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The Economics of Restoration: Current and Future Paths

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Thesis submitted to the Economics Graduate Program of the Department of Economics of the University of Brasilia in partial fulfillment of the requirements for the degree of Doctor of Economics.

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Economia da Restauração: Caminhos Atuais e Futuros

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Brasília, 20 September 2022.

I dedicate this thesis to my godfather (*in memoriam)* – my gardener in the stars.

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“Melhor do que a criatura,

fez o criador a criação.

A criatura é limitada.

O tempo, o espaço,

normas e costumes.

Erros e acertos.

A criação é ilimitada.

Excede o tempo e o meio.

Projeta-se no Cosmos.”

Cora Coralina

ECONOMIA DA RESTAURAÇÃO: CAMINHOS ATUAIS E FUTUROS

RESUMO

A Economia da Restauração é um campo interdisciplinar que visa integrar conceitos e ferramentas dos campos da economia ecológica e ambiental e da ecologia da restauração. Devido ao grande número de áreas para restauração e à escassez de recursos, há grande demanda para estudos que focam em como aplicar os conceitos e práticas econômicas em programas e projetos de restauração. A contribuição desta tese é incorporar novas ferramentas ao conjunto de recursos do campo da economia da restauração. A primeira ferramenta é a utilização de um modelo robusto de análise de trade-offs em áreas de restauração, que pode ser aplicado no nível macro, nas esferas estadual e federal, para que o governo brasileiro tenha um melhor conhecimento do potencial das regiões do país para alinhar estratégias de restauração da paisagem em larga escala. A segunda ferramenta é o uso da bibliometria para mapear como a economia tem sido incorporada à ciência da restauração, visando refinar o uso de conceitos, modelos e instrumentos econômicos para alcançar melhores resultados nos projetos de restauração. O uso da bibliometria nesta tese também pode ser expandido para outras ciências e destaca a importância da incorporação desta técnica para melhorar a qualidade dos estudos científicos. Cinco capítulos, escritos como artigos individuais, foram desenvolvidos para conduzir a investigação. Uma análise bibliométrica abre a tese mapeando a literatura e identificando os principais tópicos de pesquisa, quais são as bases que deram origem à economia da restauração e os desafios até o momento. A partir da análise bibliométrica, identificou-se o estado da arte de como vem sendo medidos, incorporados e comunicados na literatura os custos e benefícios da restauração. Esse levantamento foi apresentado no capítulo 2. No capítulo 3, voltamo-nos para os principais tópicos que precisam ser abordados para fortalecer os processos de tomada de decisão quando se trata de ações de restauração. E, nos dois capítulos finais, apresentamos dois estudos de caso para investigar como objetivos econômicos e ecológicos podem ser integrados em projetos de restauração para compatibilizar diferentes aspectos das áreas de restauração. De especial interesse foi se as atividades econômicas podem ser implementadas para financiar práticas de restauração e aumentar a resiliência ecológica. Nos trinta anos de desenvolvimento da Economia da Restauração, muito progresso foi feito em relação às práticas ecológicas e econômicas de restauração, suas ferramentas teóricas e práticas. O principal desafio agora é melhorar a comunicação e o compartilhamento de informações entre formuladores de políticas, sociedade, pesquisadores e outros atores envolvidos na restauração. Os benefícios da restauração ainda não são totalmente compartilhados ou compreendidos pela sociedade, especialmente pelas comunidades locais envolvidas nos projetos. Em relação a projetos e programas, equilibrar os resultados ecológicos e econômicos é um desafio que precisa ser abordado no início do planejamento da restauração. A viabilidade econômica dos projetos é tênue dada a complexidade e especificidade da restauração, e há pouco espaço para maximizar apenas os resultados ecológicos, uma vez que as atividades econômicas devem ser incorporadas aos projetos para equilibrar os custos da restauração. Esta tese mostra como a modelagem das prioridades de interesse é crucial e acreditamos que este trabalho é fonte de informação e ferramenta útil para formuladores de políticas e pesquisadores da área.

PALAVRAS-CHAVE: economia da restauração, economia da restauração da paisagem florestal, tomada de decisão, *trade-offs* na restauração, bibliometria.

