the equation for estimating the mean restoration cost that is presented in Chapter 3, the total restoration cost is estimated as follow:

$$Total\,restoration\,cost\ = Total\_MilkNPV - Total\_RestNPV - Total\_PESNPV \qquad (4.2)$$

Where the Total_MilkNPV is the Total NPV of milk production activity, the Total_RestNPV is the Total NPV of restoration actions, and the Total_PESNPV is the Total NPV of PES for the scenario.

Table 4.2 - Comparison of cost-benefit for the eight scenarios.

Scenario	**Economic parameters [million US$]**			**Economic indicator**	**Environmental indicators**		
	Total NPV of milk production activity	**Total NPV of restoration actions**	**Total NPV of PES**	**Total restoration cost [million US$]**	**Average number of benefited groups or species/ha**	**Total carbon stock increase [M Ton]**	**Total Soil Loss Reduction [M Ton]**
Unconstrained-whole area	-	-125.33	-	125.33	3.01	4.45	1.810
Protection PSA	-	-128.934	-	128.93	2.96	4.50	2.200
Hydric PSA	-	-128.167	-	128.17	2.78	4.51	2.030
Unconstrained-noPES	1.18	-120.99	-	122.17	2.99	4.20	2.121
BFC-noPES	1.26	-120.95	-	122.21	2.98	4.15	1.898
BFC-PESnoOB	1.27	-121.70	11.866	111.11	2.98	4.15	1.899
BFC-PESdeficit	1.27	-121.52	23.236	99.56	2.98	4.15	1.899
Unconstrained-PES	1.19	-121.74	23.43	99.50	2.99	4.20	2.122

Source: Author's production.

The Total NPV of restoration actions of all scenarios is higher than US 120 millions, for restoring no more than 600 km^2. In our Optimization model (Chapter 3), active and passive ecological restoration methods are combined in the conversion from pasture area to restored forest areas of 7,753 PRPs (46% of our PRPs). The results of our approaches are an example that passive restoration is a promising method for restoring some areas. The adoption of restoration projects based on passive restoration is essential to reduce cost. The search for cost reduction strategies is very important, especially due to the limitation of restoration funds (MOLIN et al., 2018; STRASSBURG et al., 2020). For example, restoration costs may range from US$ 50.03 (natural regeneration method) to US$ 2,102.83 (total planting method, as seedling planting) per hectare in the Brazilian Atlantic Forest.

The high costs of the scenario relate to the amount of natural regeneration potential for the remaining pasture areas in the VPP, as estimated in Lemos et al. (2021) (Chapter 2).

The authors assume maintenance of the same conditions and relations captured by the statistical models derived for 2011 for estimating the natural regeneration throughout the years. This limitation could be corroborated by our finding of only 30 km² of area that are favored to receive passive ecological restoration in 2015, which directly affects the restoration cost of our scenarios, as Table 4.2 illustrates. Considering that natural regeneration increases across time (BRANCALION et al, 2016), we suggest the adoption of a dynamic natural regeneration potential to better investigate the natural regeneration potential throughout the years. The use of dynamic natural regeneration potential could reduce the necessity of active restoration methods, and it reflects in the reduction of the restoration cost. For example, the use of natural regeneration methods could reduce implementation costs by US$ 90.6 billion (77%) compared to tree planting when the whole Atlantic Forest is investigated for receiving restoration actions (CROUZEILLES et al., 2020).

Besides the implementation costs, forest restoration is also, generally, perceived as a cost by landholders, proportional to the envisioned profits that could be obtained with agricultural activities (i.e., opportunity costs) (HISSA et al., 2020). However, the Paraiba Valley presents a low value of profit from the most predominant agricultural activity (milk activity). Profit from the milk production activity is generally low as the Revenue/Cost is equal to 0.98 in the Guaratingueta that is one of the most important municipalities of milk production activity among the municipalities of our study area (CONAB, 2010). This low profit reinforces how it could be interesting for the landowners to seek adherence to the PES programs. Our results show PES mechanisms could reduce 15% of the total restoration cost.

The VPP is a relevant area to receive PES Programs because its low suitable for agricultural practices including mechanization, irrigation and grazing (SILVA et al., 2016a), and the region is currently responsible for around less than 1% of the revenue of agricultural production in São Paulo State in 2015 (IBGE, 2021b). This reduces the land competition with more profitable uses which could then be allocated in more productive areas elsewhere, an alternative strategy for reconciling biodiversity and food production (PHALAN et al., 2016; SEPPELT et al., 2016). However, the NPV of PES is six times smaller than the NPV of restoration actions. This result reinforces the necessity of looking for other restoration strategies that could be less costly for the landholders. For example, the adoption of agroforestry systems is an income alternative for the landholders for a period longer than the financing period of the PES programs (SÃO PAULO, 2019; SHAPIRO-GARZA, 2013). This strategy is aligned with the recent context of VPP where an increase of forest restoration is observed based on agroforestry systems and strengthening the network of agroforestry professionals (DEVIDE; 2013, 2019).

In our optimization model (Chapter 3), we adopted a *maximum restorable area* (MRA) of 50% of its pasture area of PRP. Considering this strategy, the landowners could continue with the milk activity in their properties even with adhere to the PES programs. We argue that this may also be relevant from a local food security perspective, in particular considering the importance of milk and its derivatives for the small landowners diets (FAO, 2013). Based on all these analyses, we argue that our modeling approach is useful for understanding multiple economic aspects of the restoration initiatives, including the economic benefit for the landowners.

4.1.2 Analysis of environmental indicators

In Chapter 2, the biodiversity results per scenario represents the *average number of benefited groups or species per hectare in each cell*, while in Chapter 3, it represents the *sum of the mode number of benefited groups or species in all rural properties.* We standardize the biodiversity results across the scenarios by the division of the biodiversity results per the total restored area for the last five scenarios. Our results show a similar biodiversity gain for all scenarios. They indicate that restoration action can benefit 3 taxonomic groups (as mammals, birds, and others groups) or 2 taxonomic groups and a landscape structure (such as large fragments and/or high connectivity). Although the habitat restoration could benefit 3 taxonomic groups or 2 taxonomic groups and a landscape structure, the restoration action on VPP is very important as this region safeguards an extraordinary richness of tree species (JOLY et al., 2014).

Carbon results can be compared directly because the result unit [MTon] is the same for all scenarios. Our results show a similar carbon gain for all scenarios, our results indicate that 600 km² of conversion from pasture to forest contribute with a carbon stock increase of 4.3 MTon. Our carbon gain is relatively similar with the carbon gain found by Strassburg et al. (2016). These authors estimate sequester 1.68 MTon of carbon with conversion of 240 km² of pastures to forest for the Paraitinga basin, that is an area inside our study area.

Soil loss results can be compared directly because the result unit [MTon] is the same for all scenarios. As the carbon results, soil results show similar gains when we compare the scenarios from Chapter 2 with the scenarios from Chapter 3. Our results indicate that 600 km² of conversion from pasture to forest contribute with a reduction of 1.98 MTon of Soil Loss. Our soil gain is relatively similar with the soil gain found by other authors. Strassburg et al. (2016) estimate a reduction of 0.6 MTon of Soil Loss with conversion of 240 km² of pastures to forest for the Paraitinga basin, and Padovezi et al. (2018) estimate a reduction of 0.8 MTon of Soil Loss with conversion of 423 km² of pastures to forest for VPP.

5 CONCLUSIONS

In this section, we summarize our main conclusions in this thesis. In section 5.1, we synthesize the answers to scientific questions that are proposed in Chapter 1. In section 5.2, we present some implications for restoration initiatives and recommendations for public policies. In section 5.3, we conclude with some research gaps and recommendations for future works.

5.1 Synthesis of the answers to scientific questions

In this section, we summarize our main conclusions in relation to the five scientific questions of this thesis. The answers to these questions are presented below.

1- What are the relevant biophysical, land use history, and socioeconomic factors to the natural regeneration process?

To answer this question, we adopt the assumption that regenerated forest cover in the study area is 100% related to natural regeneration, and we build and compare four alternative linear regression models for 2011. Each model explores a different set of explanatory variables. The first model only explore biophysical factors (**B model**), the second one combines biophysical and forest cover in 2005 (**Eco model**), the third one considers the biophysical, forest cover and other land covers in 2005 (**BH model**), and the fourth model insert the biophysical, land covers in 2005, and socioeconomic factors in 2011 (**BHS model**).

Based on our linear regression model results (Table 2.3 in Chapter 2), there are multiple explanatory variables for explaining the natural regeneration process for each alternative model. Some variables are found to be significant ($p<0.05$) in some of the models and non-significant in others. Terrain characteristics, climate, and agricultural suitability are significant factors in all models. For the **B model** ($R^2 = 0.37$; AIC = 21900), the most important factor is the higher percentage of natural regeneration to the steep slopes with a flat curvature, in elevated areas with higher precipitation. However, the *percentage of forests (remnant and regenerated) in 2005* is the most important variable for the model that combines biophysical factors and forest cover in the **Eco Model** ($R^2 = 0.63$; AIC =

15901). Including additional land cover factors in the **BH Model** ($R^2 = 0.70$; AIC = 12382), the significant factors included in the model relate to the *percentage of degraded pasture 2005* and the *distance from planted forests (*Eucalyptus) in 2005. These factors remain as the most important ones when socioeconomic factors are included in the **BHS Model** ($R^2 = 0.71$; AIC = 12005).

2- What is the natural regeneration potential in the Paraiba Valley?

Considering that the MBC is the regression cover that is most indicated for estimating the amount of natural restoration that can support, we used the MBC for estimating the natural regeneration potential in the *Potential Component* of LuccME. Because we work with continuous data, potential is the difference between the current land cover percentage and the estimated percentage according to the linear regression models (VERBURG et al. 1999). Then, in our study, the natural regeneration potential in 2015 is the difference between the percentage of regenerated forest cover in 2015 and the MBC (our estimated percentage according to the **ECO MODEL**). Using the MBC, the natural regeneration potential in 2015 varies from 0 to 0.17 in the study area. In the region, 87% of the cells present no positive values, which means that 87% of the cells are not favorable to receive passive ecological restoration, and 13% of the cells present natural regeneration potential even at the most equal to 0.17. This 13% of cells totalize almost 30 km² of area that are favored to receive passive ecological restoration.

The use of cells with 1 km of resolution could justify the small quantities of NRP that are found inside the cells because the natural regeneration takes place in areas smaller than 1 km² on the edge of pre-existing forest. During our modelling, we assume that the regenerated forest in 2015 maintains the same conditions and relations captured by the statistical models derived for 2011, this assumption could justify the small quantities of cells with NRP. In fact the NRP is a dynamic process that increases with each passing year (BRANCALION et al., 2016), so the NRP could be higher than 30 km². A new NRP for 2015 could be estimated by using dynamic explanatory variables, in particular, through the use of a dynamic explanatory variable that represents the percentage of forests (remnant and regenerated) across the previous years. This is an interesting solution because the *percentage of forests (remnant and regenerated) in 2005* is the most relevant explanatory variable that explains around 70% of the for the natural regeneration processes in 2011 in the VPP.

3- What are the restoration implementation cost, habitat increase, carbon stock increase, reduction of soil loss, and spatial patterns of restoration of the scenarios that consider the priority areas of the PES Programs?

To answer this question, we develop an allocation modelling approach and elaborate three scenarios. Using this natural regeneration potential estimated for 2015, we simulate the allocation of regenerated forest from 2015 to 2025, this simulation allows the allocation of the increment of regenerated forest until 2025. First scenario is without restriction rules for allocating new forest increments. We call this scenario an unconstrained scenario, that is the new forest increments could be allocated in any pasture area in the whole study area. The other two scenarios present restriction rules to allocate the forest increment inside the spatial partitions of PES Programs, we call these scenarios as constrained scenarios and these scenarios could allocate new forest increments in the pasture area inside the spatial partitions of PES Programs. One of them is aligned with the spatial partition of the Hydric PSA Program, and receives the name of Hydric PSA scenario. The other constrained scenario is aligned with the spatial partition of the Protection PSA Program, and receives the name of Protection PSA scenario.

We observe the enforcement of conversion from pasture to forest within cells with lower natural regeneration potential in the constrained scenarios (Protection PSA Program and Hydric PSA Program) in comparison to the natural regeneration potential of the unconstrained scenario. This conversion within cells with lower natural regeneration potential results from the restriction to allocate new forest areas outside the spatial partition of the constrained scenarios, this restriction must be excluding the cell with higher natural regeneration potential that should be localized in areas that are outside the spatial partition of the studied PES Programs. The enforced conversion from pasture to forest within cells with lower potential increases the total cost in both scenarios. This increases the restoration cost because it is necessary to use an active (and more expensive) method for restoring the incremented area.

Regarding the environmental benefit, each scenario has positive and negative aspects in relation to each other. Although the Protected PSA and Hydric PSA Scenarios outperformed the unconstrained scenario in relation to the soil and carbon indicators, they present relatively worse biodiversity gain indicators, with a slight decrease in the average number of benefited groups or species. However, all scenarios have similar environmental gains.

The similar gains are probably justified by the spatial scale of the environmental indicators of our study. For example, to estimate the carbon gain, we use the vegetation type map with a scale of 1: 5.000.000 (IBGE, 2004) that is the same map used in the Third Brazilian Inventory of greenhouse gas emissions (MCTI, 2015). As much as our results may have been influenced by the spatial scale of the environmental indicators, our allocation modelling approach presents sophisticated strategies to investigate the cost-effectiveness of different PES programs. We suggest quantifying the environmental gain with the use of finer-scale environmental indicators. The use of data with a finer scale, probably, will evidentiate more differences in environmental gains among the scenarios.

4- How much do the restoration of the legal deficits according to the Brazilian Forest Code influence the costs, benefits, and spatial patterns of restoration in the Paraiba Valley?

