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Instituto de Biologia Robeto Alcântara Gomes

Luiz Conrado Silva

# Integrating Climate Change and Ecosystem Services into Ecological Restoration Efforts

Rio de Janeiro

2025

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Dissertação apresentada, como requisito parcial para obtenção do título de Mestre, ao Programa de Pós-Graduação em Ecologia e Evolução, da Universidade do Estado do Rio de Janeiro.

Orientadora: Prof.ª Dra. Aliny Patricia Flauzino Pires

Rio de Janeiro

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Rio de Janeiro
2025

## DEDICATION

*To all the people and ideals that make life a meaningful journey.*

## ACKNOWLEDGMENTS

First and foremost, I would like to thank the health and strength given to me by the Universe, essential elements in guiding this plan through the end. Secondly, I would like to express my deep gratitude to my advisor, Aliny Pires, for having placed her trust in me and invested her efforts in bringing this project to a successful conclusion. Her unconditional support, inspiring motivation, and precise guidance were fundamental pillars in turning this plan into reality. I am immensely grateful for her dedication and all the encouragement that enabled me to overcome challenges and achieve this goal. This represented an opportunity to transform my reality and widen my window of possibilities, inserting myself into a context of work and collaborations that really bring meaning and purpose to my life. With her gentle question at the end of each day - ‘Are you happy?’ - I have learned to intentionally make my days based on moments of happiness, fulfillment, and kindness. My respect and admiration for her personally and professionalism are certainly sources of inspiration that I will carry as seeds to spread worldwide.

My special thanks go to my co-supervisor, Julia de Niemeyer, who, although we didn't manage to formalize her co-supervision until the completion of this dissertation, was fundamental to the success of one of its most important chapters. With her solicitude and guidance, Julia played an essential role in my professional development, helping me to acquire the initial skills needed to build the tools used in this work. Her patience and availability were fundamental pillars for my academic and professional growth, guiding me every step of the way. My immense gratitude for her contribution to building the professional I am today - largely due to her dedication and generosity.

I want to thank all my coworkers for their warm welcome and for being so well received from the very first moment of my arrival at the Laboratório de Ecologia e Conservação de Ecossistemas (LECE). It is truly inspiring to be part of an atmosphere where we find stories and people of great admiration and respect who constantly motivate us to evolve and strive for excellence in multiple contexts. This atmosphere of support and inspiration has been fundamental to my personal and professional growth. The unique and special way in which each member of the group made this a truly remarkable experience, full of encounters and recognition. Lucky were those who met, shared experiences, and built memories together. My sincerest thanks to Stéphanie Vaz, Paula Andrea Casas, Tauany Rodrigues, Aline Gaglia, Helena Alves do Prado, Adalto Oliveira, Vitoria Barcellos, Vitor dos Anjos, José Gabriel M. da Cruz, and Douglas Hideki Abe.

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I am deeply grateful to my family and friends, who are a haven in times of turbulence. A special thanks to my mother and grandmother, Leni Barbosa da Silva and Carolina Barbosa Camargos, whose tireless strength and deep dedication were the foundation that allowed me to get this far and to whom I owe part of who I am today. I would also like to express my immense gratitude to the family of heart and soul that I built during my years here: Sorana Lima and Aline Shimada. Their welcome, admiration, incomparable laughter, and, sometimes, the necessary pulls on the ear brought deep meaning to my days away from home and pushed me further. For strengthening me and offering what is most valuable and cannot be bought - unconditional love - I am eternally grateful.

To the loves who have passed or who remain, who taught me the resilience of heart and wisdom of the soul. Those who, through shared feelings and experiences, helped me confront my ghosts, allowing me to become a better person, even after passing through difficult emotional moments.

To Cícero, who gave me a new meaning of life and brought me closer to my inner child, bringing me closer to connections that transcend blood ties or need to be based on social conventions. “Let the little children come to me, and do not hinder them, for the kingdom of heaven belongs to such as these” (Matthew 19:14).

I want to express my deepest gratitude to this public educational institution, which enabled me to complete this entire journey through the valuable lessons and teachings of highly qualified professionals.

Last but not least, I would like to express my gratitude to CAPES and FUNAPE, whose financial support was essential for the realization and execution of this work in such a short time.

“Se desejo, o meu desejo faz subir marés de sal e sortilégio. Vivo de cara para o vento, na chuva, e quero me molhar.

Sou como a haste fina que qualquer brisa verga, mas nenhuma espada corta.”

*Maria Bethânia*

# ABSTRACT

SILVA, Luiz Conrado. *Integrating Climate Change and Ecosystem Services into Ecological Restoration Efforts*. 2025. 92f. Dissertação (Mestrado em Ecologia e Evolução) – Instituto de Biologia Roberto Alcântara Gomes, Universidade do Estado do Rio de Janeiro, Rio de Janeiro, 2025.

Environmental degradation and biodiversity loss are urgent global challenges, and ecological restoration is a key strategy to reverse these trends by recovering essential ecosystem services. However, uncertainties in restoration strategies and the escalating impacts of climate change can threaten their success by altering biodiversity, ecological interactions, and ecosystem resilience. This dissertation explores how climate change can affect the ecosystem services provisioned by ecological restoration, by using two different approaches. In the chapter 1, it was conducted a systematic literature review over 3,033 studies identifying global trends, knowledge gaps, and challenges in integrating ecological restoration, climate change and ecosystem services. I revealed that many benefits promoted by ecological restoration are underrepresented in the ecological literature, especially when considering the impacts of climate change on them. It is argued thataddress such identified gaps is essential to ensuring the long-term benefits of ecological restoration, including its role in mitigating the impacts of climate change. In the chapter 2, I explored how climate change impacts forest restoration planning for water security by using the Rio Doce basin in Brazil as case study. This chapter demonstrates how incorporating multiple climate change scenarios can significantly alter the prioritization of areas targeted for restoration. These findings underscore the risks of ignoring climate change in restoration planning, losing the opportunity to reach their current ambitious goals. Together, these chapters emphasize the need for developing adaptive strategies to ensure the long-term effectiveness of ecological restoration in a changing climate, fostering more sustainable and resilient ecosystems.


Keywords: Climate change; ecosystem services; restoration.

**RESUMO**

SILVA, Luiz Conrado. *Integrando Mudanças Climáticas e Serviços Ecossistêmicos nos Esforços de Restauração Ecológica.* 2025. 92f. Dissertação (Mestrado em Ecologia e Evolução) – Instituto de Biologia Roberto Alcântara Gomes, Universidade do Estado do Rio de Janeiro, Rio de Janeiro, 2025.

A degradação ambiental e a perda de biodiversidade são desafios globais urgentes, e a restauração ecológica é uma estratégia fundamental para reverter essas tendências por meio da recuperação de serviços essenciais do ecossistema. No entanto, as incertezas nas estratégias de restauração e os impactos crescentes das mudanças climáticas podem ameaçar seu sucesso, alterando a biodiversidade, as interações ecológicas e a resiliência do ecossistema. Esta dissertação explora como as mudanças climáticas podem afetar os serviços ecossistêmicos fornecidos pela restauração ecológica, usando duas abordagens diferentes. No capítulo 1, foi realizada uma revisão sistemática da literatura de mais de 4.116 estudos, identificando tendências globais, lacunas de conhecimento e desafios na integração da restauração ecológica, mudanças climáticas e serviços ecossistêmicos. Revelou-se que muitos benefícios promovidos pela restauração ecológica estão sub-representados na literatura ecológica, especialmente quando se consideram os impactos das mudanças climáticas sobre eles. Argumenta-se que abordar essas lacunas identificadas é essencial para garantir os benefícios de longo prazo da restauração ecológica, incluindo seu papel na mitigação dos impactos das mudanças climáticas. No capítulo 2, explorei como as mudanças climáticas afetam o planejamento da restauração florestal para a segurança hídrica, usando a bacia do Rio Doce no Brasil como estudo de caso. Esse capítulo demonstra como a incorporação de vários cenários de mudanças climáticas pode alterar significativamente a priorização de áreas destinadas à restauração. Essas descobertas ressaltam os riscos de ignorar as mudanças climáticas no planejamento da restauração, perdendo a oportunidade de atingir suas ambiciosas metas atuais. Juntos, esses capítulos enfatizam a necessidade de desenvolver estratégias adaptativas para garantir a eficácia a longo prazo da restauração ecológica em um clima em mudança, promovendo ecossistemas mais sustentáveis e resilientes.

Palavras-chave: Mudanças climáticas; serviços ecossistêmicos; restauração.

## LIST OF FIGURES

## LIST OF TABLES

## LIST OF ABBREVIATIONS

| | |
|---|---|
| APPs | Permanent Protection Areas |
| DEM | Digital Elevation Model |
| DOC | Dissolved Organic Carbon |
| ES | Ecosystem Services |
| GHG | Greenhouse Gas |
| InVEST | Integrated Valuation of Ecosystem Services and Tradeoffs |
| LULC | Land Use and Land Cover |
| NCPs | Nature's Contribution to People |
| NDCs | Nationally Determined Contributions |
| NVPL | Native Vegetation Protection Law |
| RCP | Representative Concentration Pathway |
| SDR | Sediment Delivery Ratio |
| SOBRE | Society for Ecological Restoration |
| TNC | The Nature Conservancy |
| WoS | Web of Science |

CONTENTS

## INTRODUCTION

Environmental degradation and biodiversity loss are pressing global challenges that demand urgent and coordinated action. The Society for Ecological Restoration (SER) established ecological restoration as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (SER, 2002). This definition emphasizes that ecological restoration aims to reestablish the structure, composition, functions, and ecological processes of an ecosystem, promoting its resilience and self-sustainability. The ultimate goal may vary, ranging from the reintroduction of native species to the full recovery of the ecosystem's functionality. In this sense, ecological restoration has emerged as a critical strategy to counteract these issues, promoting the recovery of degraded ecosystems and the provisioning of essential ecosystem services such as climate regulation, water purification, and erosion control (ARONSON and ALEXANDER, 2013). However, persistent gaps and uncertainties in identifying the best restoration strategies and how to scale them up can increase the risk of project failure, leading to a low rate of successful outcomes (SUDING et al., 2015).

Climate change can compromise restoration efforts by influencing biodiversity, altering ecological interactions, and affecting the resilience of restored ecosystems (PARMESAN and YOHE, 2003). It also has the potential to shift the expected benefits of ecological restoration by modifying key aspects of the natural environment (HOBBS and HARRIS, 2001). Integrating climate change considerations into restoration projects is, therefore, essential to ensure their long-term effectiveness and to maximize socio-ecological benefits (HARRIS et al., 2006). Recognizing the impact of climate change on restoration approaches is critical for understanding the broader implications of using restoration as a solution to emerging environmental challenges.

Climate change plays a pivotal role in shaping restoration strategies and their alignment with climate mitigation goals (ALMAGRO et al., 2017; BENAYAS et al., 2009). According to UNDP Climate Promise (2023), “mitigation strategies include transitioning to renewable energy sources, improving energy efficiency, reforestation, adopting sustainable agricultural practices, and developing carbon capture and storage technologies”. The goal of mitigation is to slow down or reverse climate change by addressing its root causes. Restoration projects that fail to account for climate change may become ineffective in evaluating, quantifying, and securing expected benefits from current to future conditions (KOCH and KAPLAN, 2022).

To address this, it is crucial to understand ecosystem functioning and processes at a landscape scale. This will enable the design of more efficient and adaptive restoration initiatives (SUDING et al., 2004). Adaptation strategies aim to enhance the resilience of communities, ecosystems, and economies by minimizing vulnerabilities (UNFCC, 2022). Examples include building flood defenses, developing drought-resistant crops, improving water management, and designing infrastructure that can withstand extreme weather events. The goal is to cope with climate impacts and maintain functionality in a changing environment. It requires considering not only the direct financial costs of implementing and maintaining restoration efforts but also the long-term benefits for biodiversity, ecosystem resilience and services, and human well-being (BULLOCK et al., 2011).

Ecosystem services are defined as “any positive benefit that wildlife or ecosystems provide to people, the benefits can be direct or indirect—small or large" (NWF, 2008) and they are the benefits that nature provides to humans, arising from ecological functions that sustain life and well-being. Ecosystems regulate natural processes such as nutrient cycling, climate regulation, and water purification, which humans rely on for survival, directly related to ecosystem services (SMITH et al., 2013). These services are categorized into provisioning (e.g., food, water, raw materials), regulating (e.g., climate control, flood prevention, pollination), cultural (e.g., recreation, aesthetic, spiritual value), and supporting (e.g., soil formation, primary production, biodiversity maintenance) (IPBES, 2018). Ecosystem services are essential for human survival and economic stability but are increasingly threatened by deforestation, pollution, and climate change (WORLD HEALTH ORGANIZATION, 2025). Restoring ecosystems through conservation, sustainable land use, and ecological restoration helps maintain these critical services, ensuring resilience and long-term benefits for both people and the environment.

In this sense, this dissertation explores the intersection of ecological restoration, climate change, and ecosystem services through two distinct chapters. Chapter 1 presents a systematic review of the scientific literature, identifying global trends, knowledge gaps, and challenges in integrating ecological restoration, climate change, and ecosystem services. The review aims to provide a comprehensive understanding of the current state of knowledge, assess the challenges that remain, and highlight the importance of incorporating climate change considerations into restoration strategies to ensure their long-term benefits. Recognizing the impact of climate change on restoration approaches is key to understanding the consequences of implementing restoration as a solution to emerging socioenvironmental issues.

Chapter 2 focuses on a case study in Brazil, examining how climate change influences forest restoration planning for water quality in the Rio Doce basin—a region severely affected by the country's largest environmental disaster. This chapter evaluates how climate change alters the benefits of restoration predicted by the Native Vegetation Protection Law, a legal restoration framework, and identifies priority areas for restoration that can ensure water quality across different climate change scenarios. Together, these chapters explore the importance of adopting adaptive, climate-informed approaches to ecological restoration to ensure its resilience and effectiveness in a rapidly changing climate. By addressing these interconnected themes, this dissertation contributes to the growing body of knowledge on how ecological restoration can be optimized to address both environmental degradation and the challenges posed by climate change, ultimately supporting more sustainable and resilient ecosystems.

# 1 INTEGRATING CLIMATE CHANGE AND ECOSYSTEM SERVICES INTO ECOLOGICAL RESTORATION EFFORTS: A SYSTEMATIC REVIEW[1]

**Abstract**

Ecological restoration has emerged as a critical strategy to combat environmental degradation and biodiversity loss while ensuring the provision of essential ecosystem services. However, climate change significantly complicates restoration efforts, affecting biodiversity, ecological interactions, and the resilience of restored ecosystems. This review evaluates the intersection of ecological restoration, climate change, and ecosystem services through a scientometric analysis of 3,033 studies. Most research underscores the role of restoration in climate mitigation, yet critical gaps remain in understanding how climate change directly impacts restoration outcomes and the ecosystem services provided. The predominance of modeling studies (54%) contrasts with the limited empirical investigations (13%), leaving uncertainties regarding the real-world effectiveness of restoration under changing climate conditions. Geographically, the research is unevenly distributed, with Asia, Europe, and North America leading while vast regions, particularly in the Global South, remain underrepresented. Brazil stands out in South America, demonstrating significant advancements in restoration practices. Key findings highlight the need for integrated, climate-informed approaches that prioritize adaptive strategies, such as selecting climate-resilient species and optimizing ecosystem service delivery. Addressing these gaps is essential to maximize the socio-ecological benefits of restoration and ensure its long-term success in mitigating climate change impacts. This study advocates for a comprehensive research agenda that bridges existing knowledge gaps and enhances the scalability and resilience of restoration efforts globally.

**Keywords:** Ecological Restoration. Climate Change. Ecosystem Services. Adaptative Strategie. Scientometric Analysis.

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[1] Luiz Conrado-Silva, Paula Andrea Casas-Cortes, Tauany Rodrigues, Helena Alves Prado, Stephanie Vaz, Aline Gaglia Alves, Aliny P. F. Pires. Integrating Climate Change and Ecosystem Services into Ecological Restoration Efforts: A Systematic Review Frontiers in Ecology and the Environment (In prep.).

### 1.1. Introduction

Ecological restoration has been established as a fundamental tool to mitigate the impacts of environmental degradation and reverse biodiversity loss while restoring fundamental benefits to society (a.k.a. ecosystem services), such as climate regulation, water purification, and erosion control (ARONSON and ALEXANDER, 2013). The proclamation of the UN Decade on Restoration highlights the importance of integrating ecological restoration into global agendas as an urgent strategy to address environmental challenges (UNEP, 2020). However, when gaps and uncertainties regarding the best restoration strategies and scaling persist, the risk of project failure increases, resulting in a low rate of success (SUDING et al., 2015).

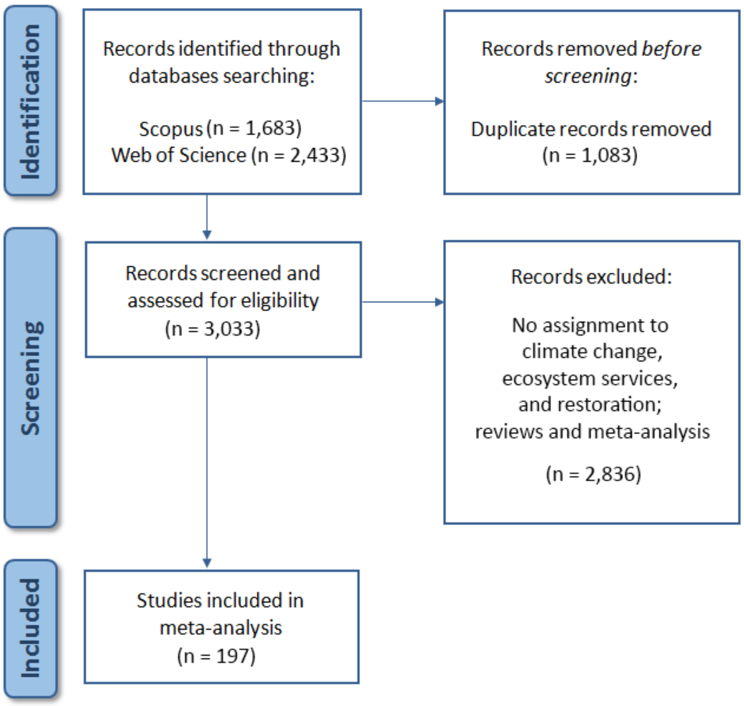
Climate change increases the uncertainty of restoration projects due to changes in climatic variables patterns, directly affecting biodiversity and altering its distribution, population dynamics, and ecological interactions (PARMESAN and YOHE, 2003). Such changes compromise the efficiency of the ecosystem in providing ecosystem services (ES), highlighting the need for restoration approaches that account for climate change (Harris et al., 2006). In the long term, the lack of integration between restoration projects and climate change may result in projects that fail to promote self-sustaining, climate-resilient ecosystems that are more vulnerable to new climate disturbances (HARRIS et al., 2006; IPCC, 2022). However, the scientific literature still lacks a clear understanding of how the potential interaction between ecological restoration, climate change, and ecosystem services provisioning interact, leading to potential biases and hindering the development of climate-resilient restoration projects.

In this context, we carried out a scientometric review to identify how the assessment of climate change's impact on ecosystem services through restoration is progressing. This review aims to understand the state-of-the-art on this topic and assess the potential challenges that still need to be faced to design best-strategy restoration projects. Recognizing the impact of climate change on restoration approaches is a key factor in understanding the consequences of implementing it as a solution to emerging environmental issues. Damaged environments are emerging as particularly relevant for ecological restoration measures because they allow us to assess the impact of restoration in the context of climate change, permitting the design of new routes and solutions that are more effective in the face of extreme climate events. Understanding the scale of degradation and evaluating the effectiveness of solutions are essential first steps toward developing and implementing more effective strategies. These solutions advocate and offer a better quality of life for future generations and biodiversity as a whole when considering benefits to be maintained in the long term. This review is an initiative to evaluate the proposals that have emerged in the scientific literature so far and to think about new approaches, solutions, and research agendas that can best guarantee the expected benefits of restoration.

## 1.2. Identifying Interactions Between Ecological Restoration, Climate Change, and Ecosystem Services

The literature research was carried out on the platforms Web of Science (WoS) and Scopus through the search of the words “restor*” AND “Climate Change” AND “Ecosystem Services” on October 9th, 2024. As a result of the research, 2433 articles were retrieved from WoS, and 1683 from Scopus, totaling 4116 articles as a result of both searches. A total of 1083 duplicates were excluded, and 3033 articles went through the first screening. In the first screening, 2559 articles that did not address climate change, ES, or restoration in any way or in a general way, without specifying it, were excluded. We also excluded articles that were identified as reviews, meta-analyses, and articles about land use and land cover change (LULC) without addressing restoration.  From this, there were 474 articles for the second screening, where 163 articles that were a review, meta-analysis, or book chapter, that were in a language other than English or Portuguese and that we couldn't access were excluded. A further 144 articles were excluded for not addressing the scope of this review since it did not deal with restoration, dealing with restoration, climate change, or ecosystem services. In the end, 197 articles that addressed the three themes (Figure 1), albeit in a more general way, and offered screening information for this scientometrics were retained for further analysis.