THE ECONOMICS OF RESTORATION: CURRENT AND FUTURE PATHS

ABSTRACT

The Economics of Restoration is an interdisciplinary field that aims to integrate concepts and tools from the fields of ecological and environmental economics and restoration ecology. Studies that focus on how to make better use of economic concepts and practices in restoration programs and projects are in great demand given a large number of areas in need of restoration, and the scarcity of resources. The contribution of this thesis is to incorporate new tools into the pool of resources of the economics of restoration field. The first tool is the use of a robust model to analyze trade-offs in restoration areas, which then can be applied at the macro level, by state and federal levels, so that the Brazilian government have a better knowledge of the potential of the regions of the country to align strategies for landscape-scale restoration. The second tool is the use of bibliometrics to map how economics has been incorporated into restoration science, aiming to refine the use of economic concepts, models and instruments to achieve better results in restoration projects. The use of bibliometrics in this thesis can be also expanded to other sciences and highlights the importance of incorporating this technique to improve the quality of scientific studies. Five chapters, written as individual papers, were developed to conduct the investigation. A bibliometric analysis opens the thesis by mapping the literature and identifying the main topics of research, what are the basis of the field and the challenges to date. From the bibliometric analysis, we were able to identify the state of the art in how costs and benefits of restoration are being measured, incorporated, and communicated in the literature. This is presented in chapter 2. In chapter 3 we turn to the main topics that need to be further addressed to strengthen the decision-making processes when it comes to restoration actions. And, in the final two chapters, we present two case studies to investigate how economic and ecological objectives can be integrated into restoration projects to account for different aspects of restoration areas. Of special interest was whether economic activities could be used to fund restoration practices to enhance ecological resilience. In the thirty years of development of the Economics of Restoration field, much progress has been made regarding tools and instruments of restoration. The current main challenge is to improve communication and sharing of information between policymakers, society, researchers, and other stakeholders involved in restoration. The benefits of restoration are not yet fully shared with or understood by society, especially by the local communities. Regarding projects and programs, balancing ecological and economic outcomes is a challenge that needs to be addressed early in the planning of restoration. The economic viability of projects is tenuous given the complexity and specificity of restoration, and there is little room to maximize only ecological outcomes since economic activities must be incorporated into projects to balance the costs of restoration. This thesis shows how modelling the priorities of interest is crucial and we believe that this work is a useful tool and information source for policymakers and researchers in the field.

KEYWORDS: economics of restoration, economics of forest landscape restoration, decision-making, restoration trade-offs, bibliometrics.

LA ECONOMÍA DE LA RESTAURACIÓN: CAMINOS ACTUALES Y FUTUROS

RESUMEN

La Economía de la Restauración es un campo interdisciplinario que tiene como objetivo integrar conceptos y herramientas de los campos de la economía ecológica y ambiental y la ecología de la restauración. Los estudios que se centran en cómo hacer un mejor uso de los conceptos y prácticas económicos en los programas y proyectos de restauración tienen una gran demanda dada la gran cantidad de áreas que necesitan restauración y la escasez de recursos. La contribución de esta tesis es incorporar nuevas herramientas al conjunto de recursos del campo de la economía de la restauración. La primera herramienta es el uso de un modelo robusto para analizar los trade-offs en las áreas de restauración, que luego se puede aplicar em el ámbito macro, a niveles estatal y federal, para que el gobierno brasileño tenga un mejor conocimiento del potencial de las regiones del país para alinear estrategias de restauración a escala de paisaje. La segunda herramienta es el uso de la bibliometría para mapear cómo la economía se ha incorporado a la ciencia de la restauración, con el objetivo de refinar el uso de conceptos, modelos e instrumentos económicos para lograr mejores resultados en los proyectos de restauración. El uso de la bibliometría en esta tesis puede ampliarse también a otras ciencias y destaca la importancia de incorporar esta técnica para mejorar la calidad de los estudios científicos. Se desarrollaron cinco capítulos, escritos como artículos individuales, para llevar a cabo la investigación. Un análisis bibliométrico abre la tesis mapeando la literatura e identificando los principales temas de investigación, cuáles son las bases del campo y los desafíos hasta ahora. A partir del análisis bibliométrico, pudimos identificar el estado del arte sobre cómo se están midiendo, incorporando y comunicando en la literatura los costos y beneficios de la restauración. Esto se presenta en el capítulo 2. En el capítulo 3 pasamos a los temas principales que deben abordarse más a fondo para fortalecer los procesos de toma de decisiones cuando se trata de acciones de restauración. Y, en los dos últimos capítulos, presentamos dos estudios de caso para investigar cómo se pueden integrar los objetivos económicos y ecológicos en los proyectos de restauración para dar cuenta de los diferentes aspectos de las áreas de restauración. De especial interés fue si las actividades económicas podrían usarse para financiar prácticas de restauración para mejorar la resiliencia ecológica. En los treinta años de desarrollo del campo de la economía de la restauración, se ha avanzado mucho en cuanto a herramientas e instrumentos de restauración. El principal desafío ahora es mejorar la comunicación y el intercambio de información entre los formuladores de políticas, la sociedad, los investigadores y otras partes interesadas involucradas en la restauración. Los beneficios de la restauración aún no son plenamente compartidos o comprendidos por la sociedad, especialmente por las comunidades locales. Con respecto a los proyectos y programas, equilibrar los resultados ecológicos y económicos es un desafío que debe abordarse desde el principio en la planificación de la restauración. La viabilidad económica de los proyectos es tenue dada la complejidad y especificidad de la restauración, y hay poco espacio para maximizar solo los resultados ecológicos, ya que las actividades económicas deben incorporarse a los proyectos para equilibrar los costos de restauración. Esta tesis muestra cómo modelar las prioridades de interés es crucial y creemos que este trabajo es una fuente de información y una herramienta útil para los formuladores de políticas e investigadores en el área.

PALABRAS CLAVE: economía de la restauración, economía de la restauración del paisaje forestal, toma de decisiones, *trade-offs* en la restauración, bibliometría.

