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Programa de Pós-Graduação em Ecologia UFRJ

UNIVERSIDADE FEDERAL DO RIO DE JANEIRO

CENTRO DE CIÊNCIAS DA SAÚDE

INSTITUTO DE BIOLOGIA

PROGRAMA DE PÓS-GRADUAÇÃO EM ECOLOGIA

INCORPORATING WATER SERVICES INTO FOREST RESTORATION SPATIAL PLANNING

VIVIANE DIB DA SILVA

Tese apresentada ao Programa de Pós-graduação em Ecologia da Universidade Federal do Rio de Janeiro, como parte dos requisitos necessários à obtenção do grau de doutorado em Ciências Biológicas (Ecologia).

Orientador: Bernardo Baeta Neves Strassburg

Rio de Janeiro, RJ – Brasil
Novembro de 2021

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"INCORPORATING WATER SERVICES INTO FOREST RESTORATION SPATIAL PLANNING"

VIVIANE DIB DA SILVA

TESE SUBMETIDA À UNIVERSIDADE FEDERAL DO RIO DE JANEIRO VISANDO A OBTENÇÃO DO GRAU DE DOUTOR EM CIÊNCIAS BIOLÓGICAS (ECOLOGIA)

Defendida em dezenove de novembro de dois mil e vinte e um

APROVADA POR:

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Programa de Pós-Graduação em Ecologia UFRJ

DIB, VIVIANE
Incorporating water services into forest restoration spatial planning
RJ [Rio de Janeiro] 2021
78 p., 29.7 cm (Instituto de Biologia/UFRJ, D.Sc., Programa de Pós-Graduação em Ecologia, 2021)
Tese - Universidade Federal do Rio de Janeiro, PPGE
1. Conservação
I. IB/UFRJ II. Título (série)

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“O rio é a coragem da água”

Autor desconhecido

Acknowledgements

When I lived abroad for the first time, doing part of this thesis, I realized my personality works quite differently in English – especially with the British accent. So, I've decided to show my gratitude to those who made this work possible in my own language.

Cursar um doutorado não estava nos meus planos. Até que a vida me mostrou que os planos são como os modelos matemáticos: servem para nos ajudar a entender como a realidade funcionaria, caso fosse possível desconsiderar uma série incontável de variáveis. Ainda assim, seguimos fazendo planos, construindo cenários, adaptando nossos objetivos e aperfeiçoando nossos algoritmos. E no caminho, descobrimos que somos capazes de conquistas que não faziam parte dos planos iniciais. Que bom que os ventos mudaram. Que bom que eu aceitei o novo caminho. E que maravilhoso foi (e está sendo) desfrutar de tudo isso ao lado de pessoas incríveis, que me ensinaram tanto.

Em primeiro lugar, agradeço ao meu orientador Bernardo Strassburg, que embarcou comigo e me guiou nessa jornada, mesmo sem me conhecer muito bem – provavelmente ele se assustou com minha personalidade, digamos, não-britânica, no início. Obrigada por todas as reuniões e dicas valiosas, pelo afeto, pela compreensão e, principalmente, pela confiança.

Ser orientada pelo Bernardo me permitiu ainda fazer parte de uma família grande, diversa, barulhenta, acolhedora e com a maior concentração de gênios e gênias por metro quadrado: o IIS. Agradeço a todos e todas, sem exceção, pelo apoio, pela troca de experiências, pelas risadas e pela amizade. Um agradecimento especial a quem colocou a mão na massa para produzir esta tese junto comigo: Carlos, querido, eu amo você. Obrigada por ser o gênio do SIG e da Ayurveda. Equipe modelagem, vocês são demais! Renata, Gabi, Diogo, Luga, Edu e Alvaro, agradeço o carinho e a dedicação especial com as camadas de água e por me ensinarem tudo que eu sei sobre a nossa querida ferramenta de priorização. Aline e Aga, obrigada por expandirem meus horizontes, pelas discussões empolgantes e por me alertarem sobre a importância da ciência dos solos. Aline, querida, obrigada ainda por ser uma excelente amiga e trilhar este caminho do doutorado junto comigo. Vero e Mari, obrigada por revisarem parte deste texto. Vocês são mulheres incríveis e me empoderaram muito ao longo desta jornada. Fer, obrigada pelas dicas de inglês de última hora e por viver tantos momentos importantes ao meu lado nos últimos cinco anos.

Back to English, I owe a massive thanks to Mark Mulligan – my supervisor at King's College – and to all the fantastic and brilliant people I met in London: Sam, Shree, Brandon, Nat, Alois, Dimitris, Seung Won, Alex, Claudia, Alejo, Aleja, Pratik, Yanan, Veronica, and Raphael. Thanks for being my family during such a challenging time.

Agradeço também aos demais autores dos capítulos desta tese: Pedro Brancalion, Sin Chan Chou, Miguel Cooper, David Ellison, Vinicius Farjalla, Solange Filoso, Paula Meli, Aliny Pires, Daniel Rodriguez, Fabio R. Scarano, Adrian Vogl e Angélica Guerra. Que honra poder discutir com vocês sobre este tema tão fascinante. Dente eles, um agradecimento especial à Aliny Pires e ao Vinicius Farjalla, que além de serem grandes amigos, fizeram parte da minha formação acadêmica desde a graduação. Obrigada por caminharem comigo e por acreditarem em mim. E ao Fábio Sacarano, por sempre ter uma palavra amiga e inspiradora.

Agradeço ao PPGE, principalmente à então coordenadora Daniela Rodrigues, que não mediu esforços para que os alunos seguissem com suas pesquisas, mesmo em tempos tão difíceis como este. Agradeço aos órgãos de fomento CNPq e CAPES, que me permitiram desenvolver esta pesquisa no Brasil e na Inglaterra. Espero que este trabalho (e as consequências dele), possam gerar importantes benefícios à sociedade.

Agradeço à Carolina Bozetti e ao Jerônimo Sansevero, cujas contribuições durante a defesa de qualificação mudaram meu olhar sobre vários aspectos da relação floresta x água. Vocês foram incríveis. Agradeço também à presente banca, por aceitar com carinho mais um compromisso neste final de ano tão difícil para todos nós. Obrigada, antecipadamente, por contribuírem com a melhoria deste trabalho.

Por fim, agradeço à minha família e aos amigos queridos de longa data, tão distantes em tempos de pandemia. Foram tantos meses longe, tanto tempo só. Eu só resisti a tudo isso, por saber que vocês estavam sempre comigo. Agradeço também aos amigos novos, que chegaram na minha vida na reta final deste processo e me trouxeram esperança de dias melhores. E a quem me fez levantar da cama todos esses dias, me enxugou as lágrimas e me arrancou as risadas mais sinceras, minha filha de quatro patas, Trevo.

Rio de Janeiro, 05 de outubro de 2021.

Resumo

Dar escala a restauração dos ecossistemas para frear os efeitos nocivos da degradação ambiental é um dos maiores desafios do século. Identificar oportunidades e áreas prioritárias para restauração (aquelas que combinam alto potencial de provisão de benefícios com alta viabilidade de restauração) aumenta a custo-efetividade das iniciativas, evitando consequências indesejadas. Desta forma, o planejamento espacial é uma estratégia crucial para o alcance dos acordos globais de restauração, planejados para as próximas décadas. Esforços recentes para a priorização global de áreas para restauração consideraram principalmente a conservação da biodiversidade e a mitigação das mudanças climáticas. Contudo, incorporar outros benefícios da restauração em abordagens de priorização é essencial para oferecer múltiplas opções aos tomadores de decisão, visando atender a demandas locais. Questões relacionadas à água necessitam de atenção especial, uma vez que a água é primordial para o desenvolvimento sustentável. Além disso, a restauração florestal é considerada um elemento crucial para políticas ambientais focadas na melhoria da segurança hídrica em todo o mundo. Visando incorporar serviços relacionados à água no planejamento espacial da restauração, nós identificamos áreas prioritárias para a restauração da mata Atlântica Brasileira (um *hotspot* global de conservação e restauração), considerando a recarga de águas subterrâneas, a melhoria da qualidade da água e os custos da restauração. Para isso, nós primeiramente esclarecemos as relações entre a restauração florestal e a água, uma vez que a restauração florestal tem sido relacionada com a redução da produção de água em todo o mundo. Nós concluímos que é preciso considerar diferentes parâmetros hidrológicos (omitidos da maioria dos estudos) e uma maior escala espaço-temporal para uma avaliação completa dos benefícios da restauração florestal para a água. Depois disso, nós desenvolvemos um índice espacialmente explícito para descrever a variabilidade do potencial de recarga de águas subterrâneas na Mata Atlântica, considerando parâmetros topográficos, geológicos, climáticos e de uso e cobertura da terra. Além disso, nós acessamos a variabilidade espacial dos impactos antrópicos na qualidade da água do bioma, utilizando o sistema de suporte a políticas públicas ‘WaterWorld’. Então, foram desenvolvidas superfícies espaciais que representam o potencial da restauração florestal em aumentar a recarga de águas subterrâneas e a qualidade da água, além dos custos associados com a restauração do bioma. Finalmente, estas superfícies espaciais alimentaram o algoritmo de priorização (baseado em programação linear) para identificar as áreas mais custo-efetivas para a restauração. Nossos resultados revelaram que o planejamento espacial pode aumentar o potencial de recarga de águas subterrâneas em até 3,5 vezes e a melhoria da qualidade da água em até 1,9 vezes, comparado com cenários onde a restauração se dá sem planejamento. A solução Compromisso (aquela que apresenta o melhor balanço entre benefícios e custos) reduziu os custos da restauração em 38%, aumentando o potencial de recarga em 2,3 vezes e a qualidade da água em 1,1 vezes. Nós acreditamos que a narrativa da água pode impulsionar inciativas de restauração e promover um argumento sólido para dar escala à restauração. Este trabalho preenche uma importante lacuna metodológica e oferece informações valiosas para orientar políticas relacionadas ao manejo da água e da restauração florestal na Mata Atlântica.

Palavras-chave: Restauração Florestal, Planejamento Espacial, Áreas Prioritárias, Recarga de Águas Subterrâneas, Qualidade da Água, Custos da Restauração.

Abstract

Scaling up ecosystem restoration to halt the harmful effects of ecosystem degradation is one of the main challenges of the century. Identifying restoration opportunities and priority areas for restoration – combining high potential for benefits delivery with high restoration feasibility – increases restoration cost-effectiveness and avoids unintended consequences. In this sense, spatial planning is a critical strategy for achieving the ambitious global restoration commitments planned for the immediate future. Recent efforts to propose priority areas to be restored globally are focused mainly on biodiversity conservation and climate change mitigation. However, incorporating other benefits from restoration in prioritization approaches is instrumental in offering decision-makers multiple options to attend to local demands. Water issues need special attention as water is at the core of sustainable development. Also, forest restoration is considered an essential element for environmental policies focused on improving water security worldwide. Aiming at incorporating water services into forest restoration spatial planning, we identified priority areas for restoration in the Brazilian Atlantic Forest – a global conservation and restoration hotspot – considering groundwater recharge, water quality improvement, and restoration costs. For that, we first clarify the linkages between forest restoration and water, as forest restoration has been linked to decreases in water yields worldwide. We concluded that hydrologic parameters omitted from most studies and broader spatial-temporal scales must be considered to fully evaluate the benefits of forest restoration on water. After that, we developed a spatially explicit index to describe the variability of the groundwater recharge potential in the Brazilian Atlantic Forest, considering topographic, geological, climatic, and land use and cover parameters. Also, we accessed the spatial variability of the human impacts on water quality in the biome, using the WaterWorld policy-support system. Then, we developed spatial surfaces representing the potential of forest restoration in increasing groundwater recharge and water quality and the costs associated with restoring the biome. Finally, these spatial surfaces fed the prioritization algorithm (based on linear programming) to identify the most cost-effective areas for restoration. Our results revealed that spatial planning could improve restoration outcomes for groundwater recharge up to 3.5 times and water quality up to 1.9 times, compared to non-planning scenarios. The Compromise solution (the most balanced solution, considering benefits and costs simultaneously) reduced restoration costs by 38%, increasing the groundwater recharge potential 2.3 times and increasing water quality improvement 1.1 times. We believe the water narrative can boost restoration initiatives and provide a solid argument to scale up restoration. This work fills a critical methodological gap and offers valuable insights to guide the Brazilian Atlantic Forest's water and forest management policies.

Keywords: Forest restoration, Spatial Planning, Priority Areas, Groundwater Recharge, Water Quality, Restoration costs.

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General Introduction

The need to restore degraded ecosystems has never been greater. Humanity is using about 1.6 times the services nature can provide (Global Footprint Network 2021). That means conservation efforts alone are not enough to prevent environmental collapse and biodiversity loss. One hundred and fifteen countries have committed to restoring approximately 1 billion hectares on land to achieve the goals of the Convention on Biological Diversity (CBD), the UNFCCC Paris Agreement, the Sustainable Development Goals, the Land Degradation Neutrality targets, and the Bonn Challenge (Sewell et al. 2020). Ecosystem restoration includes restoring degraded ecosystems and converted lands into healthy ecosystems (IPBES 2018). Although much has been done, none of the agreed global goals have been fully met (UNEP 2021). Scaling up these restoration actions to reverse the degradation of ecosystems is the challenge posed to the world by The United Nations Decade on Ecosystem Restoration, running from 2021 until 2030. Achieving the ambitious global restoration goals will require a fundamental shift in the way we value ecosystems, biodiversity, and the services we depend on (Dasgupta 2021).

Optimizing restoration outcomes

Successful restoration requires an integrated approach and involves some trade-offs regarding the restoration targets, the social and ecological benefits provided, and associated costs. Restoration benefits and costs vary considerably across space, and decisions on where to restore impact the type of benefits, their quantity, and their delivery speed. Scientifically based- spatially explicit scenarios allow decision-makers to compare the potential outcomes of a decision at global, national, or local levels (Metzger et al. 2017). They are helpful benchmarks to assess the soundness of any restoration goal. A robust restoration spatial planning – that estimates costs and benefits for each scenario, identifying their trade-offs and synergies – helps to reduce risk perception from local landowners to potential investors. Identifying restoration opportunities and priority areas for restoration – areas that combine high potential for socioenvironmental benefits with high restoration feasibility – is critical for achieving the ambitious global restoration commitments planned for the immediate future.

Some efforts to propose priority areas to be restored globally, nationally or at local levels show promising results, indicating that cost-effectiveness of restoration can increase markedly when spatial allocation is optimized (Brancalion et al. 2019, Strassburg et al. 2019, 2020, Niemeyer et al. 2020). For instance, a study showed that restoring 15% of all converted lands globally could avoid 60% of expected extinctions while sequestering almost 300 gigatons of CO_2 (Strassburg et al. 2020). Most of these studies focus on the biggest challenges of the century: biodiversity conservation and climate change mitigation. However, priority areas for restoration that focus on multiple benefits have different spatial patterns, which result in widely variable restoration outcomes. A critical aspect that needs more attention is the outcomes of ecosystem restoration for water-related services. In fact, hydrologic aspects should be investigated not only as an outcome but also as a conditional parameter for restoration success.

Native vegetation provides several water-related services (or water services), such as groundwater recharge, buffering and filtering of pollutants, streamflow regulation, reduction of soil erosion and water bodies siltation, provision of habitats, and scenic landscapes for recreation and leisure activities (UNECE 2018). Native vegetation restoration has emerged as a preferred tool to recover the water services lost when natural areas are disturbed or converted to anthropogenic land uses (Vörösmarty et al. 2010, Chazdon et al. 2017). However, the relationship between native vegetation restoration and water provision is complex and still unpredictable, especially for forest ecosystems. Forest restoration does not always work as expected in terms of improving water services. Recent assessments showed that planting trees may actually reduce water availability locally (Filoso et al. 2017, Zhang et al. 2017, Bentley and Coomes 2020), and can be especially harmful if it replaces other natural ecosystems (Farley et al. 2005).

Since more trees does not always mean more water, decide where to restore to fight water scarcity becomes a huge challenge. Despite the overall benefits of forest restoration for water services, defining priority areas simply by selecting places facing water crises can be risky. In contrast, not including water as a criterion for restoration spatial planning is also unsound. According to estimates, the global demands for water are expected to increase by 30-50 percent in the next decade, which is alarming considering that more than 2 million people already lack access to safe water (WWAP; UN-WATER 2018). Forest restoration is already a key element for environmental policies focused on improving water security worldwide (Palmer and Filoso 2009, Chazdon et al. 2017, Melo et al. 2020), such as payments for ecosystem services (Rodríguez-de-Francisco et al. 2019) and regulation of agricultural supply chains (Lambin et al. 2018). Also, the water services narrative can provide a solid argument to scale up restoration by stimulating partnerships at regional and global scales while considering local beneficiaries. Filling this gap is critical to improve the decision-making process related to international water management and governance.

Accounting for water

Defining priority areas for forest restoration focus on water demand a better understanding of forest restoration and water relationship. First, the general knowledge that forest restoration diminishes water yields must be reviewed. To do that, we need to understand better how forest restoration affects the water cycle in the long term and go beyond the catchment scale, especially looking into the feedback processes that control precipitation recycling. At the regional and continental scales, forests contribute to cloud generation, precipitation, and moisture transportation (Sheil 2018). From a hydrospace perspective, considering sources and sinks of air moisture, moisture transportation from upwind restored areas might increase water yields and land productivity in downwind basins (Ellison 2018).

Secondly, more attention must be paid to hydrologic parameters other than the annual streamflow. For instance, the observation of flow regulation and groundwater recharge – parameters that are often omitted from studies focusing on the impacts of forest restoration – can be instrumental in understanding the real effects of forest restoration on water availability. Groundwater recharge is critical as this compartment supplies freshwater to the global population and irrigated agriculture and feeds water bodies, thereby maintaining aquatic ecosystems during dry seasons (Condon and Maxwell 2019). Water quality improvement is another critical issue, considering the lack of access to adequate quantities of good quality water is the leading cause of water insecurity for many global regions (Onda et al. 2012, Gunda et al. 2019). The positive effects of forest cover on water quality are well documented (Neary et al. 2009, Gageler et al. 2014, Piffer et al. 2021) and can be helpful to define priority areas for restoration.

Thirdly, it is necessary to develop spatial surfaces linking the response of those hydrologic parameters to forest restoration at the pixel level for the region in interest. Finally, developing spatial surfaces that represent the costs associated with restoration is also necessary to define the most cost-effective areas to be restored. As resources are scarce, restoration should be encouraged in places where it is possible to adopt less costly strategies, such as the conduction of natural regeneration (Crouzeilles et al. 2020). Also, optimize food production and environmental conservation in a growing population world is a huge challenge for society. Large-scale restoration can displace agricultural activities and drive competition for land (Latawiec et al. 2015). To avoiding land conflicts and conciliate food security and forest conservation, less productive areas should be designated for restoration (dos Santos et al. 2020).

Goals

The general goal of this work is to propose a methodology to optimize forest restoration considering water services in the Brazilian Atlantic Forest. This thesis is divided into three main chapters: Chapter 1 presents a debate on forest restoration and water relationships and proposes strategies to improve restoration planning and implementation for water services. Chapter 2 presents a spatial explicit index, developed to describe the variability of the groundwater recharge potential in the Brazilian Atlantic Forest. Chapter 3 presents the priority areas for restoration in the Brazilian Atlantic Forest considering water services. In this chapter, we develop a restoration spatial planning to the Brazilian Atlantic Forest based on multicriteria prioritization, considering groundwater recharge, water quality improvement, and restoration costs reduction. The final two sections present a general discussion and conclusions on the main findings of this work.

Although this approach can be applied in different regions in the globe, we choose the Brazilian Atlantic Forest as a study case due to its relevance in biodiversity, ecosystem services delivery and its dire, degraded state (Figure 1). Recent estimates revealed a remaining vegetation cover of 28% (Rezende et al. 2018), being the habitat of more than 20,000 species (Mittermeier et al. 2011), but almost 10% of them are endangered (Paglia et al. 2008; Martinelli and Moraes 2013). Regarding water supply, this biome provides water for more than 125 million Brazilians (Joly et al. 2014). However, remote sensing data showed a reduction of 1,4% of water surface in the last 30 years, and a tendency of decrease for the next decades (Mapbiomas 2021).

In Brazil, the Native Vegetation Protection Law (Law no. 12,651/2012) requires farmers to conserve native vegetation, setting aside a Legal Reserve that occupies 20% of the property area in the Atlantic Forest. Restoring the existing legal debt for legislation compliance could increase native vegetation cover up to 35% (Rezende et al. 2018). If well planned and implemented, such effort could ensure biodiversity conservation and bring back several ecosystem services such as climate mitigation, pollination, food production, and water regulation and provision (Chazdon and Guariguata 2016, Holl

2017). Also, scaling up restoration can provide socioeconomic benefits such as jobs opportunities and income generation (Adams et al. 2016).

Figure 1: Study area. Adapted from IBGE 2019.

Chapter 1 – Into deep waters: clarifying linkages between forest restoration and water services

Contributing authors: Viviane Dib, Pedro Brancalion, Sin Chan Chou, Miguel Cooper, David Ellison, Vinicius Farjalla, Solange Filoso, Paula Meli, Aliny Pires, Daniel Rodriguez, Alvaro Iribarrem, Agnieszka Latawiec, Fabio R. Scarano, Adrian Vogl, and Bernardo Strassburg.