***Figure 1*** *– Systematic review steps. The review initially identified 3,033 articles, but after applying the inclusion criteria, only 197 studies that addressed climate change, restoration, and ecosystem services were retained.*




For each selected study, we extracted five characterizations based on the study, restoration, climate change, ecosystem services, and the interaction identified between climate change and restoration. For the characterization of the study, we extracted: i) country; ii) location; iii) biome – classified according to location, taking into account the classification of biomes standardized by DINERSTEIN et al. (2017); iv) ecosystem; v) the type of analysis tool used; and vi) timespan based on initial and final reference year of the study. The restoration was classified by: i) scale; ii) restored area – standardized in hectares; iii) ecosystem restored – standardized into forest systems, flooded systems (peatlands, wetlands, and floodplains), coastal systems (mangroves, estuary, seagrass, and saltmarsh), croplands (extractivist, forestry, and agroforestry) and new systems creation were assigned to the 'other' category, and marine systems (coral and oysters); iv) the technique of restoration used – standardized into active restoration (techniques similar to total planting, direct seeding, or any technique that required direct management for vegetation establishment), passive restoration (standardized into techniques that did not require vegetation management or secondary regeneration), and management techniques – standardized into techniques based on thining, burning or similar management; and v) restoration approach – classified into past, present and future. The climate change was characterized by: i) climate approach – classified into past, present, and future; and ii) climate scenario – standardized into Strong Mitigation for those with a radiation strength of up to 2.6 W/m² by 2100 or an average temperature increase of less than 2ºC; Moderate Mitigation for those with a radiation strength of up to 4. 5 W/m² after 2100 or an average temperature increase of more than 2ºC; Weak Mitigation for scenarios corresponding to a radiative forcing of up to 6W/m² after 2100 and Business-as-Usual for scenarios with a radiative forcing of approximately 8W/m² until the middle of 2100 or an average temperature increase of more than 4ºC according to O'NEILL et al. (2016) and CLIMATEDATA (2024). We identified only two interactions between climate change and restoration: i) Restoration as a climate solution from ES; and ii) How climate change affects ES through restoration. Finally, the ES found were grouped and standardized according to the 18 categories of Nature's Contribution to People (NCPs) by the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES, 2018). The study lines were duplicated concerning the climate scenario used and the type of ecosystem service assessed, generating 1804 observations. Observations are individual data points or records collected during the study. Each observation represents a unique combination of study conditions, such as a specific climate scenario, restoration strategy, or type of ecosystem service assessed. For instance, if the study analyzed multiple climate scenarios (e.g., current and future) and different ecosystem services (e.g., carbon sequestration and water regulation), each scenario-service combination would generate multiple data points, contributing to the total of 1804 observations at the end.

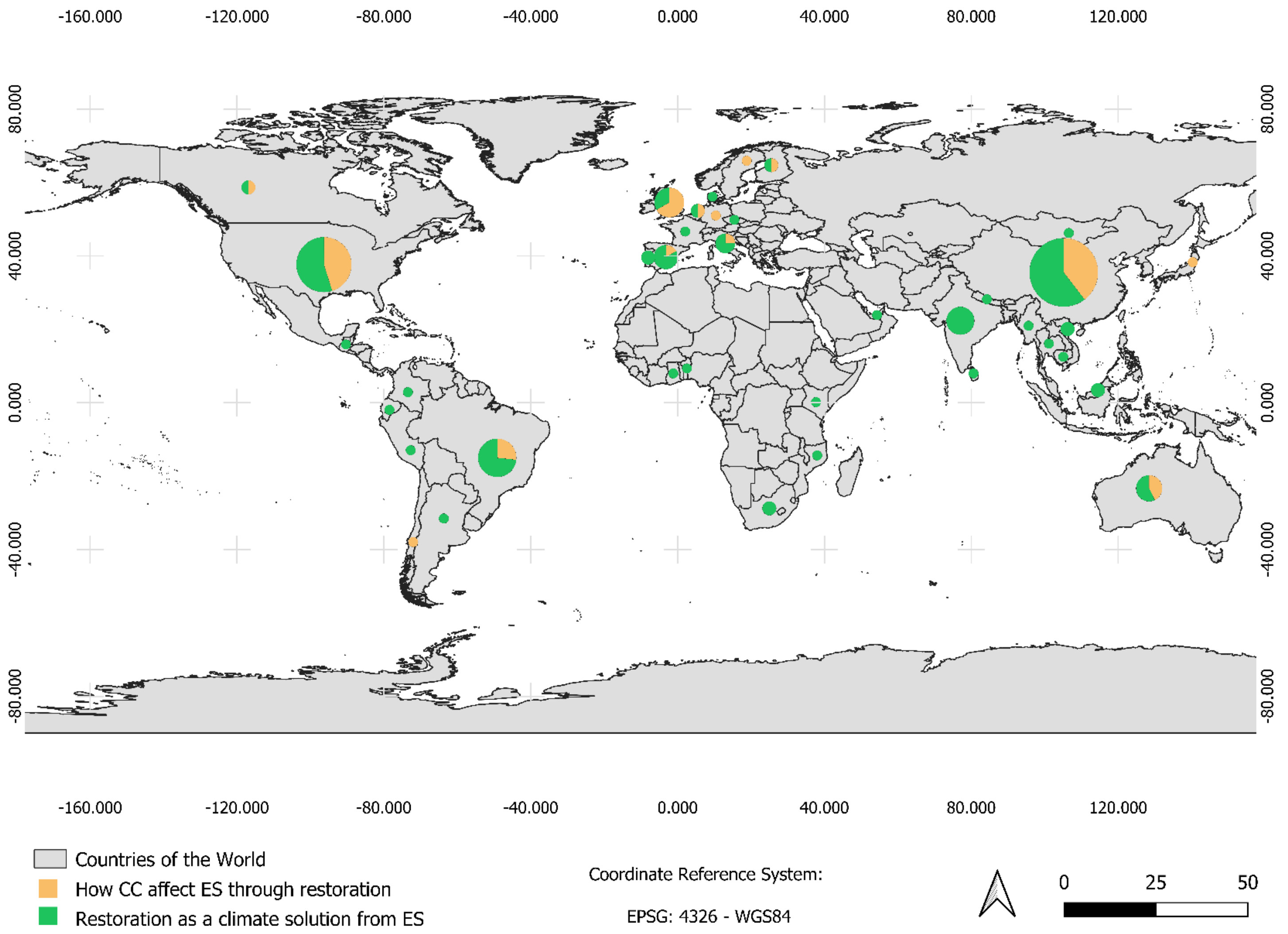
### 1.3. Global Trends in the Interaction Between Ecological Restoration and Climate Change

Most studies (68%) focus on ecological restoration's role in promoting climate mitigation worldwide. However, most of these studies do not address how climate variables can affect restoration in its context. Instead, they discuss climate change only generically to reinforce the importance of restoration for multiple ecosystem services and biodiversity, including climate mitigation. This result reinforces the missing information on how climate change can compromise restoration projects and the ecosystem services they deliver.

Over half of the studies use a modeling approach to explore the influence of climate change on ecosystem services provided by ecological restoration. In second place, with a range of 30% of studies discussed conceptually or politically the importance of climate change for restoration, mostly emphasizing the steps to achieve large-scale restoration goals to mitigate climate change. In the spotlight, we had only 13% of the studies conducting the same evaluation using an empirical or ex-situ approach. Overall, these studies focus on a historical period, analyzing past climate data and trends (such as temperature, precipitation, and extreme weather events) over a specific timeframe to understand the influence of climate variables and trends on ecosystem services and restoration response. Conceptual and political discussion are extremely important for understanding the policies and actions that need to be taken in this process and reinforcing the role of restoration in the context of climate change. However, fieldwork and more empirical approaches are critical to ensure that theoretical and modeling studies can demonstrate the real potential of restoration efforts to promote adaptation and mitigation services in the face of climate change.

Studies are geographically biased; around 84% of countries don't discuss any of these themes in an integrated way; the consequence relies on a large gap of countries that do not use scientific evidence to design restoration and climate change projects. Asia is the continent that dominates this discussion since China is the country with the greatest amount of research in the topic (Figure 2), focusing on Chinese forest systems. Europe and North America are second and third in this ranking, respectively. Europe has a good distribution of studies among countries, while in North America, the studies are concentrated in the United States (Figure 2). Despite the distribution of studies being biased toward Asia, Europe, and North America, Brazil reaches third place after China and the United States, putting South America on the rise in this issue (Figure 2). Brazil ends up being a representative country in this context for South America, as reforestation gains global prominence and the region rises in importance.

***Figure 2*** *- Proportion of studies by country. The studies in each country are divided into those that worked on 1) How climate change affects ecosystem services through restoration (in orange) and those that worked on 2) Restoration as a solution to climate from ecosystem services.*

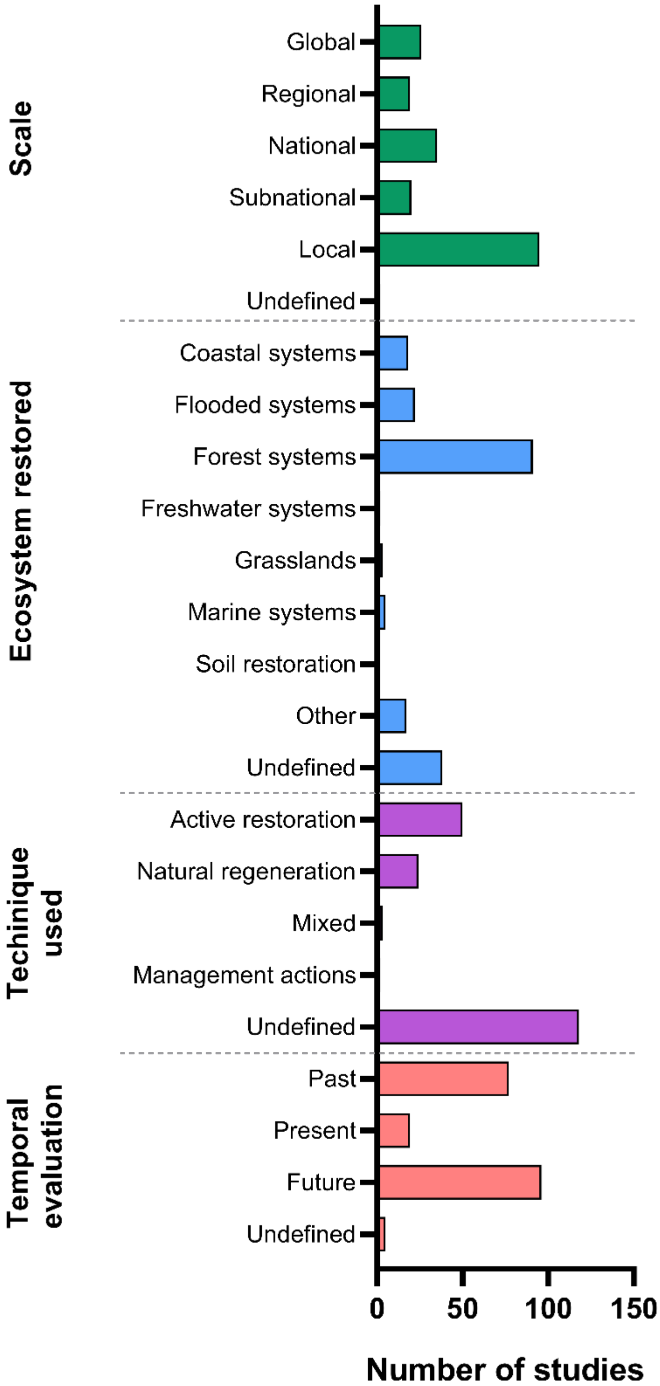


Brazil has become a global reference in ecological restoration, with various initiatives addressing environmental challenges, enhancing biodiversity, and promoting sustainable development. Notable projects include Restaura Brasil by The Nature Conservancy, which aims to restore 12 million hectares by 2030 (TNC, 2023), and the Floresta Viva Project, a collaboration between the Ministry of the Environment and BNDES, targeting the restoration of up to 30,000 hectares across all biomes (MMA, 2022). Conservation International Brazil has set ambitious goals to restore 100,000 hectares by 2025 despite political and environmental adversities challenges (CONSERVAÇÃO INTERNACIONAL, 2023). Meanwhile, the Paisagens Sustentáveis da Amazônia initiative focuses on restoring 28,000 hectares in the Amazon using nature-based solutions (CONSERVAÇÃO INTERNACIONAL, 2023). Efforts led by SOS Mata Atlântica prioritize the recovery of the Atlantic Forest, engaging local communities in reforestation (SOS MATA ATLÂNTICA, 2023), while WWF-Brazil has worked for over 15 years on large-scale landscape restoration (WWF-Brazil, 2023). Other initiatives like The Atlantic Forest Restoration Pact focus on the Atlantic Forest, with the aim of restoring 15 million hectares of degraded areas by 2050. Additionally, the Society for Ecological Restoration Brazil (SOBRE) fosters knowledge exchange and collaboration, showcasing the country’s progress in events like the Brazilian Conference on Ecological Restoration (UNEP, 2022). These efforts collectively underscore Brazil's role in advancing restoration strategies aligned with global climate and biodiversity goals. All these initiatives bring together a wide network of organizations, including civil society, companies, governments, universities, and landowners, working together to promote ecological restoration actions throughout Brazil.

## 1.4. Role of Restoration for Climate Change

Ecological restoration is mostly being discussed on a local scale, where the systems that are studied the most are forests and flooded systems (Figure 3). The restoration technique that predominates is active restoration (Figure 3). Still, there’s definitely a gap when measuring effectiveness based on a technique or how to conduct restoration processes. Thus, it is important to highlight that the restoration technique can be critical when designing ecosystem services-guided projects and choosing the most efficient tools available when planning a project implementation and development (GANN et al., 2019; METZGER et al., 2017).

***Figure 3*** *- Restoration approach of studies. A number of studies are divided by the characterization of restoration according to temporal evaluation, technique used, ecosystem restored, and scale of restoration.*




It is crucial to amplify the scope of research by analyzing how restoration influences different ecological systems and understanding the responses of these systems to restoration efforts within the context of climate change. Given the variability of biomes worldwide, assessing the impacts of a changing climate on restoration can help identify the most effective strategies for sustainable ecosystem management. Such insights can foster the recovery of ecological interactions in degraded landscapes by promoting the establishment of climate-resilient systems capable of supporting local biodiversity.

A convincing example is the long-term restoration effort at Batata Lake, located in the Amazon region of Brazil, which faced severe ecological degradation between 1979 and 1989 due to the discharge of bauxite mining tailings that buried extensive areas of the surrounding igapó forest (SOARES et al., 2017). In response, a comprehensive restoration program was launched in 1989, employing a combination of natural regeneration and active reforestation techniques. Over the past 35 years, systematic monitoring has documented the progressive recovery of the igapó vegetation, with many species now reaching advanced growth stages, including flowering and fruiting (CARDOSO et al., 2023; SCARANO et al., 2018).

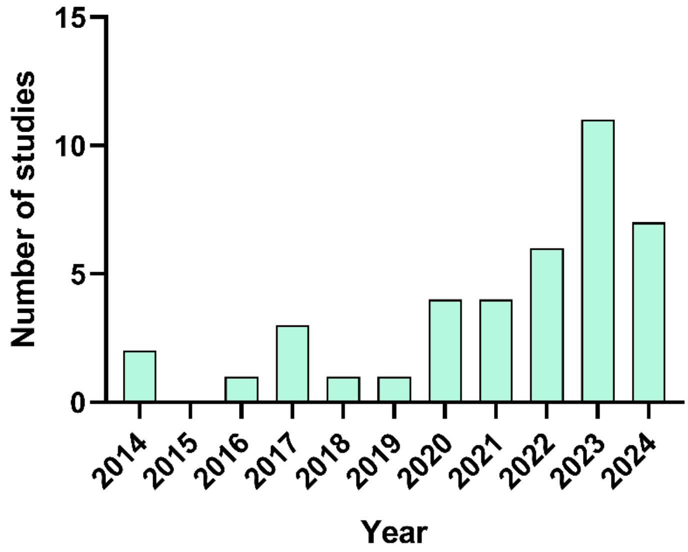
This long-term initiative highlights the importance of adopting multiple, tailored restoration strategies and maintaining robust monitoring systems. By doing so, complex ecosystems such as floodplain forests can gradually recover and regain their ecological functions. Batata Lake's case exemplifies how restoration requires sustained investment, adaptive management, and extensive monitoring to achieve meaningful ecological outcomes over time.

Restoration projects and initiatives still need to be extensively evaluated throughout their entire process, incorporating monitoring from the initial implementation phase to the desired final stages. In this sense, it is essential to adapt the available strategies to the local context, making it possible to identify the most favorable regions and conditions for their application. Only an integrated and comprehensive assessment of the entire restoration process, including a broad investigation of different degraded systems, can provide more consistent guidance for decision-making. This is essential to ensure more efficient efforts to conserve biodiversity and maintain ecosystem services. Future studies should address the existing gaps in order to better direct the efforts being made, maximizing the restoration results and its ecological benefits.

### 1.5. Finding the Gap: Incorporating Climate Change into Ecological Restoration Efforts

Around 68% of the studies evaluated bring a conceptual perspective of climate change more than exploring its actual impact on ecological restoration efforts. This is reflected in an extensive base of studies that adopt this approach solely at a theoretical level, without addressing any effects of climate on restoration projects. The majority of studies exploring the effects of climate change on restoration project future impact (51%). These studies use modeling, 68% of which under extreme climate scenarios(business-as-usual). This approach is still recent in the scientific literature, though, with studies involving the evaluation of some climatic variables to address some context of restoration starting in 2014. Despite this, the approach has only been more widely used since 2020, when the number of published articles has increased (Figure 4), which may be a response to the UN Restoration Decade efforts that argue for broader approaches to ecological restoration.

***Figure 4*** *- Number of studies through time. The first study appears in 2014, and the volume of publications begins to increase significantly from 2022 onward.*



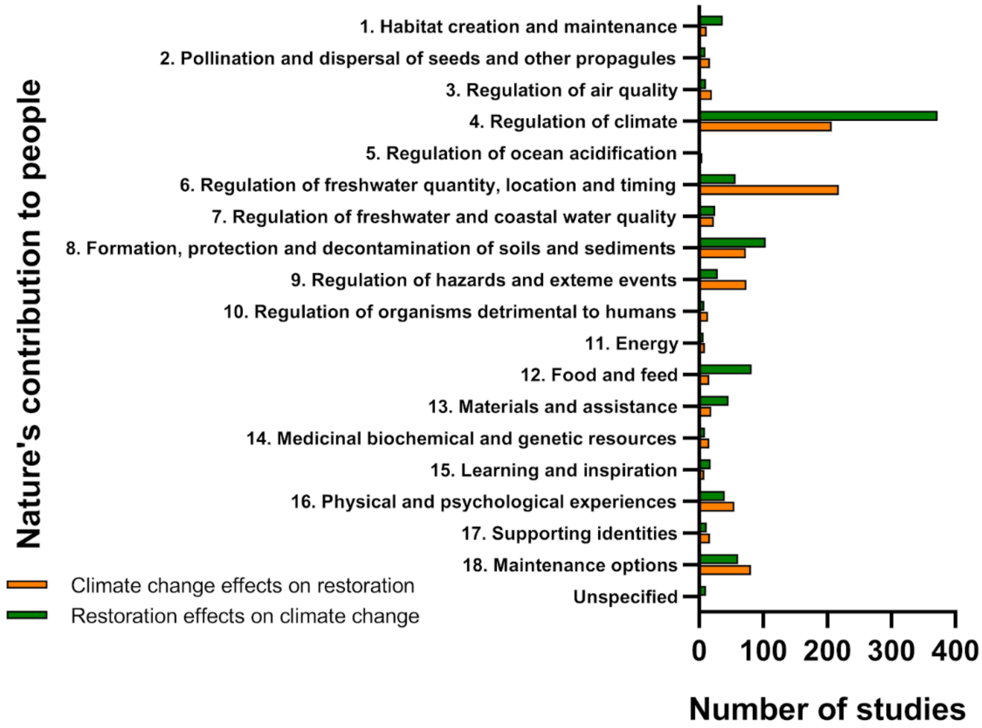

A standout study when assessments began was the work of RITSON et al. (2014), where the authors used Dissolved Organic Carbon (DOC) in a laboratory experiment to assess the influence of extreme climate change on wetland systems to guide wetland restoration and management efforts. Although this study did not offer a direct guidance to the evaluation of restoration itself, it represents one of the first initiatives to evaluate the effect of climate variables to conduct management and restoration actions. However, we recognize the importance of assessing the effects of climate variables between degraded and restored scenarios since it's the most efficient way to understand the impact that restored systems can have on improving ecosystem services and mitigating climate change, being as close as possible to reality when we talk about restoring natural systems.

One of the fundamental aspects influencing the impact of climate change on the relationship between ecosystem services and restoration is the role of water availability. Changes in precipitation patterns and the increased frequency of extreme droughts driven by climate change can significantly affect the success of restoration projects and the delivery of associated ecosystem services (CHEN and NING, 2024). For instance, water scarcity can hinder plant establishment, growth, and survival, ultimately reducing the capacity of restored ecosystems to sequester carbon, regulate water flow, and support biodiversity (WEISKOPF et al., 2020). Additionally, prioritizing restoration efforts in areas with higher resilience to changing water availability or implementing adaptive strategies, such as selecting drought-tolerant species, can enhance restoration outcomes under future climate scenarios (HAGA et al., 2022). By integrating hydrological projections and climate models into restoration planning, researchers can identify areas most vulnerable to water stress and develop strategies to mitigate these impacts, maximizing the ecosystem service benefits of restoration (HUANG et al., 2023; YU et al., 2024). Exploring such climate-driven variables is critical to understanding the dynamic interplay between restoration and ecosystem services under changing climatic conditions, ensuring the long-term sustainability of these efforts.

## 1.6. Quantifying the Benefits of Ecological Restoration in the Face of Climate Change and a New Era for Ecological Restoration Science

The role of climate change in ecological restoration design depends on the specific ecosystem services targeted for enhancement at the local level. In all of the ecosystem services used to evaluate the climate approach, the focus on the importance of restoration as a fundamental component for facing climate challenges predominated, highlighting its crucial role in this context. This issue is particularly evident in services like climate regulation (NCP 4 in Figure 5), with a focus on carbon sequestration and climate mitigation. Addressing the adverse effects of climate change on the restoration of ecosystem services in relation to climate regulation is still an emerging area (Figure 5). Consequently, the lack of research into climate effects on other ecosystem services could compromise the effectiveness of climate change mitigation through restoration on a local scale.