SHORT SUMARY

EXPANDED SUMARY

Thesis Introduction

Worldwide, changes to natural ecosystems as a result of land clearing have been increasing at an alarming rate (RUS et al., 2021). The implication of this is that the majority of the world's species are threatened by a range of risks which include climate change, habitat loss, fragmentation, disease, and invasive species, to cite a few (NG et al., 2014). Ecological restoration is recognized as being required to reduce economic and socioeconomic disruptions that came with ecological degradation, particularly in developing countries (ARONSON et al., 2010), and to achieve sustainable development goals (BIRCH et al., 2010; GROOT et al., 2013; WORTLEY; HERO; HOWES, 2013) (BLIGNAUT; ARONSON, 2020). A decade ago, Ciccarese et al. (2012) alleged that the 20th century observed significant progress in conservation, but that the twenty-first century would be a time of forest restoration.

There is a strong case for conserving the remaining pristine and undisturbed areas (CRISTESCU et al., 2013). Nonetheless, with 6 billion hectares of degraded land worldwide (OECD, 2019), restoration will play an important role. Restoration can deliver multiple benefits and offer new economic and business opportunities.

Restoration is also a strategy for reversing biodiversity losses and increasing the provision of ecosystem services (BULLOCK et al., 2011; WORTLEY; HERO; HOWES, 2013), mitigating climate change (BRANCALION et al., 2021), recovering lost ecosystem goods and services, and it contributes to economic development (BULLOCK et al., 2011; BLIGNAUT; ARONSON; WIT, 2014; BLIGNAUT; ARONSON, 2020), among other benefits (BLIGNAUT; ARONSON; DE GROOT, 2014). At a landscape scale, it can help maximize synergies and manage potential trade-offs between ecosystem services, as well as balance competing demands for land or ocean resources (OECD, 2019).

Restoration is becoming a mainstream research topic and a framework for policy-makers and managers (MAZÓN et al., 2019). The restoration success in providing economic benefits worldwide is linked to its use along with ecosystem services, biodiversity conservation, and non-market services (MENZ; DIXON; HOBBS, 2013), thus making it embedded within an economic framework (BENDOR et al., 2015). According to Iftekhar et al. (2016), a better use of economic instruments, tools, and principles can help with restoration challenges because, as stated by Brancalion et al. (2017), it is likely to fail if merely understood as a narrowly focused environmental activity.

The challenge, however, is much greater than the current efforts from ecologists and economists around the world. Due to limited resources, providing economic opportunities while meeting socio-ecological objectives is one of the challenges when deciding on the priority areas for restoration. The trade-offs between ecological and economic outcomes need to be assessed to better design prioritization frameworks. They are also needed to understand the relationships among socioeconomic goals and the revenue, if any, that could be generated from restoration activities.

At the same time, limited resources mean that restoration projects and plans should include actions able to mitigate multiple threats (NG et al., 2014), and use decision tools and methods to prioritize areas for restoration (SANTIKA et al., 2015). Hence, large areas to restore and scarcity of resources create a great demand for studies that focus on how to make better use of economic concepts and practices in restoration programs and projects.

The Economics of Restoration is an interdisciplinary field which aims to integrate concepts and tools from the fields of ecological and environmental economics and restoration ecology. Yet, better use and understanding of economic aspects and concepts are still needed. The contribution of this thesis is to investigate the advances and to understand the challenges faced by the Economics of Restoration field.

This thesis has five chapters, written as individual articles, each one addressing a particular problem that we believe will advance the economics of restoration science. They are complemented by this Introduction and a Conclusion.

Chapter 1, entitled “An Economics of Restoration literature review using bibliometric analysis”, is a bibliometric analysis of Economics of Restoration using co-authorship, direct citation, co-occurrence, co-citation, and bibliographic coupling networks. The article aims to identify important authors, documents, themes, as well as relevant countries and productive journals within the economics of restoration field of study. This chapter also identifies the economic theories and instruments that have been used to develop what started to be organized as the Economics of Restoration field. We opted to use bibliometric tools since they have been used more and more in recent years and applied in different fields of research. It is also a type of analysis that reduces the selection bias of authors when deciding which documents are important. From the bibliometric analysis, we filtered the documents that address the costs and benefits of restoration and developed the literature review presented in Chapter 2.

Entitled “The costs and benefits of forest landscape restoration: current status and the way forward”, Chapter 2 aims to contribute to the science of Economics of Restoration by identifying the state of the art around benefits, costs and financing methods, frameworks, challenges, and future developments of restoration. As mentioned in this Introduction, a major challenge in the Economics of Restoration is how to integrate ecological and economic concepts and tools. The cost-benefit analysis (CBA) is the most prominent method to decide restoration strategies for projects. Therefore, it is important to understand how benefits and costs have been estimated and the advances of these approaches. We will present and discuss that the published knowledge of benefits has advanced more than costs in the past 20 years, and how the lack of a database on costs influences the design of restoration projects. We also included a comment on investment and the roles of stakeholders.

In the previous chapters, management and governance issues were identified, and specifically, in Chapter 2, we saw that forest resources are very important to the monetary income of rural livelihoods. This implies that restoration projects cannot focus only on the ecological outcomes if long-term objectives are to be achieved. Researchers, practitioners, and policymakers are, then, challenged to decide on the objectives of projects. Identifying the research themes important and influential for the decision-making aspect of restoration is the central objective of Chapter 3, entitled “Is Economics of Restoration helping with decision-making challenges? Insights guided by Bibliometrics”. It also aims to present the key topics that need to be further addressed to strengthen the decision-making processes. Among other results, we confirm that better adjustments of society priorities to be included in restoration projects are needed to scale-up restoration worldwide. A version of this paper was published in the journal Environmental Development in 2021 (APPENDIX A).