Abstract

Although native vegetation is known to be determinant to the maintenance and protection of aquatic ecosystems (and all benefits people obtain from them), forest restoration has been linked to decreases in water yields worldwide. This apparent disconnect may reflect the limitation of studies, methods, and approaches in capturing forest and water relationships' complex nature. We argue that omitted parameters of hydrologic processes and broader spatial-temporal scales must be considered for a full evaluation of the benefits of forest restoration on water. Filling this gap is critical to improving the decision-making process related to international water management and governance. Also, we discuss strategies to improve forest restoration planning and implementation for water-related services. We believe that the water narrative can provide an excellent argument to scale up restoration by stimulating partnerships at regional and global scales while considering local beneficiaries.

Keywords: forest-water nexus, forest restoration, water governance, water availability.

Water is essential for human and wildlife survival, ecosystems' health and resilience and socioeconomic development. Water-related ecosystem services (or water services) are benefits people obtain from nature, critical to ensure human well-being, including water supply, waste assimilation, energy generation, food, and recreational opportunities. Several water-related services are derived from forest functions, such as groundwater recharge, buffering and filtering of pollutants, regulation of rainfall and snow melt that reduce soil erosion and the risk of flooding, provision of habitats and maintenance of genetic diversity, and the provision of scenic landscape of forests and water bodies for recreation and leisure activities (UNECE 2018). Forest conservation and restoration have become central pieces of environmental policies and programs worldwide focused on improving water security and sustainability (Palmer and Filoso 2009), including payments for ecosystem services (Rodríguez-de-Francisco et al. 2019) and regulation of agricultural supply chains (Lambin et al. 2018).

Forest restoration – defined as the process of assisting the recovery of a forest ecosystem that has been degraded, damaged, or destroyed – has emerged as a preferred tool to recover water provision and regulation services when native forests are disturbed or converted to anthropogenic land uses (Chazdon et al. 2017). Controversially, forest restoration has been linked to decreases in annual water yields worldwide (Filoso et al. 2017, Zhang et al. 2017). This apparent controversy may limit the adoption of forest restoration actions in this context (Ellison 2018). Here we dive into the forest-water nexus's complex nature to explore its linkages, offering guidelines that can help improve forest restoration planning and implementation for water-related services and reduce risks. We also explore the response of often omitted parameters of hydrologic processes and consider the broader spatial-temporal scales for a full evaluation of the potential benefits of forest restoration on water.

Forest-water nexus

Forests and water are interconnected in a socio-ecological system, also referred to as the forest-water nexus (Springgay et al. 2019). At catchment scales, restored forests are known to positively affect key hydrologic processes that lead to ecosystem resilience and support desired ecosystem services such as water quality, flow regulation, and flood mitigation. For instance, restored forests improve soil physical properties that support groundwater recharge and potentially increase local water availability in the long run (Ilstedt et al. 2007) (Figure 2). Forested and well-managed catchments also protect local and downstream aquatic ecosystems and people relying on them, preserving livelihoods and cultural diversity. At the regional and continental scales, forests contribute to atmospheric water recycling, including cloud generation, precipitation, and moisture transportation (Sheil 2018). From the hydrospace perspective, that considers sources and sinks of air moisture, moisture transportation from upwind restored areas might increase water yields and land productivity in downwind basins (Figure 2). Conversely, forests can reduce local water yield as trees intercept, consume, and transfer water to the atmosphere. These latter processes form the groundwork of most studies that link forest restoration to declining water availability.

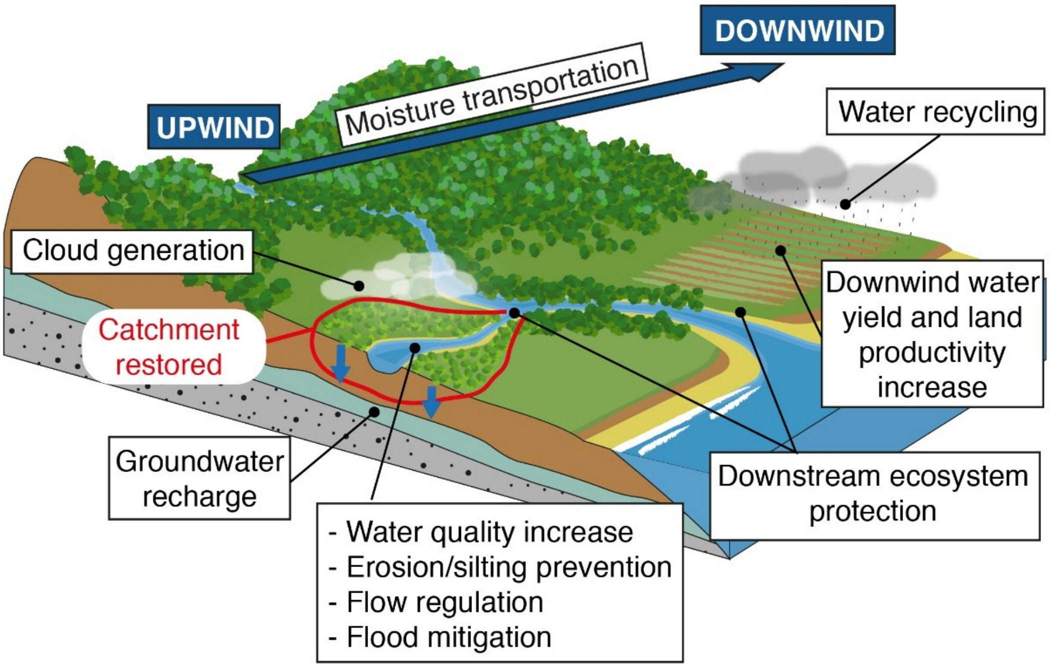

Figure 2: Representation of the hydrospace concept, highlighting potential water-related services at the local and regional scales after a catchment recovery.

The prevailing understanding that forest restoration diminishes water yields is largely based on information from studies available to date, which have a series of limitations in terms of design, spatio-temporal scale and even methods (Filoso et al. 2017). Among the most important limitations is the fact that most forest restoration projects are designed to meet catchment-scale goals and, consequently, empirical studies assessing forest restoration effects on water dynamics are typically conducted at relatively small spatial and temporal scales (less than 1 km² of catchment area and 10 years of water yield data collection – see Filoso et al. 2017). Studies that focused on longer temporal scales (e.g, > 50 years) and larger spatial scales (e.g., > 1000 km²) adopt modeling approaches, often limiting the complexity of the water cycle (Filoso et al. 2017). Perhaps more importantly, most studies are based on afforestation of nonnative species, and focus on changes in water yields (usually annual streamflow) instead of focusing on key hydrologic parameters which could be used to indicate the recovery of water yields in the long term or beyond the boundaries of small catchments. To review this paradigm of the negative impact of forest restoration on water production, we need to understand better how forest restoration affects the water cycle in the long term and beyond the catchment scale, especially the feedback processes that control precipitation recycling.

A matter of time?

In few years after restoration, vegetation can retain nutrients and sediments, contributing to soil erosion and water bodies siltation reduction and improving water quality (Gageler et al. 2014). In long temporal scales, restored forests improve soil attributes such as moisture, water storage, and infiltration due to the litter layer, root system, and soil biodiversity recovery (Figure 3). Improving soil attributes depends on the degradation level and historical land-use transitions and might take years or decades to occur (Jones et al. 2018, Lozano-Baez et al. 2019). The gain in infiltration rates can result in groundwater recharge improvement depending on climate and geophysical parameters, such as precipitation patterns, relief settings, slope, and soil type (Moeck et al. 2020). Mature forests can act as 'sponges', providing seasonal flows regulation (reducing peak flows and increasing baseflows) and overland flow reduction (Bruijnzeel 2004) (Figure 3). Seasonal flows levels and groundwater recharge rates may increase or decrease depending on the net effect of changes in infiltration and evapotranspiration.

Evapotranspiration (ET) is the amount of water exported to the atmosphere from plant transpiration and soil evaporation. Early successional restored forests exhibit higher ET profiles due to pioneer plant physiology (they usually grow faster and consume more water) and elevated evaporative rates (Giambelluca 2002). Water use tends to reduce and stabilize during the mature stage resulting in ET reduction. It suggests that initial drops in water yield gradually recover over time – indicating that any water stress caused by forest restoration may be temporary. However, strong evidence for this hypothesis is still needed. A recent study showed that the ET rates can be higher in mature forests than in secondary forests (Meerveld et al. 2020) – although authors recognize their mature forest plots had relatively many young trees. A meta-analysis conducted by Bentley and

Coomes (2020) showed that in most catchments studied, the declines in annual streamflow after forest restoration persisted after decades. However, some of the catchments showed partial flow recovery after an initial decrease. Catchments from tropical regions were underrepresented in this study.

On the one hand, we still lack evidence showing ET stabilizing and streamflow recovery after restored forest reaching mature stages (highlighted by the question marks in Figure 3). On the other hand, it is known that deforestation increases annual water yields, primarily due to the decreases in ET rates (Zhang et al. 2017). However, part of the water produced in a short period during the rainy season does not infiltrate to feed water tables or subsurface flows. This excess of water flows overland and remains unavailable for human use, increasing flooding risks, soil erosion, and water bodies siltation if not kept in reservoirs. Also, it is important to highlight that weather water yields reduction is a service or a disservice is context dependent. In this sense, the observation of flow regulation and groundwater recharge can be more helpful to understand the real effects of forest restoration on water availability in the long run than focusing only on the annual streamflow.

Water services provided by forests	Hydrologic Parameters	Tendency of change compared to a non-forested stage	
		Young forest	Mature forest
Water quality improvement	Nutrient retention	↗	↑
	Sediment retention	↗	↑
Soil attributes improvement	Soil water storage	→	↗
	Soil Moisture	→	↗
	Infiltration	→	↗
Seasonal flows regulation	Overland flow	→	↘
	Base flow	→	↗
Water production	Evapotranspiration	↗	?
	Annual streamflow	↘	?

Figure 3: Conceptual framework proposed to indicate the tendency of changes in key water services provided by forest restoration, compared to a pre-restoration stage, represented by a non-forested, degraded landscape. Horizontal arrows denote low effects, diagonal arrows denote medium effects, and vertical arrows denote high effects. Arrow orientation indicates increase or decrease of each parameter. Question marks highlight important gaps in the literature.

Hydrospace definition and modelling limitations

In large spatial scales, precipitation recycling occurs both within and beyond the catchment boundaries (Wang-erlandsson et al. 2018). Forests act as 'pumps' increasing air moisture and rain downwind. Depending on the climate conditions and land-use and cover of downwind catchments, annual water yield can also increase. A better understanding of the *full* hydrospace, i.e., considering both up- and downstream and up- and downwind interactions, is critical to guide decision-makers in addressing forest restoration-related phenomena beyond the basin. Most traditional hydrologic models, however, do not consider precipitation recycling or upwind rainfall sources and rarely consider the beneficiaries of water-related services (Ellison et al. 2019). One of the main challenges is the gap between the scale at which processes such as ET and infiltration are measured in situ and the scale the same processes are solved in the models (usually an area of several hectares to several square kilometers). Coupled land-surface-atmosphere models can assess feedback processes that control precipitation recycling (Pilotto et al. 2017). Such a modeling approach – integrated to ground level and remote sensing earth observations – could improve our ability to define atmospheric moisture flux sources and sinks, delimiting a hydrospace (Ramos et al. 2019). Some studies have already evaluated the potential impacts of upwind regions' restoration or deforestation on specific locations' water regime, highlighting the importance of cross-border land-use decisions to water management (Gebrehiwot et al. 2019, Weng et al. 2019).

Future studies must address important but unsolved questions: how long do catchments take to return to pre-disturbance water yields after forest restoration?; how and at what scale is the atmospheric moisture produced by forests re-integrated into the terrestrial hydrologic processes?; and who and where are the beneficiaries of these terrestrial hydrologic processes and atmospheric water services at various scales, relative to the area reforested? To answer these questions, restoration research must consider water-related services. Long-term and large-scale empirical studies are also needed for a more accurate picture of how forest restoration affects the climate at regional and global scales, and human, wildlife, and ecosystems health at local scales.

Restoration strategies

Forest restoration outcomes for water services depend significantly on *where* and *how* restoration interventions are implemented, and whether improvements in water services are viewed as a primary goal or a co-benefit. Deciding where to restore requires a multi-scale approach, including the selection of (i) a specific biome, ecosystem, or geopolitical boundary; (ii) a watershed or landscape within the targeted area; and (iii) a specific location. Also, it requires scientific information to maximize positive outcomes and minimize costs and unintended consequences. Decisions made at the first two scales usually consider beneficiaries' demands, climate patterns, geographical characteristics, and the potential of different ecosystem types to deliver water services.

Selecting a specific location relies on how water services are driven by the combination of restoration with local biophysical conditions (Brancalion et al. 2019). Landscape variation on elevation, slope, soil type, and water table depth significantly impacts hydrologic processes (Sheil 2018). Flat areas like hill tops and plains, especially in high altitudes, favor infiltration and groundwater recharge at the expense of surface overland flow (Figure 4). The higher the elevation, the better for restoration impacts on flood mitigation (i.e., before overland flows can gain significant speed and mass). Conversely, forest restoration in sloped areas can reduce surface overland flow, sediment export, protecting water bodies from siltation (Liu et al. 2008). Forest restoration in riparian zones also reduces pollution risks and thus maintains water quality (Fennessy and Cronk 1997, Gageler et al. 2014) (Figure 4).

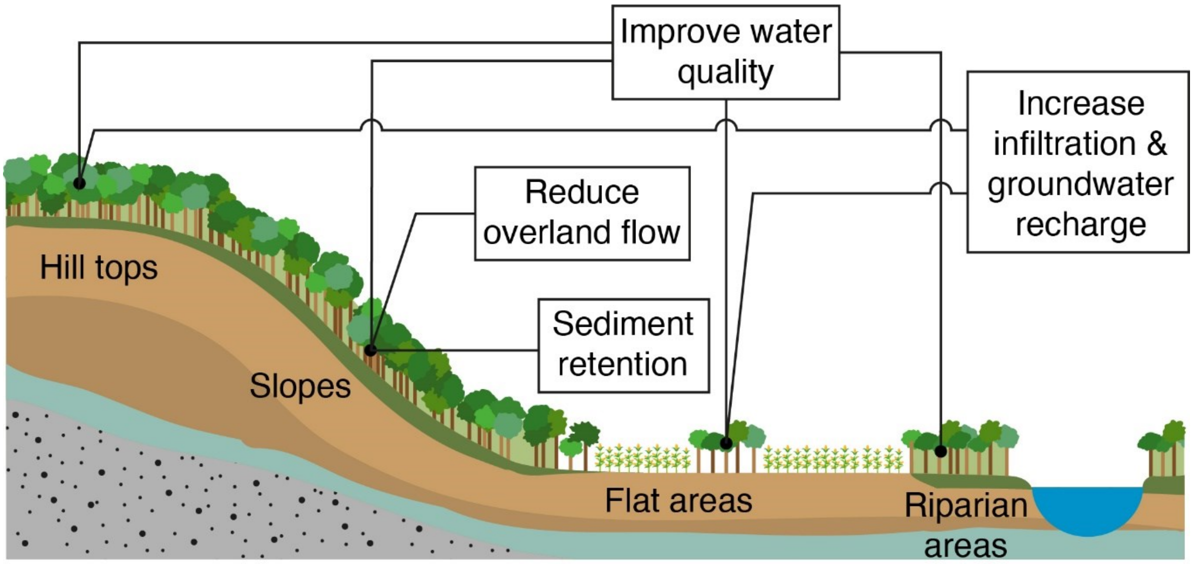

Figure 4: Landscape opportunities to favor specific water services.

Restoration strategies can vary greatly in their impacts on hydrologic processes. The variation is assumed according to the performance of each restorative approach to maximize the hydrologic processes that impact groundwater recharge. For instance, intensive agro-pastoralism results in degraded and compacted soil and thus lower infiltration rates, which can be mitigated by appropriate soil management (Kopittke et al. 2019). Agroforestry systems integrate woody species in the agricultural landscape, increasing infiltration and reducing soil evaporation and overland flows (Anderson et al. 2009, Cardinael et al. 2020). Natural forest regrowth and restoration plantations of native species maximize infiltration but also transpiration and interception, especially in closed productive forests (Ilstedt et al. 2016). Long-rotation commercial plantations (mostly dedicated to producing lumber, harvested after more than ten years) and short-rotation commercial plantations (mainly used to produce pulp and firewood, harvested within a few years after planting) present the higher transpiration profiles due to the management strategies and plant physiology (Ferraz et al. 2019). Groundwater recharge is maximized by restoration interventions that result in intermediate tree cover, which creates a favorable balance between increasing infiltration and ET reduction (Ellison et al. 2017) – as such, deciding how to restore requires an alignment between restoration strategies and goals.

At the local scale, the social dimension is paramount to guarantee restoration projects' effectiveness. Thus, as a final issue, considering *who* benefits from water services or, conversely, who might be impacted by unintended consequences on water, is fundamental to design the best spatial planning and restoration strategy (Palmer and Filoso 2009). Conflicts of interests can emerge when restoration targets are defined outside of the beneficiaries' location boundaries. Because most decision-making about water traditionally derives from catchment dynamics, the tendency is to emphasize the needs of the catchment and ignore (or not even consider) the regional hydrologic community's needs. In this sense, downwind/downstream communities are likely to be disadvantaged if upwind/upstream communities are the ones making the ultimate restoration decisions. The big challenge is to define strategies to adequately integrate regional-scale hydrologic concerns into the modeling and political decision-making framework.

How about the tropics?

Tropical forests present high ET rates and are responsible for climate regulation on regional and continental scales (Ramos et al. 2019). They are arguably among the most important areas for proving the relationship between forests and water supply, but are underrepresented in the literature (Filoso et al. 2017, Bentley and Coomes 2020). Filling this gap is critical as hydrological processes in the humid tropics differ from other regions. They usually present greater energy inputs (such as moisture fluxes from the mid latitudes and intense precipitation) and high rates of weathering, creating large volumes of water and sediment transport. Atmospheric moisture cycling also differs from other regions by its warmer and uniform temperatures and the pronounced spatial gradients of precipitation (Wohl et al. 2012). The major impact of deforestation on the water cycle in these areas is the reduction of the local evapotranspiration, thus reducing the total amount of moisture available for precipitation recycling (Bruijnzeel 2004).

Forest cover loss in the tropics has been rising steadily over the past decades and these areas hold great global restoration opportunities (Brancalion et al. 2019, Strassburg et al. 2020). Many projects of forest restoration have been proposed over the next decades to meet national and global commitments, such as the Bonn Challenge and the UNFCCC

Paris Agreement, reinforced by the ongoing UN Decade on Ecosystem Restoration (Sewell et al. 2020). Less developed countries – which also fight severe water security problems – are the ones pledging the highest amount of area for restoration (Fagan et al. 2020). The implementation of these projects can be an opportunity to developing a better understanding on the forest-water relationship, but also must be conducted based on the knowledge science can provide so far. Identifying the hydrospace around the main tropical forests, the impacts of large-scale restoration scenarios on precipitation recycling, the potential of water quality delivery, and the potential of groundwater recharge are critical to determining the priority areas to be restored in the globe.

The primary water management challenge of the future might be dealing with floods and heavy siltation due to high intensity rains for some tropical regions, while water scarcity and eutrophication for others. If this is the case, healthy forests may be one of the most effective strategies for buffering the impacts of both more intense storms and droughts. Efforts to collect tropical data should include soil parameters and water fluxes, considering groundwater, surface, and atmospheric dynamics.

Lessons for water governance

Water governance should optimize the potential benefits from restoration by adequately incorporating appropriate hydrologic processes across all relevant spatial and temporal scales. From a local perspective, forest cover may compete with other land uses that provide more immediate economic returns. Decision-making on watershed management must consider whether long-term socioeconomic benefits are likely to exceed short- and long-term implementation and maintenance costs (van Noordwijk 2019). Optimal targeting of sustainable management practices on agricultural lands can also improve water-related services provision without compromising highly productive lands' profitability (Pennington et al. 2017, Bryant et al. 2020). From a regional/global perspective, atmospheric teleconnection dynamics must be considered (Keys et al. 2017).

Regional partnerships and transboundary agreements are critical to developing and enforcing legal tools and defining target areas for forest conservation and restoration (Melo et al. 2020). Forest and water strategies should always prioritize conservation of native and undisturbed forests, as this is the method proven to be most consistently effective for maintaining water-related ecosystem services. Where conservation efforts are not enough, the spatial planning of forest restoration and the identification of priority areas to be restored is crucial to optimize benefits and minimize both unintended consequences on water-related services (e.g., local water yield declines in the early years following restoration) and costs (Figure 5).

The integration of water with other environmental agendas, such as predicted by the nexus concept, will also boost restoration initiatives. The climate agenda has promoted forest restoration as one of the best mitigation strategies, but it has failed to include local stakeholders. We believe that the water services narrative can provide a better argument to scale up restoration by stimulating partnerships at regional and global scales while considering local beneficiaries. From local to global processes, from global to local interests, water is fundamental to our lives on this planet. As we advance our knowledge of the spatial and temporal scales of forest-water related processes and the multiple services provided by them, we will be able to evaluate the impacts of forest restoration on the water cycle and thereby improve the decision-making process related to international water management and governance. Dependent on them is the achievement of the leading global environmental agendas, such as the Sustainable Development Goals of the 2030 Agenda, the Paris Agreement, and the Post-2020 Global Biodiversity Framework.