***Figure 5*** *- Distribution of of Nature's Contribution to People (NCP) by studies. Number of studies classifying ecosystem services according to the 18 categories of NCPs by IPBES.*




While much attention has been given to climate regulation, other ecosystem services require equal consideration within the context of climate change. For instance, ecosystem services that explore individuals' physical and psychological experiences, is often overlooked (Figure 5). Few studies investigate how climate change might influence physical well-being and individuals' connection to their environment in the future by restoring ecosystems. This gap in knowledge underscores the need to understand how changes in climate could alter people's identification with their surroundings and how restoration projects can enhance their sense of place and well-being.

Additionally, ecosystem services related to habitat quality, pollination, air quality regulation, energy production, food supply, and the control of invasive species demand greater focus to improve their analysis (Figure 5). Climate change has the potential to impact these food and water supplies (IPCC, 2022); it is important that we also know the level of impact on other ecosystem services and how they are changing in the landscape. Amplifying discussions around climate adaptation for those ecosystem services is essential for creating comprehensive and resilient restoration strategies for the future. For example, the regulation of air quality and pollination services is tightly linked to climatic factors such as temperature shifts and changing precipitation patterns, which influence ecosystem dynamics and species interactions (GÉRARD; VANDERPLANCK; WOOD, 2020).

Hydrological ecosystem services (NCP 5, 6, and 7 in Figure 5) and those addressing soil formation and protection (NCP 8 in Figure 5) are particularly relevant in the context of climate-informed restoration. These services are directly related to the modeling approaches for water quality and are essential for understanding the interactions between climate change and restoration. Hydrological services, such as water flow regulation, groundwater recharge, and flood prevention, are critical in mitigating extreme weather events exacerbated by climate change (DAO et al., 2024). Similarly, soil-related services, including erosion prevention and soil fertility maintenance, are foundational for sustaining terrestrial ecosystems and controlling surface runoff that is implicated in water quality (DURÁN ZUAZO and RODRIGUEZ, 2008). Failing to address these services in restoration planning could exacerbate vulnerabilities to climate extremes, such as droughts, floods, and soil degradation.

Failure to assess the impact of climate change on the benefits of ecological restoration can lead to significant risks, both environmental and socio-economic (EDWARDS et al., 2021). This could reduce the chances of success of a strategy that already has many implementation challenges. Incorporating and evaluating restoration projects through the climate lens is a way of attempting avoiding its effects on restoration implementation and prioritizing strategies to help mitigate its effects. Restoration projects that do not take climate change impacts into account may fail to achieve their intended goals, such as increasing biodiversity or enhancing ecosystem services, especially considering the needs of local people. For example, planting species that are not climate-resilient could result in low survival rates or an inability to maintain ecosystem functions (RANĐELOVIĆ et al., 2024).

Without taking climate change into account, restored ecosystems may not be able to adapt to changing temperatures, precipitation patterns, or extreme weather events, reducing their long-term stability and resilience. Climate change may also alter the provision of key ecosystem services such as carbon sequestration, water regulation, or soil fertility (YU et al., 2024). If restoration strategies do not anticipate these changes, the services they seek to enhance or restore could decline over time, and strategies need to be devised to contain these effects. Restoration projects that fail due to climate-related factors can also lead to wasted financial resources and reduced community confidence in conservation efforts. In addition, communities that depend on ecosystem services for their livelihoods, such as agriculture or water supply, may face increased vulnerability.

Exploring multiple scenarios on how climate change can alter the benefits provided by restoration efforts is a valuable tool for prioritizing and scaling restoration efforts by establishing an adaptive restoration approach. By modeling the interactions between restoration strategies and climate change, such a framework allows the identification of areas with the greatest cost-benefit potential for enhancing ecosystem services in the medium to long term. Thus, restoration projects can be strategically located to optimize single or multiple services, including carbon sequestration, improve water quality, or support pollinator habitats in regions vulnerable to climate impacts. Incorporating climate change into ecological restoration planning ensures that restoration efforts remain adaptive, effective, and resilient in the face of uncertainty. It also allows decision-makers to prioritize strategies that enhance restoration benefits while minimizing risks, ultimately contributing to long-term ecological and socio-economic sustainability.

## 1.7. Conclusion

Ecological restoration has emerged as a pivotal strategy for addressing the dual crises of environmental degradation and climate change. However, the effectiveness of restoration projects is intrinsically tied to their ability to account for climate change impacts on restoration itself and the ecosystem services it provides. This review underscores the pressing need to integrate climate-informed approaches into restoration planning and implementation, as failure to do so can undermine both ecological and socio-economic benefits.

We revealed that the global trends in restoration science remain skewed and focused on conceptual discussions on climate change, with limited empirical data to support actionable strategies. Moreover, the uneven geographical distribution of studies towards the Global North highlights significant gaps in global representation, which must be addressed to develop comprehensive, scalable solutions. While notable progress has been made in understanding the role of restoration in climate regulation, other critical ecosystem services, such as pollination, air quality, and water regulation, require more attention to fully grasp their intrinsic interactions with climate change and their importance for human well-being. In this sense, hydrological and soil-related ecosystem services emerge as particularly crucial topics for advancing climate-informed restoration. By leveraging frameworks that model the interplay between climate variables and restoration outcomes, it is possible to identify high-priority areas for maximizing the cost-benefit ratio of restoration efforts.

We conclude that ecological restoration must evolve into a more adaptive and comprehensive process to ensure its success. This process must integrate empirical research, diverse ecosystem contexts, and proactive climate strategies. Such an approach will enhance resilience, optimize ecosystem service delivery, and secure the long-term benefits of restoration for biodiversity and human well-being. Bridging current knowledge gaps and fostering global collaboration are essential steps toward achieving these goals, ensuring the protagonism of restoration science in the Anthropocene and reinforcing its role in multi-lateral agreements such as the Paris Agreement, the Kunming-Montreal Global Biodiversity Framework, and the 2030 Agenda.

## 2. ADAPTATIVE RESTORATION PLANNING TO ENHANCE WATER SECURITY IN A CHANGING CLIMATE[2]

**Abstract**

Ecosystem restoration is a global priority for recovering degraded areas and mitigating climate change. However, climate change can impact the long-term effectiveness of restoration efforts. This study evaluated the effects of climate change on restoration planning, focusing on water quality in the Doce River basin, the site of Brazil's largest environmental tragedy and one of the world's most significant mining disasters. Sediment exportation was used as a criterion for assessing water quality under three climate scenarios. Restoration of riparian vegetation was predicted to reduce sediment exportation by 75.3% but was insufficient to fully control erosion in Santo Antônio, located in the upper basin, where increased precipitation could exacerbate the problem. The findings underscore the risks of ignoring climate change in restoration planning and how climate change can alter the status of prioritization when incorporated into the analyses. Adaptive strategies are essential to ensure long-term benefits and address climatic challenges, fostering more resilient and sustainable ecosystems.

**Keywords**: Climate change. Forest restoration. InVEST · ecosystem services. Modelling. Rio Doce. Water quality.

[2] Luiz Conrado-Silva, Julia de Niemeyer, Aliny P. F. Pires. Adaptative Restoration Planning to Enhance Water Security in a Changing Climate (under review). Ambio.

## 2.1. Introduction

Ecosystem restoration has been recognised as a global priority for the recovery of degraded areas (ARONSON and ALEXANDER, 2013). Restoration is directly related to the improvement of human well-being, and it is one of the key links between socio-economic development, biodiversity protection, climate change, and ecosystem services (UNEP, 2020). The United Nations has recognised this decade as the Decade of Ecosystem Restoration, and efforts to strengthen this perspective are being conducted worldwide. At the 21st Conference of the Parties (COP21), a new agreement was adopted to accelerate the global response to climate change and enhance the capacity of countries to deal with its impacts (UNEP 2020). Each country outlined these new goals and commitments through Nationally Determined Contributions (NDCs), which set targets for reducing greenhouse gas (GHG) emissions. For example, Brazil has committed to restoring 12 million hectares of forests to reduce GHG emissions by 43% by 2030 (FEDERATIVE REPUBLIC of BRAZIL, 2024). However, despite the recognized importance of restoration, the high implementation costs and the establishment of efficient strategies to achieve the desired goals of restoration as ecosystem services and well-established vegetation (SUDING et al., 2004), especially in long-term initiatives, are still a challenge. Effective techniques for evaluating restoration success remain largely underdeveloped, leaving a poorly explored gap that may drive higher investment in maintaining restoration outcomes. Therefore, it is essential to explore more robust success indicators to improve the assessment of strategies and techniques (MOLONEY et al., 2023).

In this sense, it is crucial to understand ecosystem functioning and processes on a landscape scale to establish more efficient restoration initiatives (SUDING et al., 2004). This involves considering not only the direct financial costs of implementing and maintaining restoration processes but also the long-term benefits for biodiversity and ecosystem resilience (BULLOCK et al., 2011). Restoration efforts are also often driven by governmental initiatives, frequently undocumented in peer-reviewed literature, and lack monitoring due to limited resources, highlighting the need for improved data collection. Remote sensing could offer a scalable, cost-effective solution to track ecosystem variables like green cover, carbon storage, and temperature, enhancing restoration monitoring and outcomes (VON HOLLE; YELENIK; GORNISH, 2020). The use of multiple criteria considering biodiversity conservation, climate change mitigation potential, water security, and other factors can be essential for defining the best prioritisation strategies. This approach can provide key ecosystem services effectively while taking into account local needs and risks regarding climate change (PÖRTNER et al., 2021; WANG et al., 2024). Approaches that integrate multiple restoration strategies—such as using diverse propagule sources, restoring across various sites, or extending efforts over multiple seasons—can enhance system stability and reduce overall risk from extreme climatic events (ZABIN et al., 2022). Heterogeneity within or across restoration projects is critical for mitigating the impacts of such events and maintaining higher levels of biodiversity (TIMPANE-PADGHAM; BEECHIE; KLINGER, 2017). While this complexity presents challenges for practitioners in predicting the effects of future extreme climatic conditions on restoration outcomes, it also offers a promising pathway to bolster resilience: adopting a portfolio approach to diversify and strengthen restoration efforts (TIMPANE-PADGHAM; BEECHIE; KLINGER, 2017; ZABIN et al., 2022).

Climate change has the potential to alter the expected benefits of ecosystem restoration by affecting some key aspects of the natural environment (HOBBS and HARRIS, 2001). For example, changes in precipitation patterns may alter water availability, requiring adjustments in restoration strategies to deal with drought or wetter conditions in the future (WILLIAMS; JACKSON; KUTZBACH, 2007). Rising temperatures may also alter the geographic distribution of species, requiring a review of the ones currently targeted as priorities in restoration planning (DUKES and MOONEY, 1999). In addition, the vulnerability of ecosystems to extreme climatic events such as storms, droughts, or wildfires may increase, compromising restoration efforts and requiring additional preparedness and risk mitigation measures (HELLER and ZAVALETA, 2009; LAWLER et al., 2015), as well as increased monitoring and controlling measurements in restored areas which could increase the costs of restoration implementation. Thus, climate change plays an important role in establishing restoration strategies and their efficiency in climate mitigation (ALMAGRO et al., 2017; BENAYAS et al., 2009). Restoration projects that do not take climate effects into account may become ineffective in their methods to evaluate, quantify, and ensure the expected benefits under current and future conditions (KOCH and KAPLAN, 2022).

The central challenge we face is developing effective restoration strategies for a rapidly changing climate, where reliance on historical references alone is no longer sufficient. Historical resources remain crucial for understanding ecosystem tendencies and responses to climatic variables, serving as a guide rather than a rigid blueprint for restoration actions (HARRIS et al., 2006; HIGGS, 2003). We already possess a deep understanding of how certain species in various regions have responded to past climatic shifts, and this knowledge is being used to anticipate future changes (HARRIS et al., 2006). Recent advances in computing technology have unlocked the potential for more comprehensive analyses of the spatial and temporal dynamics of climate change, ecosystem services, and restoration. This progress underscores the need for collaboration among ecologists, climate modelers, and restoration practitioners to anticipate and address the impacts of climate change within local ecosystems effectively (SEAVY et al., 2009). Therefore, restoration efforts must strike a balance between leveraging historical insights and adopting adaptive, forward-looking strategies to address the dynamic and unpredictable challenges of a changing environment. Obtaining site-specific or watershed-specific climate predictions is also an important driver in integrating climate change into restoration actions since it can guide the identification of sites most likely to sustain desired habitats or species under future conditions, ensuring restoration efforts are both resilient and adaptive under a changing climate (TIMPANE-PADGHAM; BEECHIE; KLINGER, 2017).

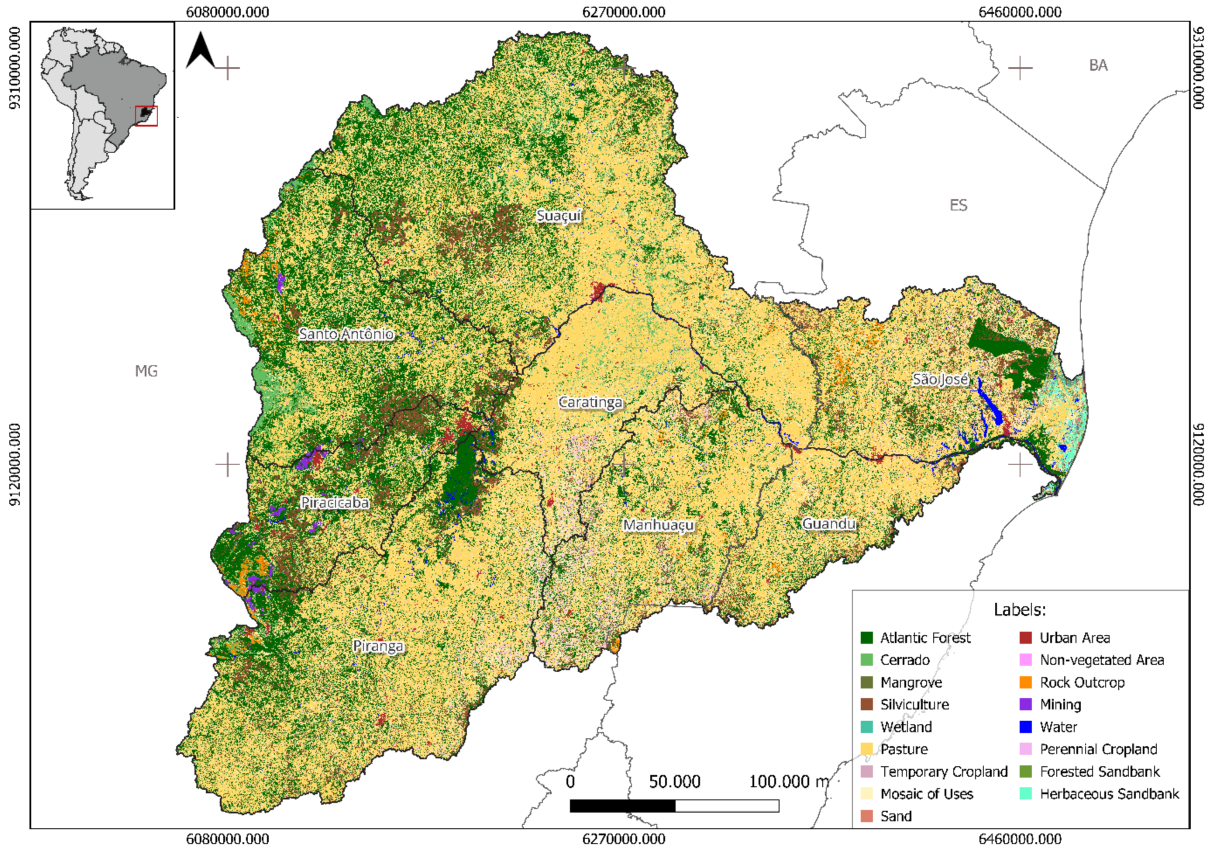
Our study aims to evaluate the impact of forest restoration on water quality under multiple climate change scenarios. For that, we based our restoration scenarios on the Brazilian Native Vegetation Protection Law (NVPL nº 12651/2012). The NVPL is one of the main policy instruments to guarantee forest restoration, especially considering the Permanent Protection Areas (APPs) that should protect and recover riparian zones and mountaintops within public and private lands (PIRES et al., 2017). It is estimated that the implementation of the NVPL can restore over 16 million hectares of native vegetation in Brazil (ROUSSEFF et al. 2012; UNEP 2020). Thus, we evaluate the impact of restoring APPs predicted by the NVPL in the Doce River basin on sediment production and exportation using the Sediment Delivery Ratio (SDR) in the software InVEST. The SDR model is based on the principle that the presence of vegetation reduces the transport of sediment and nutrients to water bodies, indirectly contributing to maintaining water quality. This mechanism is particularly relevant in the context of the Doce River basin, where the collapse of the Fundão dam—known as the “Mariana desaster”, in reference to the name of the nearby city affected—deposited large volumes of tailings, predominantly composed of clays and silt (KÜTTER et al., 2023). These materials significantly increased water turbidity, one of the factors most impacted by the disaster, compromising water quality and, consequently, aquatic biodiversity (FOESCH et al., 2020). High turbidity reduces the availability of dissolved oxygen, affecting the quality of the habitat of various aquatic organisms. Thus, the proposed modelling establishes a direct connection with one of the main vectors of water quality degradation resulting from the Mariana disaster. We have simulated this restoration effort under three climate conditions, including a baseline and two climate change scenarios (RCP 4.5 and RCP 8.5). Finally, we identified changes in the benefits provided by restoration driven by climate change and defined priority areas that can guarantee water security under different climate change scenarios.

## 2.2. Methods

### 2.2.1. Study Area

The Doce River basin is located in the Southeastern region of Brazil and covers an area of 8.6 million hectares. It is divided into eight subbasins, with 86% of its area in the state of Minas Gerais and 14% in Espírito Santo (Figure 6). The largest subbasins, Suaçuí and Piranga, together cover 45% of the area. The climate in the upper region is tropical, with a dry winter season, while the lower portion has a monsoon climate, with coastal influence (CUPOLILLO; ABREU; VIANELLO, 2022). The average annual temperature ranges from 18 to 25ºC, and rainfall is unevenly distributed throughout the year (CUPOLILLO; ABREU; VIANELLO, 2022). The dry season lasts from May to October, with rainfall ranging from 150 to 250 mm, while the rainy season lasts from November to April, with rainfall ranging from 800 to 1300 mm (CUPOLILLO; ABREU; VIANELLO, 2022). The basin is within two global biodiversity hotspots, with 98% of its area being Atlantic Forest and 2% Cerrado (CONSÓRCIO ECOPLAN - LUME, 2010).

***Figure 6:*** *Subbasin divisions in the Doce River Basin. Land use and cover map in both states of the Doce River watershed occur (Minas Gerais and Espírito Santo) using the Mapbiomas database, demonstrating the high level of degradation in the area.*




The Doce River basin includes 225 municipalities with 5 million inhabitants (IBGE 2022). The diversity of economic activities in the region has a significant impact on land use, with a predominance of coffee and sugar cane cultivation, cattle ranching, mining, industrial activities, and energy production. The growing population, combined with the over-exploitation of the basin's resources, poses a threat to soil and water quality due to the widespread convertion of native vegetation.

We chose the Doce River basin as a model because of its importance in the country and the great efforts for its recovery. In November 2015, an iron ore tailing dam ruptured, causing severe damage to the Doce River, severely compromising its biodiversity and riverine populations. Approximately 50 million cubic meters of tailing were released into the environment (AGÊNCIA BRASIL, 2021), making it the biggest environmental disaster in the country, causing the degradation of 670 km of river ecosystems in coastal and ocean areas (SÁNCHEZ et al., 2018) and the degradation of 1,469 hectares of forest, including APP areas (PINTO-COELHO, 2016).

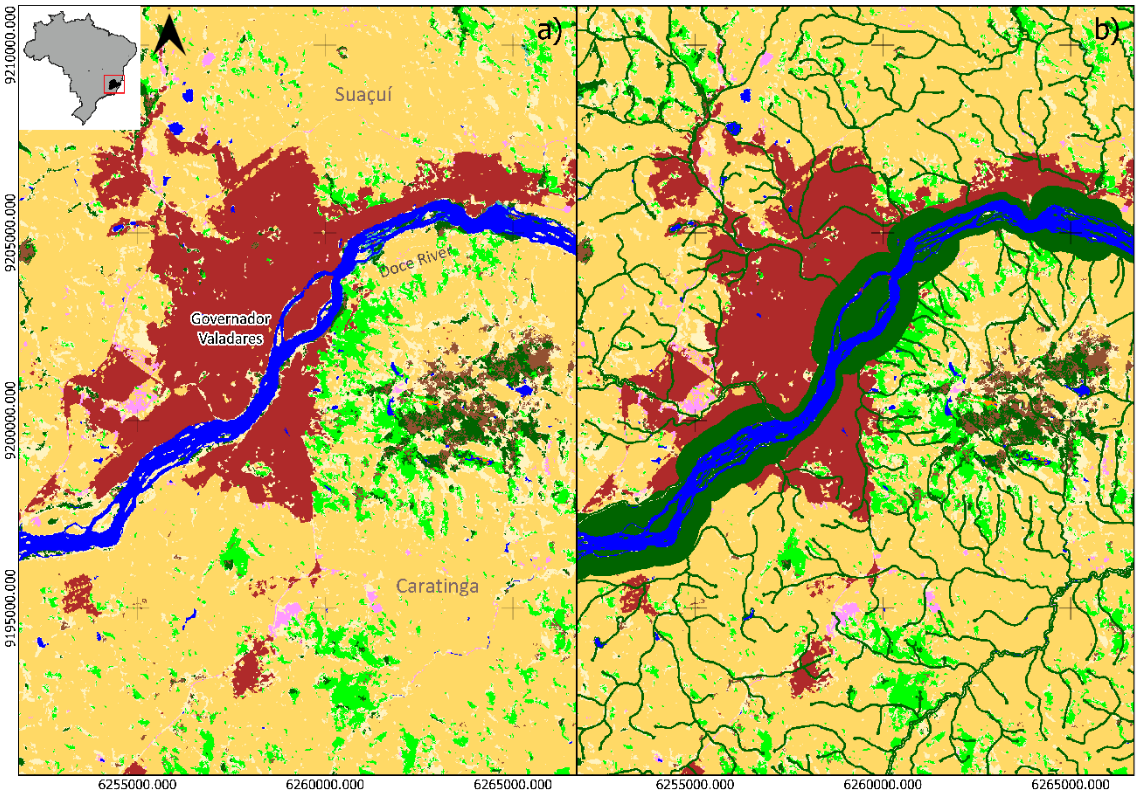
The loss of water quality constitutes the main mechanism underlying the various impacts caused by this disaster. So, reclaiming water quality has been the aim of many recovery initiatives in the watershed. It is estimated that the restoration of the native vegetation in APP areas represents one of the best restoration strategies for riverine ecosystems with the greatest ecosystem benefits, acting as an important technique for restoring aquatic environments (PIRES et al., 2017). Forest restoration can control sediment exportation and restore streambed substrate through the organic matter provided by the riparian vegetation (Pires et al., 2017). However, despite the variety of strategies that aimed to identify priority areas for restoring the 40,000 hectares established for the companies responsible for the disaster (RENOVA, 2021), none of them considered the impact of climate change on restoration strategies and, particularly, how it could affect or reshape prioritization approaches.