Chapters 4 and 5 spatially analyze trade-offs between ecological and economic management objectives relevant for restoration scenarios in Brazil and Australia. Chapter 4 - “Trade-Offs in Restoration Areas for Carbon and Koala Conservation” – addresses the Australian case and has the goal of restoring habitats for koala conservation. Production possibility frontiers (PPF) and attainment levels were derived for various restoration scenarios and prioritization objectives, including potential revenue that could be generated with carbon credits from forest biomass. This chapter is written in collaboration with Oscar Cacho from the University of New England (Australia), from the Sandwich Program in the year 2020.

Finally, Chapter 5, entitled "Carbon and conservation trade-offs in the Brazilian Savannah", aims to spatially analyze trade-offs between ecological and economic management objectives to restore areas under three scenarios: reduction in deforestation susceptibility, reduction in fire risk and reduction in vulnerability of fauna. PPF and attainment levels were derived for various restoration scenarios and prioritization objectives, including potential revenue that could be generated with carbon credits from above and below-ground carbon.

These two chapters highlight how difficult it is to align economic and ecological objectives of restoration. Identifying the potential of each area is essential to design restoration projects. In the Brazilian case, we tested different types of restoration methods, their costs, and the time needed for each one to have an impact. As important, community needs are essential to balance economic and ecological demands from different stakeholders.

Preface

The multifactorial interdependence of ecosystem processes triggers a series of functional interactions that, under shocks and disturbances, make the probability of ecosystem collapse increase as habitat size decreases. Thus, irreversible landscape loss or prohibitive restoration costs are determining factors in the risk of ecological collapse (BARBIER, 2016).

The many functional interactions cited above lead to uncertainties about the responses different habitats would give under restoration management (HODGE; ADAMS, 2016; KANGAS; OLLIKAINEN, 2019; SCEMAMA; LEVREL, 2019). When these natural responses are unclear, it is difficult to calculate the resilience of natural environments (BARBIER, 2016), anticipate the outcome of restoration actions (SCEMAMA; LEVREL, 2019) and ultimately design natural capital markets (TEYTELBOYM, 2019).

Weak and strong sustainability concepts are used to address this uncertainty. According to weak sustainability, there is no difference between natural capital and other forms of capital, and therefore exhausted natural capital can be replaced by other types of capital that are more valuable to humans, as long as the aggregate stock remains the same. On the other hand, strong sustainability advocates that not all forms of natural capital can be replaced, particularly essential goods and services that support human life, which must be kept intact to protect the well-being of future generations (BARBIER, 2016; MUELLER, 2007).

However, the differing weights these views place on the unknown values of natural capital make it difficult to reconcile the debate and, consequently, to decide on a course of action. However, a key aspect is to ensure that the value of the aggregate stock of capital is at least maintained and ideally increased over time (BARBIER, 2016).

Conserving the aggregate stock of capital is important not only from a sustainability point of view. Scemama and Levrel (2019) point out the joint relevance of the specificities of natural, human and manufactured capital contributing to the success of ecological engineering projects that can be expanded to restoration projects based on other approaches.

Concerning natural capital, emphasis is given to the influence of physical and geographical specificities on the complexity of ecosystems. This is because ecosystem functioning and resilience are not only tied to the quality of their ecological components (genetics, communities and interactions between ecosystems) but are strongly influenced by their geographical position. Human capital is also specific, requiring not only technical quality for project design, management and monitoring but also the reputation of those involved to achieve efficient ecological results. Finally, the manufactured capital required for the development of restoration projects can become highly specific when considering local project implementation characteristics – such as tractors and machinery specially adapted for sloping areas, for example (SCEMAMA; LEVREL, 2019).

A natural question that arises in the economic analysis of public goods is the size of the population receiving the benefits of restoration action. The distinction between local, national and even global public goods is directly related to the appropriate level of government funding and intervention. For example, if a local action provides nationally enjoyed benefits, a federal grant may be needed to compensate those who bear the direct costs of restoration as opposed to those who do not incur costs but observe the benefits (LOOMIS, 2000). The free rider problem is especially observed in restoration projects, as pointed out by Brancalion et al. (2017).

The question of who enjoys the benefits extends when there are concerns about intergenerational equity. If this is the objective, the discount rate to be used for a given restoration project should be decided based on the local environmental context (DESVOUSGES et al., 2018). An additional consideration to the mainstream understanding is that the discount rate should be variable and very small (STERN, 2007). This is important because the long periods needed for the development of natural systems, especially forests, can burden a generation with investment costs while another generation accumulates the project benefits (DESVOUSGES et al., 2018).

Identifying who bears costs and benefits is at the heart of discussions about cost-benefit analysis, which is strongly oriented towards defining monetary values. However, Loomis (2000) argued that the spatial dimension of public goods is an empirical issue that, until that moment, was restricted to residents of the state where the public good was located. Hence, according to the author, due to spillovers of environmental benefits, the area of influence of the public good and the consequent inclusion of affected individuals may be more important than the monetary values attributed to the natural resources themselves.