To answer this question, we develop an optimization modelling approach (BEYER et al. 2016) that used the boundary of the private rural properties (PRP) as the planning units, and the decision variable is the maximum restorable area (MRA) of each PRP. To investigate the influence of the Brazilian Forest Code (BFC) on the costs, benefits, and spatial patterns of restoration, we consider the BFC during the definition of the MRA of each PRP. The MRA is 50% of the pasture areas of the PRPs for the scenario of not enforcing the BFC, and the MRA is 50% of the pasture outside APP/LR deficit (noOB) of the PRPs for the scenario that enforces the BFC. We call the scenario of not enforcing the BFC as **Sc.1**, and we call the scenario that enforces the BFC as **Sc.2**.

Comparing the results of the two scenarios, **Sc.1** benefits a larger number of taxonomic groups (as mammals, birds, and others groups) and landscape structural parameters (such as large fragments and/or high connectivity) than **Sc.2**. Similar to biodiversity, the carbon and soil benefits of **Sc.1** are higher than **Sc.2**. On the other hand, the cost of **Sc.1** is lower than **Sc.2**. These environmental and economic differences reflect the fact that different PRPs end up being restored in the different scenarios to maximize the multiple indicators due to the obligation to restore the deficit areas. While 12,095 PRPs (72% of the our PRPs) are restored in **Sc.1**, 15,252 PRPs (90% of the our PRPs) are restored in **Sc.2.** As expected, more PRPs are selected for restoration in the BFC scenarios as restoring their legal deficits is mandatory (Figure 3.6 in Chapter 3). Even with the small differences in the cost-effectiveness between the scenarios, our results reinforce the importance of aligning restoration initiatives to the BFC compliance because this compliance contributes that the restoration actions occur across the study area and do not concentrate in specific areas.

The similar cost-effectiveness is probably justified by the spatial scale of the environmental indicators of our study. For example, to estimate the carbon gain, we use the vegetation type map with a scale of 1: 5.000.000 (IBGE, 2004) that is the same map used in the Third Brazilian Inventory of greenhouse gas emissions (MCTI, 2015). As much as our results may have been influenced by the spatial scale of the environmental indicators, our optimization modelling approach presents sophisticated strategies to investigate the cost-effectiveness of enforcement of BFC. We suggest quantifying the environmental gain with the use of finer-scale environmental indicators. The use of data with a finer scale, probably, will evidentiate more differences in cost-effectiveness between the scenarios.

5- How much do alternative PES mechanisms in legal deficits according to the Brazilian Forest Code influence the costs, benefits, and spatial patterns of restoration in the Paraiba Valley?

To answer this question, we also develop an optimization modelling approach (BEYER et al. 2016) that used the boundary of the private rural properties (PRP) as the planning units, and the decision variable is the maximum restorable area (MRA) of each PRP. To investigate the influence of the PES mechanisms in legal deficits according to the Brazilian Forest Code (BFC), we consider MRA is 50% of the pasture outside APP/LR deficit (noOB) of the PRPs for all scenarios because all scenarios enforce the BFC. The PES mechanisms explored through the payment to the landholders for restoration action in their PRP, and they are aligned with National Policy for Payment for Ecosystem Services (in Portuguese, Política Nacional de Pagamento por Serviços Ambientais - PNPSA),

The first PES mechanism is when landholders receive PES for only restoring noOB pasture areas, this mechanism is aligned with the *Article 9* of PNPSA for the situation that the PES program only can pay for restoration outside APP/LR deficit areas. The second PES mechanism is when landholders receive PES for restoring noOB pasture areas as well as deficit areas, this mechanism is aligned with the *Article 9* of PNPSA for the situation that the PES program can pay for restoration outside APP/LR deficit areas or APP/LR deficit areas.

Considering these different PES mechanisms, we investigate the influence of the PES mechanisms in costs, benefits, and spatial patterns through the three scenarios. In the first scenario, the BFC is enforced without the presence of PES mecnhanims, this is our **Sc.2**. The second scenario is enforced by the BFC and considering our first PES mechanism, we call this scenario as **Sc. 3**. The third scenario is enforced by the BFC and considering our second PES mechanism, we call this scenario as **Sc. 4**.

In the presence of the PES mechanism (**Sc.3** and **Sc.4**), the landowners could reduce around 15% of the cost for the situation where they do not receive PES (**Sc.2**), while the environmental benefits are almost similar. The same PRPs are selected in the **Sc.3** and

Sc.4, and almost all of them are selected in **Sc.2** too. This last result suggests that the payment has no effect on the selected areas in the study area.

The similar cost-effectiveness is probably justified by the spatial scale of the environmental indicators of our study. For example, to estimate the carbon gain, we use the vegetation type map with a scale of 1: 5.000.000 (IBGE, 2004) that is the same map used in the Third Brazilian Inventory of greenhouse gas emissions (MCTI, 2015). As much as our results may have been influenced by the spatial scale of the environmental indicators, our optimization modelling approach presents sophisticated strategies to investigate the cost-effectiveness of different PES mechanisms that are aligned with BFC and PNPSA. We suggest quantifying the environmental gain with the use of finer-scale environmental indicators. The use of data with a finer scale, probably, will evidentiate more differences in cost-effectiveness between the scenarios.

5.2 Implications for restoration initiatives and recommendations for public policies

Understanding the cost-effectiveness of restoration initiatives is critical for their implementation, in particular, due to limited restoration funds (BRANCALION et al., 2019). One strategic region for the restoration initiatives is the Paraiba Valley in São Paulo State (in Portuguese, *Vale do Paraíba Paulista* - VPP). This region has been undergoing a forest transition process in the last decades (SILVA et al., 2016a), and it has been chosen as the target of multiple restoration initiatives and PES programs, such as the Hydric PSA Program and Protection PSA Program.

The Hydric PSA Program is a local initiative that aims to restore forest inside 34 watersheds that are priority areas for water resources conservation; these areas are defined based on soil erosion and their relevance to the human water supply (OIKOS 2015). The Protection PSA Program is a state initiative, and it is one of the PSA programs of the Atlantic Forest Connection Project (in Portuguese, Projeto Conexão Mata Atlântica); this program aims to protect and manage of remaining and regenerating forest fragments that are relevant for biodiversity conservation, increase the carbon stock, reduction the soil erosion, and human water supply (SÃO PAULO 2019). In short, these PES programs have the objective of restoring areas that are relevant to biodiversity conservation, carbon stock increase and reduction of soil loss in VPP (LEMOS et al., 2021).

In this context, this thesis aims at contributing to advancing modelling approaches to achieve biodiversity conservation, carbon stock increase and reduction of soil loss in VPP, our approaches consider different forest landscape restoration strategies. We develop strategies to combine active and passive restoration methods, to restrict forest increment allocation in relevant areas of differents PES programs, to optimize three environmental benefits, to use irregular areas as planning units, to insert the PSE as part of the restoration cost, and to explore alternative payment rules for the PES mechanisms, in particular in relation to the enforcement of the Brazilian Forest Code and the recent National Policy for Payment for Ecosystem Services (in Portuguese, *Política Nacional de Pagamento por Serviços Ambientais* - PNPSA). All these strategies are explored through three modelling approaches.

The first modelling approach is the use of alternative statistical models for understanding the relationships between potential explanatory variables and the natural regeneration process. This approach brings two most relevant contributions for planning restoration initiatives. The first is that our approach makes it possible to understand the relation of explanatory variables with a low amount of regenerated forest cover in a specific planning unit (PU) as well as the relation of explanatory variables with a high amount of regenerated forest cover in another PU. The second one is the possibility of estimating the natural regeneration potential (NRP) considering the whole universe of PUs rather than considering a set of samples of the universe of PUs. Considering only a set of samples of the universe of PUs is the common strategy in statistical models of other studies (MOLIN et al., 2018; CROUZEILLES et al., 2020).

The second is a modelling approach that estimates the amount of NRP at at each time step, then allocates a new forest areas based on the NRP, and estimates the cost-effectiveness in the end of the processes for three scenarios aligned with the spatial partitions of Hydric PSA Program and Protection PSA Program. First scenario is without restriction rules for allocating new forest increments. We call this scenario an unconstrained scenario, that is the new forest increments could be allocated in any pasture area in the whole study area. The other two scenarios present restriction rules to allocate the forest increment inside the spatial partitions of PES Programs, we call these scenarios as constrained scenarios and these scenarios could allocate new forest increments in the pasture area inside the spatial partitions of PES Programs. One of them is aligned with the spatial partition of the Hydric PSA Program, and receives the name of Hydric PSA scenario. The other constrained scenario is aligned with the spatial partition of the Protection PSA Program, and receives the name of Protection PSA scenario. This approach brings the possibility to analyze the cost-effectiveness of different PES programs based on their spatial partitions. This possibility is the most relevant contribution of this approach for planning restoration initiatives.

The third one is a modelling approach that allocates the forest increment based on the maximization of three environmental benefits while minimizing the cost, this third approach considers scenarios aligned with Brazilian Forest Code and National Policy for Payment for Ecosystem Services (in Portuguese, Política Nacional de Pagamento por Serviços Ambientais - PNPSA), different PES mechanisms for composing the restoration cost. This approach advances in using the boundary of the private rural properties (PRP) as the PUs, and the decision variable as the maximum restorable area (MRA) of each PRP that is 50% of the pasture area of each PRP. In general, this approach contributes with the planning restoration initiatives because it brings the possibility to analyze the cost-effectiveness through the use of the irregular areas as PUs and the combination of multiple public policies and financial values of PES. This possibility is the most relevant contribution of this approach for planning restoration initiatives.

The advances of irregular areas as planning units and the possibility of using a range of indicators open an opportunity for improving the selection of prioritization areas to receive conservation action. For example, the choice of prioritization watersheds could consider a broad set of parameters that are relevant to water resources conservation, such as quality and amount of water characteristics or water uses (such as human supply, agricultural production or food security) (COOK; BAKKER, 2012). The possibility of using a range of water parameters could be useful for improving PES programs since the Hydric PSA Program (OIKOS, 2015) that is, a local initiative that prioritizes 34 watersheds as the relevant area to receive action for water resources conservation in VPP. This program identifies the priority watersheds using a set of different water parameters (such as amount of water and soil erosion) that are analyzed in each step. Our approach could collaborate with this program with an integrated analysis, as it allows multiple criterias analysis simultaneously. All these improvements could collaborate as an integrative approach to water management (COOK; BAKKER, 2012; BEYER et al., 2016).

We consider that simple adjustments in the restriction rules of our scenarios could allow an integrative investigation of BFC, PNPSA and PES programs. For example, the BFC constraints rules could be combined with the constraints rules of the scenarios presented in Lemos et al (2021), and thus the new forest allocation could be restricted to legal deficit inside areas of interest for PES programs, such as Hydric PSA Program (OIKOS, 2015) and Protection PSA Program (SÃO PAULO, 2019). Deepening the understanding of the planning of restoration strategies for compliance with BFC is of great importance, in particular, it would take 69 years to restore the legal deficit of VPP using only seedling planting, based on seedling production of the seven nurseries presented in VPP (ALUVEI; LEMOS; ANDRADE, 2020).

The VPP is a historical occupation that is strongly based on agricultural activities. The occupation began in the centuries XVI e XVIII, but it intensified with the coffee cycle in th century XIX (DEVIDE; 2013). This region is located in the Atlantic Forest Biome, that is the Brazilian Biome which has undergone the higher forest loss (RIBEIRO et al., 2009) where the remaining forest area is 12% of the original forest in the biome. These Atlantic Forest remnants are protected by a specific restrictive legislation (In portuguese, *Lei da Mata Atlântica*) (RIBEIRO et al., 2011). All this context of this Biome collaborating for it presents the greatest joint strengthening for restoration at various scales. For example, the Atlantic Forest Restoration Pact pledged to contribute with 1 Mha to the 2020 Bonn Challenge. From those, around 700,000 ha has been achieved from 2011 to 2015 (CROUZEILLES et al., 2019). Aligned to this, several other nested restoration initiatives are taking place from regional to local scales (ALARCON et al., 2017).

Among the linear regression models developed with our approach, the **Eco model** presents validation results slightly better than the other models, so this linear regression model better *aligns with our overall goal of favoring passive ecological restoration*, and the *regression cover* resulting from the **Eco model** indicates *the amount of natural restoration that can support.* We call this *regression cover* as the **maximum biophysical capacity (MBC)** for favoring the natural regeneration processes in Paraiba Valley. The MBC is used for estimating the amount of natural regeneration potential (NRP). Because we estimate the amount of NRP, it is possible to combine the active and passive restoration methods inside the planning unit. When we use the cell of 1 km x 1 km as the planning unit, the forest increment is based on the combination of restoration methods or based only on the active method. When we use the boundary of the private rural properties (PRP) as the planning unit, some PRP could be restored only based on natural regeneration.

Independent if the modelling approach quantifies the cost-effectiveness after or before the allocation of the restoration area, the three unconstrained scenarios (Unconstrained-whole area; Unconstrained-noPES and Unconstrained-PES) present the lowest cost when they are compared with their constrained scenarios. The enforced conversion from pasture to forest within restricted areas in the constrained scenarios results in allocating forest in areas with lower natural regeneration potential. As a consequence, it increases the need to use an active (and more expensive) method for restoring the incremented area, which increases the restoration cost. Our results show that PES value is six times smaller than the cost of restoration actions.

Our economic results reinforce the necessity of looking for other restoration strategies that could be less costly for the landholders. For example, the adoption of agroforestry systems is an income alternative for the landholders for a period longer than the financing period of the PES programs (PADOVEZI et al. 2018; SÃO PAULO, 2019). This method provides commodity as well non-commodity benefits such as ecosystem services, and these range benefits result in positive cash inflow-outflow (SHAPIRO-GARZA, 2013) and enhance food, nutrition and income security (SEGHIER et al., 2021). This strategy is aligned with the recent context of VPP where an increase of forest restoration is observed based on agroforestry systems and strengthening the network of agroforestry professionals (DEVIDE; 2013, 2019).