## 2.3. Climate Change and Restoration Scenarios

We developed different scenarios to assess how restoration affected annual erosion production and sediment exportation under different climate conditions. We used the latest land cover map produced by MapBiomas Brasil 2024 to characterise current land use (PROJETO MAPBIOMAS, 2022). We established a restoration scenario that sets the recovery of the APPs established by the NVPL by using the efforts conducted by the Brazilian Foundation for Sustainable Development (FBDS) (PIRES et al., 2017; RESENDE et al., 2019). APPs were mapped through supervised classification of RapidEye imagery analysis (5 m spatial resolution) and defined according to the marginal strip width values stipulated in articles 4 and 5 of the NVPL (Figure 7). For a full description of the procedures, see Pires et al. (2017); all shapefiles are available at https://geo.fbds.org.br. We combined the MapBiomas land cover map at a 10 m resolution and the APP shapefile produced by FBDS to estimate the environmental debt—i.e., non-compliance with obligations or unresolved issues related to the protection, preservation, and recovery of the environment—and to build the restoration scenario.

***Figure 7:*** *Restoration of APPs on the Doce River. The restoration of the middle portion of the Doce River basin under both current conditions (a) and a restoration scenario, (b) achieved through reforesting Permanent Protection Areas (APPs) identified by the NVPL. The figure illustrates the*

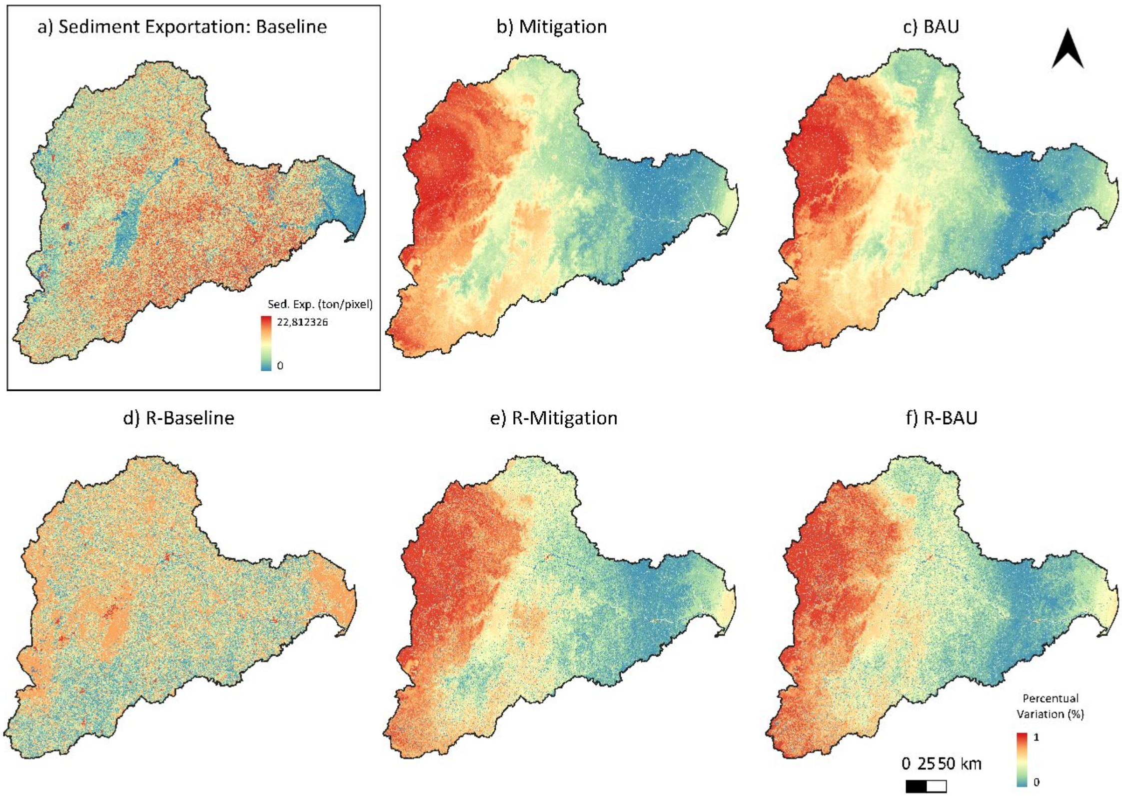
*degradation of the riparian zone within the watershed, which has experienced the loss of nearly all its forested areas in its middle portion.*




We used the *r.report* processing tool to calculate the environmental debt in QGis and obtain the area (in hectares) for each land cover and land use category, clipping maps for each subbasin shape (IBGE, 2021). Areas that were classified as pasture, silviculture, temporary cropland, mosaic of uses, urban areas, non-vegetated areas, mining, or perennial cropland in APPs were identified as environmental debt and replaced by "forest" to create the restoration scenario. The difference between the current and restoration scenarios reflects the amount of APP to be restored in each subbasin and the sum of them in the whole watershed. Areas outside the APPs were maintained with the same original land use category in all scenarios (Figure 8).

***Figure 8:*** *Map Comparison of Percentual Variation standardized between Scenarios: a) Shows the current amount of sediment being exported to the Doce River basin. Units are in tons/pixel for the baseline scenario; b) Shows the percentual normalised difference between Mitigation (RCP 4.5) and Baseline scenarios; c) Shows the percentual normalised difference between BAU (RCP 8.5) and Baseline scenarios; d) Shows the percentual normalised difference between Restoration-Baseline and Baseline scenarios; e) Shows the normalised percentual difference between Restoration-*

*Mitigation and Baseline scenario; f) Shows the normalised percentual difference between Restoration-BAU and Baseline scenario.*




Considering these two land use scenarios (current and restoration), we established three different climate scenarios, considering baseline climate conditions (base year: 2022) and the ones predicted by the Representative Concentration Pathways (RCP) 4.5 and 8.5, both for the 2070 (PANAGOS et al., 2022). While RCP 4.5 represents a moderate emissions scenario with some climate mitigation, RCP 8.5 is a high-emissions, worst-case scenario with continued fossil fuel dependence and no mitigation efforts. Climate change can affect sediment exportation in the modelling approach performed by altering the erosivity promoted by rainfall (rainfall erosivity). Rainfall erosivity measures the potential of rainfall to cause soil erosion through the impact of raindrops, especially when the infiltration capacity is exceeded (ALMAGRO et al., 2017). Therefore, erosion tends to be more pronounced with increased intensity and duration of rainfall. We calculated the rainfall erosivity factor for baseline using multiple linear regressions based on latitude, longitude, and elevation (MELLO et al., 2013; RESENDE et al., 2019). For that, we used the digital elevation model from Copernicus downscaled to 10m resolution (OPENTOPOGRAPHY, 2021). We obtained future erosivity projection maps from the European Soil Data Centre

(ESDAC) using the 1km resolution HadGEM2_ES model for 2070 to assess the impacts of climate change scenarios on sediment behaviour in the region. This model uses the same two climate change scenarios (RCP 4.5 and RCP 8.5) (PÖRTNER et al. 2022). The projections for 2070 predict a 30% increase in average erosivity for RCP 4.5 and a 34.3% increase for RCP 8.5 in Brazil and decreases from −1% to −25% in rainfall erosivity in the future (PANAGOS et al., 2022). In the Doce River basin, the erosivity decreases by 9.62% for RCP 4.5 and 7.14% for RCP 8.5, having different effects on the eight subbasins, causing an increase in erosivity in the upper Doce River and a decrease in the lower Doce River. It is worth noting that we chose to use the climate models from CMIP5 instead of CMIP6 because the later provide data at a much coarser resolution, which makes them less suitable for rainfall erosivity projections (PANAGOS et al., 2022).

In sum, we crossed the two land use conditions (current and restored) with the three climate scenarios (baseline, RCP 4.5, and RCP 8.5), producing six different scenarios: i) Baseline; ii) Mitigation (RCP 4.5); iii) Business-as-usual (BAU) (RCP 8.5); iv) Restoration - Baseline; v) Restoration - Mitigation; and vi) Restoration - BAU. A full description of the data used in each scenario is provided in Table 1.

***Table 1:*** *Development of modeling scenarios. The six scenarios used in the modelling approach proposed in this study, considering two land use conditions (current and restoration) and three climate conditions (baseline, RCP 4.5, and RCP 8.5).*

| Scenario | Assigned Name | Land Cover | Rainfall Erosivity |
|---|---|---|---|
| i) | Baseline | Current | Current |
| ii) | Mitigation | Current | RCP 4.5 |
| iii) | Business-as-usual | Current | RCP 8.5 |
| iv) | Restoration - Baseline | Restored APP | Current |
| v) | Restoration - Mitigation | Restored APP | RCP 4.5 |
| vi) | Restoration - BAU | Restored APP | RCP 8.5 |

## 2.4. Sediment Retention Modeling

We used the InVEST Sediment Delivery Ratio (SDR) model to assess annual soil retention in each scenario established. The SDR model is based on the Universal Soil Loss Equation (USLE), which calculates annual soil loss based on the connectivity between hillslope pixels and downslope drainage. This model assumes that the presence of vegetation prevents the transport of sediment into the stream. This mechanism is of particular importance in the Doce River basin, especially after the dam collapse, which led to the deposition of silt, clay, and heavy metals that strongly affected water quality (FERREIRA et al., 2020).

The Sediment Delivery Ratio (SDR) model requires several input data for accurate calculations: i) Digital Elevation Model (DEM); ii) Rainfall Erosivity (R); iii) Soil Erodibility (K) taken from the Zenodo repository at a 250 m resolution (GODOI, 2021); iv) Land Cover; v) Watershed; vi) Biophysical Table (see Table 2 in the appendix); and vii) Drainage Layer (optional) (see Table 2 in the appendix for the assigned values in the biophysical table). These data are essential to the comprehensive functionality of the SDR model, ensuring accurate and detailed assessments of soil retention in all established scenarios. All data that were not originally at a 10m resolution was downscaled for consistency. The remaining parameters essential for running the model were set to default values (K = 2; IC0 = 0.5, SDRmax = 0.8 and Lmax = 122).

We individually ran the model for all six scenarios to quantify the amount of erosion and sediment exportation in each of them. The difference generated between current and restored areas under the different climate scenarios reflects where restoration provides higher benefits under each of them. The differences observed from all scenarios and the baseline help identify the areas where restoration has provided the greatest benefit. This ensures the location of the areas where the greatest benefits occur, improving the resilience of water quality under climate change conditions.

### 2.5. Restoration Prioritisation Across Climate Scenarios

We created four maps to illustrate the priority municipalities and subbasins for restoration in the Doce River basin. Priority areas for restoration were defined based on the percentage variation in sediment exportation between the restored scenarios and the baseline in all climate scenarios. These values reflect the greatest benefits for water quality, as they reflect the areas with the greatest reduction in sediment exportation compared to the baseline. For the climate scenarios, the percentage difference of the restored climate scenarios was reduced from the climate impact so that we could access the potential value of restoration in reducing the impact of climate change on water quality. For example, if the impact of the RCP 4.5 scenario resulted in a 30% increase in sediment exportation in some subbasin, and with restoration, this value went down to -50%, this meant that the efficiency of restoration was -80% ((-50 + (- 30)). This would demonstrate that restoration not only fully offset the initial increase but further reduced sediment exportation to a negative value of -50%. This indicates that the restoration not only completely compensated for the initial increase but continued to reduce the export rate to a negative value of -55.2%. The difference values were divided by the restored area to obtain a weighted measure of the contribution for each defined area that could reflect where such benefits are concentrated. Thus, this priority value reflects how much sediment exportation is avoided per year per hectare restored in all climate scenarios. The more negative the value, the greater the water quality benefit.

The values of sediment exportation per municipality and subbasin were obtained using the "Zonal Statistics" in QGis. The values obtained for all municipalities or subbasins in each scenario were divided into quintiles to establish five priority classes: very high, high, medium, low, and very low, following decreasing in the sediment exported. Each municipality or subbasin was assigned to its priority class in all scenarios and represented in maps using QGis to establish the prioritisation maps. Finally, we produced four prioritisation maps: a map representing the priority areas when climate change is not considered (Baseline); a map considering the climate change under the RCP 4.5 scenario (RCP 4.5); a map for the RCP 8.5 scenario (RCP 8.5); and a map that integrates the priority municipalities or subbasin under all climate change scenarios (Integrated). For the integrated scenario, the intensity values for each area were established based on the average value obtained considering the values of the other three climate scenarios (Baseline, RCP 4.5, and RCP 8.5). The prioritisation values for all municipalities in each scenario can be found in Table 4 in the appendix.

## 2.6. Results

We found that 543,297 ha of native vegetation needs to be restored in the APP of the Doce River basin. This value represents 6.3% of the watershed area and 53.9% of the APP area defined by the NVPL (Table 3). The subbasins that would experience the most significant forest cover increase are Caratinga (55.63%), Manhuaçu (51.15%), and Guandu (47.85%; see Table 5 for all subbasins). These areas are also the ones most degraded, resulting in the largest APP debts.

***Table 3:*** *Comparison of Sediment Exportation Values for Restored Areas. The table illustrates the percentage difference between scenarios for sediment exportation to the Doce River basin within designated areas. The values are calculated based on total production/decrease per subbasin and are expressed in tons per year. Negative numbers indicate a decrease in sediment exportation compared to the baseline scenario, while positive numbers indicate an increase.*

| | | | | | Baseline | Climate Change Impact | | Forested Scenarios | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Sub-basins: | Area (ha) | % of Native Forest Cover for Baseline | % of Restoration Area (ha) | Percentage Variation of Forest Cover | Sediment Exportation (ton/year) | RCP 4.5 | RCP 8.5 | No Climate Change | RCP 4.5 | RCP 8.5 |
| Guandu | 523085,178 | 18,69% | 8,94% | 47,85% | 202827,9457 | -35,96% | -36,78% | -65,23% | -77,76% | -78,05% |
| Piracicaba | 568287,443 | 44,32% | 4,82% | 10,87% | 195945,3521 | 21,08% | 20,83% | -75,29% | -70,20% | -70,32% |
| Piranga | 1757124,075 | 27,59% | 7,96% | 28,85% | 408620,0479 | -0,86% | 5,85% | -67,23% | -67,84% | -65,57% |
| Suaçuí | 2154300,696 | 30,43% | 5,21% | 17,13% | 230763,8512 | -10,65% | -9,02% | -64,13% | -67,91% | -67,36% |
| Santo Antônio | 1076109,423 | 47,22% | 4,79% | 10,15% | 158284,8812 | 33,20% | 31,20% | -66,35% | -55,20% | -56,10% |
| Manhuaçu | 919298,465 | 19,51% | 7,77% | 39,82% | 283221,2671 | -22,10% | -21,65% | -65,85% | -73,46% | -73,29% |
| Caratinga | 669655,912 | 15,03% | 6,62% | 44,06% | 115955,8323 | -14,50% | -12,95% | -65,20% | -70,24% | -69,71% |
| São José | 938873,566 | 21,44% | 5,28% | 24,65% | 120617,0109 | -41,10% | -38,07% | -64,24% | -78,93% | -77,84% |
| **TOTAL** | **8606734,758** | **28,81%** | **6,31%** | **21,91%** | **1716236,188** | **-7,93%** | **-6,03%** | **-66,84%** | **-69,99%** | **-69,37%** |

Restoration under the Baseline scenario resulted in a 56.49% decrease in erosion (8M tons sediment/year) and a 66.84% decrease in sediment exportation (1.1M tons/year) (Table 3). When comparing subbasins, the reduction in erosion ranges from 54.26% to 63.37% (Table 3). In comparison, sediment exportation reduction ranges from 64.13% to 75.29% within the restored areas. The subbasins with the most significant reductions in sediment exportation caused by restoration at the Baseline scenario were Piracicaba, Piranga, and Santo Antônio (Table 3; see Table 6 for all areas in the appendix).

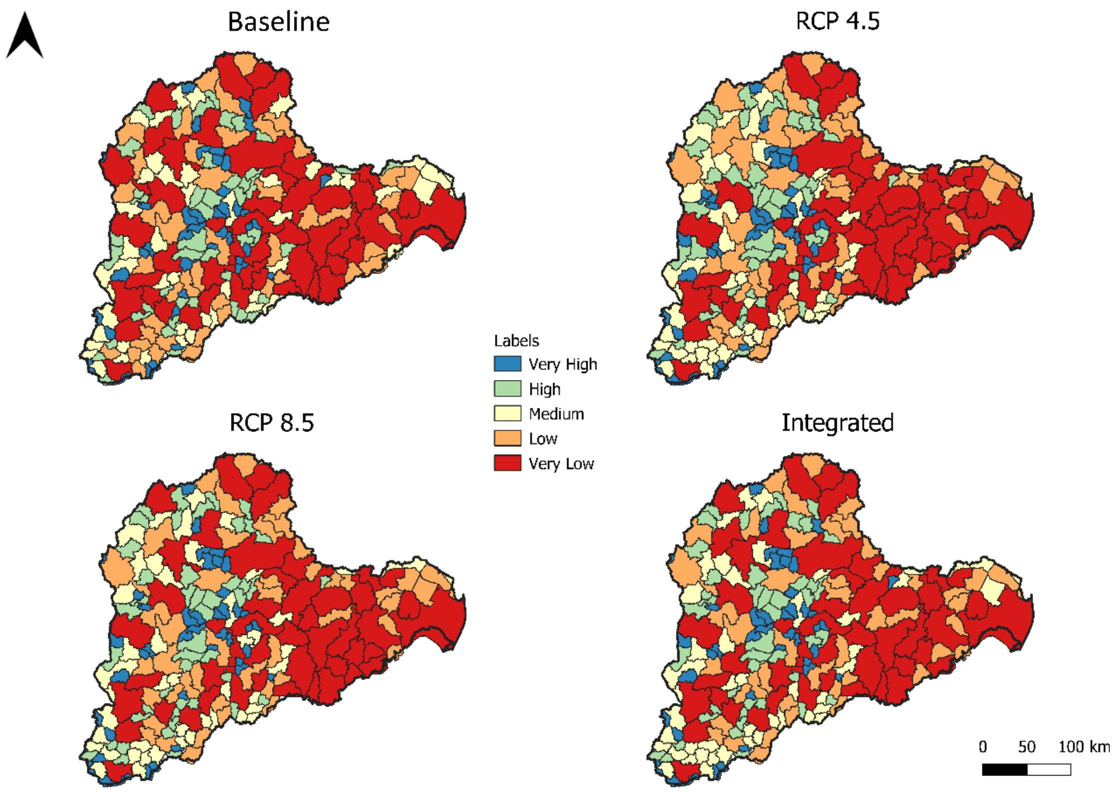
For the mitigation scenario (RCP 4.5), restoration reduced erosion by 61.2% (9.5M tons sediment/year) and total sediment exportation by 69.99% (1.2M tons sediment/year) (Table 3), considering the whole Doce River basin. Concerning subbasins, the erosion reduction rates range from 55.97% to 72.84% (Table 3). For sediment exportation, these values varied from 55.2% to 78.93% (Table 3). São José, Guandu, and Manhuaçu were the subbasins with the greatest restoration impact under the RCP 4.5 climate scenario. Santo Antônio and Piracicaba stand out here, maintaining 25.64% and 14% positive erosion production and 10.74% positive sediment exportation for Santo Antônio even after restoration was implemented (See Table 7 and Table 8 for all areas in the appendix).

In the business-as-usual scenario (RCP 8.5), total erosion in the restored areas was reduced by 60.27% (9.3M tons sediment/year) and total sediment exportation by 69.37% (1.2M tons sediment/year) for the total area. Erosion reduction rates in the subbasins range from 54.60% to 71.97%, while sediment exportation reductions range from 56.1% to 78.05% in the restored areas. The subbasins that demonstrated the most significant restoration impacts were equivalent to those in the mitigation scenario (RCP 4.5). Despite restoration efforts, Santo Antônio and Piracicaba still presented higher erosion rates. Additionally, Piranga exhibits positive increases of 3.49% for erosion and 4.1% for sediment export when restoration scenarios were not considered.