Scemama and Levrel (2019) also point to the fact that the implications of the organizational dimension of restoration were ignored amidst the focus that was given to proving that the benefits outweigh their costs. This can be a setback because, in addition to environmental uncertainties, investments in environmental projects may be subject to institutional and political uncertainties. For example, through changes in legislation or the behaviour of agents that may not be interested in the ecological quality of the project. The authors stress that high transaction costs can be critical in investment decisions and even make restoration projects unfeasible.

The theoretical answer to lowering high transaction costs is to increase the efficiency of the organization (either with market changes or hybrid governance). However, this is not always possible. Thus, the authors approach the reduction of uncertainty as a way to decrease transaction costs. This can be done by: 1) orienting the project towards the ecosystem as a whole and not a specific ecosystem service; 2) limiting project objectives to deal with less ecosystem complexity; and 3) setting an environment of mutual values and trust to reduce behavioural uncertainty among agents (SCEMAMA; LEVREL, 2019). An environment of trust and mutual values is also a factor that can increase social capital, which has been recognized as an important factor for landowner participation and community acceptance in environmental programs (BUCKINGHAM et al., 2020; MORRISON; OCZKOWSKI; GREIG, 2011).

An explanation for the uncertain behaviour of agents is the specificity of restoration investments. These are specialized, long-term investments that will lose their value if redeployed to other uses. Partners want to protect these transactions with a lock-in situation where no one benefits from breaking the relationship. To do so, the transaction costs will be higher, which limits investment incentives (SCEMAMA; LEVREL, 2019). This investment protection is also related to the fact that not all restoration projects will be successful.

Decreasing uncertainty among actors as suggested by Scemama and Levrel is related to deciding the role of markets and governments in restoration as a key step in policy design. The authors state that a hybrid organization is the best approach, complemented by adaptive management that, in the face of uncertainties, makes it possible to readjust project aspects along the way (SCEMAMA; LEVREL, 2019).

The arguments for the success of restoration projects relying not only on market or government action itself were numerous among the articles in this literature review. To cite the ones we identified as most relevant, Brancalion et al. (2017) state that without specific regulations, markets tend to make the most financially profitable decisions at the expense of ecological needs, targeting short-term rather than long-term benefits/gains. Especially for functional structures and natural organisms that depend on several decades for recomposition, such as forests, the long-term perspective is essential.

In addition, the most important sites for biodiversity conservation or restoration, watershed protection and other prospects for ecosystem services generally do not coincide with the ones that maximize profitability with carbon sequestration or timber production. Thus, market-based restoration is likely to be concentrated in lower opportunity costs areas with safe land tenure locations that are usually scattered among small property owners (BRANCALION et al., 2017).

Understanding of the appropriate role of government is still conflicting because some authors advocate that public support could be withdrawn as soon as the project is underway and risks are better known (BRANCALION et al., 2017), while others claim that a public fund is needed for the entire duration of the restoration project or program precisely because of the market failures attributed to environmental goods and services (HODGE; ADAMS, 2016).

As Teytelboym (2019) stresses, the characteristic of ecological complementarity means that ecosystems need to be protected (or consequently restored) as a whole. Thus, careful planning needs to be conducted to avoid inefficient allocation of property rights. According to this author, it is necessary to have an outside incentive or some form of coercion to participate in the market, otherwise even the most sophisticated market design is subject to failure.

To cite an example of the relations between economic development and government action, Zhang et al. (2017) studied the Chinese scenario and concluded that while economic factors have driven deforestation, economic development has also fostered reforestation by providing funding for large-scale forest management and restoration programs. The change of government paradigm and consequent adjustment of forest policies, however, was stimulated particularly by natural disasters. Gradually, the Chinese government shifted from focusing on short-term economic benefits to long-term ecological benefits, investing in services provided by forests such as climate regulation and soil and water conservation (ZHANG et al., 2017).

In this sense, restoration should be understood as an investment in ecosystems similar to other investments in the economy (BARBIER, 2016; DESVOUSGES et al., 2018). This can be done because, according to (DESVOUSGES et al., 2018), it is the flow of services natural resources provide that is valued by people, in the same way, they value financial assets for the flow of money they produce over time. This understanding adds to the ongoing efforts to assess the intrinsic value of cultural benefits and ecosystem services that are still difficult to capture by current economic approaches (BARBIER, 2016), and generally remain unaccounted for in market transactions (HOLMES et al., 2004). This understanding meets a broader view of natural capital as an asset of the economy described by (DASGUPTA, 2008, p. 3):

> "Ecosystems are capital assets. Like reproducible capital assets (roads, buildings, and machinery), ecosystems depreciate if they are misused or overused. But they differ from reproducible capital assets in three ways: (1) depreciation of natural capital is frequently irreversible (or at best the systems take a long time to recover), (2) except in a very limited sense, it isn't possible to replace a depleted or degraded ecosystem by a new one, and (3) ecosystems can collapse abruptly, without much prior warning."

The key restoration principle is to conserve biodiversity in the long-term run, but there is an urge to target results that could bring immediate and direct benefits to people (SILVA; BATISTELLA; MORAN, 2016), especially because there is a complete lack of markets for biodiversity (HUNT, 2008). The accumulated loss of forest is so high that, although efforts to reduce deforestation have been successfully employed in some forest regions, the provision of environmental goods and services will only be safe if reforestation is done in large-scale schemes. Large-scale restoration will also reduce the effects of edge fragmentation and isolation, improving the potential persistence of biodiversity (BRADBY; KEESING; WARDELL-JOHNSON, 2016; BRANCALION et al., 2017).