All the scenarios explore the cost-effectiveness of maintaining a high rate of conversion from pasture to regenerated forest (60 km²/year). In general, all scenarios result in similar environmental gains. This result is probably justified by the spatial scale of the environmental indicators of our study. For example, to estimate the carbon gain, we use the vegetation type map with a scale of 1: 5.000.000 (IBGE, 2004) that is the same map used in the Third Brazilian Inventory of greenhouse gas emissions (MCTI, 2015). We suggest quantifying the environmental gain with the use of finer-scale environmental indicators. The use of data with a finer scale, probably, will evidentiate more differences in environmental gains among the scenarios

5.3 Research gaps and recommendations for future works

The regenerated forest cover maps resulting from for 20215 (Chapter 2) show the presence of regenerated forest cover across the VPP. The diffuse regenerated forest could favor the increase of biodiversity corridors in the region. In future work, we suggest the inclusion of indicators of connectivity besides the use of finer-scale environmental indicators. This improvement in the environmental indicators could evidentiate more differences in the cost-effectiveness among our scenarios.

In this thesis, we assume maintenance of the same conditions and relations captured by the statistical models derived for 2011 for estimating the natural regeneration throughout the years. This limitation could be corroborated by our finding of only 30 km² of area that are favored to receive passive ecological restoration in 2015, which directly affects the restoration cost of our scenarios. Considering that natural regeneration increases across time (BRANCALION et al, 2016), we suggest the adoption of a dynamic natural regeneration potential to better investigate the natural regeneration potential throughout the years.

The use of dynamic natural regeneration potential could reduce the necessity of active restoration methods, and it reflects in the reduction of the restoration cost. One way to explore dynamic natural regeneration potential is actualization of the percentage of forests (remnant and regenerated) in 2005 by the percentage of forests (remnant and regenerated) in the following years. This is an interesting solution because the percentage of forests (remnant and regenerated) in 2005 is the most relevant explanatory variable that explains around 70% of the for the natural regeneration processes in the VPP.

For improving the investigation of cost-effectiveness, another suggestion is the exploration of forest restoration scenarios that consider other restoration methods (PADOVEZI et al., 2018). We believe that our approaches could be adjusted to consider ecological restoration methods with low and high seedling density (such as Enrichment Planting) as one restoration strategy, or could be adjusted for restoration methods that present revenue for the landholders. For example, different agroforestry systems could be adopted as forest restoration methods because they provide commodity as well non-commodity benefits such as ecosystem services, and these range benefits result in positive cash inflow-outflow (SHAPIRO-GARZA, 2013) and enhance food, nutrition and income security (SEGHIER et al., 2021). These strategies could reduce the restoration implementation cost (BRANCALION, et al. 2019), which could be interesting because forest restoration is also generally perceived as a cost by landholders, proportional to the envisioned profits that could be obtained with agricultural activities (i.e., opportunity costs) (HISSA et al., 2020).

We adopt some strategies during the building of the economic indicators, the first of them is considering the same profit for milk activity for all years. We adopt this strategy because we do not know the total pasture for next year, so the use of dynamic profits could be another improvement for our financial analysis (CROUZEILLES et al., 2020). The second one is considering that cost is always equal to zero during the PES program, however, financial costs of enrollment (e.g., purchasing seedlings) can limit who participates in a PES program (JACK; JAYACHANDRAN, 2019), so we suggest that futures works considering the costs of enrollment for improving the financial analysis.

Three of our scenarios direct part of the restoration forest in the legal deficit areas, the most part of the deficit areas in our study area are riparian areas. These important zones that link forest and rivers (GREGORY et al., 1991) present heterogeneous tree biomass, density and richness in communities undergoing restoration (SUGANUMA et al., 2016), and the recovery of infiltration varied depending on restoration age (LOZANO-BAEZ et al., 2019). These heterogeneities could be implemented in future studies that could reflect different environmental gains among the scenarios, while our results identified similar environmental gains among our five scenarios.

For our study area that present the predominance of small PRPs, we decide to work only with deterministically restoration of the legal deficit because small PRPs do not have LR deficit due to the absence to obligation of restoring the LR (article 67 of BFC) (FREITAS et al., 2017). For regions with large LR deficits, we suggest the optimization of the restoration of the LR deficit. The optimization of the legal deficit is explored in previous studies (STRASSBURG et al., 2018; HISSA et al., 2020) and it could be very interesting for understanding the importance of the role of Environmental Reserve Quota (in Portuguese, *Cota de Reserva Ambiental* - CRA) to regularize LR (FARIA et al., 2021).

The current version of LuccME Model does not account for the competition for pasture land with other uses, such as eucalyptus. Finally, and importantly, the explanatory variables in our model are currently not dynamic. This is particularly relevant for distance to forest areas, especially, because remnant forests are decreasing over time. Future works could consider dynamically updating such variables, in particular the changes in forest areas produced by the model itself. This might increase the *maximum biophysical capacity* of the landscape to forest growth, and consequently the local need for active methods. And it is one way for exploring forest restoration scenarios aligned with the Atlantic Forest Law (FARIA et al., 2021).

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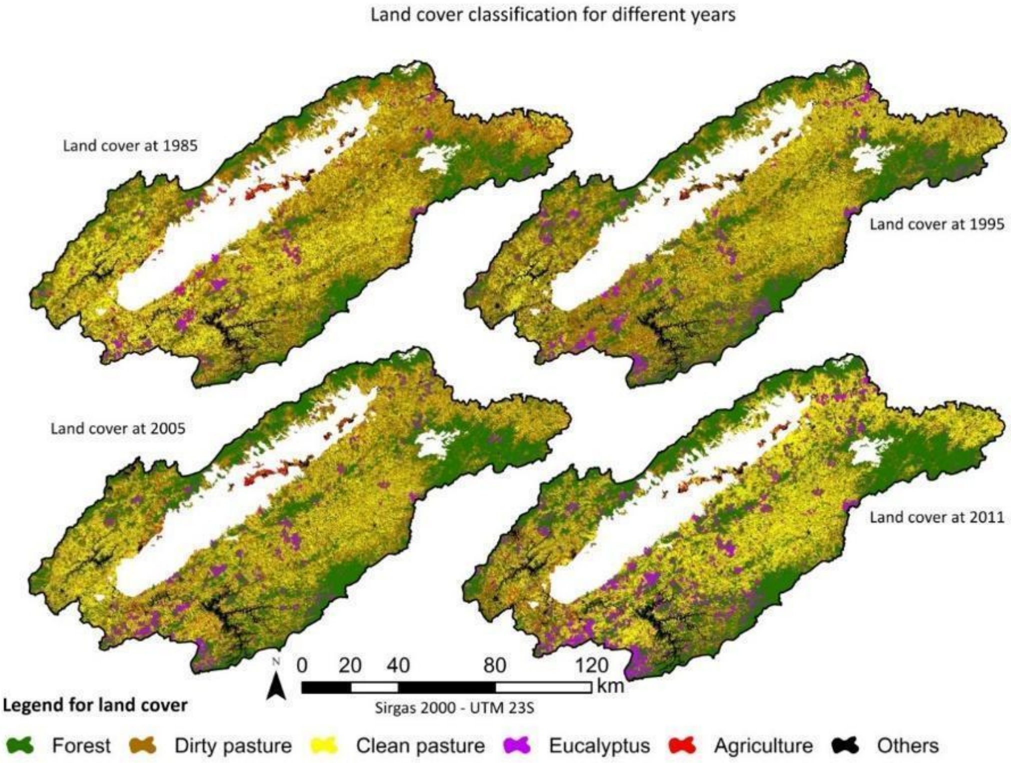
APPENDIX A - SUPPLEMENTARY MATERIAL OF CHAPTER 2

A.1 Materials and methods

A.1.1 Study area

The region is located between two major mountain ranges, the *Serra do Mar* with a maximum elevation of 1,877 m, and *Serra da Mantiqueira* with a peak at 2,791 m above sea level, and rolling hills with an elevation variation of around 200 m. The region has about 63% of its terrain dominated by land with steeper slopes (above 20%) (Silva et al. 2016a). Figure A.1 illustrates the land cover classification for 1985, 1995, 2005 and 2011.

Figure A. 1 - Land cover classification for 1985, 1995, 2005, and 2011.



Source: Lemos et al. (2021).

A.1.2 Cellular database organization

The areas of these administrative municipal units are important for explaining the choice of the size of our grid (Table A.1).

Table A.1 - Area of the 34 administrative municipal units presented in the study area.

Administrative municipal unit	Area [Km²]	Administrative municipal unit	Area [Km²]
Aparecida	121.0	Monteiro Lobato	330.9
Arapeí	152.5	Natividade da Serra	805.1
Areias	303.9	Paraibuna	720.4
Bananal	602.6	Pindamonhangaba	708.4
Caçapava	368.8	Piquete	171.2
Cachoeira Paulista	287.8	Potim	44.43
Canas	53.22	Queluz	247.9
Cruzeiro	304.4	Redenção da Serra	309.1
Cunha	1371	Roseira	130.6
Guararema	268.4	Santa Branca	270.6
Guaratinguetá	749.4	Santa Isabel	358.0
Igaratá	291.4	São José do Barreiro	567.0
Jacareí	464.0	São José dos Campos	1095
Jambeiro	184.3	São Luiz do Paraitinga	611.7
Lagoinha	255.3	Silveiras	414.5
Lavrinhas	166.4	Taubaté	624.4
Lorena	413.8	Tremembé	191.2

Source: Lemos et al. (2021).

A.1.2.1 Explanatory factors related to natural regeneration spatial patterns

We compile an initial set of twenty-four **candidate** variables that could potentially explain the natural forest regeneration process that took place in our study area from 1985 to 2011 (Table A.2). Considering that we use the candidate variables for calibrating/validating the linear regression models (B Model; Eco Model; BH Model;

BHS Model) for 2011, we adopt the land cover data for 2005 because this data is the representation of the historical land use, and we adopt socioeconomic data for 2011 because is the same date of our model date.

Table A.2 - Relevant information about candidate variables used in our study.

Category	Factor	Resolution/Scale	Data source
Biophysical	Classes of Aspect	30m/ -	WRI (2019)
	Classes of Surface curvature	30m/ -	WRI (2019)
	Classes of Slope	30m/ -	WRI (2019)
	Classes of Soil	- / 1:100,000	Rossi (2017)
	Classes of agricultural suitability	30m/ -	WRI (2019)
	Elevation	30m/ -	WRI (2019)
	Climatological Precipitation	100m/ -	Kalnay et al. (1996)
	Climatological Temperature	100m/ -	Kalnay et al. (1996)
	Waterbody	- / 1:250,000	ANA (2013)
Land cover	Remnant cover at 2005	30m/ -	Silva et al. (2016a)
	Eucalyptus cover at 2005	30m/ -	Silva et al. (2016a)
	Degraded pasture cover at 2005	30m/ -	Silva et al. (2016a)
Socioeconomic	City center	- / 1:250,000	IBGE (2010)
	Highway	- / 1:250,000	DNIT (2013)
	Railway	- / 1:250,000	DNIT (2013)
	Protected areas	- / 1:250,000	MMA (2012)
	Rural population (%) at 2011	Census/ -	SEADE (2020)
	Farm jobs/Total jobs (%) at 2011	Census/ -	SEADE (2020)
	Farm revenue/Total revenue (%) at 2011	Census/ -	SEADE (2020)
	Farm profit/ Total profit(%) at 2011	Census/ -	SEADE (2020)
	Farm credit / Rural employ units ($/Unit) at 2011	Census/ -	SEADE (2020)
	Stocking rate (animal unit/ha) at 2011	Census/ -	IBGE (2011a); Silva et al. (2016a)
	Milk productivity (l/ha) at 2011	Census/ -	IBGE (2011c); Silva et al. (2016a)
	Milk revenue ($/ha)	Census/ -	IBGE (2011c); Silva et al. (2016a)

Source: Lemos et al. (2021).

The Table A.3 shows the operation used in each candidate variable, and other relevant information about the organization of these variables.

Table A.3 - Organization of the candidate variables as cellular atributte.

Category	Factor	Operation to fill cell attribute	Attribute name
Biophysical	Classes of Aspect	Percentage	CoOri_X *
	Classes of Surface curvature	Percentage	CoCur_Y *
	Classes of Slope	Percentage	CoSlope_W *
	Classes of Soil	Percentage	CoSoi_Z *
	Classes of agricultural suitability	Percentage	CoSil_Y*
	Elevation	Average	Elev
	Climatological Precipitation	Average	Prec
	Climatological Temperature	Average	Temp
	Waterbody	Distance	d_Water
Land cover	Remnant cover at 2005	Percentage/Distance	CoFor_05/ d_For05
	Eucalyptus cover at 2005	Percentage/Distance	CoEuc_05/ d_Euc05
	Degraded pasture cover at 2005	Percentage	CoAPa_05
Socioeconomic	City center	Distance	d_City
	Highway	Distance	d_High
	Railway	Distance	d_Rail
	Protected areas	Percentage	CoPro/ d_Prot
	Rural population (%) at 2011	Average	AvPop
	Farm jobs/Total jobs (%) at 2011	Average	AvJob
	Farm revenue/Total revenue (%) at 2011	Average	AvRevT
	Farm profit/ Total profit(%) at 2011	Average	AvPro
	Farm credit / Rural employ units ($/Unit) at 2011	Average	AvCred
	Stocking rate (animal unit/ha) at 2011	Average	AvStocM
	Milk productivity (l/ha) at 2011	Average	AvProdM
	Milk revenue ($/ha)	Average	AvRevM

*X ranges from 1 to 8, Y ranges from 1 to 3. W range from 1 to 6, Z range from 1 to 11

Source: Lemos et al. (2021).