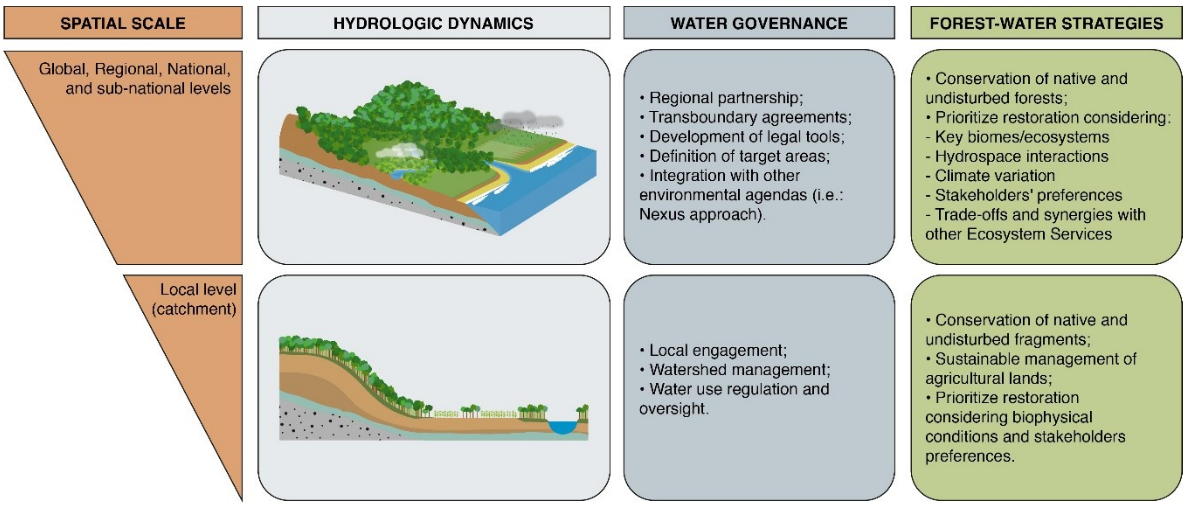

Figure 5: Hydrologic dynamics operating in local and global, regional, national, and subnational scales and their respective governance and strategies that should be adopted for better including water-related services into restoration planning and implementation.

Chapter 2 – Spatial variability of the groundwater recharge potential in the Brazilian Atlantic Forest

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Abstract

Groundwater provides water for irrigated agriculture and domestic supply worldwide and maintains surface water bodies during dry seasons. Groundwater levels are controlled by recharge, which is a critical process for sustaining the water cycle. However, modelling groundwater recharge in large scales is a challenge, due to its complexity and the scarcity of data. Here we propose a spatially explicit index (the GR index) to describe the variability of the groundwater recharge potential in the Brazilian Atlantic Forest – a global conservation hotspot and a biome crucial for ecosystem services delivery to over half of the Brazilian population. To that end, we adopted a map algebra approach combining topographic, geological, climatic, and land use and cover parameters. High GR values were found at the Eastern and Southwestern regions of the biome, and precisely, at the East Atlantic, Parana, and Uruguay hydrographic regions. Parana and Uruguay hydrographic regions feed the Guarani aquifer – one of the largest reservoirs of freshwater worldwide. Our results suggest that the GR index corresponds to the actual recharge patterns, as it is consistent with the recharge areas of the main aquifer systems in the biome. Identifying areas with relatively high groundwater recharge potential is helpful to support policies and programs focused on improving water availability, including payments for ecosystem services, initiatives of forest conservation and restoration, and implementation of agricultural sustainable practices. Our study can be an instrumental tool to inform water and forest management in the Brazilian Atlantic Forest. In addition, the methodology presented is customizable and can be replicated to any geographic region if data are available.

Keywords: groundwater recharge, water management, soil conservation, forest restoration, Brazilian Atlantic Forest.

1- Introduction

Groundwater recharge, defined as "the downward flow of water reaching the water table, adding to groundwater storage" (Healy 2010), is the primary process that regulates groundwater levels. Groundwater provides nearly half of the water used for irrigated agriculture and supplies drinking water for billions of people worldwide (Gleeson et al. 2020). This compartment also feeds surface water bodies, thereby sustaining aquatic ecosystems and their biodiversity during dry seasons (Condon and Maxwell 2019). Although recharge is one of the most important hydrologic processes in groundwater sustainability studies, it is poorly understood, mainly because recharge rates vary significantly in space and time and are difficult to measure directly or by modelling (von Freyberg et al. 2015).

A complex set of hydrologic processes controls groundwater recharge, and its magnitude is influenced by topography, geology, soil type, climate, and land use and cover (Gleeson et al. 2020, Moeck et al. 2020). Groundwater flows naturally under gravity from highlands to lowlands, with recharge happening in topographic highs and discharge in topographic lows (Freeze and Cherry 1979). Recharge is more likely to occur in relatively high and flat relief settings – as steep slope areas usually present limited storage capacity and favor high overland flows (Buda 2013); in coarse-grained and deep soils – that have relatively high permeability and can percolate water rapidly (Healy 2010); where precipitation regularly exceeds soil moisture deficits and evaporative demands (Healy 2010); and at intermediate vegetation density cover – that creates a favorable balance between water infiltration and evapotranspiration processes (Ilstedt et al. 2016; Ellison et al. 2017).

Recent estimates showed that groundwater levels are declining in many regions around the globe (Dalin et al. 2019). Land conversion results in significant changes in recharge rates over time. Soil compaction, erosion, and impervious surface associated with anthropogenic landcover reduce water infiltration. On the other hand, forest restoration can improve soil physical properties that support groundwater recharge (Ilstedt et al. 2007). Impervious surface coverage in urban basins is drastically higher than basins with other land-use types, reducing recharge (Carter and Jackson 2007). Groundwater recharge response to agricultural land use may be positive or negative, depending on management practices and their respective soil impacts. Intensive agro-pastoralism results in degraded and compacted soil and thus lower infiltration rates (Kopittke et al. 2019). However, moderate-to-high recharge rates can be found in irrigated agriculture systems, especially if water is drawn from outside the basin (Scanlon et al. 2005, Lucas and Wendland 2015).

Modelling groundwater recharge is challenging. The scarcity of field observations and spatially explicit parameters can lead to erroneous recharge estimates (Moeck et al. 2020). Also, the validation of simulated recharge rates is often lacking as direct measurements of recharge cannot be obtained at landscape scales – only at the plot scale, for example using lysimeters (von Freyberg et al. 2015). Despite these limitations, complex physically-based hydrologic models can predict the observed recharge with relative accuracy (Moeck et al., 2018). However, simulating large-scale processes is difficult due to long running times and lack of specific data at a fine spatial resolution. Current large-scale models generally oversimplify processes by generalizing relationships between climate and hydrological fluxes or not considering subsurface heterogeneity (Hartmann et al. 2017). In this sense, estimating the potential of groundwater recharge instead of estimating actual recharge rates can be a useful tool to assess the spatial variability of groundwater recharge at the landscape and identify areas with high recharge potential.

Brazil has the ninth highest annual groundwater extraction rate globally and the highest in South America (Instituto Trata Brasil 2019). Main uses of groundwater in the country are domestic supply and agricultural activities (CPRM, 2018). The Brazilian Atlantic Forest biome supplies freshwater (both surface and groundwaters) for more than 125 million people (Joly et al. 2014). The agricultural and urban expansion has been the main drivers of land-use change in the biome. Currently, more than 60% of its area is dedicated to mostly unsustainable agricultural land-uses (Souza et al. 2020). Besides its historical degradation, the biome is experiencing intense forest transformations. Old native forests are being lost, mainly on flatter terrains, and young forests are regrowing, mainly on agriculture's marginal lands (Rosa et al. 2021). These changes can impact the water cycle in different ways, including groundwater recharge patterns. Mapping the spatial variability of groundwater recharge potential is therefore paramount for guiding public polices related to water management, soil conservation, and forest conservation and restoration in the biome.

Here we aim to propose a spatially explicit index to describe the variability of the groundwater recharge potential in the Brazilian Atlantic Forest. For that, we adopted a map algebra approach combining seven parameters that drive groundwater recharge: i) terrain slope; ii) relief; iii) annual precipitation; iv) precipitation seasonality; v) soil type;

vi) clay content; and vii) land use and cover. Similar approaches have been applied in smaller scales to delineate potential areas for groundwater recharge (Neto et al. 2013) and characterize hydrological dynamics within catchments, such as recharge, infiltration, and water storage capacity (Soares et al. 2008, De Menezes et al. 2009, Schechi et al. 2013). Our index incorporates new parameters (rain patterns and soil attributes) and is applied to the entire biome for the first time. To validate our results, we will compare the index values inside and outside the recharge areas of the main aquifer systems in the biome, delimited by the Brazilian National Water Agency (ANA 2007). We hypothesized that values from inside the recharge areas are significantly higher than values from outside these areas.

2- Methods

2.1 - Study area

The Brazilian Atlantic Forest is distributed along a broad latitudinal gradient in the Brazilian coast, covering 112 Mha (Figure 1, IBGE 2019). The landscape is composed of forests remnants and fragments of vegetation within a matrix of degraded areas, pastures, agriculture, and urban areas (Joly et al. 2014). It is under constant pressure as it is home to 72% of the Brazilian population and shelters the biggest cities and the largest industrial centers in the country (Calmon et al. 2009). Despite the historic vegetation loss and fragmentation, the biome presents a great diversity of physiognomies and ecosystems. The altitudes vary from the sea level to 2891 m in elevation. The relief includes buttes (or *chapadas*, in Portuguese), tablelands (or *tabuleiros*, in Portuguese), plateaus, terraces (or *patamares*, in Portugues), depressions, hills, and plains (IBGE 2006). The climate includes tropical, temperate, and arid (Peel et al. 2007), with average annual precipitation ranging from 500 to 3300 mm (Hijmans et. al. 2005). The soils are extremely varied and include types of eutrophic and dystrophic soils, especially Ferralsols (Latossolos in the Brazilian soil classification system) and Luvisols (Argissolos in the Brazilian soil classification system) (IBGE 2001). In addition, seven out of the 12 Brazilian hydrographic regions are in this biome: South Atlantic, Uruguay, Parana, Southeast Atlantic, East Atlantic, São Francisco, and East-Northeast Atlantic.

2.2 - The Groundwater Recharge Index

To build the Groundwater Recharge Index (GR) for the Brazilian Atlantic Forest we used spatially explicit maps of parameters that drive groundwater recharge: i) relief; ii) terrain slope; iii) annual precipitation; iv) precipitation seasonality; v) soil type; vi) clay content; and vii) land use and cover (Table 1). First, we converted the vector images (Relief and Soil type) into a matricial format with 1km of spatial resolution, so the final index could be obtained at the pixel level. Also, the matricial images with resolution higher than 1km were aggregated by the average method (Slope) and the mode method (Land Use and Cover). The Clay content map – that represents the percentage of clay at the topsoil – was built through interpolation of data available at the National Soil Profile Database for Brazil (Cooper et al. 2005). All the images were reprojected to the South America Equidistant Conic projection. Finally, the images were reclassified, and classes were scored according to its recharge potential (where 0 is the minimum potential – no recharge – and 1 is the maximum).

Table 1: Source and original resolution or scale of the parameter maps used to build the GR index.

Parameter	Source	Original resolution or scale
Relief	Brazilian Institute of Geography and Statistics (IBGE 2006)	1:5,000,000
Slope	Shuttle Radar Topography Mission - SRTM (Farr et al. 2007)	90 m
Annual Precipitation	WorldClim database (Hijmans et al. 2005)	1 km
Precipitation Seasonality	WorldClim database (Hijmans et. al. 2005)	1 km
Land Use and Cover	MapBiomas Colection 5 (Souza et al. 2020)	30 m
Clay content	Own elaboration, based on data from (Cooper et al. 2005)	1 km
Soil type	Brazilian Institute of Geography and Statistics (IBGE 2006)	1:5,000,000

Relief settings were divided into five classes and classified according to altitude and slope. Recharge is most pronounced in relatively high and flat relief settings, so these formations received high scores (Table 2). Terrain slope percentages were divided into six classes, that ranged from flat (less than 3% of slope) to steep terrains (more than 75% of slope). Steep slope areas usually present limited storage capacity and favor high overland and internal lateral flows over recharge (Buda 2013). In this sense, low slopes received high scores (Table 2). Annual precipitation and precipitation seasonality were both divided into five classes. Light rain is not expected to contribute to groundwater recharge as evapotranspiration may prevent infiltration below the root zone (Taylor et al. 2013). In contrast, high-intensity precipitation events may exceed the soil's infiltration capacity and lead to greater overland flow, reducing recharge (Buda 2013). High precipitation and low seasonality classes received high scores (Table 2).

Clay content percentages were dived into three classes, as proposed by Cooper et al. 2005. Low clay content soils received high scores as clay reduces soil permeability (Table 2). Soil types were divided into five classes, following the hydrologic soil groups classification proposed by Sartori et al. (2005). This classification considers the rate of water infiltration when the soils are not protected by vegetation, are thoroughly wet, and receive precipitation from long-duration storms. Hydrologic groups associated to high infiltration rates received high scores (Table 2). Land use and cover were divided into seven classes and classified according to the balance between evapotranspiration and infiltration potential. We are not considering water irrigation or uptakes – only the effects of land use on soil properties that increase or decrease water infiltration, percolation, and evapotranspiration. Assuming most agricultural lands in the Brazilian Atlantic Forest have intensive use and traditional management, we considered negative impacts of crops, pasturelands, and urban areas in recharge patterns when comparing to natural areas. Dunes and natural areas with intermediate vegetation density received high scores (Table 2).

Table 2: Scores given to each class for each parameter used to calculate the GR index and the literature consulted.

Parameter	Class	Score	Literature consulted
Relief	Buttes and Tablelands	1	De Menezes et al. 2009, Neto et al. 2013, Soares et al. 2008
	Plateaus	0.8	
	Terraces	0.6	
	Depressions	0.4	
	Hills and Plains	0.2	
Slope (°)	< 3 %	1	Moeck et al. 2020, Neto et al. 2013, Schechi et al. 2013
	3 - 8%	0.83	
	8 - 20 %	0.67	
	20 - 45 %	0.5	
	45- 75 %	0.33	
	>75 %	0.17	
Annual Precipitation (mm/year)	>2000	1	Fu et al. 2019, Moeck et al. 2020
	1500-2000	0.8	
	1000-1500	0.6	
	500-1000	0.4	
	<500	0.2	
Precipitation Seasonality (coefficient of variation)	<50	1	
	50-60	0.8	
	60-70	0.6	
	70-80	0.4	
	>80	0.2	
Land Use and Cover	Grassland, Beach, and Dune	1	Alvarenga et al. 2012, Neto et al. 2013, Santos et al. 2013, Soares et al. 2008
	Savanna	0.86	
	Natural Forest	0.71	
	Flooded Grassland and Swamped Area	0.57	
	Forest Plantation, Agriculture, and Pastureland	0.43	
	Mangrove	0.29	
	Salt Flat and other non-forest formations	0.29	
	Rocky Outcrop, Urban Infrastructure, and Mining	0.14	
	Water bodies	0	
Clay content (%)	<15	1	Cooper et al. 2005
	15-35	0.67	
	>35	0.33	

Table 2 (continued): Scores given to each class for each parameter used to calculate the GR index and the literature consulted.

Parameter	Class	Score	Literature consulted
Soil type	Haplic Ferralsols (Latossolo Amarelo, Latossolo Vermelho-Amarelo), Rhodic Ferralsols (Latossolo vermelho), Umbric Ferralsols (Latossolo Bruno)	1	Fiori et al. 2010, Sartori et al. 2005
	Arenosols (Neossolo Quartzarênico)	0.8	
	Haplic Luvisols (Argissolo Amarelo, Argissolo Vermelho-Amarelo), Rhodic Luvisol (Argissolo Vermlho), Chromic Luvisol (Argissolo Acinzentado), Geric Nitisol (Nitossolo Háplicos), Rhodic Nitisol (Nitossolo Vermelho)	0.6	
	Cambisol (Cambissolo Háplico), Histic Cambisol (Cambissolo Húmico), Fluvisol (Neossolo Flúvico), Podzol (Espodossolo Férrico), Orsteinic Podzol (Espodossolo Ferrocarbico)	0.4	
	Gleysol salic (Gleissolo Sálico), Gleysol (Gelissolo Háplico), Chromic Luvisol (Luvissolo Crômico), Leptosol (Neossolo Litólico), Regosol (Neossolo Regolítico), Luvic Chernozem (Chernossolo Argiluvico), Leptic Chernozem (Chernossolo Rêndzico), Planosol (Planossolo Háplico), Gleyic Planosol (Planossolo Hidromórfico), Alcalic Planosolo (Planossolo Nátrico), Haplic Plinthosol (Plintossolo Háplico), Petric Plinthosol (Plintossolo Pétrico), Drainic Plinthosol (Plintossolo Méssico), Drainic Histosol (Organossolo Méssico), Chromic Vertisol (Vertissolo Crômico), Chromic Vertisol (Vertissolo Ebânico)	0.2	

We subsequently estimated the GR by pixel following equation 1, where *Sr* is the score associated with the relief class, *Ss* is the score associated with the slope class, *Sap* is the score associated with the annual precipitation class, *Sps* is the score associated with the precipitation seasonality class, *Slulc* is the score associated with the land use and cover class, *Sc* is the score associated with the clay content class, and *Sst* is the score associated with the soil type class. Final values were rescaled to vary from zero to one. All geographic analyses were carried out using the free and open-source Geographic Information System QGIS (v. 3.16) (QGIS Development Team 2019).

$$GR = Sr * Ss * Sap * Sps * Slulc * Sc * Sst \qquad eq.1$$

2.3 - Statistical analyses

We compared GR values inside and outside the recharge areas of the main aquifer systems in the biome, delimited by the Brazilian National Water Agency (ANA) (Figure 6). To do that, we randomly sampled 50.000 pixels within the biome using the Point Sampling Tool of the open-source Geographic Information System QGIS (v. 3.16) (QGIS Development Team 2019). We ran the two-sample Kolmogorov-Smirnov test (Siegel 1977) to compare the distribution of GR values of pixels located inside and outside the recharge areas. Zero values (that represent water bodies) were removed from the analysis. This analysis was performed using the "graphics" and "dgof" packages of the open-source statistical software R version 3.6.3 (R Development Core Team 2020).

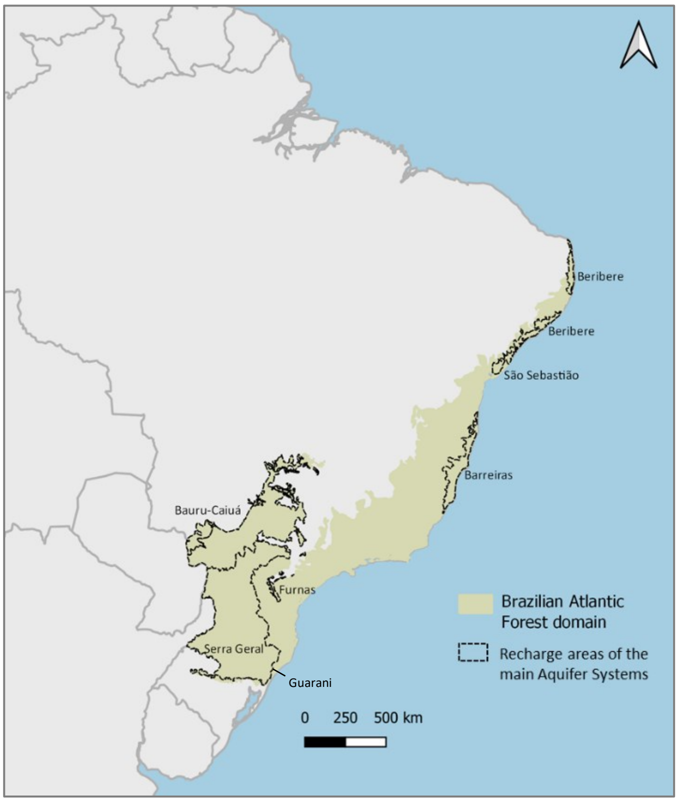

Figure 6: Recharge areas of the main Aquifer Systems in the Brazilian Atlantic Forest (adapted from ANA 2007).

3 - Results

3.1 - Thematic maps reclassification

The maps classification revealed different spatial patterns correlating each parameter to the potential of groundwater recharge in the Brazilian Atlantic Forest. Relief settings with high recharge potential (tablelands and plateaus) were found all over the biome, except in the Southeastern area and the Southern coast, dominated by hills and depressions (Figure 7). High recharge potential slopes (< 8%) were found along the coast and in the Southwestern area (Figure 8). Soil types with high recharge potential (such as Luvisols and Ferralsols) were found all over the biome (Figure 9). Low percentages of clay content in topsoil (< 15%), that represent relatively high recharge potential, were concentrated in the Southwestern area but some patches were found along the coast (Figure 10). Higher annual precipitation and lower precipitation seasonality, that represent relatively high recharge potential, were found predominantly in the Southern area and in the Eastern coast (Figures 11 and 12). Land use and cover classes with high recharge potential were associated with the native vegetation fragments in the biome, especially in grassland and savannas, but also natural forests (Figure 13).