Holmes et al. (2004) already advocated the importance of scale in the cost-benefit analysis of restoration projects. The authors claim that even a single marginal benefit of a given project can outweigh the total costs of the project. According to them, this is empirical evidence that restoration should be done even partially if funds become scarce once the project started.

Since environmental assessment studies incur high costs, the calculated functions at one primary study site began to be replicated in other target sites under the same policy, implicitly assuming perfect transfer between sites. This process, however, may lead to several errors, as spatial and individual heterogeneities mean that values are rarely transferable between different locations (DE VALCK et al., 2017). Teytelboym (2019) exemplify that in the case of carbon trading, a tonne of CO2 emitted in different parts of the world has the same effect on global temperature, but this is not the case when dealing with ecosystems and biodiversity since there is no perfect substitution to what is already lost.

De Valck et al. (2017) also introduce the perception of individuals as relevant, especially in valuation studies, where the perception of nature among respondents is conceived from their local culture and experiences. Thus, social and cultural contexts must also be taken into account when adapting the restoration project to its place of implementation (HODGE; ADAMS, 2016; SCEMAMA; LEVREL, 2019).

In defining priority areas for investment, De Valck et al. (2017) propose that surrogate sites should not only be evaluated based on their direct use values, as is usually done - especially in analyses that integrate GIS tools - but that the full spectrum of direct, indirect, use and non-use of nature needs to be included. His empirical study found that the presence of nearby surrogate sites affected both positively and negatively the same sample of individuals, due to different perceptions between values of use and non-use of nature. This suggests that the spatial context is highly driven by individual-specific characteristics (DE VALCK et al., 2017).

However, it is a challenge to persuade multiple actors and landowners in a landscape to obtain sufficient restoration to generate economies of scale. The market can be killed if an ecosystem-specific service takes too long to be generated by market-driven restoration projects. One option to circumvent this risk is to work with landowners on a smaller scale to find fast-growing native species that give faster returns while increasing the diversity of restored land (BRANCALION et al., 2017). Morrison et al. (2011) stress that understanding and increasing landowner participation in incentive programs for environmental improvement is crucial from an ecological point of view and important to achieve the economic goals of efficiency and equity of the project.

Planning for a project to deliver economic returns quickly enough to sustain the market not only strengthens the participation of landowners but can be a way to reconcile the debate between the long-term needed restoration activities and the financial mainstream of short-term contracts. According to Hodge (2019), not only the long-term but also the *ex-ante* uncertainty of investments in natural capital still challenge the conventional logic of projects with predefined periods and goals. Hodge also stresses the importance of an environment of trust between actors for the success of investments, an aspect already discussed earlier in this paper.

Still, regarding affected individuals, it is necessary to understand how people differentiate between the place of study and the place of policies, as their preferences will be influenced by these differences. In addition, the eligibility of substitute sites concerning the attributes they possess should be examined, which contributes to their relative attractiveness in an investment decision. Ideally, individuals' knowledge and perception should also be explored to define what can be considered a substitute for nature (DE VALCK et al., 2017).

Holmes et al. (2004) pointed to the challenge that ecological economists have to distinguish between ecosystem science and what people value, to improve the communication of complex ecological dynamics in economic valuation studies. As reinforced by Buckingham et al. (2020) the success of restoration relies on people and how they are connected with the surrounding ecosystem. In this sense, adjusting project goals and people's priorities in the same direction increases the positive results of restoration.

Moving forward, Brancalion et al. (2017) add that restoration activities and commodity production and infrastructure should receive the same type of incentives from markets and governments. Restoration can alleviate poverty, generate employment and income, and provide environmental goods and services to society, and it is likely to fail if merely understood as a narrowly focused environmental activity.

Finally, Moreno-Mateos et al., (2012) state that the overall loss of ecosystem function and structure will increase if current restoration efforts are used to justify further degradation. Their study focuses on wetlands, but we see no reason to believe that this would be any different for other ecosystems. Zhang et al. (2017) add that, from the Chinese experience, other countries shouldn't take for granted the model of degrading first and restoring later, as was done in that country.

The diversity of nature's goods and services means that the main challenge is to understand tradeoffs and synergies between the options in terms of ecological and financial returns (AGER et al., 2017). Additionally, restoration actions are no substitutes for conservation actions, they are complementary. However, it must be recognized that restoration and conservation may compete for resources. Where this happens, funding for traditional conservation actions should be secured to preserve species and ecosystems that are not covered by restoration (BRANCALION et al., 2017).

Blignaut et al. (2014, 2020) state that the establishment of a restoration culture begins with the recognition that through effective ecological restoration practices and related activities, it is possible to delay and even reverse the loss of at least some forms of natural capital and thereby improve the quality, quantity and flow of ecosystem services to people while delaying the alarming loss of biodiversity triggered by human activities.

Chapter 1 – A Bibliometric Analysis of the Economics of Restoration Field

1 Introduction

Bibliometrics is a method for monitoring, measuring, and studying all kinds of bibliographic data (GLÄNZEL, 2003; JOSÉ DE OLIVEIRA et al., 2019; LIU et al., 2019). The visualization of bibliometric networks is used to quantitatively analyze a given field of interest (VAN ECK; WALTMAN, 2014). Detailed information about the past, present and trends in academic literature can be obtained with bibliometrics (GLÄNZEL, 2003; LIU et al., 2019).