Aspect is classified according Marques et al. (2005), that is, as north (0°- 22.5° and 337.5°- 360°), northeast (22.5°- 67.5°), east (67.5°- 112.5°), southeast (112.5°- 157.5°), south (157.5°- 202.5°), southwest (202.5°- 247.5°), west (247.5°- 292.5°), or northwest (292.5°- 337.5°). These classes appear in CS as the cellular attributes Percentage of north facing terrain (CoOri_1), Percentage of northeast facing terrain (CoOri_2), Percentage of east facing terrain (CoOri_3), Percentage of southeast facing terrain (CoOri_4), Percentage of south facing terrain (CoOri_5), Percentage of southwest facing terrain (CoOri_6), Percentage of west facing terrain (CoOri_7), Percentage of northwest facing terrain (CoOri_8).

Surface curvature is classified according to Marques et al. (2005), that is, as concave (≤ 0.3), flat (-0.3 a +0.3), or convex (≥ 0.3). These classes appear in CS as the cellular attributes Percentage of concave surface (CoCur_1), Percentage of a flat surface (CoCur_2) and Percentage of convex surface (CoCur_3).

Slope is classified according to Marques et al. (2005), that is, as slope between 0 and 3%, slope between 3 and 8%, slope between 8 and 20%, slope between 20 and 45%, slope between 45 and 75%, slope >75%. These classes appear in CS as the cellular attributes Percentage of between 0 and 3% (CoSlope_1), Percentage of slope between 3 and 8% (CoSlope_2), Percentage of slope between 8 and 20% (CoSlope_3), Percentage of slope between 20 and 45% (CoSlope_4), Percentage of slope between 45 and 75% (CoSlope_5), and Percentage of slope >75% (CoSlope_6).

The suitability of the physical environment to perennial culture, like silviculture, is less restrictive than for annual agricultural crops (BARRETO et al., 2013), this lower restriction is the reason that we chose the silvicultural suitability for our analysis. The layer of the physical environment suitability for silviculture (WRI, 2019) is reclassified with classes low, medium and high agricultural suitability according to Barreto et al. (2013). These classes appear in CS as the cellular attributes Percentage of low agricultural suitability (CoSil_1), Percentage of medium agricultural suitability (CoSil_2), Percentage of high agricultural suitability (CoSil_3).

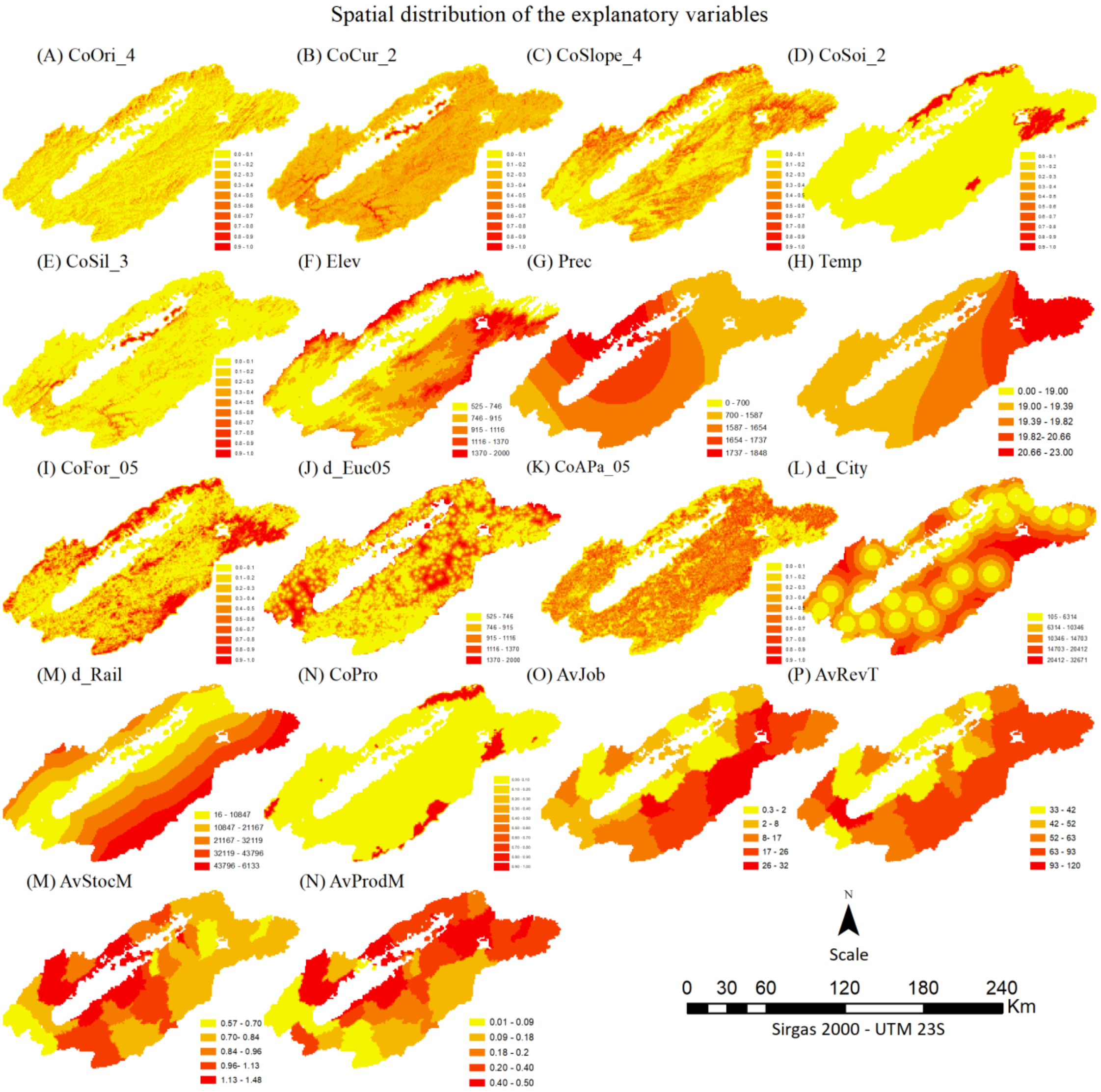
In Brazil, Conservation Units are classified as sustainable use units or integral protection units (BRASIL, 2000). In this work, sustainable use units are disregarded because they have multiple land uses (BRASIL, 2000). Integral protection units (MMA, 2012) are used as our layer of the State protection units.

Similar to Silva et al. (2016b), Rural Population, Farm jobs, Farm revenue, Farm profit, and Farm Credit were selected as variables and transformed, divided by total population, jobs, revenue, profit, and farm job establishment, respectively, to correct for municipality size and demographic heterogeneity. A similar approach of the adaptation is applied in another study that uses data with municipality resolution and aims to compare municipality conditions that have high heterogeneity values (ADAPTABRASIL, 2020). These socioeconomics variables are important to represent the rural conditions in relation to the total socio-economic conditions in the municipalities (SILVA et al., 2016b).

The Stocking rate, Milk productivity, and Milk revenue are considered as they are considered in previous study (SILVA et al., 2016a), that is by dividing the total number of animals, milk production and milk revenue in each municipality by the total area occupied as pasturelands in the respective municipality, in the same year (For example, number of animals in 2011/pasturelands in 2011).

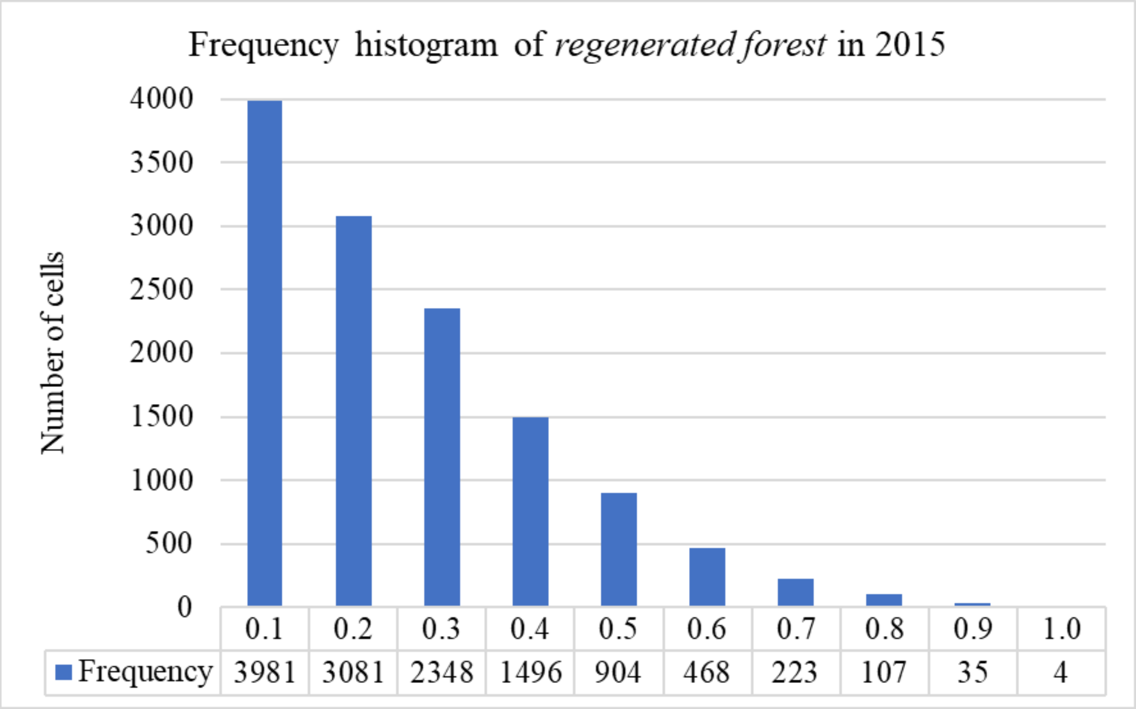
The Figure A.2 illustrates the spatial distribution of the explanatory variables, and the Figure A.3 illustrates the Regenerated forests cover histogram. Both Figures are important for illustrating the cell fill with our variables.

Figure A.2 - Spatial distribution of the explanatory variables.



Source: Lemos et al. (2021).

Figure A.3 - Regenerated forests cover histogram.



Source: Lemos et al. (2021).

A.2 Exploratory analysis and selection of alternative statistical models

All variables that receive a logarithmic transformation are saved as l**Attribute name** (For example, lCoFor_05 is the variable CoFor_05 with logarithmic transformation). The Table A.4 presents the correlation coefficient between the explanatory variables that are selected for our models.

Table A.4 - Correlation between the explanatory variables.

Variables	lCoOri4	lCoCur2	CoSlope_4	lCoSlope4	lCoSoi2	lCoSil3	Elev	Prec	lTemp	lCoFor_05	ld_Euc05	lCoAPa_05	ld_City	ld_Rail	lCoPro	AvJob	lAvRevT	lAvStocM
lCoOri4	**1.00**	0.51	0.17	0.33	0.10	0.27	0.05	0.20	0.24	0.35	-0.12	0.18	0.08	0.10	0.09	0.00	-0.02	-0.01
lCoCur2	0.51	**1.00**	0.01	0.21	-0.10	0.65	-0.18	0.32	0.43	0.23	-0.10	0.44	-0.08	-0.02	-0.07	0.07	0.10	-0.06
CoSlope_4	0.17	0.01	**1.00**	0.69	0.28	-0.53	0.40	0.05	0.08	0.50	-0.18	-0.03	0.19	0.25	0.15	0.07	-0.05	0.03
lCoSlope4	0.33	0.21	0.69	**1.00**	0.15	-0.27	0.30	0.08	0.18	0.61	-0.19	0.16	0.21	0.40	0.11	0.20	0.05	-0.06
lCoSoi2	0.10	-0.10	0.28	0.15	**1.00**	-0.33	0.63	-0.10	0.02	0.27	-0.03	-0.31	0.26	0.15	0.41	0.07	-0.01	-0.04

(To be continued)

Table A.4 – Conclusion.