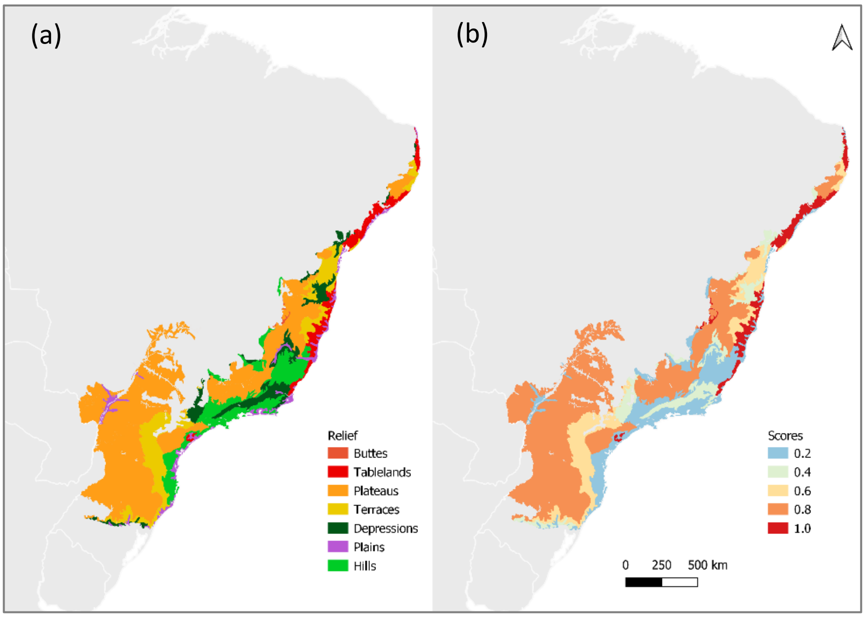

Figure 7: a) relief map of the Brazilian Atlantic Forest (adapted from IBGE 2006); b) reclassification of the relief map, considering the groundwater recharge potential of each class (higher scores mean higher recharge potential).

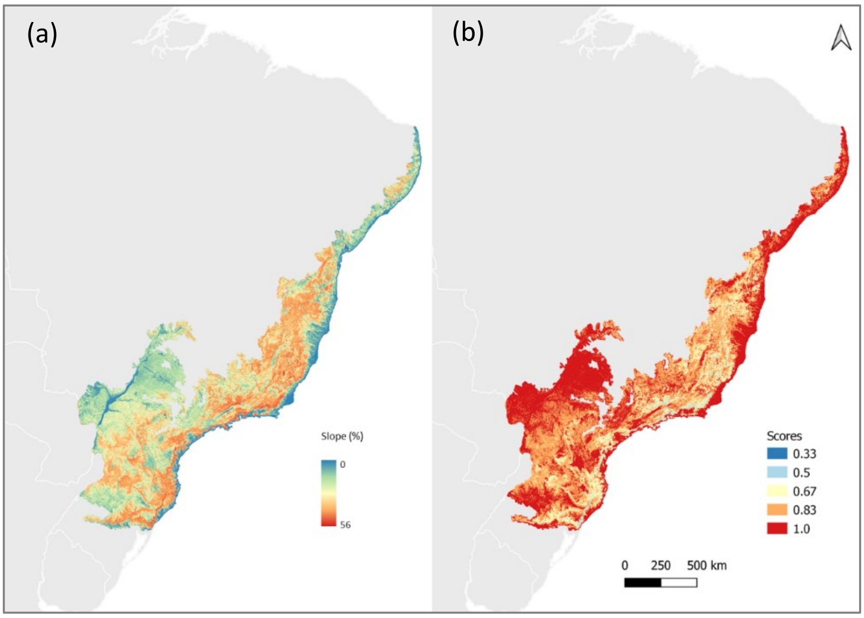

Figure 8: a) slope map of the Brazilian Atlantic Forest (adapted from Farr 2007); b) reclassification of the slope map, considering the groundwater recharge potential of each class (higher scores mean higher recharge potential).

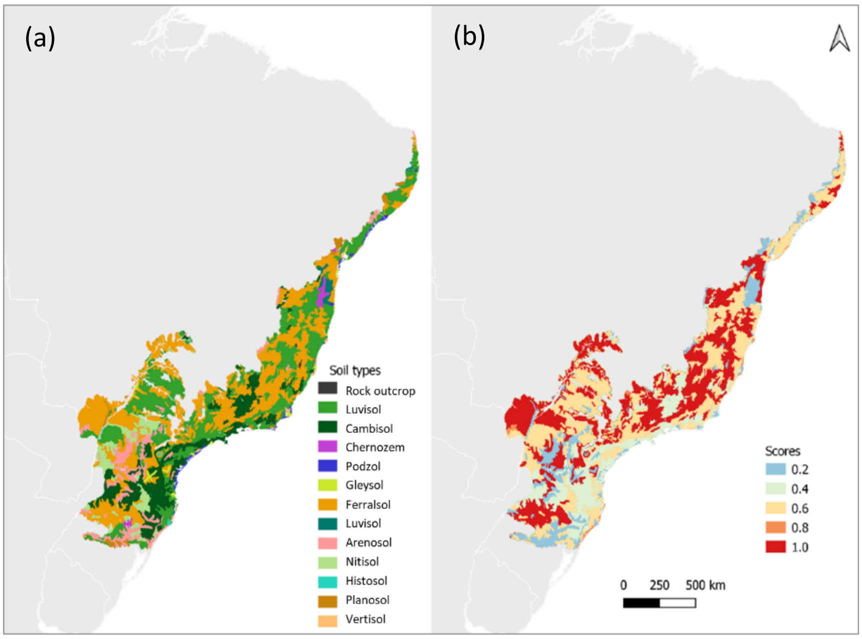

Figure 9: a) soil types map of the Brazilian Atlantic Forest (adapted from IBGE 2001); b) reclassification of the soil types map, considering the groundwater recharge potential of each class (higher scores mean higher recharge potential).

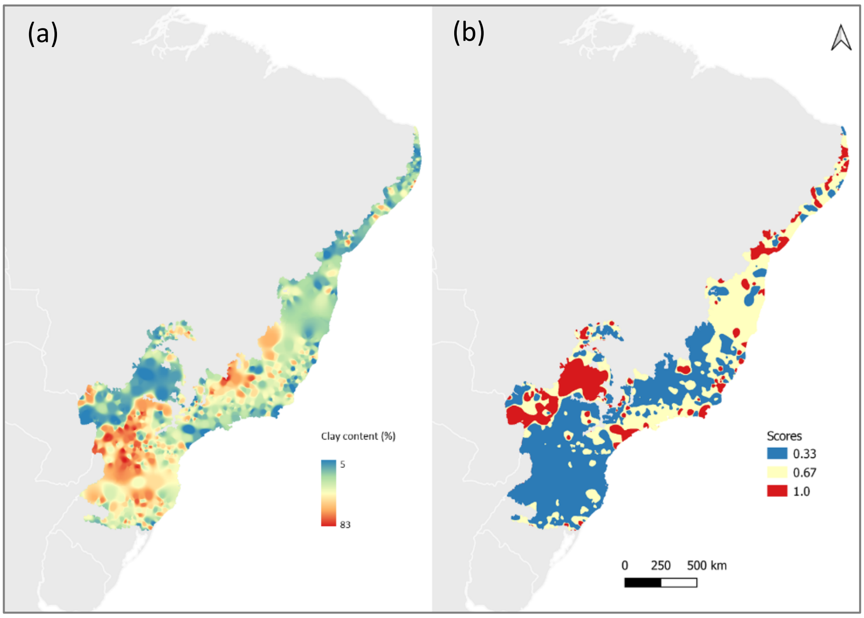

Figure 10: a) clay content map of the Brazilian Atlantic Forest (own elaboration, based on data from Cooper et al., 2005); b) reclassification of the clay content map, considering the groundwater recharge potential of each class (higher scores mean higher recharge potential).

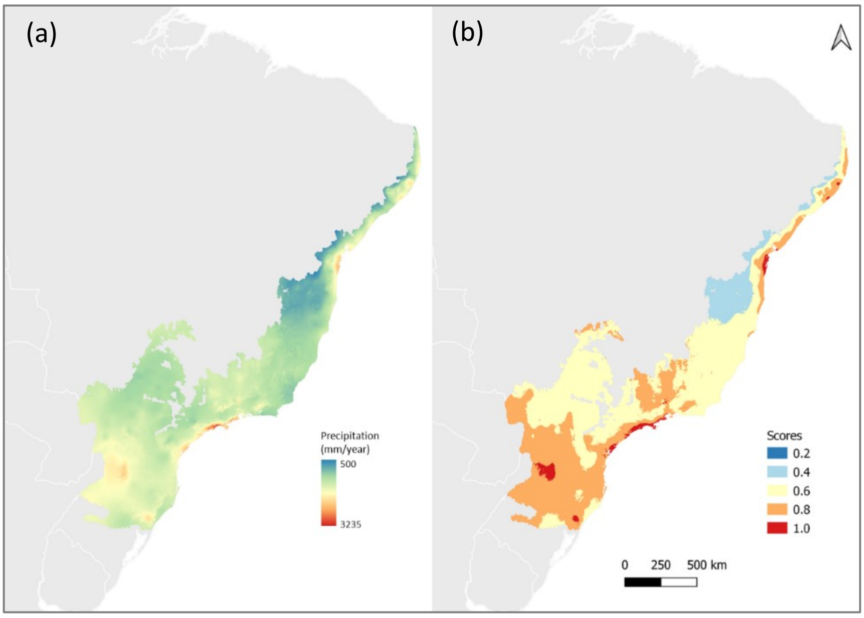

Figure 11: a) annual precipitation map of the Brazilian Atlantic Forest (adapted from Hijmans et. al. 2005); b) reclassification of the annual precipitation map, considering the groundwater recharge potential of each class (higher scores mean higher recharge potential).

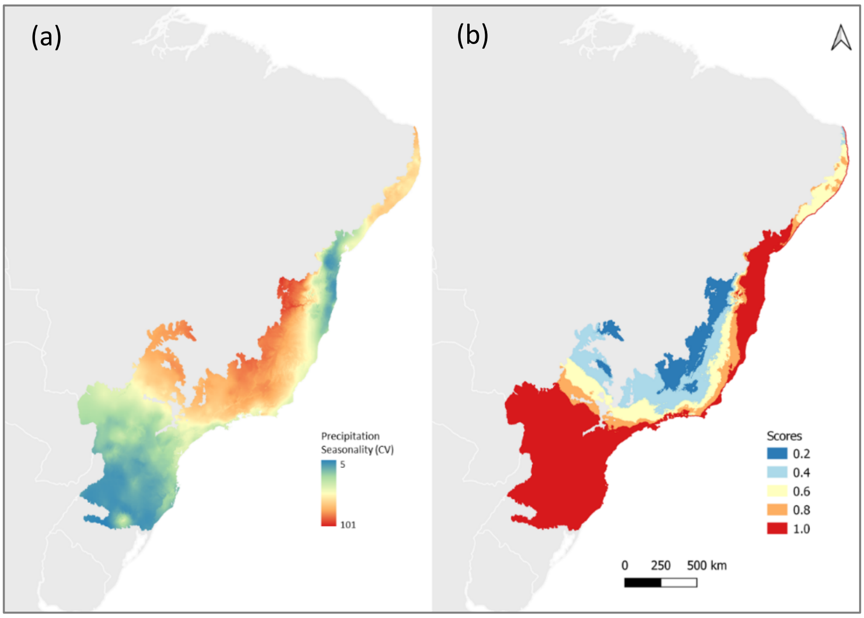

Figure 12: a) precipitation seasonality map of the Brazilian Atlantic Forest, expressed as a coefficient of variation (CV) (adapted from Hijmans et. al. 2005); b) reclassification of the precipitation seasonality map, considering the groundwater recharge potential of each class (higher scores mean higher recharge potential).

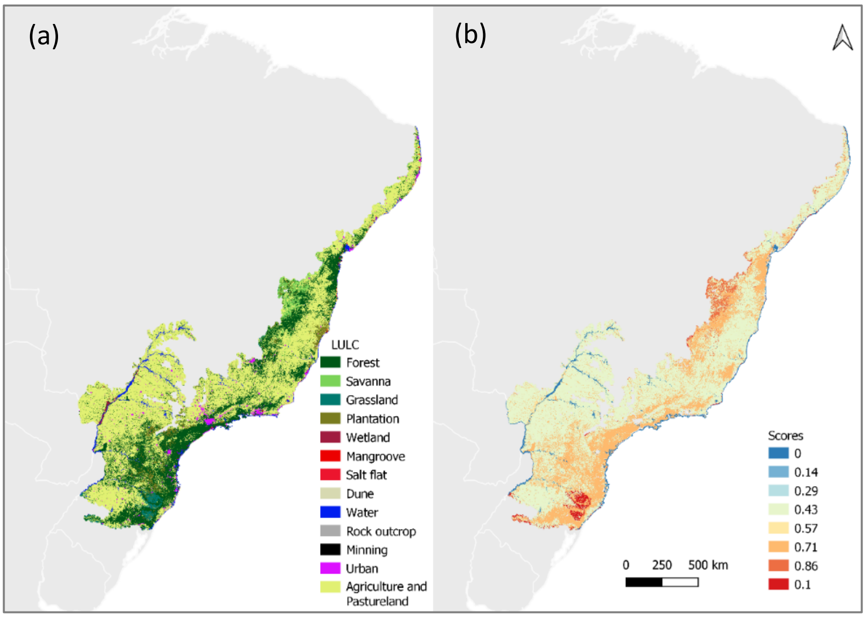

Figure 13: a) land use and cover map of the Brazilian Atlantic Forest (adapted from Souza et al., 2020); b) reclassification of the land use and cover map, considering the groundwater recharge potential of each class (higher scores mean higher recharge potential).

3.2 - Groundwater Recharge spatial variability

The GR index for the Brazilian Atlantic Forest varies from 0.0002 to 1.0, when zero values are removed (i.e., considering only the terrestrial surface), with mean value of 0.084 and standard deviation of 0.085±. The spatial variability of the index indicated a heterogeneous distribution of areas with high potential of recharge. The East Atlantic, Parana, and Uruguay hydrographic regions showed the highest values of GR (Figure 14). The GR values inside the recharge areas were significantly higher than outside areas (mean values of 0.12 and 0.05, respectively; Kolmogorov-Smirnov test: $D=0.45$; $p<0.05$; Figure 15).

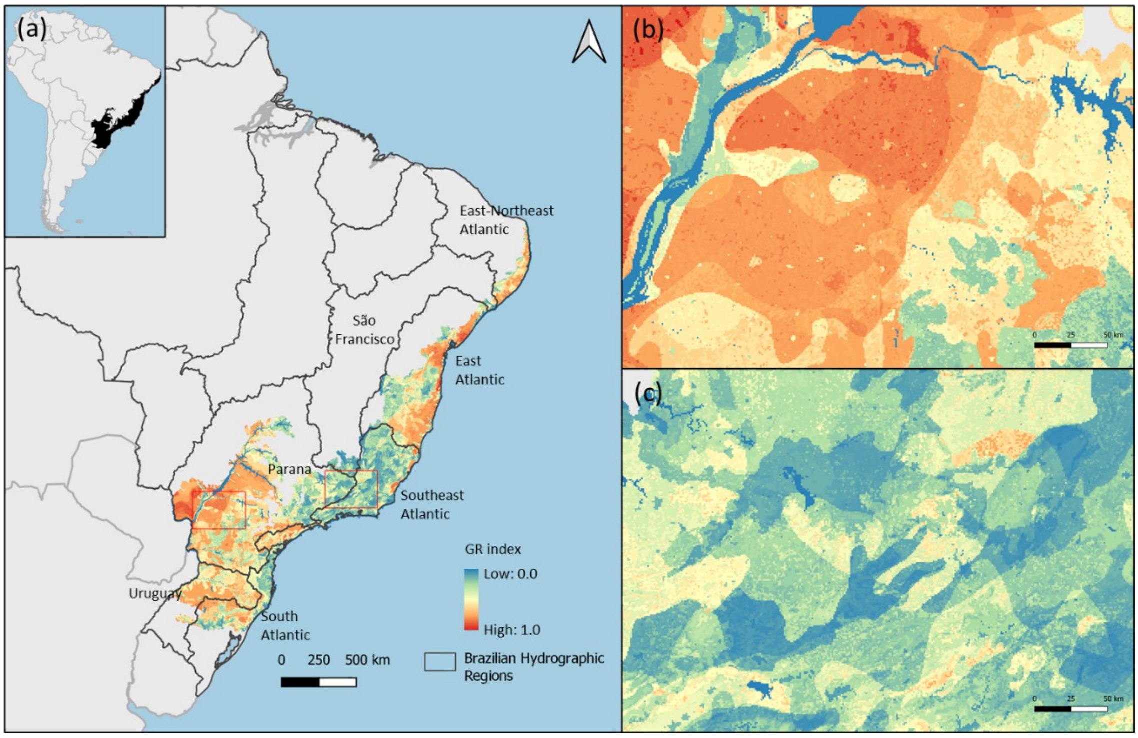

Figure 14: a) spatial variability of the Groundwater Recharge (GR) index in the Brazilian Atlantic Forest. Red squares highlight the expanded views b and c; b) expanded view of an area with high GR values, extracted from the Parana hydrographic region; c) expanded view of an area with low GR values, extracted from the border of Parana and Southeast Atlantic hydrographic regions.

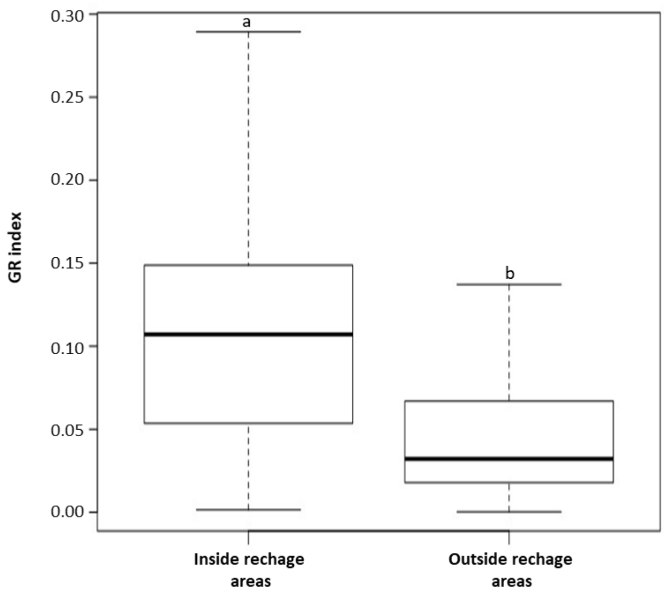

Figure 15: Variation of Groundwater Recharge (GR) index from pixels located inside and outside the recharge areas of the main aquifer systems in the Brazilian Atlantic Forest. Outliers were removed from the boxplot for a better visualization. Letters represent significative difference between groups (Two-sample Kolmogorov-Smirnov test, $p < 0.05$).

4 - Discussion

Mapping groundwater recharge at large scales, such as countries or biogeographic regions is a challenge. Here we developed a spatial explicit index to describe the variability of the groundwater recharge potential in the Brazilian Atlantic Forest, with 1km of resolution. The results suggested that the GR index corresponds to the actual patterns of the biome groundwater recharge, as pixels inside the recharge areas of the main aquifer systems showed significative higher values than pixels outside those areas. Main recharge areas in the Brazilian Atlantic Forest are in the Eastern and Southwestern regions of the biome. High GR values were found at the East Atlantic, Parana, and Uruguay hydrographic regions. East Atlantic basins feed the Barreiras aquifer system, while Parana and Uruguay basins feed the Bauru-Caiuá, Serra Geral, and Guarani aquifer systems. Comparing recharge potential throughout the Brazilian Atlantic Forest can be an instrumental tool in developing public policies related to water management, soil conservation, and forest restoration and conservation in the biome.

Modelling groundwater recharge in large scales is complex and can lead to erroneous recharge estimates (Moeck et al. 2018). However, simple techniques, applied with careful consideration of conceptual models, can be helpful to assess the spatial variability of groundwater recharge. Our results are consistent with the delimitation of the recharge areas in the biome, proposed by the Brazilian National Water Agency (ANA 2007). It suggests that the parameters chosen to build the index reflect the complexity of factors driving groundwater recharge in the Brazilian Atlantic Forest. In addition, the methodology presented is customizable and can be replicated to any geographic region if data are available. It also allows the evaluation of climate or land-use changes impacts on recharge, by replacing the current data for simulated scenarios. For instance, projections of changes in precipitation patterns and anthropogenic pressures (such as urban and agricultural expansion) can be applied to anticipate consequences to the recharge potential.

High GR values were found at the Parana and Uruguay hydrographic regions, two important basins that feed the Guarani aquifer (Foster et al. 2009). Guarani is a transboundary aquifer shared by Argentina, Brazil, Paraguay, and Uruguay, which stands as one of the largest reservoirs of freshwater worldwide (Sindico et al. 2018). Our results reinforce the strategic importance of protecting and restoring these basins to guarantee water security in Brazil and South America. However, it is important to highlight spatial trade-offs between areas with high potential of groundwater recharge and the provision of other water services, especially water quality improvement. Flat areas, especially in high altitudes, favor infiltration and groundwater recharge. On the other hand, forest conservation and restoration in steep slope areas can reduce surface overland flow and sediment exportation to water bodies (Liu et al. 2008). The Southeast Atlantic hydrographic region presented the lowest GR values. In contrast, this area plays a critical role in water supply and hydroelectricity generation for Rio de Janeiro and São Paulo – the two most populated cities in Brazil (Kelman 2015, Hunt. et al. 2018). Conservation and restoration efforts in this area should focus on water quality issues rather than groundwater recharge.