### 2.7. Priority Areas for Restoration

There are 225 municipalities in the Doce River basin, and 152 of them maintained their priority class under all climate conditions: 39 (very high), 27 (high), 23 (medium), 26 (low), and 37 (very low, see Table 9 in the appendix). Under the mitigation scenario (RCP 4.5), 33 municipalities moved up one priority class, while 159 municipalities remained in the same priority class observed in the Baseline scenario. Twenty-five municipalities with a very high priority for restoration were found in the upper Doce, 20 in the medium Doce, and none throughout the lower Doce (Figure 9). Check Figure 10 in the appendix to see the prioritisation for subbasins.

***Figure 9:*** *Maps of Restoration Priority Areas based on the municipalities present in the Rio Doce basin. Maps showing priority restoration areas by the municipality were classified into five prioritisation classes based on quartile percentage variations. Prioritisation is organised according to specific climate scenarios.*




In the business-as-usual scenario (RCP 8.5), the overall changes were similar to the ones observed in the mitigation scenario (Table 9). The number of subbasins changing accordingly is similar in both RCP 4.5 and RCP 8.5 scenarios, but with few municipalities changing their priority class depending on the climate change scenario (Figure 9).

## 2.8. Discussion

Restoration is key to promoting human well-being by recovering critical ecosystem services in degraded areas worldwide. Identifying how climate change can affect the effectiveness of restoration strategies is crucial to ensuring their long-term benefits. However, current efforts often overlook climate analyses. Our results demonstrate that incorporating future climate projections into the analysis alters prioritisation strategies. This shift occurs due to the displacement of climate conditions across the watershed, which can intensify impacts in certain regions and, consequently, change the prioritisation context.

We revealed that restoration was able to reduce erosion and sediment exportation in all climate scenarios, with a higher efficiency in the headwaters. Restoration stood out as having the greatest effects in areas with the highest restoration debts, with higher elevations, and in areas where restoration recovers anthropic land uses, especially associated with mining activity (soil exposure). We argue that the high potential of recovering ecosystem services in these areas may be due to the faster recovery of biophysical attributes within them (SIDLE et al., 2006). Prioritising the restoration of these areas can be crucial for maintaining ecosystem structure and ensuring their high conservation potential, which acts as an important factor for returning landscape attributes more quickly (BRUIJNZEEL, 2004; Li et al., 2017).

As a consequence of climate change, headwater areas are expected to be more negatively impacted by increased rainfall because they are commonly high-slope areas (NEARING et al., 2004; PANAGOS et al., 2022). This makes headwaters more vulnerable to extreme climate events regarding sediment exportation, even though they represent the most conserved areas in the basin (DE VENTE AND POESEN, 2005; MERZDORF, 2024). In the Doce River basin, municipalities in Santo Antônio, Piracicaba, and Piranga subbasin require meticulous consideration to ensure that climate change will not disrupt their ecosystem services provisioning. These results became even more evident when considering the business-as-usual scenario (RCP 8.5), which promoted an expansion of vulnerable regions due to increased rainfall, leading to a larger area being affected. In contrast to the predicted effects of climate change on the Doce River headwaters, a reduction in the average rainfall in the most degraded downstream areas is expected. Consequently, we predicted a reduction in erosion under both mitigation (RCP 4.5) and business-as-usual (RCP 8.5) scenarios. In general, we did not predict great changes between climate change scenarios in the Doce River basin, but this may not be true for other regions and can be context-dependent (STEYERBERG, 2019; ZHANG et al., 2024). For example, precipitation in the United States is expected to vary significantly under the two climate change scenarios. Under RCP 8.5, precipitation is projected to increase by an average of 17% by 2080, with some regions experiencing increases of up to 36%. In contrast, under RCP 4.5, precipitation is projected to decrease by approximately 7% compared to RCP 8.5, with reductions of up to 18% in certain areas. These changes may lead to increased erosion under the RCP 8.5 scenario and lower erosion projections under the RCP 4.5 scenario (FIX et al., 2018).

Our results demonstrated that climatic factors can invert the prioritisation of areas to be restored. Changes in precipitation, for example, can alter local water viability, which can require adjustments in the restoration strategies to deal with such consequences (PETERS-LIDARD et al., 2021). Adding future climate change predictions is crucial for determining the best practices for landscape management and restoration (HARRIS et al., 2006; SÁNCHEZ et al., 2018; SEAVY et al., 2009). We highlight that by including climate change in restoration efforts by using approaches similar to the one used here, it would be possible to establish an adaptive restoration planning, ensuring long-term restoration benefits (SÁNCHEZ et al., 2018; TIMPANE-PADGHAM; BEECHIE; KLINGER, 2017). These are being highlighted as prerequisites for restoration worldwide, including in the Doce River basin (SÁNCHEZ et al., 2018).

In the Doce River basin, the first restoration strategies prioritised the regions most affected by the collapse of the Fundão dam (RENOVA, 2021). Currently, other prioritisation strategies, focusing on the municipalities with the highest environmental debts in APPs and the lower conservation levels, indicate the lower and middle portion of the Doce River basin (UFV and UFMG, 2019; WWF, 2023). However, restoring the most degraded areas may not represent the areas where the greatest ecosystem benefits are concentrated under climate change (ABHILASH, 2021). Considering the many challenges for large-scale restoration, we reinforce that prioritisation strategies should reflect where the greatest benefits can be achieved, such as reduced erosion and increased water regulation, or even where investments will yield the greatest returns in the long term (SÁNCHEZ et al., 2018). Only by considering ecosystem services as a priority in restoration efforts we can balance the return of degraded environment to its self-sufficiency, human needs, and cost-effective measures.

Additionally, although the APP restoration predicted reduced the negative impacts of climate change, it was not sufficient to reduce the high rates of erosion and sediment exportation under all climate conditions, which contined to be higher than the current rates. We reinforce that restoration must be amplified over the legal NVPL aspects to guarantee ecosystem services provisioning in some regions. Specifically, forest restoration in the upper portion of watersheds would be critical to controlling sediment exportation (SAAD et al., 2018, ZHAO et al., 2020). By including those conserved areas in restoration efforts, we can ensure higher resilience for the whole watershed, with perceived benefits (e.g. reduced overland flow and increased sediment retention) in the downstream region (DIB et al., 2023). Strategies like this can be crucial to optimise benefits, minimise costs and prevent unintended consequences for large-scale restoration projects (DIB et al., 2023; ZABIN et al., 2022). Conserved areas also offer a greater variety of opportunities for restoration, including cheaper and ecologically relevant strategies such as natural regeneration (CROUZEILLES et al., 2017; ERICKSON-DAVIS, 2017), which can be especially relevant in the context of climate change (SÁNCHEZ et al., 2018). Failure to comply with legal restoration efforts, combined with a rising deforestation rate, could result in dire consequences for water-related ecosystem services provisioning (CORDON, 2020; RAJ et al., 2022).

However, it is important to note we used restoration scenarios that often do not consider potentially restorable areas despite being outlined in legal instruments. This should be taken into account when interpreting the results. Additionally, we adopted a 10 m scale, which should be considered when applying this protocol to other areas, as this resolution better captures the local context for implementing riparian fragments. We also emphasize the need to incorporate sensitivity analyses into the responses of the climate model used (HadGEM2_ES) to reduce uncertainties related to the climate variability predicted across models (SEAVY et al., 2009; TIMPANE-PADGHAM; BEECHIE; KLINGER, 2017). Furthermore, we highlight that the best available data were used to construct our modeling approach. Models represent a partial view of reality (GIERE, 2004), and although we used the most reliable data available to understand the complex and dynamic interplay of climate change, restoration, and ecosystem services in the context of the Doce River basin, it is important to develop new data to improve the analytical capacity of the models worldwide and to improve the evaluation of climate impacts over the future (HARRIS et al., 2006). It is important, for example, that variables that measure the contribution of forests at different stages of succession, especially in restoration contexts, are evaluated and incorporated into the models (ZABIN et al., 2022), as well as the functional diversity of restoring species. This would make it possible to predict the results for sediment exportation more accurately in different management, restoration, or ecological succession scenarios. After all, the value of a well-preserved forest is different from that of a forest undergoing natural regeneration (CROUZEILLES et al., 2017), highlighting the need for different approaches in the models. We consider these initiatives essential for the application of this protocol in other areas and for its integration into political and municipal decision-making strategies regarding the restoration efforts being established.

By considering climate change and the provision of ecosystem services in restoration strategies, it is possible to ensure the best results in the long term (BUSTAMANTE et al., 2019; SÁNCHEZ et al., 2018). We conclude that climate change is a key aspect in defining the long-term benefits of restoration, and prioritisation efforts need to incorporate these criteria to enable and enhance the ongoing actions (Sánchez et al., 2018). We provided a replicable protocol that could be applied to other regions to establish adaptive restoration strategies worldwide, but reinforce that it can be strongly dependent on the climate change predicted for each region. In addition, multi-criteria strategies can help to reach the greatest benefits and common returns when thinking about better restoration prioritisation protocols. Rethinking strategies that help build more efficient solutions has become an ever greater priority in dealing with climate change in time to protect people and nature.

## 2.9. Conclusion:

The most conserved areas play a fundamental role in the context of restoration, as they represent regions where the greatest concentration of benefits is found, facilitating the recovery of the landscape's biophysical attributes. Incorporating these areas into restoration strategies can favour the more effective recovery of ecosystem services, especially in a climate change scenario. Therefore, ensuring that these areas are integrated into ecological restoration planning represents a strategic direction to maximise environmental and social benefits.

In addition, including climate change in restoration planning can determine where efforts should be prioritised to ensure the best results. This approach makes it possible to structure more effective mitigation and adaptation strategies, contributing to the containment of climate impacts and being able to promote the targeting of efforts where the greatest benefits can be achieved in the long term. In the context of the Doce River basin, climate change could reverse the maintenance of ecosystem services in some regions, making them critical warning points, as is the case observed in the Santo Antônio subbasin. Identifying these areas is essential in order to anticipate impacts and promote preventive actions that guarantee the continuity of ecosystem services that are essential for environmental balance and human well-being. Santo Antônio is a significant region where this impact is occurring, but it is important that these same risks are identified for other global regions.

In the face of the challenges posed by climate change, it is clear that incorporating climate variables into restoration approaches changes the context for prioritising areas, since they displace resources and amplify impacts on certain regions. This scenario requires a strategic approach that considers the dynamics of ecosystem services and their response to future climate conditions.

Finally, we emphasise the importance of replicating this protocol to other regions, allowing for the development of adaptive restoration strategies aligned with climate change. This initiative will ensure that ecological restoration actions are effective in the long term, promoting the sustainability and maintenance of ecosystems in the face of emerging climate challenges.

## GENERAL CONCLUSION

Ecological restoration is a powerful tool for tackling environmental degradation and climate change, but its effectiveness depends on the ability to integrate climate projections and more adaptive strategies. As demonstrated in Chapter 1, the scientific literature still lacks empirical studies that assess the direct impacts of climate change on restoration outcomes, especially in the Global South. In addition, most research focuses on climate regulation, leaving aside other equally important ecosystem services such as pollination, air quality, and especially services that take into account important social and cultural connections with nature such as learning and inspiration.

Chapter 2 demonstrates the importance of considering climate change in restoration planning as key to define the best cost-benefit strategy. By using Rio Doce basin, we show how prioritization areas can be modified when climate change is considered, highlighting the relevance of integrating climate factors for effective restoration planning and implementation. Another crucial point addressed is the need to explore potential benefits of restoring less degraded areas, since these areas can play a fundamental role in providing key ecosystem services.

Finally, ecological restoration must evolve into a more adaptive and comprehensive process, incorporating climate projections, the diversity of ecosystem contexts, and proactive strategies. Global collaboration and the development of replicable protocols, such as the one presented in Chapter 2, are essential to maximize the benefits of restoration, including evaluations and analysis at larger scales and ensuring ecosystem resilience in face of climate uncertainties. By prioritizing the integration of climate-informed approaches, restoration can become an effective solution to the environmental and socioeconomic challenges of the Anthropocene, contributing to long-term ecological sustainability and human well-being.

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## **APPENDIX -** Supplementary Material

***Table 2:*** *Biophysical table presenting descriptions, values, and references for cover-management (c-factor) and support practice (p-factor) factors used in the Universal Soil Loss Equation (USLE). These values range from 0 to 1. A smaller c-factor (close to 0) suggests that the land use and land cover type contribute less to erosion, while a p-factor value close to 1 indicates the absence of erosion-reduction practices. In our study, we assigned a value of 1 to all the p-factors, as we did not find any information about erosion-reduction practices for the study region in the available literature.*

| LULC | lucode | usle_c | REF_usle_c | usle_p | REF_usle_p |
|---|---|---|---|---|---|
| Atlantic Forest | 3 | 0.012 | Silva 2009; Martins et al. 2010 | 1 | Borges & Almeida 2019 |
| Cerrado | 4 | 0.013 | Oliveira et al. 2015; Silva 2009 | 1 | Borges & Almeida 2019 |
| Mangrove | 5 | 0.01 | Duarte et al. 2016 | 1 | Borges & Almeida 2019 |
| Silviculture | 9 | 0.016 | Silva 2009 | 1 | Borges & Almeida 2019 |
| Wetland | 11 | 0.01 | Duarte et al. 2016 | 1 | Borges & Almeida 2019 |
| Pasture | 15 | 0.052 | Silva 2009 | 1 | Borges & Almeida 2019 |
| Temporary Cropland (Sugarcane) | 19 | 0.29 | Ruhoff 2006 | 1 | Borges & Almeida 2019 |
| Mosaic of Uses (Pasture and agriculture) | 21 | 0.052 | Silva 2009 | 1 | Borges & Almeida 2019 |
| Sand | 23 | 0.1 | Ribeiro & Alves 2007 (reajusted by the author) | 1 | Borges & Almeida 2019 |
| Urban Area | 24 | 0.0001 | Ribeiro & Alves 2007 | 1 | Borges & Almeida 2019 |
| Non-vegetated Area | 25 | 0.0042 | Hoffmann Oliveira 2020 | 1 | Borges & Almeida 2019 |
| Rock Outcrop | 29 | 0.0001 | Ribeiro & Alves 2007 | 1 | Borges & Almeida 2019 |
| Mining | 30 | 1 | Silva 2004 | 1 | Borges & Almeida 2019 |
| Water | 33 | 0.01 | Duarte et al. 2016 | 1 | Borges & Almeida 2019 |
| Perennial Cropland (Coffee) | 36 | 0.25 | Bertoni & Lombardi 1983 | 1 | Borges & Almeida 2019 |
| Forested Sandbank | 49 | 0.013 | Silva 2009 | 1 | Borges & Almeida 2019 |
| Herbaceous Sandbank | 50 | 0.013 | Silva 2009 | 1 | Borges & Almeida 2019 |

***Table 4:*** *Table of municipalities prioritization for each scenario. The table displays the prioritisation levels for each scenario. Municipalities with a prioritisation intensity of 5 belong to the "very high" category.*

| Baseline | | | RCP 4.5 | | | RCP 8.5 | | | Integrated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **NM_MUN** | **UF** | **Priority** | **NM_MUN** | **UF** | **Priority** | **NM_MUN** | **UF** | **Priority** | **NM_MUN** | **UF** | **Priority** |
| Abre Campo | MG | Very Low | Abre Campo | MG | Very Low | Abre Campo | MG | Very Low | Abre Campo | MG | Very Low |
| Acaiaca | MG | High | Acaiaca | MG | High | Acaiaca | MG | High | Acaiaca | MG | High |
| Açucena | MG | Low | Açucena | MG | Low | Açucena | MG | Low | Açucena | MG | Low |
| Afonso Cláudio | ES | Very Low | Afonso Cláudio | ES | Very Low | Afonso Cláudio | ES | Very Low | Afonso Cláudio | ES | Very Low |
| Água Boa | MG | Very Low | Água Boa | MG | Very Low | Água Boa | MG | Very Low | Água Boa | MG | Very Low |
| Águia Branca | ES | Very Low | Águia Branca | ES | Very Low | Águia Branca | ES | Very Low | Águia Branca | ES | Very Low |
| Aimorés | MG | Very Low | Aimorés | MG | Very Low | Aimorés | MG | Very Low | Aimorés | MG | Very Low |
| Alpercata | MG | High | Alpercata | MG | Medium | Alpercata | MG | Medium | Alpercata | MG | Medium |
| Alto Jequitibá | MG | High | Alto Jequitibá | MG | Medium | Alto Jequitibá | MG | Medium | Alto Jequitibá | MG | Medium |
| Alto Rio Doce | MG | Very Low | Alto Rio Doce | MG | Very Low | Alto Rio Doce | MG | Very Low | Alto Rio Doce | MG | Very Low |
| Alto Rio Novo | ES | Medium | Alto Rio Novo | ES | Low | Alto Rio Novo | ES | Low | Alto Rio Novo | ES | Low |
| Alvarenga | MG | Medium | Alvarenga | MG | Medium | Alvarenga | MG | Medium | Alvarenga | MG | Medium |
| Alvinópolis | MG | Very Low | Alvinópolis | MG | Very Low | Alvinópolis | MG | Very Low | Alvinópolis | MG | Very Low |
| Alvorada de Minas | MG | High | Alvorada de Minas | MG | High | Alvorada de Minas | MG | High | Alvorada de Minas | MG | High |
| Amparo do Serra | MG | High | Amparo do Serra | MG | High | Amparo do Serra | MG | High | Amparo do Serra | MG | High |
| Antônio Dias | MG | Low | Antônio Dias | MG | Low | Antônio Dias | MG | Low | Antônio Dias | MG | Low |
| Araponga | MG | Low | Araponga | MG | Low | Araponga | MG | Low | Araponga | MG | Low |
| Baixo Guandu | ES | Very Low | Baixo Guandu | ES | Very Low | Baixo Guandu | ES | Very Low | Baixo Guandu | ES | Very Low |
| Barão de Cocais | MG | High | Barão de Cocais | MG | High | Barão de Cocais | MG | High | Barão de Cocais | MG | High |
| Barra Longa | MG | Very Low | Barra Longa | MG | Very Low | Barra Longa | MG | Low | Barra Longa | MG | Very Low |
| Bela Vista de Minas | MG | Very High | Bela Vista de Minas | MG | Very High | Bela Vista de Minas | MG | Very High | Bela Vista de Minas | MG | Very High |
| Belo Oriente | MG | High | Belo Oriente | MG | High | Belo Oriente | MG | High | Belo Oriente | MG | High |
| Bom Jesus do Amparo | MG | High | Bom Jesus do Amparo | MG | Very High | Bom Jesus do Amparo | MG | Very High | Bom Jesus do Amparo | MG | Very High |
| Bom Jesus do Galho | MG | Low | Bom Jesus do Galho | MG | Low | Bom Jesus do Galho | MG | Low | Bom Jesus do Galho | MG | Low |

| Baseline | | | RCP 4.5 | | | RCP 8.5 | | | Integrated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| NM_MUN | UF | Priority | NM_MUN | UF | Priority | NM_MUN | UF | Priority | NM_MUN | UF | Priority |
| Brás Pires | MG | Low | Brás Pires | MG | Medium | Brás Pires | MG | Medium | Brás Pires | MG | Medium |
| Braúnas | MG | Medium | Braúnas | MG | High | Braúnas | MG | High | Braúnas | MG | High |
| Brejetuba | ES | Very Low | Brejetuba | ES | Very Low | Brejetuba | ES | Very Low | Brejetuba | ES | Very Low |
| Bugre | MG | Very High | Bugre | MG | Very High | Bugre | MG | Very High | Bugre | MG | Very High |
| Cajuri | MG | Very High | Cajuri | MG | Very High | Cajuri | MG | Very High | Cajuri | MG | Very High |
| Campanário | MG | Medium | Campanário | MG | Low | Campanário | MG | Low | Campanário | MG | Low |
| Canaã | MG | Medium | Canaã | MG | Medium | Canaã | MG | Medium | Canaã | MG | Medium |
| Cantagalo | MG | Very High | Cantagalo | MG | Very High | Cantagalo | MG | Very High | Cantagalo | MG | Very High |
| Capela Nova | MG | High | Capela Nova | MG | Very High | Capela Nova | MG | Very High | Capela Nova | MG | High |
| Capitão Andrade | MG | Medium | Capitão Andrade | MG | Low | Capitão Andrade | MG | Low | Capitão Andrade | MG | Low |
| Caputira | MG | Medium | Caputira | MG | Medium | Caputira | MG | Medium | Caputira | MG | Medium |
| Caranaíba | MG | Medium | Caranaíba | MG | High | Caranaíba | MG | High | Caranaíba | MG | High |
| Carandaí | MG | Very High | Carandaí | MG | Very High | Carandaí | MG | Very High | Carandaí | MG | Very High |
| Caratinga | MG | Very Low | Caratinga | MG | Very Low | Caratinga | MG | Very Low | Caratinga | MG | Very Low |
| Carmésia | MG | Medium | Carmésia | MG | High | Carmésia | MG | High | Carmésia | MG | High |
| Catas Altas | MG | Very High | Catas Altas | MG | Very High | Catas Altas | MG | Very High | Catas Altas | MG | Very High |
| Catas Altas da Noruega | MG | Very High | Catas Altas da Noruega | MG | Very High | Catas Altas da Noruega | MG | Very High | Catas Altas da Noruega | MG | Very High |
| Chalé | MG | Low | Chalé | MG | Low | Chalé | MG | Low | Chalé | MG | Low |
| Cipotânea | MG | Medium | Cipotânea | MG | Medium | Cipotânea | MG | High | Cipotânea | MG | Medium |
| Coimbra | MG | High | Coimbra | MG | High | Coimbra | MG | High | Coimbra | MG | High |
| Colatina | ES | Very Low | Colatina | ES | Very Low | Colatina | ES | Very Low | Colatina | ES | Very Low |
| Coluna | MG | Medium | Coluna | MG | High | Coluna | MG | High | Coluna | MG | Medium |
| Conceição de Ipanema | MG | Medium | Conceição de Ipanema | MG | Medium | Conceição de Ipanema | MG | Medium | Conceição de Ipanema | MG | Medium |
| Conceição do Mato Dentro | MG | Very Low | Conceição do Mato Dentro | MG | Low | Conceição do Mato Dentro | MG | Low | Conceição do Mato Dentro | MG | Low |
| Congonhas do Norte | MG | Very High | Congonhas do Norte | MG | Very High | Congonhas do Norte | MG | Very High | Congonhas do Norte | MG | Very High |