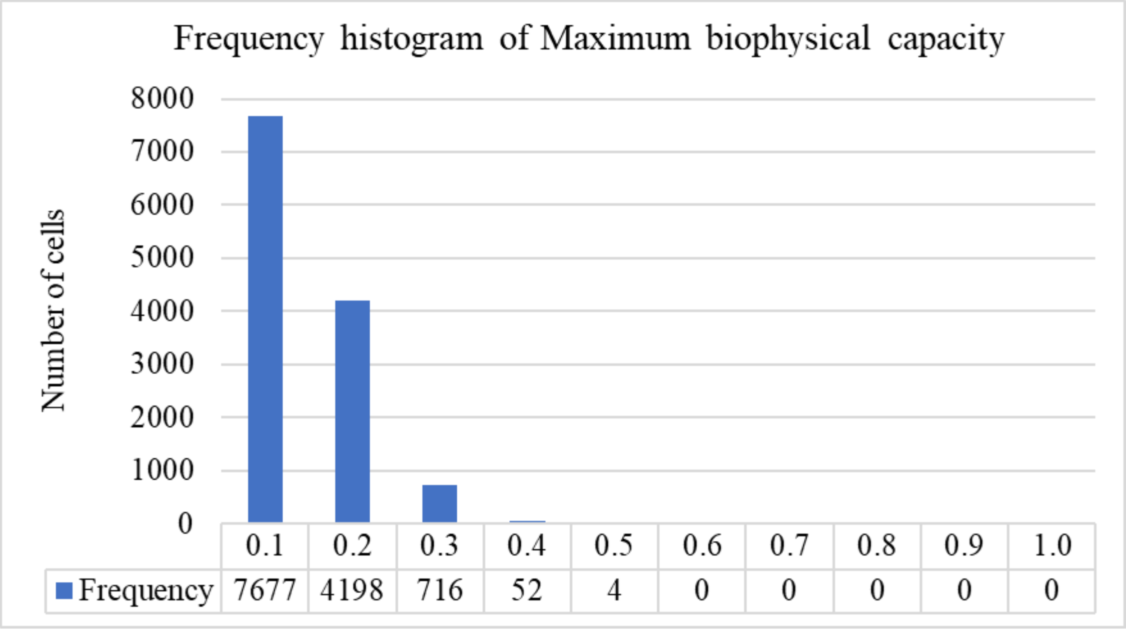
Variables	lCoOri4	lCoCur2	CoSlope_4	lCoSlope4	lCoSoi2	lCoSil3	Elev	Prec	lTemp	lCoFor_05	ld_Euc05	lCoAPa_05	ld_City	ld_Rail	lCoPro	AvJob	lAvRevT	lAvStocM
lCoSil3	0.27	0.65	-0.53	-0.27	-0.33	**1.00**	-0.50	0.14	0.17	-0.18	0.04	0.37	-0.20	-0.19	-0.21	0.01	0.11	-0.06
Elev	0.05	-0.18	0.40	0.30	0.63	-0.50	**1.00**	-0.03	0.01	0.40	-0.12	-0.32	0.45	0.44	0.32	0.28	0.06	-0.03
Prec	0.20	0.32	0.05	0.08	-0.10	0.14	-0.03	**1.00**	0.73	0.14	-0.09	0.13	0.05	0.03	-0.17	-0.17	-0.23	0.41
lTemp	0.24	0.43	0.08	0.18	0.02	0.17	0.01	0.73	**1.00**	0.19	-0.03	0.18	0.02	0.05	0.02	0.06	0.05	-0.05
lCoFor_05	0.35	0.23	0.50	0.61	0.27	-0.18	0.40	0.14	0.19	**1.00**	-0.40	-0.09	0.30	0.39	0.24	0.16	0.07	-0.05
ld_Euc05	-0.12	-0.10	-0.18	-0.19	-0.03	0.04	-0.12	-0.09	-0.03	-0.40	**1.00**	0.17	-0.12	-0.18	-0.09	-0.04	-0.01	-0.10
lCoAPa_05	0.18	0.44	-0.03	0.16	-0.31	0.37	-0.32	0.13	0.18	-0.09	0.17	**1.00**	-0.16	-0.09	-0.34	0.01	0.03	-0.08
ld_City	0.08	-0.08	0.19	0.21	0.26	-0.20	0.45	0.05	0.02	0.30	-0.12	-0.16	**1.00**	0.40	0.22	0.09	-0.07	0.10
ld_Rail	0.10	-0.02	0.25	0.40	0.15	-0.19	0.44	0.03	0.05	0.39	-0.18	-0.09	0.40	**1.00**	0.14	0.53	0.24	0.03
lCoPro	0.09	-0.07	0.15	0.11	0.41	-0.21	0.32	-0.17	0.02	0.24	-0.09	-0.34	0.22	0.14	**1.00**	0.07	0.02	-0.12
AvJob	0.00	0.07	0.07	0.20	0.07	0.01	0.28	-0.17	0.06	0.16	-0.04	0.01	0.09	0.53	0.07	**1.00**	0.66	-0.33
lAvRevT	-0.02	0.10	-0.05	0.05	-0.01	0.11	0.06	-0.23	0.05	0.07	-0.01	0.03	-0.07	0.24	0.02	0.66	**1.00**	-0.51
lAvStocM	-0.01	-0.06	0.03	-0.06	-0.04	-0.06	-0.03	0.41	-0.05	-0.05	-0.10	-0.08	0.10	0.03	-0.12	-0.33	-0.51	**1.00**

Source: Lemos et al. (2021).

A.3 LuccME modelling approach

One of the outputs of LuccME is the regression value (Reg) by cell. This value is the projected value of the dependent variable (that is the estimated percentage) according to the linear regression models. As output of the LuccME framework, we identify the regression (Reg) value using the linear regression models which captures the relationship between regenerated forest and its underlying ecological processes (**Eco Model**). For simplifying our analysis, the Reg values are constant in each time step of our analysis because we do not use dynamic explanatory variables (AGUIAR et al. 2016). The Reg values from the **Eco Model** indicate the maximum biophysical capacity of the landscape to forest regeneration.

Figure A.4 - Maximum biophysical capacity histogram.



	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Frequency	7677	4198	716	52	4	0	0	0	0	0

Source: Lemos et al. (2021).

A.4 Scenarios: alternative assumptions about the scale restoration commitments

Another output of LuccME is the potential value by cell, which is the difference between the current land cover percentage in each time step and regression value (Reg) by cell (in our case, the Reg values are from the **Eco Model**). Potential (Pot) <= 0 indicates that the cell cannot receive demand for the considered land cover class. While Pot >0 indicates that the cell can receive demand for the considered land cover class (Verburg et al. 1999). For each scenario (Atlantic Forest Restoration Pact, Protection PSA Program and Hydric PSA Program), we identify the potential (Pot) for 2015. We used Pot2015 because 2015 is the first year of our scenarios. In our case, regenerated forest as a *proxy* of natural regeneration (Section 2.2), so we consider the regenerated forest potential in 2015 as the natural regeneration potential in 2015.

The third output is the total of the incremented area of regenerated forest for each cell. For each scenario (Atlantic Forest Restoration Pact, Protection PSA Program and Hydric PSA Program), we identify the incremented area of regenerated forest for each cell for 2025. We use the (Inc2025) because 2025 is the last year of our scenarios.

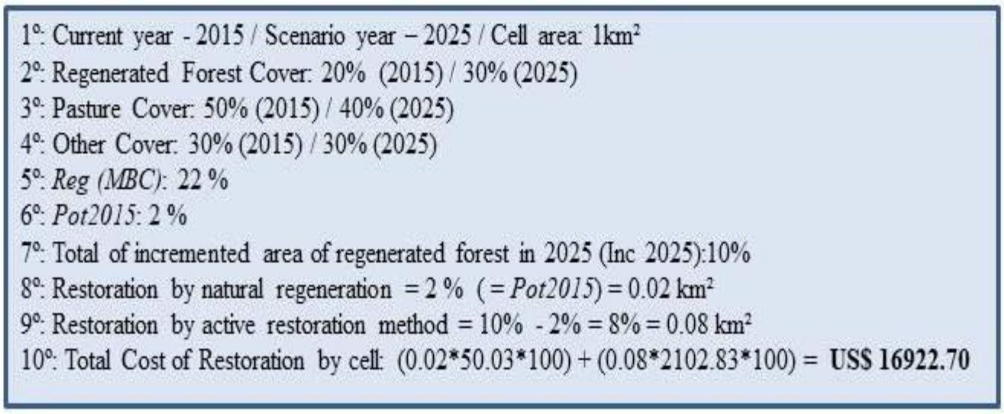
A.5 Indicators for comparing the scenarios: cost, carbon, biodiversity and soil

Cost of restoration (US$): For each cell of each scenario, the first step is the identification of the signal of the natural regeneration potential estimated in 2015 (Pot2015), that is the difference between the regenerated forest cover percentage in 2015 and regression (Reg) value by cell (in our case, the Reg values are from the **Eco Model**).

- Pot2015<=0 indicates that the cell can not receive demand of natural regeneration
    - When Pot2015<=0 and Inc2025>0, the Inc2025 need to be regenerated with active restoration methods
- Pot2015>0 indicates that the cell can receive demand for natural regeneration.
    - When Pot2015>=Inc2025 indicates that natural regeneration potential is enough for restoring all the regenerated forest increment, so for this cell the natural regeneration, a passive restoration method is sufficient for restoring the cell.
    - When Pot2015<Inc2025 indicates that natural regeneration potential is deficient for restoring all the regenerated forest increment, so natural regeneration needs to be combined with active ones to achieve better outcomes (RODRIGUES et al., 2011).
        - The difference (Inc2025–Pot2015) is the area that needs to be regenerated with active restoration methods (US$ 2102.83/ha) while the Pot2015 is the area that can be regenerated by natural regeneration (US$50.03/ha).

The Figure A.5 illustrates the one example of calculating the cost of restoration in one cell. Figure A.6 illustrates the spatial distribution of the cost of restoration.

Figure A.5 - Example of calculating the cost of restoration in one cell.



1°: Current year - 2015 / Scenario year – 2025 / Cell area: 1km²

2°: Regenerated Forest Cover: 20% (2015) / 30% (2025)

3°: Pasture Cover: 50% (2015) / 40% (2025)

4°: Other Cover: 30% (2015) / 30% (2025)

5°: *Reg (MBC)*: 22 %

6°: *Pot2015*: 2 %

7°: Total of incremented area of regenerated forest in 2025 (Inc 2025):10%

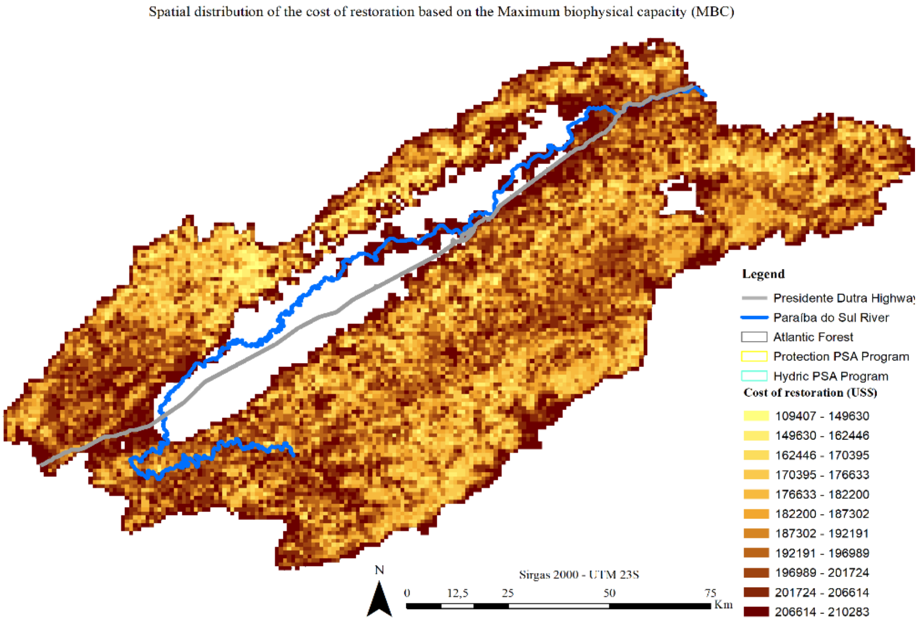
8°: Restoration by natural regeneration = 2 % (= *Pot2015*) = 0.02 km²

9°: Restoration by active restoration method = 10% - 2% = 8% = 0.08 km²

10°: Total Cost of Restoration by cell: (0.02*50.03*100) + (0.08*2102.83*100) = **US$ 16922.70**

Source: Lemos et al. (2021).

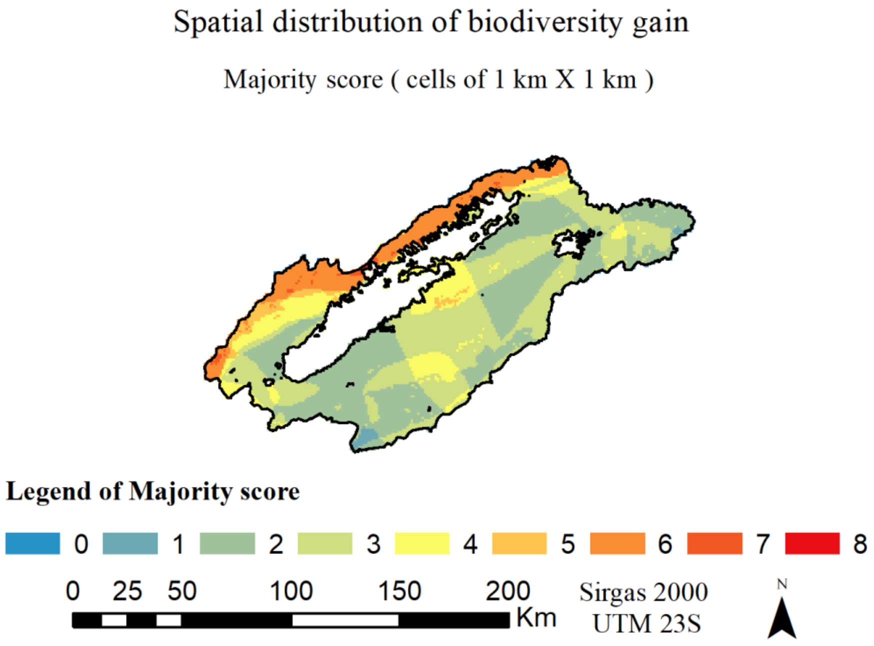
Figure A.6 - Spatial distribution of the cost of restoration.



Source: Lemos et al. (2021).

Biodiversity benefit (Average number of benefited groups or species/ha): Guiding by Convention on Biological Diversity (CBD), an important synthesis map identifies priority areas for biodiversity restoration based on specialist studies (JOLY et al., 2010). The map defines a score of priority areas for biodiversity restoration, this score ranges from 0 (no priority) to 8 (high priority) and reflects the number of recommendations made by the team of experts. This team of experts is composed of specialists in each taxonomic group recorded in the area (seven taxonomic groups) and specialists of the evaluation of landscape ecology. The higher score indicates that a bigger number of groups or species that inhabit the area could benefit from restoration actions, as reconnecting fragments of native vegetation. Using this synthesis map, the Atlantic Forest in Paraiba Valley presents different scores of priority areas for biodiversity restoration (Figure A.7).

Figure A.7 - Spatial distribution of Biodiversity gain.



Source: Lemos et al. (2021).