Although the proposed index incorporates several parameters that drive groundwater recharge, some limitations should be highlighted. First, the GR index does not illustrate actual recharge rates and cannot be used to estimate the amount of water that reaches the water table in a given area. Its primary applicability is the comparison of the groundwater recharge potential among different planning units. Secondly, despite the replicability of the index, it is important to notice that the scores given to each parameter must consider regions' particularities. For instance, the recharge potential of forest formations in another biogeographic region can be higher or lower than in the Brazilian Atlantic Forest. Finally, we have not incorporated in our analysis information on the agricultural management practices, which can affect the impacts of crops and pasturelands on groundwater recharge. Depending on the study area, goals, and data availability, these and other parameters, such as temperature patterns or indexes of aridity and topographic wetness, can be incorporated into the equation.

Identifying areas with relatively high groundwater recharge potential is helpful to support policies and programs focused on improving water availability, including payments for ecosystem services, initiatives of forest conservation and restoration, and implementation of agricultural sustainable practices. The smallest planning unit in this study is represented by pixels of 1km of resolution but values can be aggregated to characterize the recharge potential of rural properties, conservation units, watersheds, municipalities, ecoregions, and so on. In addition, optimistic scenarios such as deforestation decrease or forest restoration, can be applied to inform policymakers regarding the benefits of environmental legislation compliance. Considering the positive impacts of forest restoration on groundwater recharge, our results can be used to evaluate the potential of recharge increase in response to forest cover expansion, helping the development of spatial planning strategies for restoration in the Brazilian Atlantic Forest.

Chapter 3 – Optimizing Forest Restoration to Improve Water Services in the Brazilian Atlantic Forest

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Abstract

Scaling up ecosystem restoration actions is the challenge posed to the world by The United Nations Decade on Ecosystem Restoration (2021-2030). Efforts have been made to identify priority areas to be restored in the Brazilian Atlantic Forest – a global restoration hotspot – seeking to enhance biodiversity conservation and climate change mitigation. However, incorporating water issues in prioritization approaches remains a challenge. Here we identify priority areas for restoration in the biome considering water services maximization (groundwater recharge and water quality improvement) and cost reduction. For that, we applied a multicriteria spatial prioritization approach based on linear programming. Our results showed that restoring the biome's legal debt (6% of all converted lands) can improve groundwater recharge potential up to 3.5 times and water quality up to 1.9 times compared to a non-spatial planned restoration scenario. The Compromise solution can deliver a considerable fraction of recharge and water quality benefits at a significantly lower cost, saving up to R$ 53 billion. Forest restoration is considered a key element for environmental policies focused on improving water security worldwide. Our results revealed that substantial water benefits can be achieved in the biome at relatively low restoration costs. This work offers useful insights to guide the Brazilian Atlantic Forest's water and forest management policies.

Keywords: forest restoration, spatial planning, water services, groundwater recharge, water quality, Brazilian Atlantic Forest.

1- Introduction

Ecosystem restoration is recognized as a cross-cutting instrument for achieving the Sustainable Development Goals and the biodiversity, climate, desertification, and land degradation agendas (Abhilash 2021, Mansourian et al. 2021). The negative effects of ecosystem degradation have driven ambitious targets for restoration at national and global levels, reinforced by The United Nations Decade on Ecosystem Restoration, running from 2021 to 2030 (Sewell et al. 2020). Brazil has made an ambitious pledge of 12 Mha of native vegetation restoration to contribute to the Bonn Challenge – a global goal to bring 350 Mha of degraded and deforested landscapes into restoration by 2030 (www. bonnchallenge.org). This restoration commitment is also part of Brazil's pledge to the Paris Climate Agreement (www.unfcc.int) and its National Policy for Native Vegetation Recovery (PLANAVEG). In this sense, the Brazilian Atlantic Forest – one of the world's most threatened biodiversity conservation hotspots – holds great restoration opportunities, being considered a restoration hotspot (Brancalion et al. 2019, Strassburg et al. 2020). New data on vegetation cover in the biome bring hope for achieving national and global restoration commitments (Rezende et al. 2018).

Much has been done in the last decades, as documented by the Atlantic Forest Restoration Pact – a movement created to restore degraded or deforested lands in the biome – but there is still a long way to go (Crouzeilles et al. 2019). The biome is experiencing intense transformations, where some old native forests are being lost and young forests are regrowing extensively, mainly on agriculture's marginal lands (Rosa et al. 2021). Strategic spatial planning can help to achieve restoration commitments by increasing the cost-effectiveness of restoration, as it considers the spatial distribution of benefits and associated costs (Brancalion et al. 2019, Strassburg et al. 2019, 2020, Niemeyer et al. 2020). Efforts have been made to identify priority areas to be restored in the Brazilian Atlantic Forest, seeking to enhance biodiversity conservation and climate change mitigation. It has been demonstrated that strategic spatial planning can triple conservation gains and halve costs (Strassburg et al. 2019). However, incorporating other benefits from restoration in multicriteria prioritization approaches, such as pollination, water resource conservation, and income generation is critical to offering decision-makers multiple options to attend local and regional demands.

Forest restoration is considered a key element for environmental policies focused on improving water security worldwide (Palmer and Filoso 2009, Chazdon et al. 2017, Melo et al. 2020). In the Brazilian Atlantic Forest, it triggers several restoration and conservation initiatives including the Payments for Ecosystem Services programs (Richards et al. 2015, Viani et al. 2019). However, planning forest restoration to tackle water issues is especially tricky, as the relationship between forest restoration and water provision is complex and still unpredictable (Dib et al. in prep; Chapter one). Recent assessments showed that planting trees may reduce water availability locally because they intercept, consume, and transfer water to the atmosphere (Filoso et al. 2017, Zhang et al. 2017, Bentley and Coomes 2020). In contrast, forest restoration can improve several water-related services, such as water quality, flow regulation, and flood mitigation, besides protecting aquatic ecosystems and people relying on them (Ellison et al. 2017, Ellison 2018). Also, restored forests improve soil physical properties that support groundwater recharge and potentially increase local water availability in the long run (Ilstedt et al. 2007).

Although the overall contribution of forest restoration to aquatic ecosystems is well documented, defining priority areas simply by selecting places facing water scarcity can be risky. To incorporate water criteria into forest restoration planning, attention should be paid to hydrologic parameters other than the annual streamflow – considered in most studies that link forest restoration to declining water. For instance, the observation of groundwater recharge can be instrumental in understanding the real effects of forest restoration on water availability, as this compartment feeds surface water bodies, thereby maintaining aquatic ecosystems during dry seasons (Condon and Maxwell 2019). Water quality improvement is another critical issue, considering the lack of access to adequate quantities of good quality water is one aspect of water insecurity (Gunda et al. 2019). However, studies that seeks to identify priority areas for restoration considering water services are underrepresented, especially considering groundwater recharge and water quality, key elements for water security.

Here we aim to identify priority areas to be restored in the Brazilian Atlantic Forest considering water services maximization (groundwater recharge and water quality improvement) and cost reduction (opportunity and implementation costs). Also, we aim to evaluate the synergies and trade-offs among scenarios of maximization of each criterion individually and combined. Finally, we aim to propose a Compromise scenario, that considers all benefits and costs simultaneously. For that, we will apply a multicriteria spatial prioritization approach, based on linear programming.

2 - Methods

2.1 - Study area

The Brazilian Atlantic Forest extends over 112 Mha, covering 15 Brazilian states. It is the most populated biome in the country and provides water for more than 125 million people (Joly et al. 2014). However, remote sensing data showed a reduction of 1,4% of water surface in the last 30 years and a tendency of decrease for the next decades (Mapbiomas 2021). The water quality in the region is affected mainly by the lack of wastewater treatment, the discharge of fertilizers from agriculture and effluents of industrial plants, and the contamination of groundwater (Val et al. 2019). We considered the limits of the biome as established by the Brazilian Ministry of Environment and the Brazilian Institute for Geography and Statistics (IBGE 2019).

2.2 - Spatial planning approach

The spatial planning approach adopted in this study followed the methodology proposed by Strassburg et al. (2019) and consists of five main steps: i) define restoration targets, optimization criteria, and scenarios; ii) develop spatial surfaces of benefits and costs; iii) implement a multicriteria spatial prioritization based on linear programing; iv) quantify benefits and costs in each scenario and evaluate the synergies and trade-offs among them; and v) validate and disseminate the results. Linear programming can find exact solutions that can perform at least 30% better than mainstream Spatial Conservation Planning software (Beyer et al. 2016). It can also be better customized, allowing the incorporation of restoration aspects relevant to different socioecological contexts.

2.2.1 - Restoration target, criteria, and scenarios

In Brazil, the Native Vegetation Protection Law (Law no. 12,651/2012) requires farmers to conserve native vegetation, setting aside a Legal Reserve (LR) that occupies 20% of the property area in the Atlantic Forest. Farmers can offset LR debits either by implementing restoration in their own properties or by financing restoration offsets elsewhere within the biome. This mechanism allows the spatial planning of LR allocation so that restoration can occur at the most cost-effective areas. In this sense, we based our restoration target on the total LR debit estimated to Brazilian Atlantic Forest - circa 5 million hectares (Soares-filho et al. 2014). It represents approximately 6% of all restorable areas of the biome that includes agricultural, silvicultural, and pasturelands. The Native Vegetation Protection Law also designate environmentally sensitive areas as

Areas of Permanent Preservation (APP), aiming to conserve water resources and prevent soil erosion. APPs include both riparian preservation areas that protect riverside forest buffers, and preservation areas at hilltops, high elevations, and steep slopes. Despite the evident importance of these areas in protecting water resources and delivering water services, APP debits were not included in our restoration target as their location is already fixed at the landscape.

Optimization criteria are the benefits and costs the prioritization approach seeks to maximize and minimize, respectively. The benefits of forest restoration to water services are represented by groundwater recharge and water quality improvement. Restoration costs includes the opportunity cost for restoration of the land (the potential loss of revenue from areas being restored) and the cost associated with restoring it, actively or passively (hereafter, implementation cost). We developed scenarios that represent single-criterion solutions (maximization of groundwater recharge, water quality, or minimization of costs), a scenario that considers both benefits regardless the costs, and a 'Compromise' scenario, represented by the maximization of both benefits and minimization of costs simultaneously. Single-criterion solutions deliver the maximum gain of benefits (or the minimum cost), while the Compromise scenario delivers a more cost-effective solution. We also developed a 'Control' scenario, where restoration is uniformly dispersed across all restorable areas, as a benchmark for no spatial prioritization.

2.2.2 - Spatial surfaces of benefits and costs

Groundwater Recharge

The groundwater recharge spatial surface is represented by the potential of forest restoration in increasing the Groundwater Recharge index (GR). The GR is based on seven parameters that drive recharge potential (Dib et al., in prep; Chapter two). To estimate the GR response to forest restoration we simulated the restoration of all restorable areas of the biome, replacing agricultural, silvicultural, and pasturelands by natural forest. The difference between simulated and baseline scenarios represents the potential gain in GR after restoration. We divided the total gain in GR by the percentage of restorable areas in each planning unit (1km-pixel) to estimate the potential of forest restoration in increasing GR per hectare restored (equation 1). To calculate the percentage of restorable areas we used the 30m resolution Mapbiomas land cover dataset, collection

5 (Souza et al. 2020). All geographic analyses were carried out using the free and open-source Geographic Information System QGIS (v. 3.16) (QGIS Development Team, 2019).

$$GRp = \frac{(GRs - GRb)}{RAi} \qquad eq. 1$$

Where, GRp is the potential of forest restoration in increasing the Groundwater Recharge index (GR) per hectare; GRs represents simulated GR; GRb represents baseline GR; and RA represents the percentage of restorable areas in each planning unit i.

Water Quality

The water quality spatial surface is represented by the potential of forest restoration in reducing the Human Footprint on Water Quality index (HFWQ). The HFWQ is an indicator of the potential level of water contamination by human activities (Mulligan 2009). To build the HFWQ for the Brazilian Atlantic Forest, we used the WaterWorld Policy Support System v2.92, hereinafter 'WaterWorld' (Mulligan 2013, van Soesbergen and Mulligan 2018). WaterWorld is a spatial explicit hydrological model that uses remotely sensed and globally available data sets to map water services. WaterWorld can be used to understand the hydrological responses associated with specific activities under current conditions and under scenarios for land use, land management, and climate change. Assuming natural areas have a positive impact on water quality, the proportion of overland flow at a point that is derived from natural areas upstream is thus an indicator of the potential quality of water received.

The HFWQ is the percent of overland flow at any point that fell as rainfall on potentially contaminating land uses upstream, both point (urban, roads, mining, oil, and gas) and non-point (cropland and pastureland). It is calculated by cumulating the downstream overland flow from polluting and non-polluting land uses and expressing the former as a proportion of the total. It is thus a measure of the ecosystem service of dilution of contaminated overland flow from human land uses, by clean overland flow from natural areas. Overland flow is calculated as the downstream cumulated water balance based on rainfall, fog, snowmelt, and actual evapotranspiration. Each land use class has an associated pollution intensity fraction that reflects the usual fractional cover and intensity of contaminant inputs for each land use (Table 3). Different land use types represent various degrees of risk to water resources, with urban and agricultural areas being the land use types most responsible for water quality degradation globally. Agricultural and urban effluents are also the greatest sources of diffuse pollution of Brazilian freshwater systems (Mello et al. 2020). The impacts on water quality are thus the magnitude and distributions of human land uses upstream in relation to where the rainfall falls.

Table 3: HFWQ intensity fractions for different land uses.

Land uses	HFWQ intensity fraction
Mining	0.001
Oil and gas exploration	0.001
Pastureland	0.001
Roads	0.01
Cropland	0.1
Urban Infrastructure	0.1

To estimate the HFWQ response to forest restoration we calculated HFWQ for a baseline and a simulated scenario. To build the baseline scenario we adopted the MODIS land cover dataset, collection 5 (Friedl et al. 2010). To build the simulated scenario, we simulated the restoration of all restorable areas of the biome, such as agricultural, silvicultural, and pasturelands. In WaterWorld, each planning unit (1km-pixel) has a combination of three land-cover types: bare ground, herbaceous cover, and tree cover. These cover types determine the structural properties of vegetation that control evapotranspiration and fog inputs (impacting water quantity). We considered as forested areas the ones that currently have ≥75% tree cover per pixel. In the simulated scenario, all restorable areas were converted to natural forests, with a combination of 85%, 15%, and 0% of tree cover, herbaceous cover, and bare ground, respectively. This combination is the most common found in pixels at the actual forest remnants in the Brazilian Atlantic Forest.

We estimated the HFWQ for both scenarios, the difference between them, and the Sensitivity of HFWQ to tree cover change at the pixel level. The Sensitivity measure is calculated by the fraction of change in HFWQ per change in tree cover (equation 2). After that we estimated the average of Sensitivity per catchment, considering catchments of third order, to minimize the effects of spatial interdependence among pixels. Catchments with higher values of sensitivity represent areas where water quality could be most benefited from forest restoration. We divided the sensitivity of HFWQ to tree cover change by the percentage of restorable areas in each planning unit (1km-pixel) to estimate the potential of forest restoration in improve water quality (i. e., reducing the HFWQ) per hectare restored (equation 3). To calculate the percentage of restorable areas we used the 30m resolution Mapbiomas land cover dataset, collection 5 (Souza et al. 2020). All geographic analyses were carried out using WaterWorld Policy Support System v2.92 (Mulligan 2013) and the free and open-source Geographic Information System QGIS (v. 3.16) (QGIS Development Team 2019).

$$S = \frac{(HFWQs - HFWQb)}{(TCs - TCb)} \qquad eq. 2$$

$$WQp = \frac{S}{RAi} \qquad eq. 3$$

Where, S is the Sensitivity of HFWQ to tree cover change; $HFWQs$ and $HFWQb$ are the Human Footprint on Water Quality in simulated and baseline scenarios, respectively; TCs and TCb are the percentage of tree cover in simulated and baseline scenarios, respectively; WQp is the potential of forest restoration in increasing water quality per hectare; and RA is the percentage of restorable areas in each planning unit i.

Opportunity costs

Opportunity costs represent the potential loss of revenue when productive areas are replaced by natural forests. We estimated opportunity costs of agriculture, livestock, and silviculture production in the Brazilian Atlantic Forest, following the methodology proposed by Crouzeilles et al. (2020), described in equations 4 – 6. We used official information on gross production for permanent agriculture, crops (including crop rotation), logging, milk, eggs, honey, wool, and meat at the municipality level (IBGE 2018a-e). To obtain the combined opportunity cost layer, we used the average between agriculture, livestock, and silviculture values, weighted by the proportion of each land use with respect to the total area of agricultural, pasturelands, and silvicultural lands in the planning unit (1km-pixels). We adopted the 30m-resolution Mapbiomas land cover dataset, collection 5 (Souza et al. 2020) to calculate land use percentages.

$$AO = (Pc + Ac)/Aa \qquad eq.4$$

$$LO = (Me + Mi + Eg + Ho + Wo)/Pa \qquad eq.5$$

$$SO = Tb/Sa \qquad eq.6$$

Where, AO is the opportunity cost of agriculture (R$/km²), Pc and Ac are the gross value of permanent and annual crop yields (R$), respectively, and Aa is the agricultural area (km²); LO is the opportunity cost of livestock (R$/km²), Me, Eg, Ho, and Wo are the gross value of meat, eggs, honey, and wool production (R$), respectively, and Pa is the pastureland area (km²); SO is the opportunity cost of silviculture (R$/km²), Tb is the gross value of timber production (R$), and Sa is the silvicultural area (km²).

Implementation costs

Restoration costs vary widely according to the strategies applied, ranging from lower-cost approaches for natural regeneration (passive or assisted) to higher-cost approaches for active restoration (for example, tree plantings using nursery stock). We calculated implementation costs in the Brazilian Atlantic Forest considering minimum and maximum values of restoration costs estimated to the biome, as a function of the potential for natural regeneration, as described in equation 7. We used the information on restoration costs estimated to the different Brazilian biomes according to the strategy applied and the environmental conditions (Benini & Adeodato 2017). We established costs of 'passive natural regeneration' as the minimum value of implementation cost (R$ 18,500 per km²) and an average between 'planting' and 'enrichment' with nursery-grown seedlings under unfavorable conditions, as the maximum value (R$ 1,699,700 per km²). The potential for natural regeneration in the biome was proposed by Crouzeilles et al. (2020). In this study, the authors adopted environmental and socioeconomic factors as explanatory variables to predict the probability of natural regeneration in the Brazilian Atlantic Forest. Thus, implementation cost will be higher as the potential for natural regeneration is lower.

$$IC = Maxc - ((Maxc - Minc) * Rpi) \qquad eq.7$$

Where IC represents the implementation costs (R$/km²); $Minc$ and $Maxc$ are the minimum and maximum costs of restoration estimated to the biome (R$/km²), and Rp is the potential for natural regeneration to each planning unit i.

2.2.3 - Multicriteria optimization algorithm

To identify the priority areas for restoration, we run a multicriteria optimization algorithm based on Integer Linear Programming (ILP). ILP identifies solutions to maximize the objective function, that determines how much forest to restore in each planning unit (1km-pixels). The objective function (equation 8) aims to maximize benefits (groundwater recharge and water quality improvement) and minimize costs (opportunity and restoration costs). The maximization of the objective function was restricted to the planning unit level, where the proportion of restorable areas represents the sum of agricultural, silvicultural, and pasturelands over the total area. The first constraint ensures that the proportion of the planning unit restored ranges from zero to a maximum value, represented by the proportion of restorable areas in each planning unit (equation 9). The second constraint limits the total area to be restored in the biome, represented by the restoration target (equation 10).

$$\max \sum_{i}^{np} x_i \frac{w_{gr} GRp_i + w_{wq} WQp_i}{OC_i + IC_i} \qquad eq. 8$$

$$\text{subject to } x_i \leq \sum_{j}^{nc} U_{ij} \qquad eq. 9$$

$$\sum_{i}^{np} x_i \leq A \qquad eq. 10$$

Where x is the decision variable representing the proportion of the planning unit i to be restored, np is the total number of planning units, *GRp* and *WQp* are the potential of the planning unit i in improving groundwater recharge and water quality, respectively, *OC* and *IC* are the opportunity and implementation costs of restoring the planning unit i, respectively, parameters w_{gr} and w_{wq} are weights given to each benefit, *U* is the proportion of the anthropogenic use (agricultural, silvicultural, or pastureland) j in each planning unit i, nc is the number of anthropogenic uses classes, and *A* is the total area to be restored (51,700 km^2).

The control scenario uniformly constrain restoration to a fixed proportion of the restorable area in each planning unit. In this case, the parameter x is fixed to 5.9%, that represents the proportion of our restoration target over all restorable areas in the biome. Alternative scenarios involved removal of components of this model (for instance, groundwater-focused solution was created by removing *WQp*, *IC* and *OC* components). To create the Compromise scenario, we tested a few combinations of weights between *GRp* and *WQp* to balancing the gains of both benefits. Also, final values of the input layers (of benefits and costs) were rescaled to vary from zero to one before running the analysis to minimize differences among them. Exact solutions to this linear programming problem were found using the software Gurobi 9.1.1 (www.gurobi.com).

3 – Results

3.1 - Spatial surfaces of benefits and costs

The potential of groundwater recharge increasing with forest restoration varies from 0 to 0.15 (dimensionless quantity), with mean value of 0.04 and standard deviation of $\pm$0.04. The potential of water quality increasing with forest restoration varies from 0 to 0.10 (dimensionless quantity), with mean value of 0.05 and standard deviation of $\pm$0.02. We removed outliers from both layers before running the prioritization analysis. The distinct spatial variability of both indexes indicated a heterogeneous distribution of areas with high potential of recharge and high potential of water quality improvement (Figures 16-c and 17-c). Integrated opportunity costs vary from 2.0 to 5.6 million R$/km², with mean value of 1.2 million R$/km² and standard deviation of $\pm$518,615 (Figure 18-d). Agricultural lands present the highest opportunity costs compared to silvicultural and pasturelands (Figure 18-a-c). Implementation costs vary from 18.5 thousand RS/km² to 1.7 million R$/km², with mean value of 938.9 thousand R$/km² and standard deviation of +332,540 (Figure 19-b).