The use of bibliometric analysis has been observed for different topics related to environmental sciences and economics. There are bibliometric studies related to deforestation (ALEIXANDRE-BENAVENT et al., 2018), environmental taxes (BASHIR et al., 2021), sustainable development[1] (DU et al., 2021), ecosystem services (DRAGOS; DRAGOS, 2013; LIU et al., 2019; VALENTINA et al., 2018; VANDERWILDE; NEWELL, 2021), forest fires in tropical forests (JUÁREZ-OROZCO; SIEBE; FERNÁNDEZ Y FERNÁNDEZ, 2017), bioeconomy (BAMBO; POURIS, 2020), circular economy (MARTINHO; MOURÃO, 2020; RUIZ-REAL et al., 2018), Environmental Kuznets Curve (SARKODIE; STREZOV, 2019), climate change adaptation (WANG; ZHAO; WANG, 2018), and carbon tax (ZHANG et al., 2016), to cite a few. Most of these studies only use Web of Science (WoS) database, and a few use co-citation and/or bibliographic coupling.

Specifically for the Economics of Restoration, Bendor et al. (2015), Blignaut et al. (2014), and Iftekhar et al. (2016) conducted traditional literature reviews without using bibliometrics. Guan et al. (2019) and Romanelli et al. (2018), on the other hand, have conducted bibliometric analysis on ecological restoration as a research field, but they have only used co-authorship, co-occurrence and/or co-word in their analysis, and none of them focused on nor identified economic aspects within the ecological restoration field.

In this paper, we conduct a bibliometric investigation using co-authorship, direct citation, co-occurrence, co-citation, and bibliographic coupling networks. A *co-authorship* link occurs when authors, countries, organizations, or journals collaborate. A *direct citation* link occurs when articles, authors, journals, countries, or organizations cite one another. A *co-occurrence* link occurs when two keywords or terms are used together. A *co-citation* occurs when two papers are cited together by a third one (SMALL, 1973). Finally, a *bibliographic coupling* link occurs when two papers cite one (or more) papers in common (KESSLER, 1963).

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[1] See Appendix B for a Glossary of environmental related terms used throughout the thesis.

Bibliographic coupling and co-citation complement each other. They were used in this study for information retrieval, but they can be used as well for research evaluation, especially when combined with the other analyses mentioned.

The results from research evaluation using bibliometrics can be used to help formulate decisions on research policies and funding (JOSÉ DE OLIVEIRA et al., 2019). Although not without controversy (AKSNES; LANGFELDT; WOUTERS, 2019), direct citation is used as a measure to determine the relevance of documents, authors, or journals. Co-citation is more influenced by citation metrics, where heavily co-cited documents tend to be highly cited as well (GLÄNZEL, 2003; SMALL, 1973). It can be interpreted that co-citation reveals the structure of core documents that form the basis of a discipline, the important documents that helped develop that science. On the other hand, bibliographic coupling reflects the documents that cite together, being less influenced by citation, and due to this fact, it can identify core documents that represent emerging research topics (AKSNES ET AL., 2019; GLÄNZEL, 2003; MARIANO and SANTOS, 2017; TRUJILLO and LONG, 2018). The co-authorship analyses are used to understand patterns of collaboration and the co-occurrence of keywords or terms reveals the important topics addressed by publications in the field.

This article is a bibliometric analysis of the Economics of Restoration using co-authorship, direct citation, co-occurrence, co-citation, and bibliographic coupling networks. Its aim is to identify important authors, documents, themes, as well as relevant countries and productive journals within the economics of restoration field of study.

Following this introduction, the second section presents the methods, tools and materials used. The third section presents the results and discussions with the bibliometric maps and qualitative graphs. The fourth section presents the conclusion.

2 Methods

2.1 Bibliographic sources

The bibliographic sources used were Scopus, Web of Science (WoS) and Lens. The following keywords were used as search parameters: economics of restoration AND forest* OR landscape* OR ecosystem OR ecological OR savannah. No filter was used regarding document types, research areas, language, or time span. The search took place on January 23, 2022, for WoS and Scopus, and on January 25, 2022, for Lens. Since the metadata from each database are different, VOSviewer creates networks and maps for each database separately. Duplicates between databases were not excluded. Details about the search parameters are in Table 1.

Table 1 – Search parameters, filters, and results for WoS, Scopus and Lens.

Search parameters	**Filters**		
Date	23/01/2022 – WoS and Scopus 25/01/2022 – Lens		
Keywords and boolean operators	economics of restoration AND forest* OR landscape* OR ecosystem OR ecological OR savannah		
Time span	No filter		
Bibliographic bases	Scopus, WoS, Lens		
Research area	No filter		
Type of documents	No filter		
Language	No filter		
Results	**WoS**	**Scopus**	**Lens**
	1,626	780	14,594

Source: results of the study.