Carbon benefit (Ton): We adopt that the regenerated forest presents 44% of the mean carbon stock of pristine forest based on the recommendations of the Third Brazilian Inventory of greenhouse gas emissions to the UNFCCC (MCTI, 2015). For identifying the vegetation types present in our study area, we use the vegetation type map with scale of 1: 5.000.000 (IBGE, 2004) that is the same map used in the Third Brazilian Inventory of greenhouse gas emissions (MCTI, 2015). For each vegetation type present in our study area (Table A.5), we calculate the difference between the mean *carbon stock* in regenerated forest (44% of pristine forest) and the mean *carbon stock of pasture cover*. This difference indicates the mean carbon stock removal with conversion from pasture to regenerated forest (ton/ha) that represents the mean carbon stock increase by vegetation type (Ton/ha) (Tables A.8).

Table A.5 - Vegetation type present in our study area.

Vegetation Type	Vegetation type acronym*	Mean carbon stock (ton/ha) in pristine forest	Mean carbon stock (ton/ha) in regenerated forest (44% of pristine forest)
High-Montane Dense Ombrophylous Forest	Dl	105.50	46.42
Montane Dense Ombrophylous Forest	Dm	177.80	78.23
SubMontane Dense Ombrophylous Forest	Ds	151.40	66.62
Montane Seasonal Semideciduous Forest	Cm	106.90	47.04
SubMontane Seasonal Semideciduous Forest	Cs	123.10	54.16

*Vegetation acronym used in the Third Brazilian Inventory of greenhouse gas emissions to the UNFCCC (MCTI, 2015)

Source: Lemos et al. (2021).

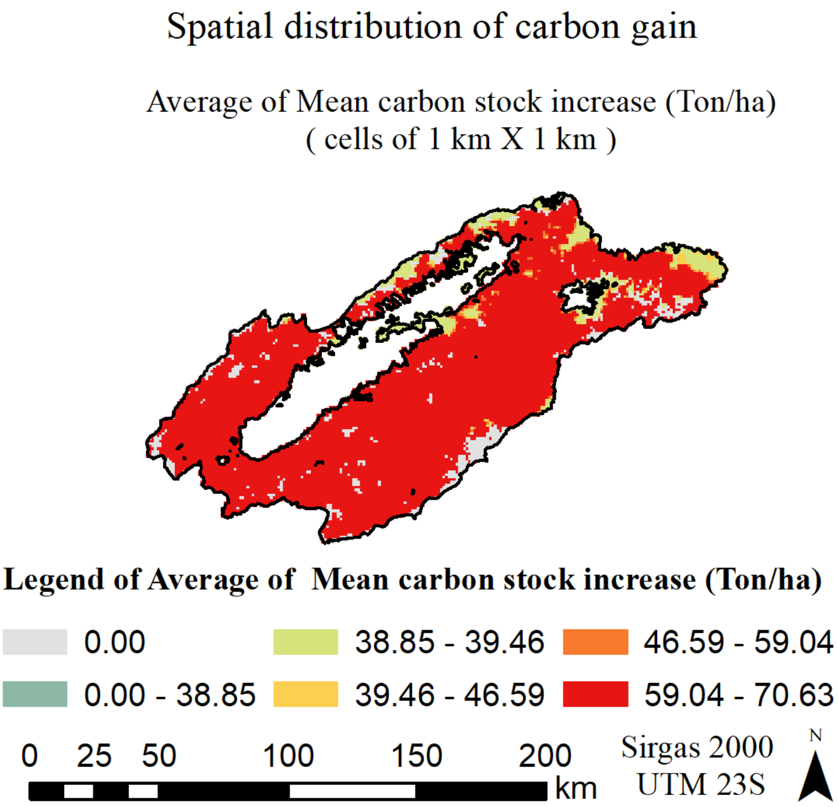
Table A. 6 - Mean carbon stock increase by vegetation type (Ton/ha).

Cover	Mean carbon stock (ton/ha)	Mean carbon stock removal with conversion from pasture to regenerated forest (ton/ha)	Mean carbon stock increase by vegetation type acronym	Vegetation type
Pasture	7.57	-	-	-
Regenerated forest of Dl	46.42	38.85	rDl	1
Regenerated forest of Dm	78.23	70.66	rDm	2
Regenerated forest of Ds	66.62	59.05	rDs	3
Regenerated forest of Cm	47.04	39.47	rCm	4
Regenerated forest of Cs	54.16	46.59	rCs	5

Source: Lemos et al. (2021.)

For each cell, we calculate the mean carbon stock increase (Ton/ha) using the area-weighted average of vegetation type area inside the cell (Figure A.8).

Figure A.8 - Spatial distribution of Carbon gain.



Source: Lemos et al. (2021).

Soil benefit (Ton): Considering that our scenarios are from 2015 to 2025, the reduction of soil loss [ton/ha/year] is estimated through the difference among the annual soil loss rates [ton/ha/year] for 2015 and 2025. The annual soil loss rates [ton/ha/year] are calculated through the Universal Soil Loss Equation (USLE) in InVEST Sediment Delivery Ratio (SDR) model. The input data is the same input data used in Padovezi et al. (2018) which the source is WRI (2019) (Table A.7).

Table A.7 - Input data used in InVEST.

Original data	Source in WRI (2019)	Resolution/Scale	Input data in InVEST
Precipitation	Bioclim	1km/-	Rainfall erosion index (Factor R)
Soil	IAC	- /1:500.000	Soil erodibility factor (K-Factor)
Land cover	Ronquin et al. (2016)	30m/-	Cover and management factor (C-factor)
Elevation	STRM	90m/-	Topographic factor (LS-Factor)

Source: Lemos et al. (2021).

For 2015, we use the land cover data of Ronquin et al. (2016) that is the same data used in all our analyses. For 2025, we change the pasture cover to forest cover of the land cover data of Ronquin et al. (2016) for simulating the conversion from pasture to regenerated forest area between 2015-2025. The Support practice factor (P-Factor) is equal to 1 (one) for all land cover classes based on Padovezi et al. (2018), the authors justify the value 1 for all land cover classes due to the absence of information about the differences in soil management between the land cover classes. For each land cover class, we use the Cover and management factor (C-factor) based on Medeiros et al (2016) and Padovezi et al. (2018) (Table A.8).

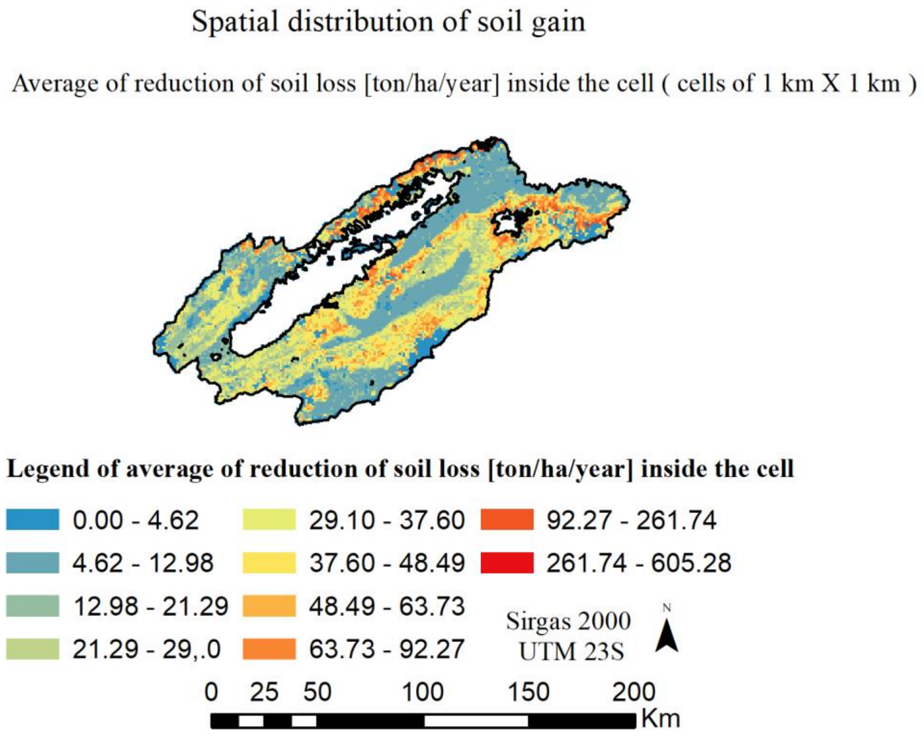
Table A.8 - Cover and management factor (C-factor) used in our analysis.

Land cover class	C-factor	Source
Forest	0.0001	Medeiros et al (2016)
Pasture	0.0610	Medeiros et al (2016)
Eucalyptus	0.0030	Medeiros et al (2016)
Crops	0.4238	Medeiros et al (2016)
Water	0.0001	Padovezi et al (2018)
Built-up areas	0.0100	Padovezi et al (2018)
Bare soil	1.0000	Padovezi et al (2018)

Source: Lemos et al. (2021).

For each cell, we calculate the mean reduction of soil loss [ton/ha/year] using the area-weighted average of reduction of soil loss [ton/ha/year] inside the cell (Figure A.9).

Figure A.9 - Spatial distribution of Soil gain.



Source: Lemos et al. (2021).

A.6 Alternative allocation scenarios

We test several preliminary rounds until the identification of the best components and variables for our simulation. Table A.9 presents the parameters that better capture the change processes. We show only the parameters that are different from the default parameters of LuucME. There are other parameters (eg. MinChange) that are necessary to run the LuccME but they are not described because they are the default of the LuccME (LUCCME, 2016).

Table A.9 - LuccME parameters.

General parameters		
Spatial scale	Extent	Atlantic Forest in São Paulo' s Paraiba Valley
Temporal scale	Resolution	Regular cells of 1km X 1km
	Extent	2015 - 2025 (Scenarios)
	Resolution	Yearly
	Calibration/validation	2011 - 2015 (Silva et al., 2016; Ronquim et al., 2016)
Land use/cover classes	Percentage of regenerated forest, pasture, no-data (Eucalyptus, crops, others) in the cell	

Potential: *PotentialCLinearRegression*

Regeneration spatial determinants		Std B	Significance
Constant	Regression constant	-0.745	0.00000
lCoFor_05	% of forests (remnant and regenerated) in 2005 (Log) (Source: Silva et al. (2016)	0.704	0.00000
lCoCur2	% of surface with flat curvature (Log) (WRI, 2019)	0.157	0.00000
lCoSoi2	% of Humic Cambisol (Log) (Rossi, 2017)	-0.053	0.00000
lCoSil3	% of high agricultural suitability (Log) (WRI, 2019)	-0.027	0.00427
lCoSlope4	% of slope between 20º and 45º (Log) (WRI, 2019)	0.096	0.00000
Prec	Average of Precipitation (Kalnay et al.,1996)	0.076	0.00000
lTemp	Average of Temperature (Log) (Kalnay et al., 1996)	-0.074	0.00000
Elev	Average of Elevation (WRI, 2019)	-0.032	0.00006

(To be continued)

Table A.9 – Conclusion.

General parameters		
Allocation: *ClueLikeAllocation parameters*		
Regeneration spatial determinants		
maxDifference	the maximum difference between the land demand value informed by the user and the amount allocated by the model to each land use type	50km^2
complementarLU	the land use type which will be recomputed in the end if the total percentages do not amount exactly 100%	CoPas_15 (% of pasture cover) (Source: Ronquim et al., 2016)
Static	the variable can increase or decrease in each cell, or only change in the direction of the demand.	-1 (only changes in the direction of the demand)
Demand: *PreComputed Values*		
Restoration rate (km2/year)	Uses predetermined values of land demand provided by the user for each time-step	60km^2/year

Source: Lemos et al. (2021).

This metric allows us to establish the level of similarity between simulated and observed maps at different resolutions (in 2015, in our case), through sampling windows that increase at each time-step, as shown in Figure A.10.

Figure A.10 - Example of multiple resolution validation (cell aggregation through sampling Windows. Source: LuccME (2016).

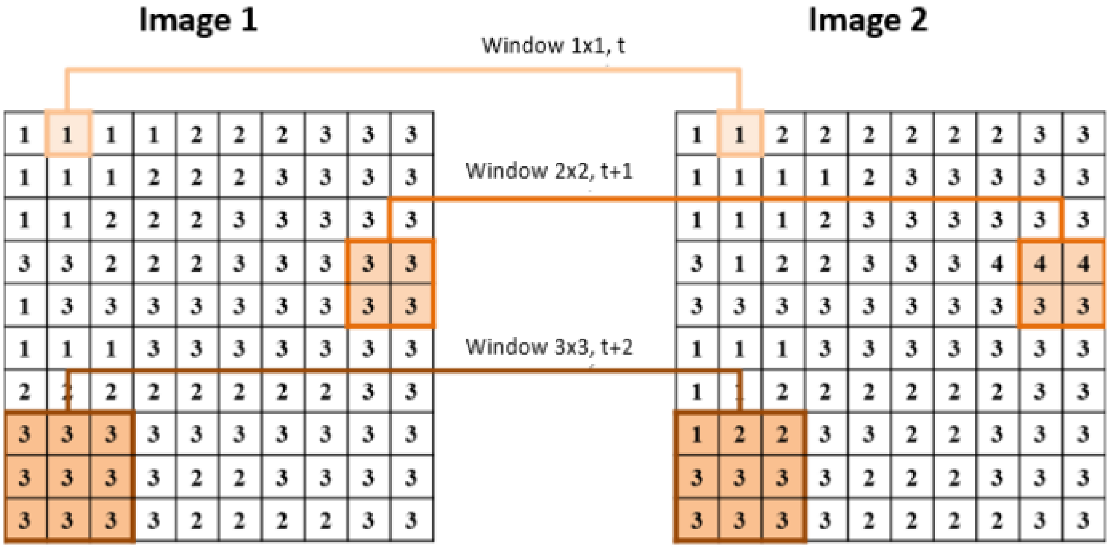


Image 1

1	1	1	1	2	2	2	3	3	3
1	1	1	2	2	2	3	3	3	3
1	1	2	2	2	3	3	3	3	3
3	3	2	2	2	3	3	3	3	3
1	3	3	3	3	3	3	3	3	3
1	1	1	3	3	3	3	3	3	3
2	2	2	2	2	2	2	2	3	3
3	3	3	3	3	3	3	3	3	3
3	3	3	3	2	2	3	3	3	3
3	3	3	3	2	2	2	2	3	3

Image 2

1	1	2	2	2	2	2	2	3	3
1	1	1	1	2	3	3	3	3	3
1	1	1	2	3	3	3	3	3	3
3	1	2	2	3	3	3	4	4	4
3	3	3	3	3	3	3	3	3	3
1	1	1	3	3	3	3	3	3	3
1	1	2	2	2	2	2	2	3	3
1	2	2	3	3	2	2	3	3	3
3	3	3	3	2	2	2	3	3	3
3	3	3	3	2	2	2	2	3	3

Source: Lemos et al. (2021).