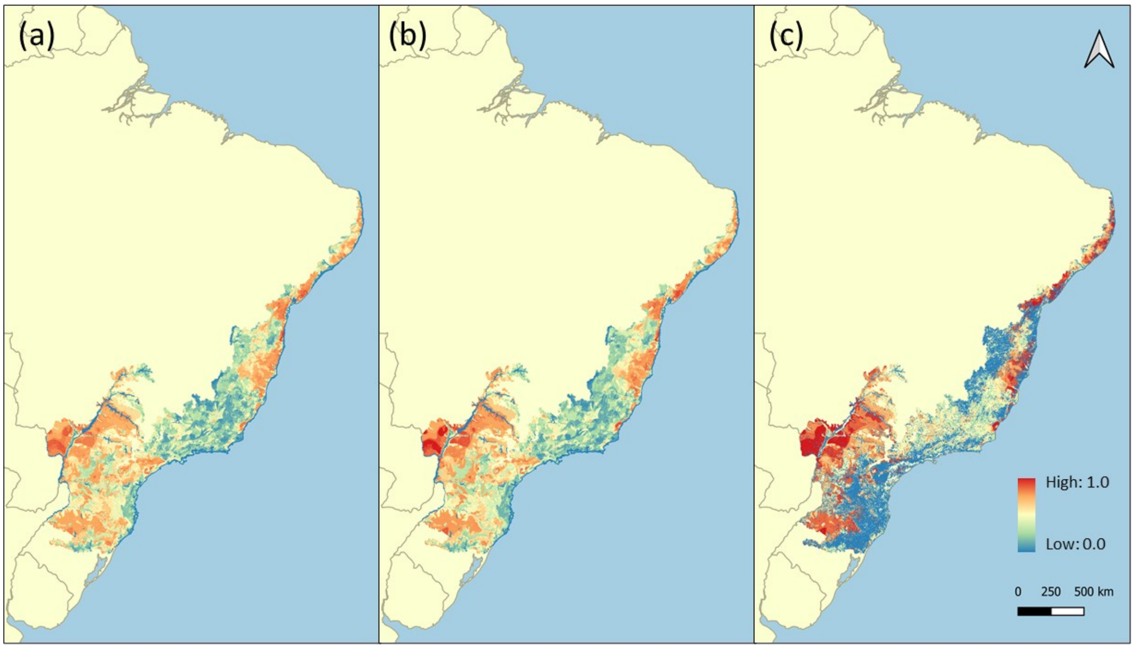

Figure 16: Groundwater Recharge index (GR) in baseline (a) and simulated (b) scenarios, and the potential of GR (GR*p*) increasing with forest restoration per hectare (c). Indexes' values were rescaled to vary from zero to one.

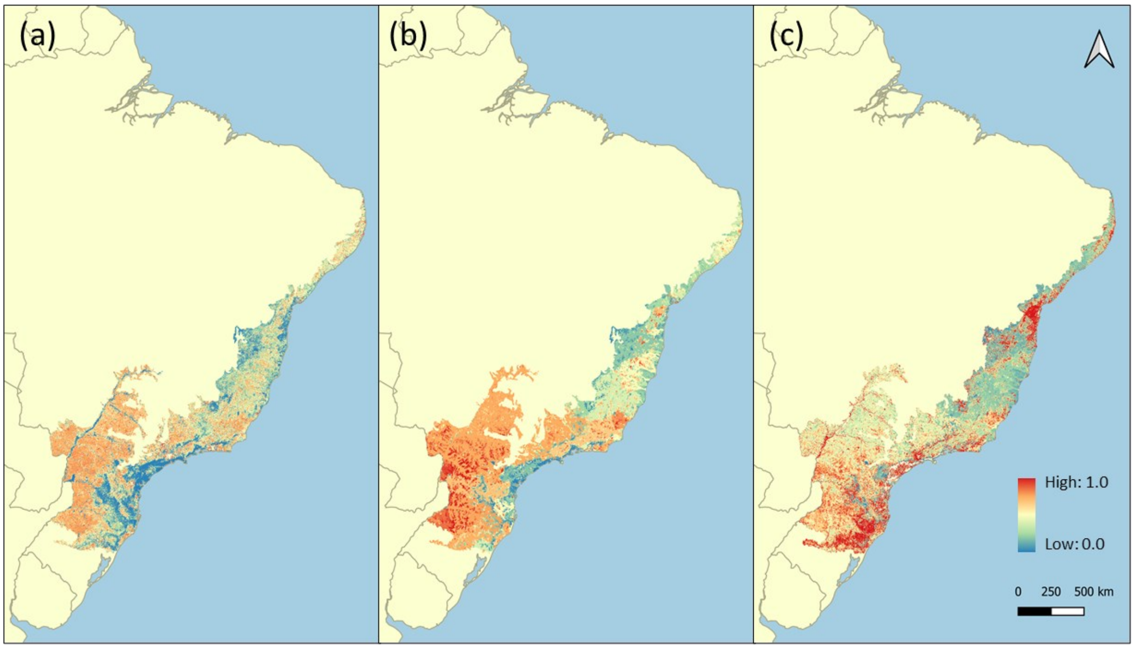

Figure 17: Human Footprint on Water Quality index (HFWQ) per catchment (a), HFWQ Sensitivity to forest restoration per catchment (b), and the potential of HFWQ decreasing (WQ*p*) with forest restoration per hectare (c). Indexes' values were rescaled to vary from zero to one.

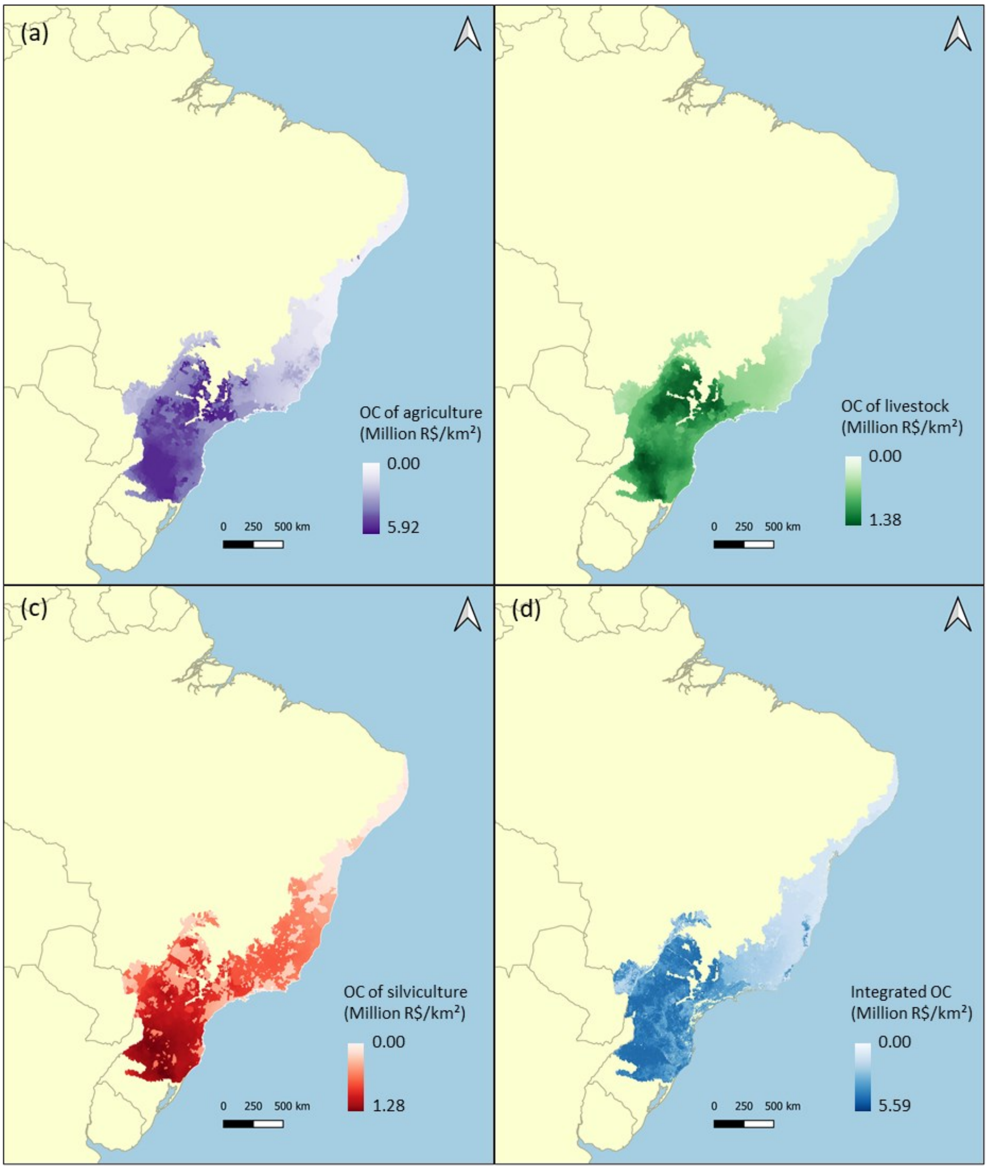

Figure 18: opportunity costs (OC) of agriculture (a), livestock (b), silviculture (c), and the integrated opportunity costs (d).

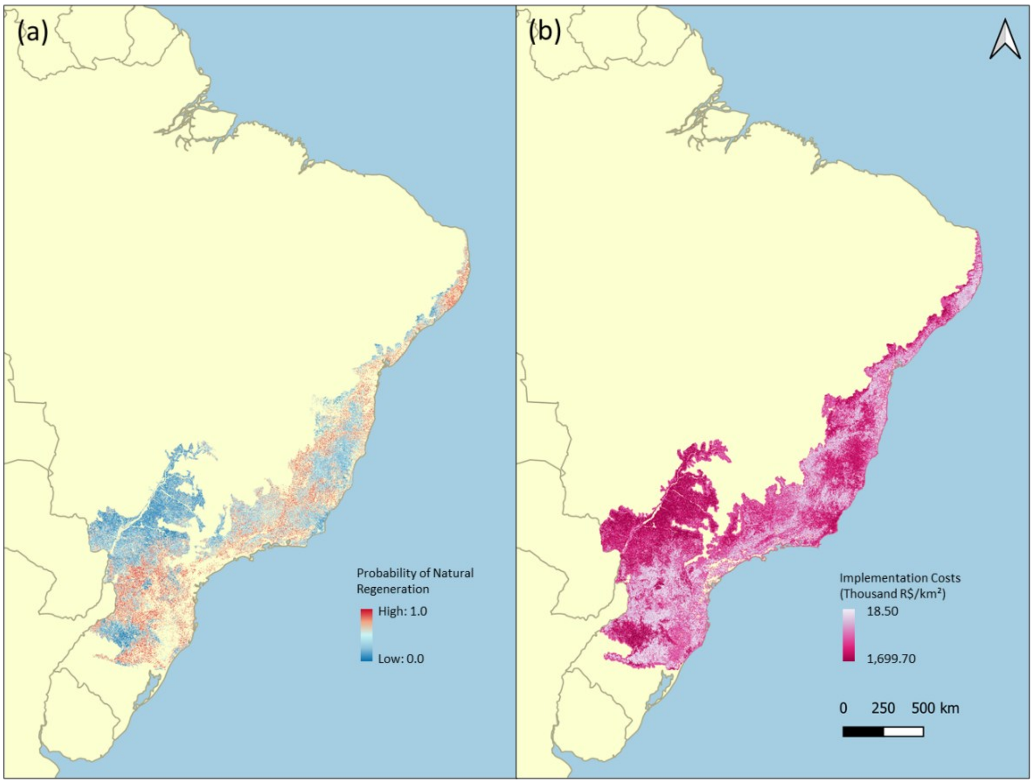

Figure 19: probability of natural regeneration, adapted from (Crouzeilles et al. 2020), and implementation costs of forest restoration (b).

3.2 - Priority areas for restoration

Priority areas for restoration that focus solely on groundwater recharge, water quality improvement, or cost minimization have different spatial patterns (Figure 20 a-c), which result in variable restoration outcomes. The spatial patterns for individual criteria vary considerably, which highlights the role of the joint optimization in capturing synergies (Figure 20-d). Spatial prioritization can reduce restoration costs by 48%, increase groundwater recharge potential 3.5 times, and increase water quality improvement 1.9 times, when single-criterion solutions are compared to the control scenario. The scenario that delivered a substantial fraction of both sets of benefits simultaneously and considerably reduced costs was chosen as the Compromise solution (Figure 21 – scenario v). The Compromise solution reduced costs by 38%, while increased groundwater recharge potential 2.3 times, and water quality improvement 1.1 times, when compared to the control scenario.

The groundwater-focused solution delivers 57% of the potential water quality gains, whereas the water quality-focused solution provides only 15% of the potential groundwater recharge gains (Table 4). The scenario that minimizes costs is considerably cheaper, but performs poorly in environmental terms, especially for groundwater recharge, delivering only 26% of its potential gains (Table 4). On the other hand, the scenario that maximizes both benefits regardless the costs (Benefits only) performs well in environmental terms (Table 4), but is the most expensive solution – approximately R$ 127 billion (Table 5). Although single-criterion solutions do not perform well for the other criteria, the Compromise solution delivers 67% and 57% of potential groundwater recharge and water quality gains, respectively, and 81% of the potential cost reduction (Table 4). The compromise solution costs approximately R$ 74 billion (Table 5), which means a reduction of costs in R$ 45 billion (38% - compared to the control scenario) and R$ 53 billion (42% - compared to the most expensive scenario).

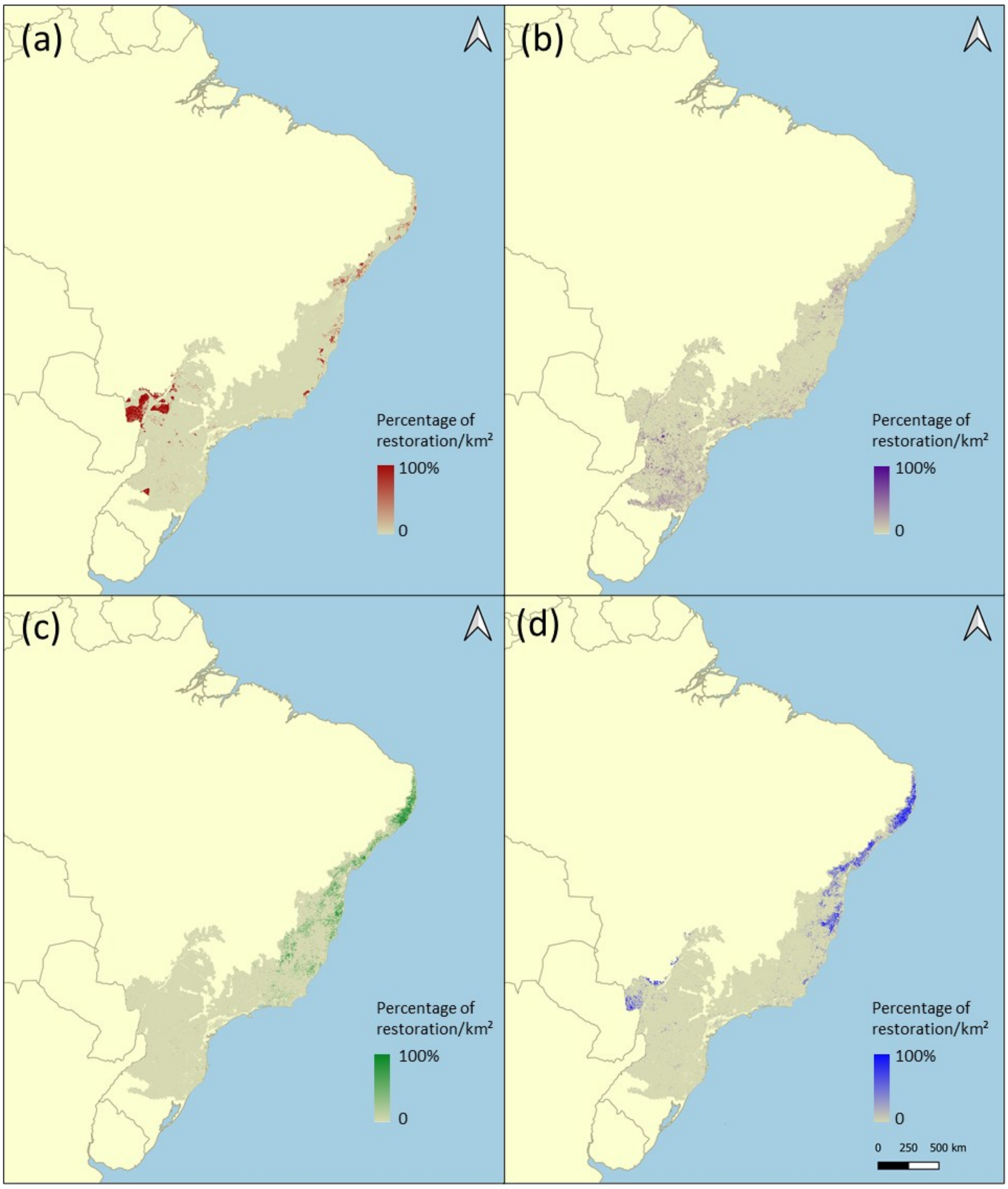

Figure 20: Priority areas for restoration in The Brazilian Atlantic Forest, focused on (a) improving groundwater recharge; (b) improving water quality; (c) reducing costs; and (d) all the three criteria (Compromise solution).

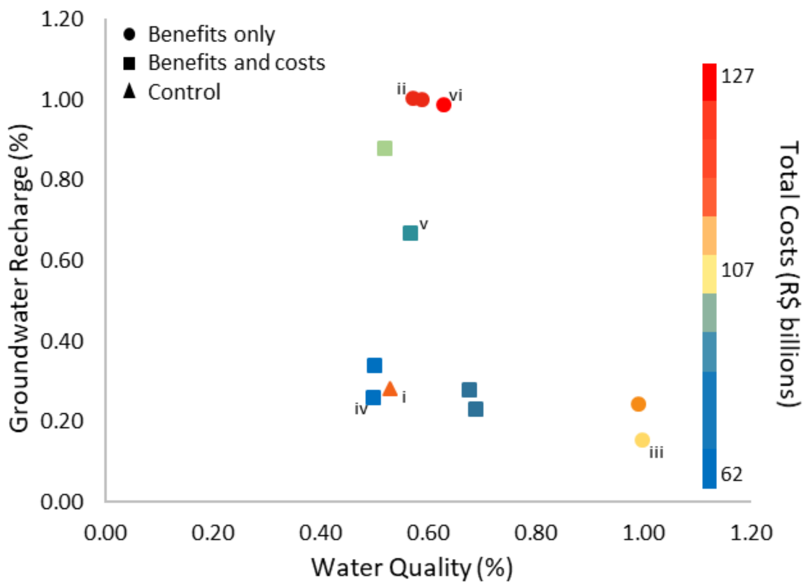

Figure 21: Percentage of benefits gained in different scenarios (groundwater recharge – GR; and water quality - WQ) compared to the maximum potential delivered by single solutions. Dots represent the scenarios, including weight combinations between benefits. Circles are scenarios that considered benefits only (GR and/or WQ), squares are scenarios that considered benefits and costs or costs only, and the triangle is the control scenario. The following scenarios were considered for further comparison in this study: i) Control; ii) Maximum GR; iii) Maximum WQ; iv) Minimum Costs; v) Compromise; and vi) Benefits only.

Table 4: Percentage of benefits gain e costs reduction in the different scenarios, compared to the maximum potential delivered by single solutions, highlighted in bold.

Scenario	Benefits gain		Costs reduction
	GR	WQ	
Maximum GR	**1.00**	0.57	0.05
Maximum WQ	0.15	**1.00**	0.27
Minimum Costs	0.26	0.50	**1.00**
GR and WQ (Benefits only)	0.98	0.63	-0.05
Compromise	0.67	0.57	0.81
Control	0.28	0.53	0.08

Table 5: Restoration costs in the different scenarios. GR is Groundwater Recharge and WQ is Water Quality.

Scenario	Restoration costs					
	Opportunity		Implementation		Total	
	Total area (R$ billions)	R$/ha	Total area (R$ billions)	R$/ha	Total area (R$ billions)	R$/ha
GR and WQ (Benefits only)	65	12,657.52	62	11,920.44	127	24,577.96
Maximum GR	60	11,590.11	61	11,820.99	121	23,411.09
Control	66	12,774.91	53	10,268.27	119	23,043.18
Maximum WQ	65	12,570.03	42	8,169.16	107	20,739.19
Compromise	35	6,831.17	38	7,428.35	74	14,259.51
Minimum Costs	33	6,420.41	29	5,575.75	62	11,996.17

4 – Discussion

Restoring 6% of converted lands in the Brazilian Atlantic Forest could improve groundwater recharge potential up to 3.5 times and water quality up to 1.9 times when strategic planning is applied. Priority areas for restoration focusing on groundwater recharge are concentrated in the regions that feed the main aquifers systems of the biome. In contrast, priority areas focusing on water quality are scattered throughout the landscape. The less costly areas are in the Northeast, which presents relatively low productivity lands and a high probability of natural regeneration, resulting in low opportunity and implementation costs. If benefits and costs are optimized simultaneously, restoration can deliver a substantial fraction of both benefits at a significantly lower cost, saving up to R$ 53 billion. Our results have several implications for public policies related to forest restoration and water management in the biome. Also, our work fills a critical methodological gap, allowing the incorporation of water services into multicriteria prioritization approaches for forest restoration.