| Baseline | | | RCP 4.5 | | | RCP 8.5 | | | Integrated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **NM_MUN** | **UF** | **Priority** | **NM_MUN** | **UF** | **Priority** | **NM_MUN** | **UF** | **Priority** | **NM_MUN** | **UF** | **Priority** |
| Conselheiro Lafaiete | MG | Very High | Conselheiro Lafaiete | MG | Very High | Conselheiro Lafaiete | MG | Very High | Conselheiro Lafaiete | MG | Very High |
| Conselheiro Pena | MG | Very Low | Conselheiro Pena | MG | Very Low | Conselheiro Pena | MG | Very Low | Conselheiro Pena | MG | Very Low |
| Coroaci | MG | Low | Coroaci | MG | Low | Coroaci | MG | Low | Coroaci | MG | Low |
| Coronel Fabriciano | MG | Very High | Coronel Fabriciano | MG | Very High | Coronel Fabriciano | MG | Very High | Coronel Fabriciano | MG | Very High |
| Córrego Novo | MG | High | Córrego Novo | MG | High | Córrego Novo | MG | High | Córrego Novo | MG | High |
| Cristiano Otoni | MG | Very High | Cristiano Otoni | MG | Very High | Cristiano Otoni | MG | Very High | Cristiano Otoni | MG | Very High |
| Cuparaque | MG | Medium | Cuparaque | MG | Low | Cuparaque | MG | Low | Cuparaque | MG | Medium |
| Desterro do Melo | MG | High | Desterro do Melo | MG | Very High | Desterro do Melo | MG | Very High | Desterro do Melo | MG | Very High |
| Diogo de Vasconcelos | MG | High | Diogo de Vasconcelos | MG | High | Diogo de Vasconcelos | MG | High | Diogo de Vasconcelos | MG | High |
| Dionísio | MG | High | Dionísio | MG | High | Dionísio | MG | High | Dionísio | MG | High |
| Divinésia | MG | Very High | Divinésia | MG | Very High | Divinésia | MG | Very High | Divinésia | MG | Very High |
| Divino das Laranjeiras | MG | Low | Divino das Laranjeiras | MG | Low | Divino das Laranjeiras | MG | Low | Divino das Laranjeiras | MG | Low |
| Divinolândia de Minas | MG | Very High | Divinolândia de Minas | MG | Very High | Divinolândia de Minas | MG | Very High | Divinolândia de Minas | MG | Very High |
| Dom Cavati | MG | Very High | Dom Cavati | MG | Very High | Dom Cavati | MG | Very High | Dom Cavati | MG | Very High |
| Dom Joaquim | MG | Low | Dom Joaquim | MG | Medium | Dom Joaquim | MG | Medium | Dom Joaquim | MG | Medium |
| Dom Silvério | MG | Medium | Dom Silvério | MG | Medium | Dom Silvério | MG | Medium | Dom Silvério | MG | Medium |
| Dores de Guanhães | MG | Medium | Dores de Guanhães | MG | High | Dores de Guanhães | MG | Medium | Dores de Guanhães | MG | Medium |
| Dores do Turvo | MG | Low | Dores do Turvo | MG | Medium | Dores do Turvo | MG | Medium | Dores do Turvo | MG | Medium |
| Durandé | MG | Low | Durandé | MG | Low | Durandé | MG | Low | Durandé | MG | Low |
| Engenheiro Caldas | MG | High | Engenheiro Caldas | MG | Medium | Engenheiro Caldas | MG | High | Engenheiro Caldas | MG | High |

| Baseline | | | RCP 4.5 | | | RCP 8.5 | | | Integrated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **NM_MUN** | **UF** | **Priority** | **NM_MUN** | **UF** | **Priority** | **NM_MUN** | **UF** | **Priority** | **NM_MUN** | **UF** | **Priority** |
| Entre Folhas | MG | Very High | Entre Folhas | MG | Very High | Entre Folhas | MG | Very High | Entre Folhas | MG | Very High |
| Ervália | MG | Low | Ervália | MG | Low | Ervália | MG | Low | Ervália | MG | Low |
| Fernandes Tourinho | MG | High | Fernandes Tourinho | MG | High | Fernandes Tourinho | MG | High | Fernandes Tourinho | MG | High |
| Ferros | MG | Very Low | Ferros | MG | Very Low | Ferros | MG | Very Low | Ferros | MG | Very Low |
| Franciscópolis | MG | Very Low | Franciscópolis | MG | Very Low | Franciscópolis | MG | Very Low | Franciscópolis | MG | Very Low |
| Frei Inocêncio | MG | Low | Frei Inocêncio | MG | Low | Frei Inocêncio | MG | Low | Frei Inocêncio | MG | Low |
| Frei Lagonegro | MG | Very High | Frei Lagonegro | MG | Very High | Frei Lagonegro | MG | Very High | Frei Lagonegro | MG | Very High |
| Galiléia | MG | Very Low | Galiléia | MG | Very Low | Galiléia | MG | Very Low | Galiléia | MG | Very Low |
| Goiabeira | MG | Very High | Goiabeira | MG | High | Goiabeira | MG | High | Goiabeira | MG | Very High |
| Gonzaga | MG | High | Gonzaga | MG | Very High | Gonzaga | MG | Very High | Gonzaga | MG | Very High |
| Governador Lindenberg | ES | Low | Governador Lindenberg | ES | Very Low | Governador Lindenberg | ES | Low | Governador Lindenberg | ES | Low |
| Governador Valadares | MG | Very Low | Governador Valadares | MG | Very Low | Governador Valadares | MG | Very Low | Governador Valadares | MG | Very Low |
| Guanhães | MG | Very Low | Guanhães | MG | Low | Guanhães | MG | Very Low | Guanhães | MG | Very Low |
| Guaraciaba | MG | Low | Guaraciaba | MG | Low | Guaraciaba | MG | Low | Guaraciaba | MG | Low |
| Iapu | MG | Medium | Iapu | MG | Medium | Iapu | MG | Medium | Iapu | MG | Medium |
| Imbé de Minas | MG | High | Imbé de Minas | MG | High | Imbé de Minas | MG | Medium | Imbé de Minas | MG | High |
| Inhapim | MG | Very Low | Inhapim | MG | Very Low | Inhapim | MG | Very Low | Inhapim | MG | Very Low |
| Ipaba | MG | Very High | Ipaba | MG | Very High | Ipaba | MG | Very High | Ipaba | MG | Very High |
| Ipanema | MG | Low | Ipanema | MG | Low | Ipanema | MG | Low | Ipanema | MG | Low |
| Ipatinga | MG | Very High | Ipatinga | MG | Very High | Ipatinga | MG | Very High | Ipatinga | MG | Very High |
| Itabira | MG | Very Low | Itabira | MG | Very Low | Itabira | MG | Very Low | Itabira | MG | Very Low |
| Itaguaçu | ES | Very Low | Itaguaçu | ES | Very Low | Itaguaçu | ES | Very Low | Itaguaçu | ES | Very Low |
| Itambacuri | MG | Very Low | Itambacuri | MG | Very Low | Itambacuri | MG | Very Low | Itambacuri | MG | Very Low |
| Itambé do Mato Dentro | MG | Medium | Itambé do Mato Dentro | MG | High | Itambé do Mato Dentro | MG | High | Itambé do Mato Dentro | MG | High |
| Itanhomi | MG | Low | Itanhomi | MG | Low | Itanhomi | MG | Low | Itanhomi | MG | Low |

| Baseline | | | RCP 4.5 | | | RCP 8.5 | | | Integrated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **NM_MUN** | **UF** | **Priority** | **NM_MUN** | **UF** | **Priority** | **NM_MUN** | **UF** | **Priority** | **NM_MUN** | **UF** | **Priority** |
| Itarana | ES | Low | Itarana | ES | Low | Itarana | ES | Very Low | Itarana | ES | Low |
| Itaverava | MG | Medium | Itaverava | MG | Medium | Itaverava | MG | Medium | Itaverava | MG | Medium |
| Itueta | MG | Low | Itueta | MG | Very Low | Itueta | MG | Low | Itueta | MG | Low |
| Iúna | ES | Medium | Iúna | ES | Low | Iúna | ES | Low | Iúna | ES | Low |
| Jaguaraçu | MG | Very High | Jaguaraçu | MG | Very High | Jaguaraçu | MG | Very High | Jaguaraçu | MG | Very High |
| Jaguaré | ES | Medium | Jaguaré | ES | Low | Jaguaré | ES | Low | Jaguaré | ES | Low |
| Jampruca | MG | Low | Jampruca | MG | Low | Jampruca | MG | Low | Jampruca | MG | Low |
| Jequeri | MG | Very Low | Jequeri | MG | Very Low | Jequeri | MG | Very Low | Jequeri | MG | Very Low |
| Joanésia | MG | Medium | Joanésia | MG | High | Joanésia | MG | High | Joanésia | MG | High |
| João Monlevade | MG | Very High | João Monlevade | MG | Very High | João Monlevade | MG | Very High | João Monlevade | MG | Very High |
| João Neiva | ES | Medium | João Neiva | ES | Low | João Neiva | ES | Low | João Neiva | ES | Low |
| José Raydan | MG | High | José Raydan | MG | High | José Raydan | MG | High | José Raydan | MG | High |
| Lajinha | MG | Very Low | Lajinha | MG | Very Low | Lajinha | MG | Very Low | Lajinha | MG | Very Low |
| Lamim | MG | High | Lamim | MG | High | Lamim | MG | High | Lamim | MG | High |
| Laranja da Terra | ES | Very Low | Laranja da Terra | ES | Very Low | Laranja da Terra | ES | Very Low | Laranja da Terra | ES | Very Low |
| Linhares | ES | Very Low | Linhares | ES | Very Low | Linhares | ES | Very Low | Linhares | ES | Very Low |
| Luisburgo | MG | High | Luisburgo | MG | Medium | Luisburgo | MG | Medium | Luisburgo | MG | Medium |
| Malacacheta | MG | Low | Malacacheta | MG | Low | Malacacheta | MG | Low | Malacacheta | MG | Low |
| Manhuaçu | MG | Very Low | Manhuaçu | MG | Very Low | Manhuaçu | MG | Very Low | Manhuaçu | MG | Very Low |
| Manhumirim | MG | Medium | Manhumirim | MG | Medium | Manhumirim | MG | Medium | Manhumirim | MG | Medium |
| Mantenópolis | ES | High | Mantenópolis | ES | Medium | Mantenópolis | ES | Medium | Mantenópolis | ES | Medium |
| Mariana | MG | Very Low | Mariana | MG | Very Low | Mariana | MG | Very Low | Mariana | MG | Very Low |
| Marilac | MG | Very High | Marilac | MG | High | Marilac | MG | High | Marilac | MG | Very High |
| Marilândia | ES | Low | Marilândia | ES | Low | Marilândia | ES | Low | Marilândia | ES | Low |
| Marliéria | MG | High | Marliéria | MG | High | Marliéria | MG | High | Marliéria | MG | High |
| Martins Soares | MG | High | Martins Soares | MG | High | Martins Soares | MG | High | Martins Soares | MG | High |
| Materlândia | MG | Medium | Materlândia | MG | Medium | Materlândia | MG | Medium | Materlândia | MG | Medium |

| Baseline | | | RCP 4.5 | | | RCP 8.5 | | | Integrated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| NM_MUN | UF | Priority | NM_MUN | UF | Priority | NM_MUN | UF | Priority | NM_MUN | UF | Priority |
| Mathias Lobato | MG | High | Mathias Lobato | MG | High | Mathias Lobato | MG | High | Mathias Lobato | MG | High |
| Matipó | MG | Low | Matipó | MG | Low | Matipó | MG | Low | Matipó | MG | Low |
| Mercês | MG | Very High | Mercês | MG | Very High | Mercês | MG | Very High | Mercês | MG | Very High |
| Mesquita | MG | High | Mesquita | MG | High | Mesquita | MG | High | Mesquita | MG | High |
| Morro do Pilar | MG | Low | Morro do Pilar | MG | Medium | Morro do Pilar | MG | Medium | Morro do Pilar | MG | Medium |
| Mutum | MG | Very Low | Mutum | MG | Very Low | Mutum | MG | Very Low | Mutum | MG | Very Low |
| Nacip Raydan | MG | High | Nacip Raydan | MG | High | Nacip Raydan | MG | High | Nacip Raydan | MG | High |
| Naque | MG | Very High | Naque | MG | Very High | Naque | MG | Very High | Naque | MG | Very High |
| Nova Era | MG | Medium | Nova Era | MG | Medium | Nova Era | MG | Medium | Nova Era | MG | Medium |
| Nova Venécia | ES | High | Nova Venécia | ES | Medium | Nova Venécia | ES | Medium | Nova Venécia | ES | Medium |
| Oratórios | MG | Very High | Oratórios | MG | High | Oratórios | MG | High | Oratórios | MG | High |
| Ouro Branco | MG | Very High | Ouro Branco | MG | Very High | Ouro Branco | MG | Very High | Ouro Branco | MG | Very High |
| Ouro Preto | MG | Medium | Ouro Preto | MG | Medium | Ouro Preto | MG | Medium | Ouro Preto | MG | Medium |
| Pancas | ES | Very Low | Pancas | ES | Very Low | Pancas | ES | Very Low | Pancas | ES | Very Low |
| Passabém | MG | Very High | Passabém | MG | Very High | Passabém | MG | Very High | Passabém | MG | Very High |
| Paula Cândido | MG | Low | Paula Cândido | MG | Medium | Paula Cândido | MG | Medium | Paula Cândido | MG | Medium |
| Paulistas | MG | High | Paulistas | MG | High | Paulistas | MG | High | Paulistas | MG | High |
| Peçanha | MG | Very Low | Peçanha | MG | Low | Peçanha | MG | Very Low | Peçanha | MG | Very Low |
| Pedra Bonita | MG | Medium | Pedra Bonita | MG | Medium | Pedra Bonita | MG | Medium | Pedra Bonita | MG | Medium |
| Pedra do Anta | MG | Medium | Pedra do Anta | MG | Medium | Pedra do Anta | MG | Medium | Pedra do Anta | MG | Medium |
| Periquito | MG | High | Periquito | MG | High | Periquito | MG | High | Periquito | MG | High |
| Piedade de Caratinga | MG | Very High | Piedade de Caratinga | MG | Very High | Piedade de Caratinga | MG | Very High | Piedade de Caratinga | MG | Very High |
| Piedade de Ponte Nova | MG | Very High | Piedade de Ponte Nova | MG | High | Piedade de Ponte Nova | MG | Very High | Piedade de Ponte Nova | MG | Very High |
| Pingo-d'Água | MG | Very High | Pingo-d'Água | MG | Very High | Pingo-d'Água | MG | Very High | Pingo-d'Água | MG | Very High |
| Piranga | MG | Very Low | Piranga | MG | Very Low | Piranga | MG | Very Low | Piranga | MG | Very Low |
| Pocrane | MG | Very Low | Pocrane | MG | Very Low | Pocrane | MG | Very Low | Pocrane | MG | Very Low |
| Ponte Nova | MG | Very Low | Ponte Nova | MG | Very Low | Ponte Nova | MG | Very Low | Ponte Nova | MG | Very Low |
| Porto Firme | MG | Low | Porto Firme | MG | Low | Porto Firme | MG | Low | Porto Firme | MG | Low |

| Baseline | | | RCP 4.5 | | | RCP 8.5 | | | Integrated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| NM_MUN | UF | Priority | NM_MUN | UF | Priority | NM_MUN | UF | Priority | NM_MUN | UF | Priority |
| Presidente Bernardes | MG | Low | Presidente Bernardes | MG | Medium | Presidente Bernardes | MG | Medium | Presidente Bernardes | MG | Medium |
| Raul Soares | MG | Very Low | Raul Soares | MG | Very Low | Raul Soares | MG | Very Low | Raul Soares | MG | Very Low |
| Reduto | MG | Medium | Reduto | MG | Medium | Reduto | MG | Medium | Reduto | MG | Medium |
| Resplendor | MG | Very Low | Resplendor | MG | Very Low | Resplendor | MG | Very Low | Resplendor | MG | Very Low |
| Ressaquinha | MG | Very High | Ressaquinha | MG | Very High | Ressaquinha | MG | Very High | Ressaquinha | MG | Very High |
| Rio Bananal | ES | Very Low | Rio Bananal | ES | Very Low | Rio Bananal | ES | Very Low | Rio Bananal | ES | Very Low |
| Rio Casca | MG | Low | Rio Casca | MG | Low | Rio Casca | MG | Low | Rio Casca | MG | Low |
| Rio Doce | MG | High | Rio Doce | MG | High | Rio Doce | MG | High | Rio Doce | MG | High |
| Rio Espera | MG | Low | Rio Espera | MG | Medium | Rio Espera | MG | Medium | Rio Espera | MG | Medium |
| Rio Piracicaba | MG | Low | Rio Piracicaba | MG | Low | Rio Piracicaba | MG | Low | Rio Piracicaba | MG | Low |
| Rio Vermelho | MG | Very Low | Rio Vermelho | MG | Low | Rio Vermelho | MG | Very Low | Rio Vermelho | MG | Very Low |
| Sabinópolis | MG | Very Low | Sabinópolis | MG | Low | Sabinópolis | MG | Low | Sabinópolis | MG | Very Low |
| Santa Bárbara | MG | Medium | Santa Bárbara | MG | Medium | Santa Bárbara | MG | Medium | Santa Bárbara | MG | Medium |
| Santa Bárbara do Leste | MG | Very High | Santa Bárbara do Leste | MG | Very High | Santa Bárbara do Leste | MG | Very High | Santa Bárbara do Leste | MG | Very High |
| Santa Cruz do Escalvado | MG | Low | Santa Cruz do Escalvado | MG | Low | Santa Cruz do Escalvado | MG | Low | Santa Cruz do Escalvado | MG | Low |
| Santa Efigênia de Minas | MG | Very High | Santa Efigênia de Minas | MG | Very High | Santa Efigênia de Minas | MG | Very High | Santa Efigênia de Minas | MG | Very High |
| Santa Margarida | MG | Low | Santa Margarida | MG | Low | Santa Margarida | MG | Low | Santa Margarida | MG | Low |
| Santa Maria de Itabira | MG | Low | Santa Maria de Itabira | MG | Medium | Santa Maria de Itabira | MG | Low | Santa Maria de Itabira | MG | Low |
| Santa Maria do Suaçuí | MG | Low | Santa Maria do Suaçuí | MG | Low | Santa Maria do Suaçuí | MG | Low | Santa Maria do Suaçuí | MG | Low |
| Santa Rita de Minas | MG | Very High | Santa Rita de Minas | MG | Very High | Santa Rita de Minas | MG | Very High | Santa Rita de Minas | MG | Very High |
| Santa Rita do Itueto | MG | Low | Santa Rita do Itueto | MG | Very Low | Santa Rita do Itueto | MG | Very Low | Santa Rita do Itueto | MG | Low |
| Santa Teresa | ES | Low | Santa Teresa | ES | Very Low | Santa Teresa | ES | Very Low | Santa Teresa | ES | Very Low |

| Baseline | | | RCP 4.5 | | | RCP 8.5 | | | Integrated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| NM_MUN | UF | Priority | NM_MUN | UF | Priority | NM_MUN | UF | Priority | NM_MUN | UF | Priority |
| Santana do Manhuaçu | MG | Very Low | Santana do Manhuaçu | MG | Very Low | Santana do Manhuaçu | MG | Very Low | Santana do Manhuaçu | MG | Very Low |
| Santana do Paraíso | MG | High | Santana do Paraíso | MG | High | Santana do Paraíso | MG | High | Santana do Paraíso | MG | High |
| Santana dos Montes | MG | Medium | Santana dos Montes | MG | Medium | Santana dos Montes | MG | Medium | Santana dos Montes | MG | Medium |
| Santo Antônio do Grama | MG | High | Santo Antônio do Grama | MG | High | Santo Antônio do Grama | MG | High | Santo Antônio do Grama | MG | High |
| Santo Antônio do Itambé | MG | Medium | Santo Antônio do Itambé | MG | High | Santo Antônio do Itambé | MG | High | Santo Antônio do Itambé | MG | High |
| Santo Antônio do Rio Abaixo | MG | High | Santo Antônio do Rio Abaixo | MG | Very High | Santo Antônio do Rio Abaixo | MG | Very High | Santo Antônio do Rio Abaixo | MG | High |
| São Domingos das Dores | MG | Very High | São Domingos das Dores | MG | Very High | São Domingos das Dores | MG | Very High | São Domingos das Dores | MG | Very High |
| São Domingos do Norte | ES | Medium | São Domingos do Norte | ES | Low | São Domingos do Norte | ES | Low | São Domingos do Norte | ES | Low |
| São Domingos do Prata | MG | Very Low | São Domingos do Prata | MG | Low | São Domingos do Prata | MG | Low | São Domingos do Prata | MG | Very Low |
| São Gabriel da Palha | ES | Low | São Gabriel da Palha | ES | Very Low | São Gabriel da Palha | ES | Very Low | São Gabriel da Palha | ES | Very Low |
| São Geraldo da Piedade | MG | Very High | São Geraldo da Piedade | MG | Very High | São Geraldo da Piedade | MG | Very High | São Geraldo da Piedade | MG | Very High |
| São Geraldo do Baixio | MG | Medium | São Geraldo do Baixio | MG | Low | São Geraldo do Baixio | MG | Low | São Geraldo do Baixio | MG | Low |
| São Gonçalo do Rio Abaixo | MG | Medium | São Gonçalo do Rio Abaixo | MG | High | São Gonçalo do Rio Abaixo | MG | Medium | São Gonçalo do Rio Abaixo | MG | Medium |
| São João do Manhuaçu | MG | High | São João do Manhuaçu | MG | High | São João do Manhuaçu | MG | High | São João do Manhuaçu | MG | High |
| São João do Oriente | MG | Very High | São João do Oriente | MG | Very High | São João do Oriente | MG | Very High | São João do Oriente | MG | Very High |