The results of the simulations are validated by the validation metric of multiple resolutions implemented in LuccME. The Diff (%) takes into account only the areas that have undergone some change process, so it is a more specific validation system for each type of land use because only considering the modified areas. The Ext (%) takes into account the accumulated historical pattern for the different types of land use, that is, considering all cells. Based on our validations results, the Ecological (Eco) Model presented the best results in relation to other models (Table A.10).

Table A.10 - Validation results for our four alternative linear regression models.

Natural regeneration cover validation								
Validation	Hit percentage				Hit percentage			
Accpeted error	0%		5%		0%		5%	
Window	Diff* (%)	Ext** (%)	Diff (%)	Ext (%)	Diff (%)	Ext(%)	Diff (%)	Ext(%)
	Biophysical (B) Model				Ecological (Eco) Model			
1	46	87	59	90	55	89	68	93
2	52	90	71	94	59	92	79	96
3	56	92	76	95	62	93	83	97
4	58	92	80	96	64	93	86	97
5	60	93	83	97	65	94	87	98
6	61	93	86	97	66	94	89	98
7	63	93	87	98	67	94	90	98
8	64	94	88	98	68	94	90	98
9	65	94	89	98	69	95	91	98
10	65	94	89	98	69	95	91	98
Window	Biophysical, History of land use (BH) Model				Biophysical, History of land use, Socio-economic (BHS) Model			
1	54	89	67	92	53	89	66	92
2	58	91	77	95	58	91	76	95
3	61	93	82	97	61	92	81	96
4	63	93	84	97	62	93	84	97
5	64	93	87	98	64	93	86	97
6	65	94	88	98	65	94	87	98
7	66	94	90	98	66	94	90	98
8	67	94	90	98	67	94	90	98
9	67	94	91	98	67	94	92	99
10	68	94	92	99	68	94	92	99

*Diff (%) takes into account only the areas that have undergone some change process.

**Ext (%) takes into account the accumulated historical pattern for the different types of land use

Source: LemosS et al. (2021).

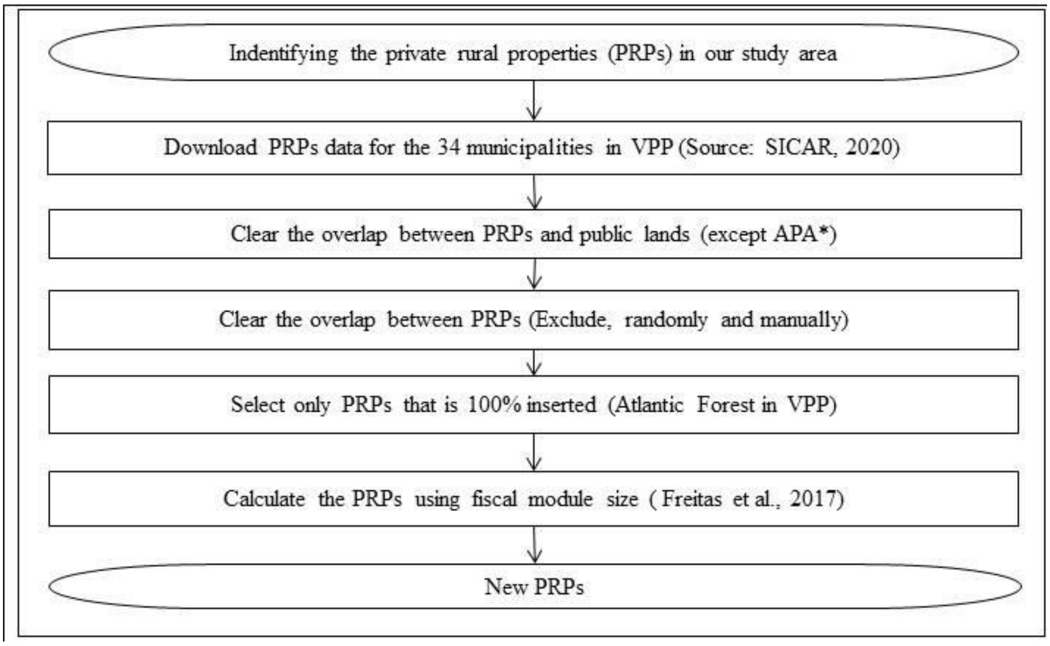
APPENDIX B - SUPPLEMENTARY MATERIAL OF CHAPTER 3

B.1 Cellular database organization

B.1.1 Cleaning the CAR

We use the rural cadastral information (in portuguese, *Cadastro Ambiental Rural* - CAR) data, downloaded from SICAR on February, 18th, 2020. The first step is cleaned the overlap among PRPs and public lands (MMA, 2012) where public lands (except the public land classified as Area of Environmental Protection, in Portuguese, *Área de Proteção Ambiental* -APA) always prevail on PRPs, in this moment we disregard APA because this is a special class of public land that allow the presence of PRPs inside them (SPAROVECK et al., 2019). After this step, we exclude the overlap among the PRPs. This execution is operated randomically and manually (Figure B.1).

Figure B.1 - Identification of the private rural properties.



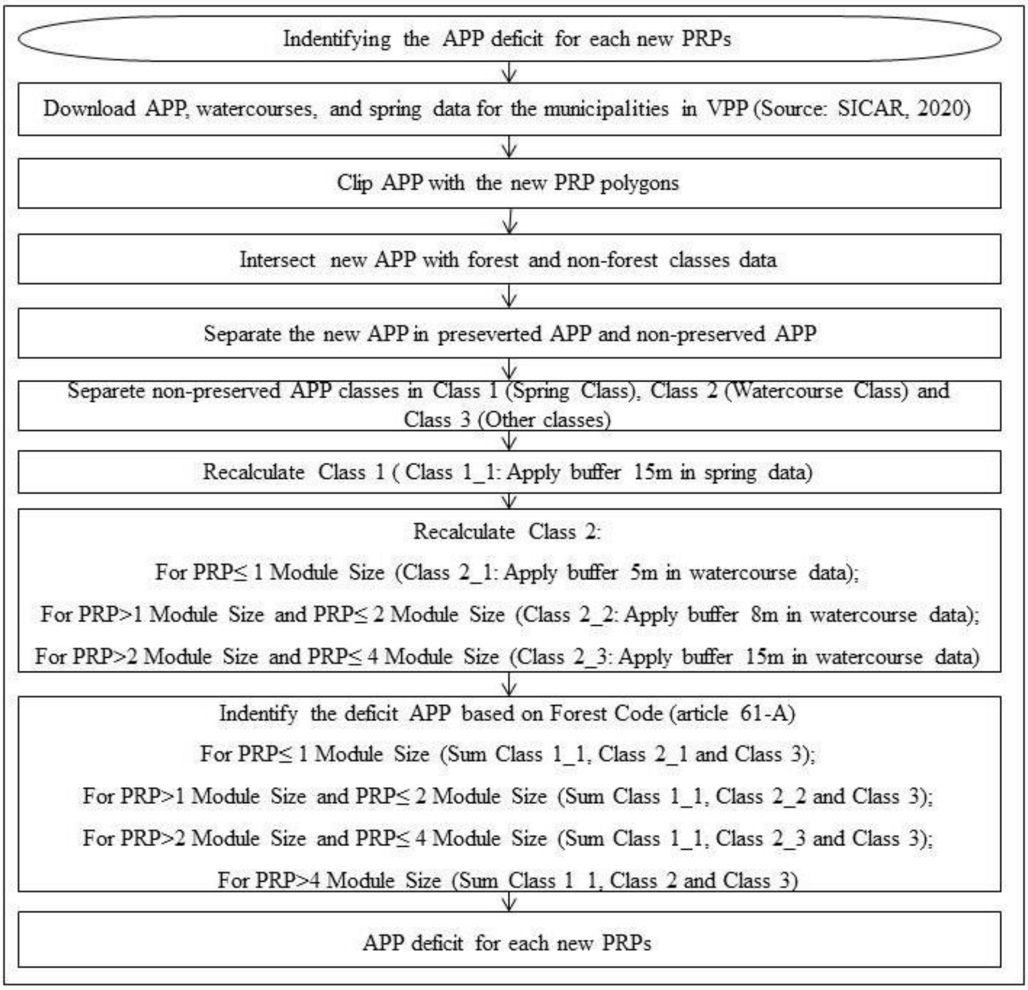
*APA is a public land classified as Area of Environmental Protection (in Portuguese, *Área de Proteção Ambiental*) that allows the presence of PRPs inside them (SPAROVECK et al., 2019).

Source: Author's production.

B.1.2 Detailed process for estimating the deficits

Using the polygons of our new PRPs, we clip the APP data declared on CAR. The new APP is intersected with the land cover map (RONQUIM et al., 2016), that is, previously, reclassified as forest and non-forest classes. Ronquim et al. (2016) is a vectoral data elaborated using Landsat-8 data. This intersection allows the separation of the new APP in preseverted APP and non-preserved APP, where preseverted APP is the APP with forest cover, and non-preserved APP is the APP with non-forest cover. The non-preserved APP are used for calculating the new APP that is the APP that need to be restored, for the spring non-preserved APP, we create a buffer of 15m in the spring, and intersect this buffer with the reclassified land cover data for identifying the area of the spring APP that need to be restored. For the watercourse non-preserved APP, we create a buffer in the watercourse of the property based on the Article 61-A, which results in different buffer sizes. These buffers are intersected with the reclassified land cover data for identifying the area of the watercourse APP that need to be restored. For the other non-preserved APP classes (for example, the lakes, steep slopes, hilltops, and mangroves), we intersect these non-preserved APP with the reclassified land cover data for identifying the area of the other APP that need to be restored. All these operations are illustrated in Figure B.2.

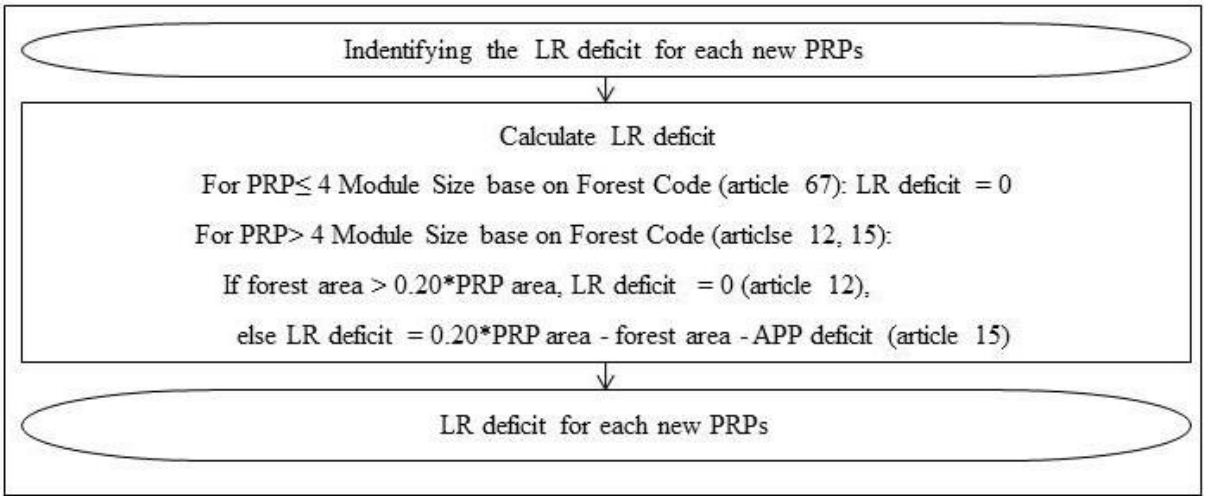
Figure B.2 - Identification of APP deficit.



Source: Author's production.

In relation to the LR deficit, we consider that small PRPs do not have LR deficit, because this PRP class does not have the obligation of restoring the LR (article 67). For calculating the LR deficit for medium and large PRPs, we intersect the polygons of medium and large PRPs with the land cover map (RONQUIM et al., 2016), that is, previously, reclassified as forest and non-forest classes. For medium and large PRPs with forest cover equals or bigger than 20% of the PRP area, the RPR does not have LR deficit (article 12), and when the forest cover is smaller than 20% of the PRP, the LR deficit is counted as 20% of the PRP size less the sum areas of forest cover in the PRP and the APP deficit of the PRP (article 15) (Figure B.3).

Figure B.3 - Identification of LR deficit.



Source: Author's production.