According to the groundwater-focused solution, priority areas are primarily concentrated in the Paraná River basin, a critical recharge area of the biome that feeds the Guarani Aquifer – one of the largest reservoirs of freshwater worldwide (Foster et al. 2009, Sindico et al. 2018). This region is covered mainly by productive agricultural and pasturelands with a low probability of natural regeneration, thus presenting relatively high opportunity and implementation costs. In contrast, priority areas defined according to the water quality-focused solution are widely distributed across the biome. This spatial pattern occurs as ecological processes related to water quality, such as soil retention and nutrient filtering, tend to enhance with small restored sites dispersed in the landscape and placed close to the rivers (Mitchell et al. 2015). It also explains why the Control scenario (where restoration is uniformly dispersed across the restorable areas) delivers more than 50% of the potential water quality gains and less than 30% of the groundwater recharge gains (see Table 4).

According to the cost-focused solution, priority areas are concentrated in the Northeast portion of the biome. This region is at the border with the Caatinga biome and presents low agricultural yields due to the soil and climate conditions. The potential for natural regeneration varies in this area but is relatively high, close to forest fragments along the coast. These characteristics result in lower opportunity and implementation costs, but the area performs poorly regarding the benefits evaluated, especially the groundwater recharge. On the other hand, solving the optimization for all three criteria simultaneously provided a considerably cost-effective solution. The Compromise solution can deliver a substantial fraction of recharge and water quality benefits, being R$ 53 bi less costly than the solution focused on both benefits regardless of the cost. It means that the restoration cost per hectare dropped by almost 10 thousand reais. As monetary resources are scarce, this difference is decisive to increase projects feasibility and reduce risks, helping to scale up restoration in the biome.

Although we strived to incorporate aspects of the complex relationship between forest restoration and water services in our analyses, some limitations should be highlighted. First, our methodology does not consider the location of the water services' beneficiaries. It means that our prioritization is based on potential ecosystem services – the overall ecosystem service supply in a given area (Goldenberg et al. 2017). Consider the spatial arrangement of water services consuming areas could improve the restoration outcomes for water management, as areas with high demands would be prioritized. Secondly, as the indexes used to describe the water services are dimensionless, it is impossible to estimate the amount of water that reaches the water tables or is filtered (or 'cleaned') after restoration. Finally, we have not considered the restoration scenarios' local impacts on water quantity or regional impacts on air moisture provision and rain generation. Further research should tackle these two aspects of the water cycle to avoid unintended consequences in terms of water availability and predict potential changes in precipitation patterns in regions downwind of the restored areas.

Despite the identified constraints, our work presents innovative evidence to inform decision-makers and has several implications for public policies related to forest restoration and water management. The maps introduced here illustrate essential prioritization information for restoring the Brazilian Atlantic Forest. Also, the high degree of customization to context-specific environment features and restoration goals allows its replication in any region in the globe if spatial data are available. Finally, the methodology presented here allows incorporating water issues in multicriteria prioritization approaches, expanding the analysis of benefits from forest restoration. Our results show that substantial water benefits can be achieved in the biome at relatively low restoration costs. Considering the recent water crises in the region (Nobre et al. 2016) – that also interfere with power generation and food production – we believe the water narrative can strengthen restoration initiatives and provide a solid argument to scale up restoration in the Brazilian Atlantic Forest.

General Discussion

Although multiple policy initiatives promote forest restoration as a solution to water crises, the prevailing scientific understanding is that forest restoration diminishes water availability on terrestrial surfaces. This controversy might hamper the scaling-up of forest restoration and requires an in-depth examination. This study assessed the linkages between forest restoration and water services to advance the understanding on this front. Also, we proposed a method to add water issues in multicriteria spatial prioritization approaches. The work brings several novelties to the field, such as i) the most up-to-date assessment on forest restoration and water relationships, idealized in collaboration with leading specialists behind some of the recent scientific synthesis and decision support tools, and experts in multiple fields – from soil-water dynamics to atmospheric circulation; ii) the development of a spatially explicit index aiming to describe the variability of the groundwater recharge potential in the Brazilian Atlantic Forest; iii) the assessment of the spatial variability of the human impacts on water quality in the Brazilian Atlantic Forest; and iv) the proposal of priority areas for restoration in the Brazilian Atlantic Forest, considering cost minimization and, for the first time, water services improvement.

Among the primary water management challenges of the future are water scarcity, water pollution, and the impacts of high-intensity rain events, such as floods and heavy siltation. In this sense, it is important to notice whether water yields reduction is a service or a disservice depends on the local context. Therefore, forests conservation and restoration may be one of the most effective strategies for buffering the impacts of both intense storms and droughts. Our debate on forest restoration and water clarifies why estimates in the literature and real-world case studies vary widely and why our ability to predict these interactions is still limited. Long-term and large-scale empirical studies are needed for a more accurate picture of how forest restoration affects the water cycle at global, regional, and local scales. Also, more studies in the tropics could add new insights to the topic, as the hydrological processes in these areas differ from other regions. However, recent scientific synthesis has underrepresented empirical evidence on forest and water relationships in the tropics.

Although predicting impacts of forest restoration on water remains a challenge, restoration initiatives must be conducted based on the knowledge science can provide so far. For instance, spatial planning can be implemented by incorporating aspects of flow regulation and water quality as restoration criteria. Using the Brazilian Atlantic Forest as a study case, we showed that spatial prioritization could increase the cost-effectiveness of forest restoration, considering groundwater recharge and water quality improvement. Also, we identify spatial trade-offs between the forest restoration outcomes for both benefits analyzed. The study led by Strasburg and co-authors [1] also pointed to spatial trade-offs between carbon sequestration and biodiversity conservation benefits from forest restoration in the Brazilian Atlantic Forest. The spatial patterns for individual criteria vary considerably, highlighting the importance of multicriteria approaches and joint optimization in capturing synergies. Including water criteria in spatial prioritization is the main contribution of this study, filling an essential methodological gap.

This work has several implications for public policies related to water management and forest restoration. The Brazilian Ministry of Environment is already adopting our approach as key prioritization information for supporting the National Plan for the Recovery of Native Vegetation (PLANAVEG). Precisely, the water quality-focused solution map is available at the summary for public policies "Prioritizing areas for forest recovery in the Brazilian Atlantic Forest" [2], developed by the International Institute for Sustainability (IIS) in partnership with the World Resources Institute (WRI), and the WRI Brazil. In this summary, we presented priority areas for restoration in the Brazilian Atlantic Forest, considering biodiversity conservation, climate change mitigation, water quality improvement, and cost minimization. In addition, the groundwater recharge-focused solution is being replicated for the Pampa, Pantanal, and Caatinga biomes, in the scope of the project "Conservation, Restoration and Sustainable Management Strategies to Enhance Caatinga, Pampa and Pantanal Biodiversity - Land GEF," leading by the IIS [3].

Brazil leads the world in renewable freshwater resources but faces challenges in managing and conserving freshwater ecosystems due to anthropogenic impacts, divergent regulation, and regional heterogeneities in availability and demand. Therefore, it is crucial to notice that forest restoration is just one of the strategies to fight the water crisis. Finally,

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1- Strassburg, B. B. N. et al. (2019). Strategic approaches to restoring ecosystems can triple conservation gains and halve costs. Nature Ecology and Evolution, 3(1), 62–70.

2- This document is available in Portuguese at: https://www.iis-rio.org/publicacoes/sumario-priorizacao-de-areas-para-recuperacao-florestal-na-mata-atlantica-brasileira/ and was produced in the scope of the project: "Unlocking the Commercial, Financial and Economic Opportunities of Forest and Landscape Restoration in Brazil". For more information, access: https://www.iis-rio.org/en/projects/3315/

3- This project is coordinated by the Department of Protected Areas of the Secretariat for Biodiversity (DAP / SBio) of the Ministry of Environment (MMA), financed with resources from the Global Environment Facility (GEF) and has the Inter-American Development Bank (IDB) as the implementing agency, in addition to the Brazilian Biodiversity Fund (FUNBIO) as executing agency. For more information, access: https://www.iis-rio.org/en/projects/gef-terrestre-conservation-restoration-and-sustainable-management-strategies-to-enhance-caatinga-pampa-and-pantanal-biodiversity/

to incorporate the hydrosolidarity concept – the notion that water management should include considerations of ethics and equity – in the decision-making process regarding forest restoration and water, future studies should focus on: i) understanding local and regional impacts of large-scale restoration scenarios on water; ii) considering the beneficiaries of water services in prioritization approaches; iii) incorporating the avoided costs on water treatment to a better assessment of the total costs associated to forest restoration initiatives; and iv) considering water services together with other restoration benefits (such as biodiversity conservation, climate change mitigation, pollination, and jobs and income generation) to provide multiple options to decision-makers, seeking to fulfill local interests and demands.

Conclusions

Overall, we concluded that:

- To assess the complete impact of forest restoration on water, we must understand how forest restoration affects the water cycle in the long term and beyond the catchment scale. Also, attention must be paid to other hydrological processes, such as flow regulation, groundwater recharge, and water quality improvement rather than the annual streamflow.
- Long-term and large-scale empirical studies are needed for a more accurate picture of how forest restoration affects the water cycle, especially in the tropics, as the hydrological processes in these areas differ from other regions.
- Impacts of forest restoration on water vary according to where and how restoration interventions are implemented. Therefore, spatial planning and the careful consideration of the restoration strategy are critical to guarantee restoration success and avoid unintended consequences.
- Groundwater recharge potential in the Brazilian Atlantic Forest is more pronounced at the Eastern and Southwestern regions of the biome, and precisely, at the East Atlantic, Parana, and Uruguay hydrographic regions.
- There is a spatial trade-off between forest restoration outcomes for groundwater recharge and water quality improvement in the Brazilian Atlantic Forest: the best areas for recharge improvement are primarily concentrated in the Paraná River basin, while the best areas for water quality improvement are widely distributed across the biome.
- Forest restoration can deliver substantial water benefits at relatively low restoration costs in the Brazilian Atlantic Forest if strategic spatial planning is applied.
- The Compromise solution for forest restoration presented in this work can deliver a considerable fraction of recharge and water quality benefits and reduce restoration costs up to R$ 53 bi.
- This work offers useful insights to guide the Brazilian Atlantic Forest's water and forest management policies.

References

Abhilash, P. C. 2021. Restoring the Unrestored: Strategies for Restoring Global Land during the UN Decade on Ecosystem Restoration (UN-DER). Land 10:1–17.

Adams, C., S. T. Rodrigues, M. Calmon, and C. Kumar. 2016. Impacts of large-scale forest restoration on socioeconomic status and local livelihoods: what we know and do not know. Biotropica 48:731–744.

Alvarenga, C. C., Mello, C. R. de, Mello, J. M. de, Silva, A. M. da, & Curi, N. 2012. Índice de qualidade do solo associado à recarga de água subterrânea (IQS RA) na Bacia Hidrográfica do Alto Rio Grande, MG. Revista Brasileira de Ciência Do Solo, 36(5), 1608–1619. doi: 10.1590/S0100-06832012000500025

ANA - Agência Nacional de Águas. 2007. Caderno de recursos hídricos 2 - Disponibilidades e Demandas de Recursos Hídricos no Brasil. https://arquivos.ana.gov.br/institucional/sge/CEDOC/Catalogo/2007/DisponibilidadeEDemandasBrasil.pdf

Anderson, S. H., R. P. Udawatta, T. Seobi, and H. E. Garrett. 2009. Soil water content and infiltration in agroforestry buffer strips. Agroforestry Systems 75:5–16.

Benini, R., and S. Adeodato. 2017. Forest restoration economy.

Bentley, L., and D. A. Coomes. 2020. Partial river flow recovery with forest age is rare in the decades following establishment. Global Change Biology 26:1458–1473.

Beyer, H. L., Y. Dujardin, M. E. Watts, and H. P. Possingham. 2016. Solving conservation planning problems with integer linear programming. Ecological Modelling 328:14–22.

Brancalion, P. H. S., A. Niamir, E. Broadbent, R. Crouzeilles, F. S. M. Barros, A. M. Almeyda Zambrano, A. Baccini, J. Aronson, S. Goetz, J. Leighton Reid, B. B. N. Strassburg, S. Wilson, and R. L. Chazdon. 2019. Global restoration opportunities in tropical rainforest landscapes. Science Advances 5:1–12.

Bruijnzeel, L. A. 2004. Hydrological functions of tropical forests: Not seeing the soil for the trees? Page Agriculture, Ecosystems and Environment.

Bryant, B. P., T. R. Kelsey, A. L. Vogl, S. A. Wolny, D. MacEwan, P. C. Selmants, T. Biswas, and H. S. Butterfield. 2020. Shaping Land Use Change and Ecosystem Restoration in a Water-Stressed Agricultural Landscape to Achieve Multiple Benefits. Frontiers in Sustainable Food Systems 4:1–15.

Buda, A. R. 2013. Surface-Runoff Generation and Forms of Overland Flow. Page Treatise on Geomorphology. Elsevier Ltd.

Calmon, M.; Lino, C.F.; Nave, A.G.; Pinto, L.P.; Rodrigues, R.R. 2009. Pacto pela Restauração da Mata Atlântica: um movimento pela valorização da floresta. In: Fujihara, M.A.; Cavalcanti, R.; Guimarães, A.; Garlipp, R. O Valor das Florestas.

Terra das Artes Editora: Rio de Janeiro. p. 330-335.

Cardinael, R., Z. Mao, C. Chenu, and P. Hinsinger. 2020. Belowground functioning of agroforestry systems: recent advances and perspectives. Plant and Soil 453:1–13.

Carter, T., and C. R. Jackson. 2007. Vegetated roofs for stormwater management at multiple spatial scales. Landscape and Urban Planning 80:84–94.

Chazdon, R. L., P. H. S. Brancalion, D. Lamb, L. Laestadius, M. Calmon, and C. Kumar. 2017. A Policy-Driven Knowledge Agenda for Global Forest and Landscape Restoration. Conservation Letters 10:125–132.

Chazdon, R. L., and M. R. Guariguata. 2016. Natural regeneration as a tool for large-scale forest restoration in the tropics: prospects and challenges. Biotropica 48:716–730.

Condon, L. E., and R. M. Maxwell. 2019. Simulating the sensitivity of evapotranspiration and streamflow to large-scale groundwater depletion. Science Advances 5.

Cooper, M., L. M. S. Mendes, W. L. C. Silva, and G. Sparovek. 2005. A National Soil Profile Database for Brazil Available to International Scientists. Soil Science Society of America Journal 69:649.

CPRM. 2018. SIAGAS: Sistema de Informações de Águas Subterrâneas.

http://siagasweb.cprm.gov.br/ layout/

Crouzeilles, R., H. L. Beyer, L. M. Monteiro, R. Feltran-Barbieri, A. C. M. Pessôa, F. S. M. Barros, D. B. Lindenmayer, E. D. S. M. Lino, C. E. V. Grelle, R. L. Chazdon, M. Matsumoto, M. Rosa, A. E. Latawiec, and B. B. N. Strassburg. 2020. Achieving cost-effective landscape-scale forest restoration through targeted natural regeneration. Conservation Letters 13:1–9.

Crouzeilles, R., E. Santiami, M. Rosa, L. Pugliese, P. H. S. Brancalion, R. R. Rodrigues, J. P. Metzger, M. Calmon, C. A. de M. Scaramuzza, M. H. Matsumoto, A. Padovezi, R. de M. Benini, R. B. Chaves, T. Metzker, R. B. Fernandes, F. R. Scarano, J. Schmitt, G. Lui, P. Christ, R. M. Vieira, M. M. D. Senta, G. A. Malaguti, B. B. N. Strassburg, and S. Pinto. 2019. There is hope for achieving ambitious Atlantic Forest restoration commitments. Perspectives in Ecology and Conservation:3–6.

Dalin, C., M. Taniguchi, and T. R. Green. 2019. Unsustainable groundwater use for global food production and related international trade. Global Sustainability 2:1–11.

Dasgupta, P. 2021. The Economics of Biodiversity: The Dasgupta Review. London:

HM Treasury.

Ellison, D. 2018. From Myth to Concept and Beyond – The BioGeoPhysical Revolution and the Forest-Water Paradigm.

Ellison, D., C. E. Morris, B. Locatelli, D. Sheil, J. Cohen, D. Murdiyarso, V. Gutierrez, M. van Noordwijk, I. F. Creed, J. Pokorny, D. Gaveau, D. V. Spracklen, A. B.

Tobella, U. Ilstedt, A. J. Teuling, S. G. Gebrehiwot, D. C. Sands, B. Muys, B. Verbist, E. Springgay, Y. Sugandi, and C. A. Sullivan. 2017. Trees, forests and water: Cool insights for a hot world. Global Environmental Change 43:51–61.

Ellison, D., L. Wang-Erlandsson, and M. van Noordwijk. 2019. Upwind forests: managing moisture recycling for nature-based resilience. Page Unasylva: An international journal of forestry and forest industries.

Fagan, M. E., J. L. Reid, M. B. Holland, J. G. Drew, and R. A. Zahawi. 2020. How feasible are global forest restoration commitments? Conservation Letters 13:1–8.

Farley, K. A., E. G. Jobbágy, and R. B. Jackson. 2005. Effects of afforestation on water yield: A global synthesis with implications for policy. Global Change Biology 11:1565–1576.

Farr, T.G., Rosen, P.A., Caro, E., et al., 2007. The shuttle radar topography mission. Rev. Geophys., http://dx.doi.org/ 10.1029/2005RG000183

Fennessy, M. S., and J. K. Cronk. 1997. The effectiveness and restoration potential of riparian ecotones for the management of nonpoint source pollution, particularly nitrate. Critical Reviews in Environmental Science and Technology 27:285–317.

Ferraz, S. F. de B., C. B. Rodrigues, L. G. Garcia, C. A. Alvares, and W. de P. Lima. 2019. Effects of Eucalyptus plantations on streamflow in Brazil: Moving beyond the water use debate. Forest Ecology and Management 453.

Filoso, S., M. O. Bezerra, K. C. B. Weiss, S. Filoso, and M. A. Palmer. 2017. Impacts of forest restoration on water yield : A systematic review. PLOS One 12:1–26.

Fiori, J. P. de O., Campos, J. E. G., & Almeida, L. 2010. Variabilidade da condutividade hidraulica das principais classes de solos do estado de goias. Geociencias, 29(2), 229–235.

Foster, S., R. Hirata, A. Vidla, G. Schmidt, and H. Garduño. 2009. Sustainable Groundwater Groundwater Management : Management Concepts Lessons and Tools from Practice The Guarani Aquifer Initiative – Towards Realistic Groundwater Management in a Transboundary Context. GW Mate, The World Bank:28.

Freeze, R.A., & Cherry, J.A. 1979. Ground water. Prentice-Hall, Englewood Cliffs, NJ.

von Freyberg, J., C. Moeck, and M. Schirmer. 2015. Estimation of groundwater recharge and drought severity with varying model complexity. Journal of Hydrology 527:844–857.

Friedl, M. A., D. Sulla-Menashe, B. Tan, A. Schneider, N. Ramankutty, A. Sibley, and X. Huang. 2010. MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets. Remote Sensing of Environment 114:168–182.

Fu, G., Crosbie, R. S., Barron, O., Charles, S. P., Dawes, W., Shi, X., Van Niel, T., & Li, C. 2019. Attributing variations of temporal and spatial groundwater recharge: A statistical analysis of climatic and non-climatic factors. Journal of Hydrology, 568, 816–834. doi: 10.1016/j.jhydrol.2018.11.022

Gageler, R., M. Bonner, G. Kirchhof, M. Amos, N. Robinson, S. Schmidt, and L. P. Shoo. 2014. Early response of soil properties and function to riparian rainforest restoration. PLoS ONE 9.

Gebrehiwot, S. G., D. Ellison, W. Bewket, Y. Seleshi, and B. I. K. Bishop. 2019. The Nile Basin waters and the West African rainforest : Rethinking the boundaries:1–8.

Giambelluca, T. W. 2002. Hydrology of altered tropical forest. Hydrological Processes 16:1665–1669.

Gleeson, T., M. Cuthbert, G. Ferguson, and D. Perrone. 2020. Global Groundwater Sustainability, Resources, and Systems in the Anthropocene. Annual Review of Earth and Planetary Sciences 48:431–463.

Global Footprint Network. 2021. Ecological Footprint. https://www.

footprintnetwork.org/our-work/ecological-footprint/

Goldenberg, R., Z. Kalantari, V. Cvetkovic, U. Mörtberg, B. Deal, and G. Destouni. 2017. Distinction, quantification and mapping of potential and realized supply-demand of flow-dependent ecosystem services. Science of the Total Environment 593–594:599–609.

Gunda, T., D. Hess, G. M. Hornberger, and S. Worland. 2019. Water security in practice: The quantity-quality-society nexus. Water Security 6:100022.

Hartmann, A., T. Gleeson, Y. Wada, and T. Wagener. 2017. Enhanced groundwater recharge rates and altered recharge sensitivity to climate variability through subsurface heterogeneity. Proceedings of the National Academy of Sciences of the United States of America 114:2842–2847.

Healy, R.W. 2010. Estimating Groundwater Recharge. Cambridge University Press.

Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., & Jarvis, A. 2005. Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology*, *25*(15), 1965–1978. doi: 10.1002/joc.1276

Hijmans, R. J., S. E. Cameron, J. L. Parra, P. G. Jones, and A. Jarvis. 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25:1965–1978.

Holl, K. D. 2017. Restoring tropical forests from the bottom up: How can ambitious forest restoration targets be implemented on the ground? Science 355:455–456.

Hunt., J. D., D. Stilpen, and M. A. V. de Freitas. 2018. A review of the causes, impacts and solutions for electricity supply crises in Brazil. Renewable and Sustainable Energy Reviews 88:208–222.

IBGE - Instituto Brasileiro de Geografia e Estatística. 2001. Solos do Brasil 1:5.000.000. https://geoftp.ibge.gov.br/informacoes_ambientais/pedologia/mapas/brasil/solos.pd f

IBGE - Instituto Brasileiro de Geografia e Estatística. 2006. Unidades de Relevo do Brasil 1:5.000.000. https://geoftp.ibge.gov.br/informacoes_ambientais/geomorfologia/mapas/brasil/relevo_2006.pdf

IBGE - Instituto Brasileiro de Geografia e Estatística. 2018a. Produção da Extração Vegetal e da Silvicultura: quantidade produzida e valor da produção na silvicultura, por tipo de produto da silvicultura.

IBGE - Instituto Brasileiro de Geografia e Estatística. 2018b. Produção Agrícola Municipal: área plantada ou destinada à colheita, área colhida, quantidade produzida, rendimento médio e valor da produção das lavouras temporárias e permanentes.

IBGE - Instituto Brasileiro de Geografia e Estatística. 2018c. Pesquisa da Pecuária Municipal: produção de origem animal, por tipo de produto.

IBGE - Instituto Brasileiro de Geografia e Estatística. 2018d. Pesquisa da Pecuária Municipal: Efetivo dos rebanhos, por tipo de rebanho.

IBGE - Instituto Brasileiro de Geografia e Estatística. 2018e. Pesquisa Trimestral do Abate de Animais: quantidade e peso total das carcaças dos animais abatidos, por tipo de rebanho.

IBGE - Instituto Brasileiro de Geografia e Estatística. 2019. Biomas e Sistema Costeiro do Brasil 1:12.000.000. https://www.ibge.gov.br/apps/biomas/

Ilstedt, U., A. Bargués Tobella, H. R. Bazié, J. Bayala, E. Verbeeten, G. Nyberg, J. Sanou, L. Benegas, D. Murdiyarso, H. Laudon, D. Sheil, and A. Malmer. 2016. Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics. Scientific Reports 6:21930.

Ilstedt, U., A. Malmer, E. Verbeeten, and D. Murdiyarso. 2007. The effect of afforestation on water infiltration in the tropics: A systematic review and meta-analysis. Forest Ecology and Management 251:45–51.

Instituto Trata Brasil. 2019. A revolução silenciosa das águas subterrâneas no Brasil: uma análise da importância do recurso e os riscos pela falta de saneamento. Accessed in: http://www.tratabrasil.org.br/images/estudos/itb/aguas-subterraneas-e-saneamento-basico/Estudo_aguas_subterraneas_FINAL.pdf

IPBES. 2018. Summary for policymakers of the assessment report on land degradation and restoration of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Scholes, R., Montanarella, L., Brainich, A., Barger, N., ten Brink, B., Cantele, M., Erasmus, B., Fisher, J., Gardner, T., Holland, T.G., et al., Eds.; Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services: Bonn, Germany.

Joly, C. A., J. P. Metzger, and M. Tabarelli. 2014. Experiences from the Brazilian Atlantic Forest: Ecological findings and conservation initiatives. New Phytologist 204:459–473.

Jones, H. P., P. C. Jones, E. B. Barbier, R. C. Blackburn, J. M. R. Benayas, K. D. Holl, M. McCrackin, P. Meli, D. Montoya, and D. Moreno-Mateos. 2018. Restoration and repair of Earth's damaged ecosystems. In review.

Kelman, J. 2015. Water Supply to the Two Largest Brazilian Metropolitan Regions. Aquatic Procedia 5:13–21.

Keys, P. W., L. Wang-erlandsson, L. J. Gordon, V. Galaz, and J. Ebbesson. 2017. Approaching moisture recycling governance. Global Environmental Change 45:15–23.

Kopittke, P. M., N. W. Menzies, P. Wang, B. A. McKenna, and E. Lombi. 2019. Soil and the intensification of agriculture for global food security. Environment International 132:105078.

Lambin, E. F., H. K. Gibbs, R. Heilmayr, K. M. Carlson, L. C. Fleck, R. D. Garrett, Y. Le Polain De Waroux, C. L. McDermott, D. McLaughlin, P. Newton, C. Nolte, P. Pacheco, L. L. Rausch, C. Streck, T. Thorlakson, and N. F. Walker. 2018. The role of supply-chain initiatives in reducing deforestation. Nature Climate Change 8:109–116.

Latawiec, A. E., B. B. N. Strassburg, P. H. S. Brancalion, R. R. Rodrigues, and T. Gardner. 2015. Creating space for large-scale restoration in tropical agricultural landscapes. Frontiers in Ecology and the Environment 13:211–218.

Liu, X., X. Zhang, and M. Zhang. 2008. Major Factors Influencing the Efficacy of Vegetated Buffers on Sediment Trapping: A Review and Analysis. Journal of Environmental Quality 37:1667–1674.

Lozano-Baez, S. E., M. Cooper, S. F. de B. Ferraz, R. R. Rodrigues, M. Castellini, and S. Di Prima. 2019. Recovery of soil hydraulic properties for assisted passive and active restoration: Assessing historical land use and forest structure. Water (Switzerland) 11.

Lucas, M., and E. Wendland. 2015. Recharge estimates for various land uses in the Guarani aquifer system outcrop area. Hydrological Sciences Journal 61:1253–1262.

Mansourian, S., N. Berrahmouni, J. Blaser, N. Dudley, S. Maginnis, M. Mumba, and D. Vallauri. 2021. Reflecting on twenty years of forest landscape restoration. Restoration Ecology.

Mapbiomas. 2021. Collection 6. Available at: http://mapbiomas.org.

Martinelli, G., Moraes, M.A., 2013. Livro vermelho da flora do Brasil. Centro Nacional de Conservação da Flora, Rio de Janeiro.

Meerveld, H. J. I. Van, J. P. G. Jones, C. P. Ghimire, B. W. Zwartendijk, J. Lahitiana, M. Ravelona, and M. Mulligan. 2020. Forest regeneration can positively contribute to local hydrological ecosystem services : Implications for forest landscape restoration:1–11.

Mello, K. De, R. H. Taniwaki, F. R. de Paula, R. A. Valente, T. O. Randhir, D. R. Macedo, C. G. Leal, C. B. Rodrigues, and R. M. Hughes. 2020. Multiscale land use impacts on water quality: Assessment, planning, and future perspectives in Brazil. Journal of Environmental Management 270:110879.

Melo, F. P. L., L. Parry, P. H. S. Brancalion, S. R. R. Pinto, J. Freitas, A. P. Manhães, P. Meli, G. Ganade, and R. L. Chazdon. 2020. Adding forests to the water–energy–food nexus. Nature Sustainability.

De Menezes, M. D., J. A. Junqueira Jr., C. R. De Mello, A. M. Da Silva, N. Curi, and J. J. Marques. 2009. Hydrological dynamics of two springs, associated to land use, soil characteristics and physical-hydrological attributes at lavrinha creek watershed - Mantiqueira Mountains (MG). Scientia Forestalis/Forest Sciences:175–184.

Metzger, J. P., K. Esler, C. Krug, M. Arias, L. Tambosi, R. Crouzeilles, A. L. Acosta, P. H. Brancalion, F. D'Albertas, G. T. Duarte, L. C. Garcia, J. A. Grytnes, D. Hagen, A. V. F. Jardim, C. Kamiyama, A. E. Latawiec, R. R. Rodrigues, P. G. Ruggiero, G. Sparovek, B. Strassburg, A. M. Saraiva, and C. Joly. 2017. Best practice for the use of scenarios for restoration planning. Current Opinion in Environmental Sustainability 29:14–25.

Mitchell, M. G. E., A. F. Suarez-Castro, M. Martinez-Harms, M. Maron, C. McAlpine, K. J. Gaston, K. Johansen, and J. R. Rhodes. 2015. Reframing landscape fragmentation's effects on ecosystem services. Trends in Ecology and Evolution 30:190–198.

Mittermeier, R.A., Turner, W.R., Larsen, F.W., Brooks, T.M., Gascon, C., 2011. Global biodiversity conservation: the critical role of hotspots. In: Zachos, F.E., Habel, J.C. (Eds.), Biodiversity Hotspots. Springer, Berlin, Heidelberg, pp. 3–22, http://dx.doi.org/10.1007/978-3-642-20992-5 1.

Moeck, C., J. von Freyberg, and M. Schirmer. 2018. Groundwater recharge predictions in contrasted climate: The effect of model complexity and calibration period on recharge rates. Environmental Modelling and Software 103:74–89.

Moeck, C., N. Grech-Cumbo, J. Podgorski, A. Bretzler, J. J. Gurdak, M. Berg, and M. Schirmer. 2020. A global-scale dataset of direct natural groundwater recharge rates: A review of variables, processes and relationships. Science of the Total Environment 717:137042.

Mulligan, M. 2009. The human water quality footprint : agricultural, industrial, and urban impacts on the quality of available water globally and in the Andean region. Proceedings of the International Conference on Integrated Water Resource Management and Climate Change:11.

Mulligan, M. 2013. WaterWorld: a self-parameterising, physically based model for application in data-poor but problem-rich environments globally. Hydrology Research 44:748.

Neary, D. G., G. G. Ice, and C. R. Jackson. 2009. Linkages between forest soils and water quality and quantity. Forest Ecology and Management 258:2269–2281.

Neto, J. O. M., R. M. Chagas, and A. V. M. Júnior. 2013. Delimitação de áreas potenciais de recarga subterrânea na bacia hidrográfica do Rio Siriri , Sergipe 9:1–10.

Niemeyer, J., F. S. M. Barros, D. S. Silva, R. Crouzeilles, and M. M. Vale. 2020. Planning forest restoration within private land holdings with conservation co-benefits at the landscape scale. Science of the Total Environment 717:135262.

Nobre, C. A., J. A. Marengo, M. E. Seluchi, L. A. Cuartas, and L. M. Alves. 2016. Some Characteristics and Impacts of the Drought and Water Crisis in Southeastern Brazil during 2014 and 2015. Journal of Water Resource and Protection 08:252–262.

van Noordwijk, M. 2019. Integrated natural resource management as pathway to poverty reduction: Innovating practices, institutions and policies. Agricultural Systems 172:60–71.

Onda, K., J. Lobuglio, and J. Bartram. 2012. Global access to safe water: Accounting for water quality and the resulting impact on MDG progress. International Journal of Environmental Research and Public Health 9:880–894.

Paglia, A.P., da Fonseca, G.A.B., da Silva, J.M.C., 2008. A Fauna Brasileira Ameac¸ ada de Extinc¸ ão: síntese taxonômica e geográfica. In: Machado, A.B.M., Drummond, G.M., Paglia, A.P. (Eds.), Livro Vermelho Da Fauna Brasileira Ameac¸ ada de Extinção, Biodiversidade. Ministério do Meio Ambiente: Ministério da Educac¸ ão, Brasília, DF, pp. 63–70.

Palmer, M. A., and S. Filoso. 2009. Restoration of ecosystem services for environmental markets. Science 325:575–576.

Peel, M. C., B. L. Finlayson, and T. A. McMahon. 2007. Updated world map of the Koppen-Geiger climate classification. Hydrol. Earth Syst. Sci. 11:1633–1644.

Pennington, D. N., B. Dalzell, E. Nelson, D. Mulla, S. Taff, P. Hawthorne, and S. Polasky. 2017. Cost-effective Land Use Planning: Optimizing Land Use and Land Management Patterns to Maximize Social Benefits. Ecological Economics 139:75–90.

Piffer, P. R., L. R. Tambosi, S. F. de Barros Ferraz, J. P. Metzger, and M. Uriarte. 2021. Native forest cover safeguards stream water quality under a changing climate. Ecological Applications 0:1–12.

Pilotto, I. L., D. A. Rodríguez, S. Chan Chou, J. Tomasella, G. Sampaio, and J. L. Gomes. 2017. Effects of the surface heterogeneities on the local climate of a fragmented landscape in Amazonia using a tile approach in the Eta/Noah-MP model. Quarterly Journal of the Royal Meteorological Society 143:1565–1580.

QGIS Development Team. 2019. QGIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.osgeo.org

R Core Team. 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.r-project.org/index.html

Ramos, A. M., R. C. Blamey, I. Algarra, R. Nieto, L. Gimeno, R. Tomé, C. J. C. Reason, and R. M. Trigo. 2019. From Amazonia to southern Africa: atmospheric moisture transport through low-level jets and atmospheric rivers. Annals of the New York Academy of Sciences 1436:217–230.

Rezende, C. L., F. R. Scarano, E. D. Assad, C. A. Joly, J. P. Metzger, M. Tabarelli, G. A. Fonseca, and R. A. Mittermeier. 2018. From hotspot to hopespot : An opportunity for the Brazilian Atlantic. Perspectives in Ecology and Conservation.

Richards, R. C., J. Rerolle, J. Aronson, P. H. Pereira, H. Gonçalves, and P. H. S. Brancalion. 2015. Governing a pioneer program on payment for watershed services: Stakeholder involvement, legal frameworks and early lessons from the Atlantic forest of Brazil. Ecosystem Services 16:23–32.

Rodríguez-de-Francisco, J. C., B. Duarte-Abadía, and R. Boelens. 2019. Payment for ecosystem services and the water-energy-food nexus: Securing resource flows for the affluent? Water (Switzerland) 11:1–18.

Rosa, M. R., P. H. S. Brancalion, R. Crouzeilles, L. R. Tambosi, P. R. Piffer, F. E. B. Lenti, M. Hirota, E. Santiami, and J. P. Metzger. 2021. Hidden destruction of older forests threatens Brazil's Atlantic Forest and challenges restoration programs. Science Advances 7:1–9.

Santos, J., & Pereira, E. 2013. Carta De Susceptibilidade A Infiltração Da Água No Solo Na Sub-Bacia Do Rio Maracanã-Ma. Cad. Pesq., *20*, 63–71.

dos Santos, J. S., R. Feltran-Barbieri, E. S. Fonte, A. Balmford, V. Maioli, A. Latawiec, B. B. N. Strassburg, and B. T. Phalan. 2020. Characterising the spatial distribution of opportunities and constraints for land sparing in Brazil. Scientific Reports 10:1–11.

Sartori, A., A. M. Genovez, and F. Lombardi Neto. 2005. Classificação hidrológica de solos brasileiros para a estimativa da chuva excedente com o método do serviço de conservação do solo dos Estados Unidos Parte 2 : Aplicação. Revista Brasileira de Recursos Hídricos 10:19–29.

Scanlon, B. R., R. C. Reedy, D. A. Stonestrom, D. E. Prudic, and K. F. Dennehy. 2005. Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. Global Change Biology 11:1577–1593.

Schechi, R. G., R. de C. Bianchi, R. Z. Guimarães, and N. E. Rizzi. 2013. Avaliação da capacidade potencial de armazenamento de água na bacia hidrográfica do rio pequeno, são josé dos pinhais, PR. Floresta 43:191–204.

Sewell, A., S. Van Der Esch, and H. Lowenhardt. 2020. Goals and Commitments for the Restoration Decade. Pbl.

Sheil, D. 2018. Forests, atmospheric water and an uncertain future: the new biology of the global water cycle. Forest Ecosystems 5:19.

Siegel, S. Estatística não-paramétrica para as ciências do comportamento. 1977. São Paulo, McGraw-Hill, Brasil. 348 p.

Sindico, F., R. Hirata, and A. Manganelli. 2018. The Guarani Aquifer System: From a Beacon of hope to a question mark in the governance of transboundary aquifers. Journal of Hydrology: Regional Studies 20:49–59.

Soares-filho, B., R. Rajão, M. Macedo, A. Carneiro, W. Costa, M. Coe, H. Rodrigues, and A. Alencar. 2014. Cracking Brazil ' s Forest Code. Science 344:363–364.

Soares, P. V., S. Y. Pereira, S. S. J. Coelho, G. de P. Bernardes, and S. A. Barbosa. 2008. Mapa de infiltração do alto e médio Vale do Paraíba do Sul com base em elementos do meio físico e na precipitação. Revista Ambiente e Agua 3.

van Soesbergen, A., and M. Mulligan. 2018. Potential outcomes of multi-variable climate change on water resources in the Santa Basin, Peru. International Journal of Water Resources Development 34:150–165.

Souza, C. M., J. Z. Shimbo, M. R. Rosa, L. L. Parente, A. A. Alencar, B. F. T. Rudorff, H. Hasenack, M. Matsumoto, L. G. Ferreira, P. W. M. Souza-Filho, S. W. de Oliveira, W. F. Rocha, A. V. Fonseca, C. B. Marques, C. G. Diniz, D. Costa, D. Monteiro, E. R. Rosa, E. Vélez-Martin, E. J. Weber, F. E. B. Lenti, F. F. Paternost, F. G. C. Pareyn, J. V. Siqueira, J. L. Viera, L. C. F. Neto, M. M. Saraiva, M. H. Sales, M. P. G. Salgado, R. Vasconcelos, S. Galano, V. V. Mesquita, and T. Azevedo. 2020. Reconstructing three decades of land use and land cover changes in brazilian biomes with landsat archive and earth engine. Remote Sensing 12.

Springgay, E., S. C. Ramirez, S. Janzen, and V. V. Brito. 2019. The Forest – Water Nexus : An International Perspective:1–20.

Strassburg, B. B. N., H. L. Beyer, R. Crouzeilles, A. Iribarrem, F. Barros, M. F. de Siqueira, A. Sánchez-Tapia, A. Balmford, J. B. B. Sansevero, P. H. S. Brancalion, E. N. Broadbent, R. L. Chazdon, A. O. Filho, T. A. Gardner, A. Gordon, A. Latawiec, R. Loyola, J. P. Metzger, M. Mills, H. P. Possingham, R. R. Rodrigues, C. A. de M. Scaramuzza, F. R. Scarano, L. Tambosi, and M. Uriarte. 2019. Strategic approaches to restoring ecosystems can triple conservation gains and halve costs. Nature Ecology and Evolution 3:62–70.

Strassburg, B. B. N., A. Iribarrem, and H. L. Beyer. 2020. Global priority areas for ecosystem restoration.

Taylor, R. G., B. Scanlon, P. Döll, M. Rodell, R. Van Beek, Y. Wada, L. Longuevergne, M. Leblanc, J. S. Famiglietti, M. Edmunds, L. Konikow, T. R. Green, J. Chen, M. Taniguchi, M. F. P. Bierkens, A. Macdonald, Y. Fan, R. M. Maxwell, Y. Yechieli, J. J. Gurdak, D. M. Allen, M. Shamsudduha, K. Hiscock, P. J. F. Yeh, I. Holman, and H. Treidel. 2013. Ground water and climate change. Nature Climate Change 3:322–329.

UNECE. 2018. Forests and water: valuation and payments for forest ecosystem services Available at: www.unece.org/ fileadmin/DAM/timber/publications/sp-44- forests-water-web.pdf

UNEP. 2021. Making Peace with Nature: A Scientific Blueprint to Tackle the Climate, Biodiversity and Pollution Emergencies. Nairobi: UNEP. https://www.unep.org/resources/making-peace-nature.

Val, A.L., Bicudo, C. E. M., Bicudo, D. C., Spilki, D. G., Nogueira, I. S, Hespanhol, I., Cirilo, J. A., Tundisi, j. g., Val, P., Hirata, R., Azevedo, S., Crestana, S., & Ciminelli, V. S. T. 2019. Water Quality in Brazil. In: Water Quality in the Americas Risks and Opportunities.

Viani, R. A. G., H. Bracale, and D. Taffarello. 2019. Lessons learned from thewater producer project in the atlantic forest, Brazil. Forests 10:1–20.

Vörösmarty, C. J., P. B. McIntyre, M. O. Gessner, D. Dudgeon, a Prusevich, P. Green, S. Glidden, S. E. Bunn, C. a Sullivan, C. R. Liermann, and P. M. Davies. 2010. Global threats to human water security and river biodiversity. Nature 467:555–561.

Wang-erlandsson, L., I. Fetzer, P. W. Keys, R. J. Van Der Ent, and H. H. G. Savenije. 2018. Remote land use impacts on river flows through atmospheric teleconnections:4311–4328.

Weng, W., L. Costa, M. K. B. Lüdeke, and D. C. Zemp. 2019. Aerial river management by smart cross-border reforestation. Land Use Policy 84:105–113.

Wohl, E., A. Barros, N. Brunsell, N. a. Chappell, M. Coe, T. Giambelluca, S. Goldsmith, R. Harmon, J. M. H. Hendrickx, J. Juvik, J. McDonnell, and F. Ogden. 2012. The hydrology of the humid tropics. Nature Climate Change 2:655–662.

WWAP (United Nations World Water Assessment Programme)/UN-Water. 2018. The United Nations World Water Development Report 2018: Nature-Based Solutions for Water. Paris, UNESCO.

Zhang, M., N. Liu, R. Harper, Q. Li, K. Liu, X. Wei, D. Ning, Y. Hou, and S. Liu. 2017. A global review on hydrological responses to forest change across multiple spatial scales: Importance of scale, climate, forest type and hydrological regime. Journal of Hydrology 546:44–59.