| Baseline | | | RCP 4.5 | | | RCP 8.5 | | | Integrated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| NM_MUN | UF | Priority | NM_MUN | UF | Priority | NM_MUN | UF | Priority | NM_MUN | UF | Priority |
| São João Evangelista | MG | Low | São João Evangelista | MG | Medium | São João Evangelista | MG | Medium | São João Evangelista | MG | Low |
| São José da Safira | MG | Very High | São José da Safira | MG | High | São José da Safira | MG | High | São José da Safira | MG | High |
| São José do Goiabal | MG | Very High | São José do Goiabal | MG | High | São José do Goiabal | MG | High | São José do Goiabal | MG | High |
| São José do Jacuri | MG | Medium | São José do Jacuri | MG | Medium | São José do Jacuri | MG | Medium | São José do Jacuri | MG | Medium |
| São José do Mantimento | MG | Very High | São José do Mantimento | MG | Very High | São José do Mantimento | MG | Very High | São José do Mantimento | MG | Very High |
| São Mateus | ES | Medium | São Mateus | ES | Low | São Mateus | ES | Medium | São Mateus | ES | Medium |
| São Miguel do Anta | MG | Medium | São Miguel do Anta | MG | Medium | São Miguel do Anta | MG | Medium | São Miguel do Anta | MG | Medium |
| São Pedro do Suaçuí | MG | High | São Pedro do Suaçuí | MG | High | São Pedro do Suaçuí | MG | High | São Pedro do Suaçuí | MG | High |
| São Pedro dos Ferros | MG | Low | São Pedro dos Ferros | MG | Low | São Pedro dos Ferros | MG | Low | São Pedro dos Ferros | MG | Low |
| São Roque do Canaã | ES | Low | São Roque do Canaã | ES | Very Low | São Roque do Canaã | ES | Very Low | São Roque do Canaã | ES | Low |
| São Sebastião do Anta | MG | Very High | São Sebastião do Anta | MG | Very High | São Sebastião do Anta | MG | Very High | São Sebastião do Anta | MG | Very High |
| São Sebastião do Maranhão | MG | Low | São Sebastião do Maranhão | MG | Low | São Sebastião do Maranhão | MG | Low | São Sebastião do Maranhão | MG | Low |
| São Sebastião do Rio Preto | MG | High | São Sebastião do Rio Preto | MG | Very High | São Sebastião do Rio Preto | MG | High | São Sebastião do Rio Preto | MG | High |
| Sardoá | MG | Very High | Sardoá | MG | Very High | Sardoá | MG | Very High | Sardoá | MG | Very High |
| Sem-Peixe | MG | Medium | Sem-Peixe | MG | Medium | Sem-Peixe | MG | Medium | Sem-Peixe | MG | Medium |
| Senador Firmino | MG | Medium | Senador Firmino | MG | Medium | Senador Firmino | MG | Medium | Senador Firmino | MG | Medium |
| Senhora de Oliveira | MG | Medium | Senhora de Oliveira | MG | Medium | Senhora de Oliveira | MG | High | Senhora de Oliveira | MG | Medium |

| Baseline | | | RCP 4.5 | | | RCP 8.5 | | | Integrated | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| NM_MUN | UF | Priority | NM_MUN | UF | Priority | NM_MUN | UF | Priority | NM_MUN | UF | Priority |
| Senhora do Porto | MG | Medium | Senhora do Porto | MG | Medium | Senhora do Porto | MG | Medium | Senhora do Porto | MG | Medium |
| Senhora dos Remédios | MG | Medium | Senhora dos Remédios | MG | Medium | Senhora dos Remédios | MG | Medium | Senhora dos Remédios | MG | Medium |
| Sericita | MG | Medium | Sericita | MG | Medium | Sericita | MG | Medium | Sericita | MG | Medium |
| Serra Azul de Minas | MG | High | Serra Azul de Minas | MG | High | Serra Azul de Minas | MG | High | Serra Azul de Minas | MG | High |
| Serro | MG | Low | Serro | MG | Medium | Serro | MG | Medium | Serro | MG | Low |
| Simonésia | MG | Very Low | Simonésia | MG | Low | Simonésia | MG | Low | Simonésia | MG | Low |
| Sobrália | MG | High | Sobrália | MG | High | Sobrália | MG | High | Sobrália | MG | High |
| Sooretama | ES | Medium | Sooretama | ES | Low | Sooretama | ES | Low | Sooretama | ES | Medium |
| Taparuba | MG | High | Taparuba | MG | Medium | Taparuba | MG | Medium | Taparuba | MG | Medium |
| Tarumirim | MG | Very Low | Tarumirim | MG | Very Low | Tarumirim | MG | Very Low | Tarumirim | MG | Very Low |
| Teixeiras | MG | High | Teixeiras | MG | Medium | Teixeiras | MG | High | Teixeiras | MG | High |
| Timóteo | MG | Very High | Timóteo | MG | Very High | Timóteo | MG | Very High | Timóteo | MG | Very High |
| Tumiritinga | MG | Very Low | Tumiritinga | MG | Very Low | Tumiritinga | MG | Very Low | Tumiritinga | MG | Very Low |
| Ubá | MG | Very High | Ubá | MG | Very High | Ubá | MG | Very High | Ubá | MG | Very High |
| Ubaporanga | MG | High | Ubaporanga | MG | High | Ubaporanga | MG | Medium | Ubaporanga | MG | High |
| Urucânia | MG | High | Urucânia | MG | Medium | Urucânia | MG | High | Urucânia | MG | High |
| Vargem Alegre | MG | Very High | Vargem Alegre | MG | Very High | Vargem Alegre | MG | Very High | Vargem Alegre | MG | Very High |
| Vermelho Novo | MG | High | Vermelho Novo | MG | High | Vermelho Novo | MG | High | Vermelho Novo | MG | High |
| Viçosa | MG | Low | Viçosa | MG | Low | Viçosa | MG | Low | Viçosa | MG | Low |
| Vila Valério | ES | Low | Vila Valério | ES | Very Low | Vila Valério | ES | Low | Vila Valério | ES | Low |
| Virginópolis | MG | Low | Virginópolis | MG | Medium | Virginópolis | MG | Medium | Virginópolis | MG | Medium |
| Virgolândia | MG | High | Virgolândia | MG | High | Virgolândia | MG | Medium | Virgolândia | MG | High |

***Table 5**: Table describing changes in forest cover for the subbasins. The table shows the values of the restorable areas in hectares, as well as the change in vegetation cover for each subbasin and their respective percentages.*

| Subbasins: | Total Area (ha) | Total Area Covered by NVPL (ha) | Restored Area (ha) | % of Restorable Areas | % of Restoble Areas on NVPL | Forest Cover of Baseline (ha) | % of Forest Cover | New Forest Cover with Restoration (ha) | % of New Forest Cover | % of Forest Gain |
|---|---|---|---|---|---|---|---|---|---|---|
| Guandu | 523085,2 | 73429,69 | 46779,3 | 8,94% | 63,71% | 97757,13 | 18,69% | 144536,4 | 27,63% | 47,85% |
| Piracicaba | 568287,4 | 74749,71 | 27373,83 | 4,82% | 36,62% | 251837,2 | 44,32% | 279211,1 | 49,13% | 10,87% |
| Piranga | 1757124 | 242641,1 | 139868 | 7,96% | 57,64% | 484793 | 27,59% | 624661 | 35,55% | 28,85% |
| Suaçuí | 2154301 | 211703,5 | 112333 | 5,21% | 53,06% | 655650 | 30,43% | 767983 | 35,65% | 17,13% |
| Santo Antônio | 1076109 | 140595,4 | 51559 | 4,79% | 36,67% | 508128 | 47,22% | 559687 | 52,01% | 10,15% |
| Manhuaçu | 919298,5 | 112922,2 | 71416,4 | 7,77% | 63,24% | 179352,3 | 19,51% | 250768,7 | 27,28% | 39,82% |
| Caratinga | 669655,9 | 65170,33 | 44355,52 | 6,62% | 68,06% | 100664,9 | 15,03% | 145021,2 | 21,66% | 44,06% |
| São José | 938873,6 | 86740,88 | 49612,74 | 5,28% | 57,20% | 201275,5 | 21,44% | 250888,2 | 26,72% | 24,65% |
| **TOTAL** | **8606735** | **1007959** | **543297,8** | **6,31%** | **53,90%** | **2479459** | **28,81%** | **3022755** | **35,12%** | **21,91%** |

***Table 6:** Comparison of USLE Values for Restored Areas. This table shows the percentual difference between scenarios only for restored areas. Values refer only to areas within APPs and are based on total production/decrease per subbasin. The table shows the current amount of erosion produced in the Doce River basin. The units are in tons per year, and the percentage difference between scenarios is displayed. Negative numbers indicate that the erosion percentage is decreasing in the target scenario compared to the baseline, while positive numbers indicate an increase in erosion percentage compared to the baseline.*

| | **Baseline** | **Climate Change Impact** | | **Forested Scenarios** | | |
|---|---|---|---|---|---|---|
| **Subbasins:** | **USLE (ton/year)** | **RCP 4.5** | **RCP 8.5** | **Baseline** | **RCP 4.5** | **RCP 8.5** |
| **Guandu** | 1749613,48 | -36,07% | -36,54% | -55,77% | -71,74% | -71,97% |
| **Piracicaba** | 1356608,78 | 20,03% | 19,74% | -63,37% | -55,97% | -56,19% |
| **Piranga** | 3729792,72 | -1,89% | 5,16% | -56,80% | -57,65% | -54,60% |
| **Suaçuí** | 2394852,3 | -10,85% | -9,03% | -55,76% | -60,41% | -59,65% |
| **Santo Antônio** | 1430739,27 | 32,59% | 30,23% | -56,80% | -42,51% | -43,62% |
| **Manhuaçu** | 2516868,42 | -22,62% | -21,88% | -56,82% | -66,61% | -66,31% |
| **Caratinga** | 1140006,33 | -15,08% | -13,12% | -57,37% | -63,68% | -62,91% |
| **São José** | 1211344,51 | -40,59% | -37,09% | -54,26% | -72,84% | -71,23% |

***Table 7:*** *Comparison of USLE Values for Total Area Between Subbasins. This table shows the percentual difference between scenarios. The values refer to the total amount of sediment being produced or decreasing throughout the reference subbasin. The table shows the current amount of erosion produced in the Doce River basin, considering the total area. The units follow the same rates as in the previous tables.*

| | Baseline | Climate Change Impact | | Forested Scenarios | | |
|---|---|---|---|---|---|---|
| **Subbasins:** | **USLE (ton/year)** | **RCP 4.5** | **RCP 8.5** | **Baseline** | **RCP 4.5** | **RCP 8.5** |
| **Guandu** | 18545002,41 | -36,99% | -37,41% | -5,63% | -40,60% | -40,98% |
| **Piracicaba** | 16233855,28 | 20,86% | 20,95% | -5,72% | 14,00% | 14,10% |
| **Piranga** | 45037767,51 | -3,00% | 3,49% | -5,04% | -7,95% | -1,81% |
| **Suaçuí** | 49383582,14 | -11,51% | -9,97% | -2,93% | -14,13% | -12,63% |
| **Santo Antônio** | 21651736,15 | 31,08% | 29,56% | -4,11% | 25,64% | 24,21% |
| **Manhuaçu** | 34524618,05 | -22,72% | -21,82% | -4,44% | -26,16% | -25,29% |
| **Caratinga** | 21151241,58 | -14,25% | -12,68% | -3,29% | -17,04% | -15,53% |
| **São José** | 18947699,58 | -41,60% | -38,05% | -3,76% | -43,84% | -40,41% |
| **TOTAL** | **225475502,7** | **-9,99%** | **-7,94%** | **-4,22%** | **-13,84%** | **-11,88%** |

***Table 8:*** *Comparison of Sediment Exportation Values for Total Area Between Subbasin. This table shows the percentual difference between scenarios. The values refer to the total amount of sediment exportation being produced or decreased throughout the reference subbasin. The table shows the current amount of sediment exportation in the Doce River basin, considering the total area. The units follow the same rates as in the previous tables.*

| | Baseline | Climate Change Impact | | Forested Scenarios | | |
|---|---|---|---|---|---|---|
| **Subbasins:** | **Sediment Exportation (ton/year)** | **RCP 4.5** | **RCP 8.5** | **Baseline** | **RCP 4.5** | **RCP 8.5** |
| **Guandu** | 1494282,347 | -36,74% | -37,40% | -19,22% | -49,01% | -49,54% |
| **Piracicaba** | 1531576,487 | 22,29% | 22,50% | -23,24% | -6,25% | -5,99% |
| **Piranga** | 3380485,768 | -2,24% | 4,10% | -19,62% | -21,71% | -16,60% |
| **Suaçuí** | 3112164,927 | -11,34% | -9,85% | -12,68% | -22,63% | -21,34% |
| **Santo Antônio** | 1559927,252 | 31,99% | 30,59% | -15,94% | 10,74% | 9,48% |
| **Manhuaçu** | 2671501,184 | -22,13% | -21,55% | -16,57% | -35,06% | -34,55% |
| **Caratinga** | 1447467,859 | -13,94% | -12,63% | -14,20% | -26,16% | -25,04% |
| **São José** | 1243104,928 | -41,92% | -38,76% | -16,67% | -51,63% | -49,00% |
| **TOTAL** | **16440510,75** | **-8,83%** | **-6,97%** | **-17,06%** | **-24,67%** | **-23,14%** |

***Table 9:*** *The following table illustrates the changes in priority classes between scenarios for different municipalities. A value of zero indicates that a municipality is not changing priority class, 1 indicates an increase in priority level, and -1 indicates a decrease in priority level.*

| Municipalities | States | Restored Area (ha) | % to be restored | Baseline | RCP 4.5 | RCP 8.5 | Integrated | Changes in RCP 4.5 | Changes in RCP 8.5 | Changes between RCP 8.5 and 4.5 | Changes between Integrated and Baseline |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Abre Campo | MG | 6528 | 13.8731 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Acaiaca | MG | 1413 | 13.86844 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Açucena | MG | 4782 | 5.864448 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Afonso Cláudio | ES | 15117 | 16.06162 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Água Boa | MG | 8940 | 6.770963 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Águia Branca | ES | 5264 | 11.58328 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Aimorés | MG | 13312 | 9.868687 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Alpercata | MG | 2200 | 13.17586 | 4 | 3 | 3 | 3 | -1 | -1 | 0 | -1 |
| Alto Jequitibá | MG | 2164 | 14.21141 | 4 | 3 | 3 | 3 | -1 | -1 | 0 | -1 |
| Alto Rio Doce | MG | 8058 | 15.55439 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Alto Rio Novo | ES | 2648 | 11.63358 | 3 | 2 | 2 | 2 | -1 | -1 | 0 | -1 |
| Alvarenga | MG | 2579 | 9.271142 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |
| Alvinópolis | MG | 8330 | 13.89623 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Alvorada de Minas | MG | 2267 | 6.061368 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Amparo do Serra | MG | 1955 | 14.35537 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Antônio Dias | MG | 4214 | 5.354096 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Araponga | MG | 3539 | 11.64938 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Baixo Guandu | ES | 10648 | 11.71347 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Barão de Cocais | MG | 2218 | 6.520844 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Barra Longa | MG | 5790 | 15.09275 | 1 | 1 | 2 | 1 | 0 | 1 | 1 | 0 |
| Bela Vista de Minas | MG | 793 | 7.265697 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Belo Oriente | MG | 1857 | 5.54479 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Bom Jesus do Amparo | MG | 1480 | 7.566037 | 4 | 5 | 5 | 5 | 1 | 1 | 0 | 1 |

| Municipalities | States | Restored Area (ha) | % to be restored | Baseline | RCP 4.5 | RCP 8.5 | Integrated | Changes in RCP 4.5 | Changes in RCP 8.5 | Changes between RCP 8.5 and 4.5 | Changes between Integrated and Baseline |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bom Jesus do Galho | MG | 4560 | 7.698944 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Brás Pires | MG | 3596 | 16.10022 | 2 | 3 | 3 | 3 | 1 | 1 | 0 | 1 |
| Braúnas | MG | 2164 | 5.720056 | 3 | 4 | 4 | 4 | 1 | 1 | 0 | 1 |
| Brejetuba | ES | 5868 | 16.55738 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Bugre | MG | 1131 | 7.003486 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Cajuri | MG | 1076 | 12.95792 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Campanário | MG | 2766 | 6.252289 | 3 | 2 | 2 | 2 | -1 | -1 | 0 | -1 |
| Canaã | MG | 2471 | 14.12807 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |
| Cantagalo | MG | 1127 | 7.944732 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Capela Nova | MG | 1591 | 14.32391 | 4 | 5 | 5 | 4 | 1 | 1 | 0 | 0 |
| Capitão Andrade | MG | 2835 | 10.15809 | 3 | 2 | 2 | 2 | -1 | -1 | 0 | -1 |
| Caputira | MG | 2406 | 12.81805 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |
| Caranaíba | MG | 2451 | 15.32354 | 3 | 4 | 4 | 4 | 1 | 1 | 0 | 1 |
| Carandaí | MG | 649 | 1.331883 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Caratinga | MG | 10309 | 8.191635 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Carmésia | MG | 2172 | 8.382767 | 3 | 4 | 4 | 4 | 1 | 1 | 0 | 1 |
| Catas Altas | MG | 1546 | 6.44054 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Catas Altas da Noruega | MG | 1210 | 8.54387 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Chalé | MG | 4346 | 20.43503 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Cipotânea | MG | 2615 | 17.03816 | 3 | 3 | 4 | 3 | 0 | 1 | 1 | 0 |
| Coimbra | MG | 1419 | 13.27719 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Colatina | ES | 17795 | 12.7269 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Coluna | MG | 2525 | 7.245503 | 3 | 4 | 4 | 3 | 1 | 1 | 0 | 0 |
| Conceição de Ipanema | MG | 2376 | 9.356725 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |

| Municipalities | States | Restored Area (ha) | % to be restored | Baseline | RCP 4.5 | RCP 8.5 | Integrated | Changes in RCP 4.5 | Changes in RCP 8.5 | Changes between RCP 8.5 and 4.5 | Changes between Integrated and Baseline |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Conceição do Mato Dentro | MG | 7765 | 4.51443 | 1 | 2 | 2 | 2 | 1 | 1 | 0 | 1 |
| Congonhas do Norte | MG | 239 | 0.589147 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Conselheiro Lafaiete | MG | 140 | 0.378127 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Conselheiro Pena | MG | 14947 | 10.0729 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Coroaci | MG | 4126 | 7.159789 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Coronel Fabriciano | MG | 1094 | 4.944588 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Córrego Novo | MG | 1488 | 7.24493 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Cristiano Otoni | MG | 109 | 0.820338 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Cuparaque | MG | 2145 | 9.459757 | 3 | 2 | 2 | 3 | -1 | -1 | 0 | 0 |
| Desterro do Melo | MG | 1481 | 10.40913 | 4 | 5 | 5 | 5 | 1 | 1 | 0 | 1 |
| Diogo de Vasconcelos | MG | 2115 | 12.81112 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Dionísio | MG | 1765 | 5.200737 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Divinésia | MG | 1105 | 9.446867 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Divino das Laranjeiras | MG | 3411 | 9.966428 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Divinolândia de Minas | MG | 1026 | 7.707332 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Dom Cavati | MG | 738 | 12.39919 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Dom Joaquim | MG | 3263 | 8.18219 | 2 | 3 | 3 | 3 | 1 | 1 | 0 | 1 |
| Dom Silvério | MG | 2543 | 13.0429 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |

| Municipalities | States | Restored Area (ha) | % to be restored | Baseline | RCP 4.5 | RCP 8.5 | Integrated | Changes in RCP 4.5 | Changes in RCP 8.5 | Changes between RCP 8.5 and 4.5 | Changes between Integrated and Baseline |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Dores de Guanhães | MG | 3109 | 8.136102 | 3 | 4 | 3 | 3 | 1 | 0 | -1 | 0 |
| Dores do Turvo | MG | 3463 | 14.98038 | 2 | 3 | 3 | 3 | 1 | 1 | 0 | 1 |
| Durandé | MG | 3512 | 16.15002 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Engenheiro Caldas | MG | 1780 | 9.515765 | 4 | 3 | 4 | 4 | -1 | 0 | 1 | 0 |
| Entre Folhas | MG | 918 | 10.75067 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Ervália | MG | 4834 | 13.52209 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Fernandes Tourinho | MG | 1332 | 8.77037 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Ferros | MG | 9357 | 8.593936 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Franciscópolis | MG | 4821 | 6.723034 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Frei Inocêncio | MG | 4093 | 8.716727 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Frei Lagonegro | MG | 1288 | 7.690746 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Galiléia | MG | 7454 | 10.34842 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Goiabeira | MG | 957 | 8.510979 | 5 | 4 | 4 | 5 | -1 | -1 | 0 | 0 |
| Gonzaga | MG | 1387 | 6.625332 | 4 | 5 | 5 | 5 | 1 | 1 | 0 | 1 |
| Governador Lindenberg | ES | 3522 | 9.782899 | 2 | 1 | 2 | 2 | -1 | 0 | 1 | 0 |
| Governador Valadares | MG | 22340 | 9.537324 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Guanhães | MG | 7810 | 7.264278 | 1 | 2 | 1 | 1 | 1 | 0 | -1 | 0 |
| Guaraciaba | MG | 5028 | 14.42357 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Iapu | MG | 2934 | 8.604257 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |
| Imbé de Minas | MG | 2056 | 10.45061 | 4 | 4 | 3 | 4 | 0 | -1 | -1 | 0 |
| Inhapim | MG | 8729 | 10.17338 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Ipaba | MG | 648 | 5.722056 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Ipanema | MG | 4199 | 9.195407 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |

| Municipalities | States | Restored Area (ha) | % to be restored | Baseline | RCP 4.5 | RCP 8.5 | Integrated | Changes in RCP 4.5 | Changes in RCP 8.5 | Changes between RCP 8.5 and 4.5 | Changes between Integrated and Baseline |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ipatinga | MG | 895 | 5.428059 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Itabira | MG | 9749 | 7.776158 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Itaguaçu | ES | 5615 | 10.49492 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Itambacuri | MG | 9324 | 6.569857 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Itambé do Mato Dentro | MG | 2417 | 6.35484 | 3 | 4 | 4 | 4 | 1 | 1 | 0 | 1 |
| Itanhomi | MG | 4830 | 9.880473 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Itarana | ES | 3692 | 12.50724 | 2 | 2 | 1 | 2 | 0 | -1 | -1 | 0 |
| Itaverava | MG | 3171 | 11.15685 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |
| Itueta | MG | 4158 | 9.185378 | 2 | 1 | 2 | 2 | -1 | 0 | 1 | 0 |
| Iúna | ES | 2721 | 5.907692 | 3 | 2 | 2 | 2 | -1 | -1 | 0 | -1 |
| Jaguaraçu | MG | 830 | 5.068393 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Jaguaré | ES | 2663 | 4.036371 | 3 | 2 | 2 | 2 | -1 | -1 | 0 | -1 |
| Jampruca | MG | 3912 | 7.565341 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Jequeri | MG | 7622 | 13.91137 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Joanésia | MG | 2025 | 8.680109 | 3 | 4 | 4 | 4 | 1 | 1 | 0 | 1 |
| João Monlevade | MG | 812 | 8.188951 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| João Neiva | ES | 2508 | 8.80819 | 3 | 2 | 2 | 2 | -1 | -1 | 0 | -1 |
| José Raydan | MG | 1358 | 7.510148 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Lajinha | MG | 7156 | 16.56788 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Lamim | MG | 1913 | 16.12958 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Laranja da Terra | ES | 5894 | 12.85861 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Linhares | ES | 16764 | 4.794834 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Luisburgo | MG | 2065 | 14.20044 | 4 | 3 | 3 | 3 | -1 | -1 | 0 | -1 |
| Malacacheta | MG | 3873 | 5.320888 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Manhuaçu | MG | 7542 | 12.00348 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Manhumirim | MG | 2474 | 13.52652 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |

| Municipalities | States | Restored Area (ha) | % to be restored | Baseline | RCP 4.5 | RCP 8.5 | Integrated | Changes in RCP 4.5 | Changes in RCP 8.5 | Changes between RCP 8.5 and 4.5 | Changes between Integrated and Baseline |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Mantenópolis | ES | 1782 | 5.544182 | 4 | 3 | 3 | 3 | -1 | -1 | 0 | -1 |
| Mariana | MG | 9198 | 7.702176 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Marilac | MG | 1103 | 6.94545 | 5 | 4 | 4 | 5 | -1 | -1 | 0 | 0 |
| Marilândia | ES | 3454 | 10.54199 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Marliéria | MG | 1763 | 3.230044 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Martins Soares | MG | 1575 | 13.90507 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Materlândia | MG | 2924 | 10.42313 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |
| Mathias Lobato | MG | 1630 | 9.460408 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Matipó | MG | 3944 | 14.77209 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Mercês | MG | 564 | 1.619429 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Mesquita | MG | 1995 | 7.256181 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Morro do Pilar | MG | 3377 | 7.07154 | 2 | 3 | 3 | 3 | 1 | 1 | 0 | 1 |
| Mutum | MG | 17081 | 13.6558 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Nacip Raydan | MG | 1311 | 5.614729 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Naque | MG | 818 | 6.432183 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Nova Era | MG | 3053 | 8.435426 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |
| Nova Venécia | ES | 1997 | 1.387219 | 4 | 3 | 3 | 3 | -1 | -1 | 0 | -1 |
| Oratórios | MG | 1229 | 13.79845 | 5 | 4 | 4 | 4 | -1 | -1 | 0 | -1 |
| Ouro Branco | MG | 645 | 2.492985 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Ouro Preto | MG | 3617 | 2.903204 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |
| Pancas | ES | 9013 | 10.7574 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Passabém | MG | 1291 | 13.70736 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Paula Cândido | MG | 3370 | 12.55958 | 2 | 3 | 3 | 3 | 1 | 1 | 0 | 1 |
| Paulistas | MG | 2011 | 9.117535 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Peçanha | MG | 6769 | 6.79178 | 1 | 2 | 1 | 1 | 1 | 0 | -1 | 0 |
| Pedra Bonita | MG | 2267 | 13.03413 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |
| Pedra do Anta | MG | 2402 | 13.87092 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |
| Periquito | MG | 1720 | 7.513969 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |

| Municipalities | States | Restored Area (ha) | % to be restored | Baseline | RCP 4.5 | RCP 8.5 | Integrated | Changes in RCP 4.5 | Changes in RCP 8.5 | Changes between RCP 8.5 and 4.5 | Changes between Integrated and Baseline |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Piedade de Caratinga | MG | 991 | 9.063057 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Piedade de Ponte Nova | MG | 1143 | 13.65053 | 5 | 4 | 5 | 5 | -1 | 0 | 1 | 0 |
| Pingo-d'Água | MG | 403 | 6.053778 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Piranga | MG | 7980 | 12.11271 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Pocrane | MG | 6355 | 9.195938 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Ponte Nova | MG | 6951 | 14.76916 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Porto Firme | MG | 4211 | 14.78701 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Presidente Bernardes | MG | 3386 | 14.29911 | 2 | 3 | 3 | 3 | 1 | 1 | 0 | 1 |
| Raul Soares | MG | 8404 | 11.00916 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Reduto | MG | 2335 | 15.37611 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |
| Resplendor | MG | 10619 | 9.816084 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Ressaquinha | MG | 486 | 2.654838 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Rio Bananal | ES | 6852 | 10.67408 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Rio Casca | MG | 4433 | 11.53283 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Rio Doce | MG | 1508 | 13.45299 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Rio Espera | MG | 3749 | 15.71236 | 2 | 3 | 3 | 3 | 1 | 1 | 0 | 1 |
| Rio Piracicaba | MG | 4760 | 12.76013 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Rio Vermelho | MG | 7802 | 7.908279 | 1 | 2 | 1 | 1 | 1 | 0 | -1 | 0 |
| Sabinópolis | MG | 7017 | 7.628741 | 1 | 2 | 2 | 1 | 1 | 1 | 0 | 0 |
| Santa Bárbara | MG | 3310 | 4.835611 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |
| Santa Bárbara do Leste | MG | 1025 | 9.543584 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Santa Cruz do Escalvado | MG | 3592 | 13.88341 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |

| Municipalities | States | Restored Area (ha) | % to be restored | Baseline | RCP 4.5 | RCP 8.5 | Integrated | Changes in RCP 4.5 | Changes in RCP 8.5 | Changes between RCP 8.5 and 4.5 | Changes between Integrated and Baseline |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Santa Margarida | MG | 3466 | 13.55336 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Santa Maria de Itabira | MG | 4541 | 7.600751 | 2 | 3 | 2 | 2 | 1 | 0 | -1 | 0 |
| Santa Maria do Suaçuí | MG | 3216 | 5.153458 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Santa Rita de Minas | MG | 712 | 10.44708 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Santa Rita do Itueto | MG | 4736 | 9.763318 | 2 | 1 | 1 | 2 | -1 | -1 | 0 | 0 |
| Santa Teresa | ES | 4626 | 6.772743 | 2 | 1 | 1 | 1 | -1 | -1 | 0 | -1 |
| Santana do Manhuaçu | MG | 5198 | 14.96422 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Santana do Paraíso | MG | 1617 | 5.857274 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Santana dos Montes | MG | 3185 | 16.20329 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |
| Santo Antônio do Grama | MG | 1822 | 13.99246 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Santo Antônio do Itambé | MG | 2221 | 7.264414 | 3 | 4 | 4 | 4 | 1 | 1 | 0 | 1 |
| Santo Antônio do Rio Abaixo | MG | 1744 | 16.25819 | 4 | 5 | 5 | 4 | 1 | 1 | 0 | 0 |
| São Domingos das Dores | MG | 597 | 9.808593 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| São Domingos do Norte | ES | 2973 | 9.95713 | 3 | 2 | 2 | 2 | -1 | -1 | 0 | -1 |
| São Domingos do Prata | MG | 6227 | 8.372234 | 1 | 2 | 2 | 1 | 1 | 1 | 0 | 0 |

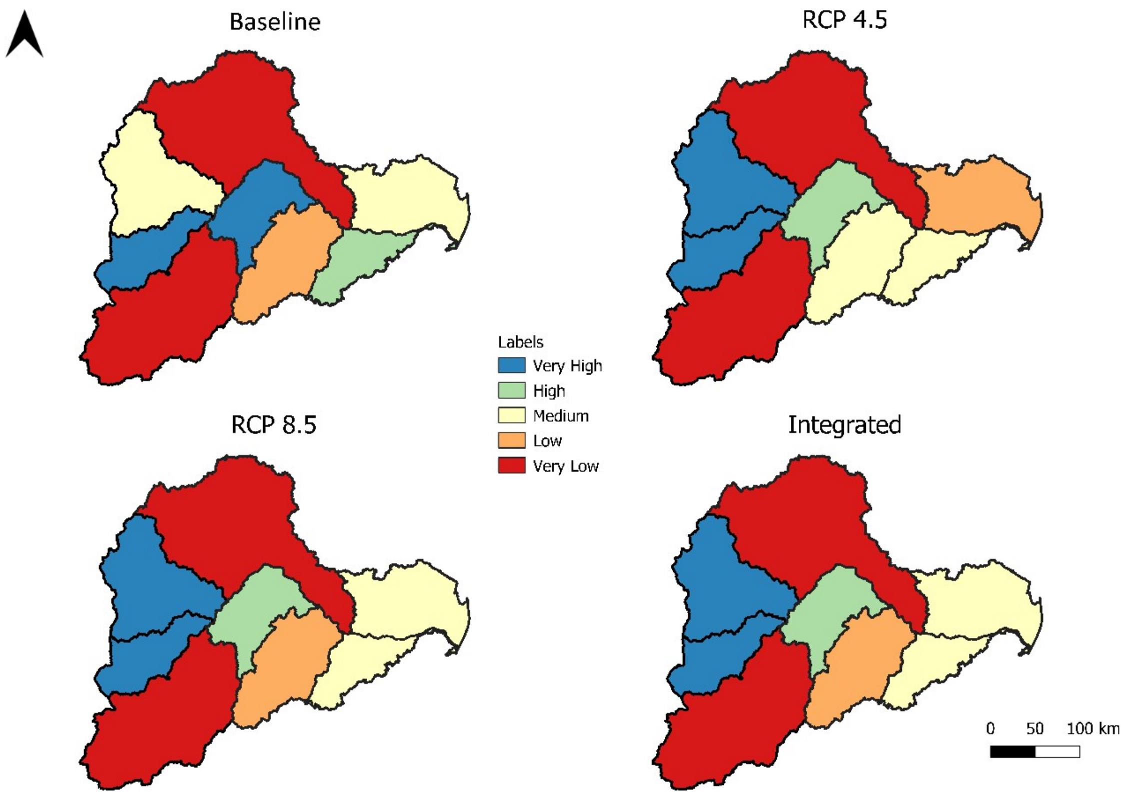
| Municipalities | States | Restored Area (ha) | % to be restored | Baseline | RCP 4.5 | RCP 8.5 | Integrated | Changes in RCP 4.5 | Changes in RCP 8.5 | Changes between RCP 8.5 and 4.5 | Changes between Integrated and Baseline |
|---|---|---|---|---|---|---|---|---|---|---|---|
| São Gabriel da Palha | ES | 4348 | 9.997999 | 2 | 1 | 1 | 1 | -1 | -1 | 0 | -1 |
| São Geraldo da Piedade | MG | 992 | 6.511921 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| São Geraldo do Baixio | MG | 2675 | 9.521132 | 3 | 2 | 2 | 2 | -1 | -1 | 0 | -1 |
| São Gonçalo do Rio Abaixo | MG | 3089 | 8.490276 | 3 | 4 | 3 | 3 | 1 | 0 | -1 | 0 |
| São João do Manhuaçu | MG | 1980 | 13.83686 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| São João do Oriente | MG | 1099 | 9.149032 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| São João Evangelista | MG | 4082 | 8.536481 | 2 | 3 | 3 | 2 | 1 | 1 | 0 | 0 |
| São José da Safira | MG | 1131 | 5.287987 | 5 | 4 | 4 | 4 | -1 | -1 | 0 | -1 |
| São José do Goiabal | MG | 1283 | 6.767663 | 5 | 4 | 4 | 4 | -1 | -1 | 0 | -1 |
| São José do Jacuri | MG | 2627 | 7.611272 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |
| São José do Mantimento | MG | 840 | 15.35621 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| São Mateus | ES | 2208 | 0.941157 | 3 | 2 | 3 | 3 | -1 | 0 | 1 | 0 |
| São Miguel do Anta | MG | 2250 | 14.79183 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |
| São Pedro do Suaçuí | MG | 2052 | 6.660046 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |

| Municipalities | States | Restored Area (ha) | % to be restored | Baseline | RCP 4.5 | RCP 8.5 | Integrated | Changes in RCP 4.5 | Changes in RCP 8.5 | Changes between RCP 8.5 and 4.5 | Changes between Integrated and Baseline |
|---|---|---|---|---|---|---|---|---|---|---|---|
| São Pedro dos Ferros | MG | 3921 | 9.735834 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| São Roque do Canaã | ES | 4293 | 12.55469 | 2 | 1 | 1 | 2 | -1 | -1 | 0 | 0 |
| São Sebastião do Anta | MG | 797 | 9.88613 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| São Sebastião do Maranhão | MG | 3465 | 6.691385 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| São Sebastião do Rio Preto | MG | 1964 | 15.34351 | 4 | 5 | 4 | 4 | 1 | 0 | -1 | 0 |
| Sardoá | MG | 1097 | 7.730578 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Sem-Peixe | MG | 2272 | 12.86276 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |
| Senador Firmino | MG | 3184 | 19.1237 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |
| Senhora de Oliveira | MG | 2620 | 15.34416 | 3 | 3 | 4 | 3 | 0 | 1 | 1 | 0 |
| Senhora do Porto | MG | 3090 | 8.10326 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |
| Senhora dos Remédios | MG | 3175 | 13.35071 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |
| Sericita | MG | 2182 | 13.14363 | 3 | 3 | 3 | 3 | 0 | 0 | 0 | 0 |
| Serra Azul de Minas | MG | 2058 | 9.414671 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Serro | MG | 4674 | 3.838028 | 2 | 3 | 3 | 2 | 1 | 1 | 0 | 0 |
| Simonésia | MG | 5265 | 10.82124 | 1 | 2 | 2 | 2 | 1 | 1 | 0 | 1 |
| Sobrália | MG | 1718 | 8.308066 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Sooretama | ES | 2276 | 3.877105 | 3 | 2 | 2 | 3 | -1 | -1 | 0 | 0 |
| Taparuba | MG | 1839 | 9.524451 | 4 | 3 | 3 | 3 | -1 | -1 | 0 | -1 |

| Municipalities | States | Restored Area (ha) | % to be restored | Baseline | RCP 4.5 | RCP 8.5 | Integrated | Changes in RCP 4.5 | Changes in RCP 8.5 | Changes between RCP 8.5 and 4.5 | Changes between Integrated and Baseline |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tarumirim | MG | 7218 | 9.863984 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Teixeiras | MG | 2086 | 12.51087 | 4 | 3 | 4 | 4 | -1 | 0 | 1 | 0 |
| Timóteo | MG | 695 | 4.813653 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Tumiritinga | MG | 6047 | 12.09223 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| Ubá | MG | 1139 | 2.795421 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Ubaporanga | MG | 2069 | 10.94448 | 4 | 4 | 3 | 4 | 0 | -1 | -1 | 0 |
| Urucânia | MG | 1875 | 13.50942 | 4 | 3 | 4 | 4 | -1 | 0 | 1 | 0 |
| Vargem Alegre | MG | 1061 | 9.094494 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 |
| Vermelho Novo | MG | 1398 | 12.13099 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Viçosa | MG | 3787 | 12.64787 | 2 | 2 | 2 | 2 | 0 | 0 | 0 | 0 |
| Vila Valério | ES | 3801 | 8.081336 | 2 | 1 | 2 | 2 | -1 | 0 | 1 | 0 |
| Virginópolis | MG | 3335 | 7.581648 | 2 | 3 | 3 | 3 | 1 | 1 | 0 | 1 |
| Virgolândia | MG | 2086 | 7.422906 | 4 | 4 | 3 | 4 | 0 | -1 | -1 | 0 |

## Differences observed across subbasins

***Figure 10:*** *Maps of Restoration Priority Areas based on subbasins. Maps showing priority restoration areas were classified into five prioritisation classes based on quartile percentage variations. Prioritisation is organised according to specific scenarios.*




In Piracicaba, restoration reduces erosion by 6.68% and sediment exportation by 28.54%. However, NVPL restoration alone is also inadequate to control erosion exacerbated by climate change, leading to a 14% erosion balance even on restored sites. Nonetheless, NVPL restoration effectively decreases sediment exportation in Piracicaba, resulting in a final value of 6.86% lower than the baseline. In the restored areas, restoration is also effective in reducing erosion by 76%, leaving a negative erosion balance of 55.97%. Restoration efficiency for sediment exportation is 91.28%, reducing exportation rates to 70.20% negative.

The effects of restoration for RCP 8.5 are very similar to the results of RCP 4.5 for Santo Antônio and Piracicaba. In Santo Antônio, the NVPL is still not effective in reducing erosion or even limiting sediment exportation due to climate change. Still, for the restored areas, this effect is positive, reducing erosion and sediment exportation to rates lower than baseline. In Piracicaba, the same results were held: the restoration of the NVPL mitigates the effects of climate change by reducing both erosion and sediment exportation rates to values lower than baseline. The effects are even more positive when we take a closer look at the restored areas.

For Piranga, one of the subbasins, also in critical condition during extreme climate change events, restoration is a key factor in a region with important characteristics in the basin. Piranga, like Santo Antônio and Piracicaba, occupies one of the highest-altitude regions in the basin. It is where the Doce River rises, and the municipality of Mariana is located, the region where the Fundão dam collapse took place. Also, the Piranga subbasin is where the Rio Doce State Park is situated, and despite that, only 27.59% of native vegetation remains, a relatively low percentage compared to the most degraded areas (20% of remaining forest cover). Perhaps the limited remaining forest explains why Piranga is the second basin with the most restoration liabilities for the NVPL.

Restoration in Piranga reduces erosion by 5.3% and sediment exportation by 20.7%, lowering rates that would be much higher under the influence of climate change. Erosion reaches a negative value of 1.81% in Piranga, and sediment exportation is reduced by 16.6% with the restoration of the NVPL in the RCP 8.5 scenario. When we look closely at the restored areas, the erosion values can effectively reduce erosion by 59.76% and sediment exportation by 71.42%.

The erosion reduction occurs even in areas with the lowest levels of forest cover, such as Guandu, São José, and Manhuaçu, which have only 20% of their area with remaining cover, and erosion reduction can reach rates of up to 41.60%, like in São José, for example, solely due to climate change.

At lower Doce, restoration in areas affected by climate change alone will reduce erosion, acting as an additional force for sediment containment. This means that if, under the influence of climate change, the predicted erosion reduction for São José, for example, was -40.60% in the RCP 4.5 scenario, when this scenario is restored, the erosion reduction reduces to -72.84%, resulting in a net effect of 32.24% on this area. The same impact can be observed for both erosion and sediment exportation to the Guandu, Manhuaçu, Caratinga, Suaçuí, and Piranga subbasins in this decreasing order of magnitude for the RCP 4.5 scenario. In the RCP 8.5 scenario, Piranga changes course and begins to export more sediment and erosion due to the influence of climate change, as described above.

The restoration of these areas is also crucial to mitigate the impact of the mining that takes place in these areas since, even today, there are levels of dissolved Fe, Al, as well Mn in the water above the limits determined by CONAMA regulation 357/05 for class 2 according to the monthly water monitoring report issued by the Water Report (VIANA, 2018; RENOVA, 2023). Other studies also highlight the occurrence of other metals present in the water resulting from the dam collapse (DE ANDADE SOARES et al. 2024; FERREIRA et al., 2020; ZANOTELLI, 2024), as well as the 2021 Report of the Aquatic Biodiversity Monitoring Program for Environmental Area I also reports impacts of the same order of contamination since the dam burst (PMBA, 2022), as well as impacts of permanent duration, affecting biodiversity at different trophic levels of contamination (PMBA, 2022).

The municipalities that have demonstrated the highest effectiveness in any circumstance and are situated in the upper Doce should be prioritized first to ensure better sediment containment and management conditions for the basin’s security under any climate conditions.

Restoration of these areas could locally reduce erosion and sediment exportation, exerting an impact on the lower region where the sediment is transported. Restoration and conservation of native vegetation in these areas are important tools to reduce the impact of climate change on most vulnerable areas, safeguarding the maintenance of the regions that have the worst impact on the basin. At lower Doce, where the impact of climate change is relatively low, strategies for the restoration and conservation of natural landscapes are still fundamental for maintaining water quality for the local population, structurally contributing to the reduction of sedimentation impacts, and protecting terrestrial and aquatic biodiversity.

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