B.1.3 Pasture area inside PRP and APP

To identify the pasture cover inside APP deficit, we intersect the APP deficit with the cover data of Ronquim et al. (2016), and we quantify the pasture cover class that resulted from this intersection, that is the pasture cover inside APP deficit. To identify the pasture inside LR and in noOB, firstly, we discount pasture cover inside APP deficit from the total pasture cover inside the PRP, which results in the partial pasture cover inside the PRP. Secondly, we compare the value of LR deficit of PRP with the partial pasture cover present in the PRP, where (1) PRPs with value of LR deficit is equals or smaller than the partial pasture cover, we consider that all LR deficit could be quantify as pasture cover, and the remaining of partial pasture cover in the PRP could be quantify as pasture cover in noOB. (2) For the PRPs with value of LR deficit is bigger than the partial pasture cover, we consider the partial pasture cover could be quantify as LR deficit, and PRP does not presented pasture cover in noOB, that means that this PRP does not have pasture cover in areas outside APP and LR.

B.2 Optimization model details

Decision variables capture the results of the optimization, the most simple type of decision variable is the continuous variable that can take any value between its lower and upper bounds. A constraint captures a restriction on the values that a set of decision variables may take, the simplest example is a linear constraint, which states that a linear expression on a set of decision variables takes a value that is either less-than-or-equal, greater-than-or-equal, or equal to another linear expression. The objective tells the solver which is the best solution given a set of feasible solutions, the best solution is identified using an objective function, which is the function on which the decision variables are subject to a set of constraints. The simplest and most common objective function is linear, that is, minimizing or maximizing a linear function on the decision variables. While typical optimization models have a single objective function, real-world optimization problems often have multiple and competing objectives (GUROBI, 2021).

Although the multiple objectives may have different units, these objectives can be combined in a unique single objective function using the “scalarisation technique”, in which additional parameters control the relative weighting among the objectives. In general the different objectives are at least partially conflicting, implying that not every criterion can be optimised simultaneously. These trade-offs result in a Pareto frontier describing 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. A strong approach to informing this subjective decision is to evaluate the objective function across a range of weights and to plot the trade-off (BEYER, et al., 2016).

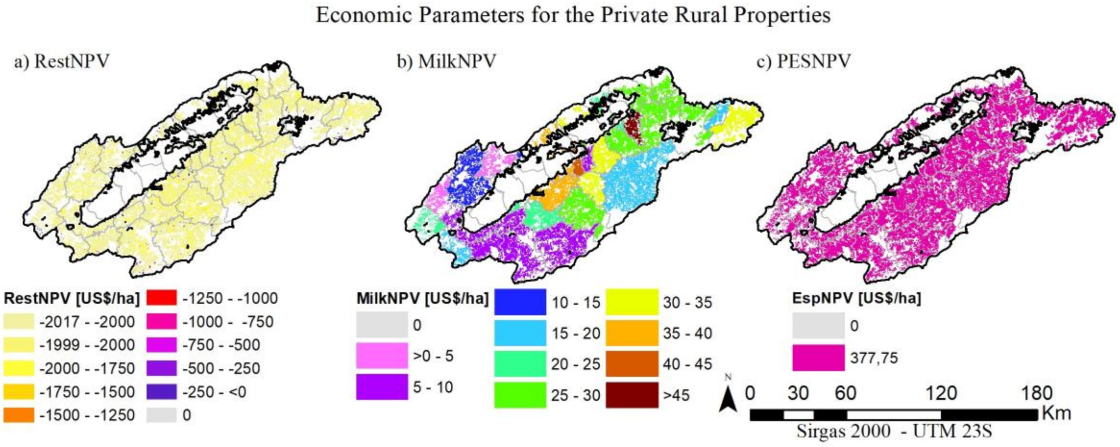
We also present the cost-effectiveness of the three objectives for four situations that are for each one of the three single-objective solutions and for the best balance solution. As our study has three environmental benefits, our Pareto font is a triangle on the surface of a sphere formed by three great circular arcs intersecting pairwise in three vertices (WEISSTEIN, 2021), not just a line as it would be for two objectives in other both studies that used linear programming to explore the optimal distribution of restoration (STRASSBURG et al., 2018, 2020). For describing the Pareto front as a spherical triangle, each vertice is the three single-objective extremes, the circular arcs are the trade-offs among pairs of objectives, and the best balance solution is localized in the one point in the superficie of the triangle.

The scripts that implement the proposed model were written in R. We use the Gurobi Optimizer to solve LP models through the Gurobi R interface (BEYER, et al., 2016; GUROBI, 2021).

B.3 Complementary results

The PRPs with total cost or MRA equals zero are removed because they can not contribute to the optimization process. It resulted in the discard of 766 and 794 of our PRPs in **Sc.1/Sc.5** and **Sc.2/Sc.3/Sc.4**, respectively, with no available pasture area according to the scenario assumptions. No PRPs present a total cost equal to zero. This difference of PRP number among (28 PRPs) **Sc.1/Sc.5** and **Sc.2/Sc.3/Sc.4** is because deficit areas is the total available pasture area for the 28 PRPs, and the deficit areas could be accounted as available pasture area in **Sc.1/Sc.5** but not could be accounted for **Sc.2/Sc.3/Sc.4**.

Figure B.4 - Characterization of the economic parameters of the Private Rural Properties.



*a) RestNPV - Net Present Value of restoration actions, b) MilkNPV - Net Present Value of milk production activity, c)PESNPV - Net Present Value of Ecosystem Services Payments.

Source: Author's production.

We show absolute benefit gains for the best balance solution and the three single-objective solutions from scenario 2 to scenario 5 in Table B.1.

Table B.1 - Absolute benefit gain for the best balance solution and the three single-objective solutions from scenario 2 to scenario 5.

Sc.	**Solution**	**Environmental benefit**			
		Biodiversity [sum of majority number of benefited groups or species]	**Carbon [M Ton]**	**Soil [M Ton]**	**Cost [Million US$]**
Sc.2	Best balance	178813	4.1548	1.898	122.211
	Biodiversity single-objective	190235	4.1486	1.519	122.195
	Carbon single-objective	178489	4.1631	1.505	122.189
	Soil single-objective	178768	4.1548	1.899	122.211
Sc.3	Best balance	178762	4.1548	1.899	111.105
	Biodiversity single-objective	190250	4.1486	1.520	111.089
	Carbon single-objective	178505	4.1632	1.505	111.083
	Soil single-objective	178762	4.1548	1.899	111.105
Sc.4	Best balance	178762	4.1548	1.899	99.555
	Biodiversity single-objective	190250	4.1486	1.520	99.539
	Carbon single-objective	178505	4.1632	1.505	99.533
	Soil single-objective	178762	4.1548	1.899	99.555
Sc.5	Best balance	179388	4.2003	2.122	99.504
	Biodiversity single-objective	193673	4.1859	1.592	99.500
	Carbon single-objective	179241	4.2029	1.583	99.492
	Soil single-objective	179388	4.2003	2.122	99.504

Source: Author's production.

The cost-effectiveness solution values for the best balance solution and the three single-objective solutions for the all scenarios in the Table B.2.

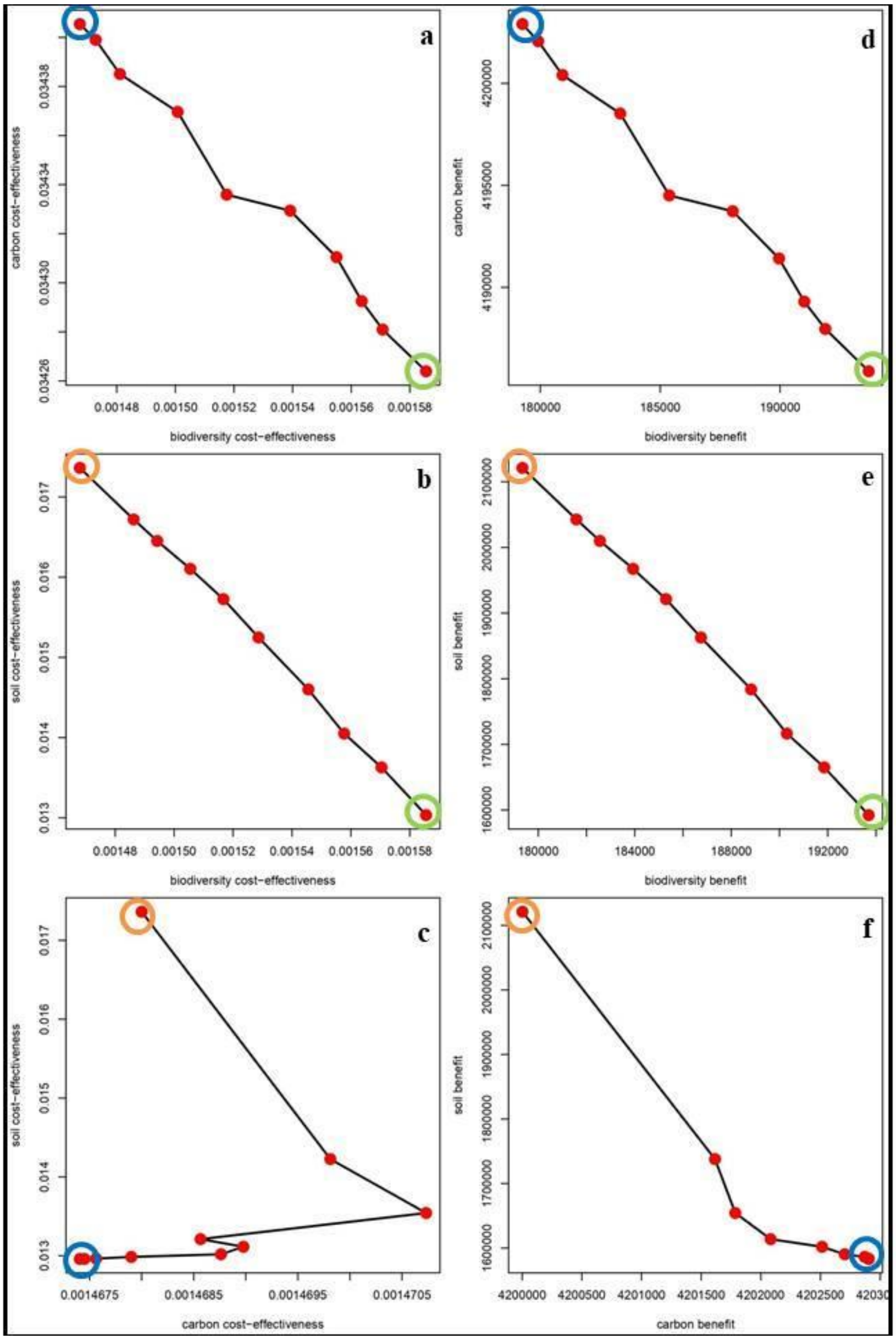
Table B.2 - Cost-effectiveness solution values for the best balance solution and the three single-objective solutions for all scenarios.

Scenario	**Solution**	**Cost-effectiveness**		
		Biodiversity/ Cost	**Carbon/Cost**	**Soil/Cost**
Sc.1	Best balance	0.001468	0.034378	0.017362
	Biodiversity single-objective	0.001586	0.034264	0.013033
	Carbon single-objective	0.001467	0.034405	0.012960
	Soil single-objective	0.001468	0.034378	0.017362
Sc.2	Best balance	0.001463	0.033997	0.015533
	Biodiversity single-objective	0.001557	0.033950	0.012433
	Carbon single-objective	0.001461	0.034071	0.012315
	Soil single-objective	0.001463	0.033997	0.015536
Sc.3	Best balance	0.001609	0.037395	0.017088
	Biodiversity single-objective	0.001713	0.037345	0.013678
	Carbon single-objective	0.001607	0.037478	0.013546
	Soil single-objective	0.001609	0.037395	0.017088
Sc.4	Best balance	0.001796	0.041734	0.019071
	Biodiversity single-objective	0.001911	0.041678	0.015266
	Carbon single-objective	0.001793	0.041827	0.015118
	Soil single-objective	0.001796	0.041734	0.019071
Sc.5	Best balance	0.001803	0.042212	0.021322
	Biodiversity single-objective	0.001946	0.042069	0.015998
	Carbon single-objective	0.001802	0.042244	0.015910
	Soil single-objective	0.001803	0.042212	0.021322

Source: Author's production.

The Figure A.5 a-c presents the cost-effectiveness values and the Figure B.5 d-f presents the absolute value of our three restoration objectives. The biodiversity extreme is highlighted by the green circle, the carbon extreme by the blue circle, and soil extreme by the orange circle. The curves that connect pairs of these extremes are trade-offs among pairs of objectives, these curves are the circular arcs that compose the spherical triangle of our Pareto front.

Figure B.5 - Cost-effectiveness solution values (a -c) and the absolute benefit gain (d- e) for the three restoration objectives for scenario 5.



*biodiversity extreme is green circle, carbon extreme is blue circle, and soil extreme is orange circle.
Source: Author's production.

APPENDIX C - SUPPLEMENTARY MATERIAL OF CHAPTER 4

To estimate the NPV of the restoration action (RestNPV) for the three first scenarios, we adopt the same parameter that we use to estimate the NPV of the last five scenarios, that is (1) we split the total implementation cost in implementation and maintenance costs, (2) we use the revenue equals to zero because we use ecological forest restoration methods which do not have revenue (PADOVEZI et al., 2018), (3) we use the discount rate equals to 10% by year, that is the forest activity in Brazil based on Prata and Rodriguez (2014), and (4) we adopt the restoration project duration equal to 3 years with 7 maintenance activities based on Haddad and Bastos (2019). The NPV of milk production activity (MilkNPV) and the NPV of PES (PESNPV) are not estimated because the three scenarios only capture the total restoration cost in the area based on the natural regeneration potential.

Table C.1 - NPV of restoration actions of the scenarios of Chapter 2.

Scenario	**Restoration cost in Chapter 2**	**NPV of restoration actions**
Unconstrained - whole area	130.650	-125.327
Protection PSA	134.410	-128.934
Hydric PSA	133.610	-128.166

Source: Author's production.