2.2 Software

Developed by van Eck and Waltman (2010), VOSviewer (version 1.6.18) is a free software tool to generate and analyze bibliometric networks using maps based on network data. VOSviewer uses bibliographic databases to construct networks of researchers, keywords, scientific publications, countries, research organizations, terms, and scientific journals. Items in these networks can be connected by co-authorship, co-citation, bibliographic coupling, direct citation, or co-occurrence links. To visualize and explore the maps, the software provides three visualization options: network, overlay, and density visualizations. For more information about VOSviewer please refer to the website https://www.vosviewer.com/.

Zotero (version 5.0.96.3) is an open-source reference manager software. We used it to retrieve information on the items in the bibliometric networks. More information about Zotero can be found at https://www.zotero.org/. Supporting tables were created with Microsoft Excel 2016 and graphs were made using Google Sheets.

2.3 Bibliometric indicators and maps

A bibliometric network can be visually represented by a bibliometric map. Each map shows an analysis based on bibliometric indicators, that can be applied for different units of analysis. Table 2 shows the unit of analysis used in each map of this study.

Table 2 – Type of analysis and unit of analysis used in this study.

Type of analysis	Unit of analysis
Co-citation	The cited references of the documents exported from the databases.
Bibliographic coupling	The documents exported from the databases.
Direct citation	Two units were used in different maps: • The journals in which the documents exported from the databases were published. • The authors who published the documents exported from the databases.
Co-authorship	The countries of the authors.
Co-occurrence	The author keywords of the documents exported from the databases.

Source: results of the study.

In the final maps, VOSviewer refers as 'items' all cited references, documents, countries, authors, journals, and keywords that were used in the analysis. A link occurs when two items are connected by the analysis (co-citation link, bibliographic coupling link, etc.), and for each pair of items there can be just one link. An important metric of the link is its strength, measured by how many times two items occur together in any given analysis. The more two items occur together, the stronger is their link (VAN ECK and WALTMAN, 2020).

VOSviewer can calculate several weight and score attributes depending on the type of unit of analysis. Table 3 shows the attributes used in this study.

Table 3 – Weights, Scores, attributes, and databases for each bibliometric analysis.			
Type of analysis	**Weights (W) and Scores (S) used**	**Attribute**	**Databases used**
Co-citation	W – total link strength	The total strength of the co-citation links of a given cited reference with other cited references.	WoS
Bibliographic coupling	W – total link strength	The total strength of the bibliographic coupling links of a given document with other documents.	Wos Scopus Lens
Direct citation	W - citations	The number of direct citations a given journal or author received.	Wos Scopus Lens
Co-authorship	W – documents S – average citations	W – the number of documents published by a country. S – the average number of citations the documents published by each country.	Wos Scopus
Co-occurrence	W – occurrences S – average publication year	W – the number of occurrences of an author keyword. S – the average year in which the documents containing the keyword were published.	Wos Scopus
Source: adapted from van Eck and Waltman (2021, 2014).			

VOSviewer offers three visualizations for the maps: network, overlay and density. Table 4 shows which analysis was used with each visualization and what the visualizations represents. In the network and overlay maps, the size of an item in relation to other items is related to its importance, with bigger items being more important. The density map presents the color sequence light blue – yellow – orange – red in order of importance, with the red points being interpreted as more important and the light blue points in a map being interpreted as less important. This classification is an indicator of the importance of items in comparison with others and their significance for the research-field topics of the bibliometric analysis. It is not meant to evaluate items in terms of the quality of their contents.

Table 4 – Representation of each visualization of a network and the analysis used.

Map visualization	Analysis used with the map visualization	Representation
Network	Co-citation Bibliographic coupling	Items represented by their label and a circle. The size of the label and the circle of each item is determined by the standard weight attributes. The higher the weight is, the larger the label and the circle of an item. The link is represented by a line between two items. In the network visualization, it is possible to observe that each item is attributed to a unique cluster. A cluster is a group of items that can be potentially close to each other, and the number of clusters is calculated by an arbitrary resolution parameter set by the user. Each cluster has its own color, and the color of an item represents the cluster which it belongs to.
Overlay	Co-authorship Co-occurrence	Items represented by their label and a circle. The size of the label and the circle of each item is determined by the standard weight attributes. The higher the weight is, the larger the label and the circle of an item. The link is represented by a line between two items. The items are also attributed with a color related to the score parameter used.
Density	Co-citation Bibliographic coupling Direct citation of journals Direct citation of authors Co-occurrence	Items represented by their label and the color of a given point in the map indicate the density of items at that point. The color range from light blue to yellow and finally to red. The closer to red the color of the point is, the larger the number of items in the neighborhood of that point and the higher the weights of the items in the neighborhood. Thus, the closer to light blue the color of the point is, the smaller the number of items in the neighborhood of that point and the lower the weights of the items in the neighborhood.

Source: results of the study.

The relatedness of the items in terms of the bibliometric links is approximately the distance between the items, as calculated by the Visualization of Similarities (VOS) technique. The closer two items are to each other, the stronger is their relatedness. Items in the same cluster (color) also have a strong relatedness with each other. However, since VOSviewer uses a distance-based approach to place the items in the maps, the distance between items is more important than the cluster to which they belong when it comes to assessing the structure of the science field of interest. We refer to van Eck and Waltman (2014, 2010) for more details on the VOS and clustering technique adopted by VOSviewer.

2.4 VOSviewer inputs and thresholds

To calculate the networks and construct the maps, VOSviewer requires a set of inputs and thresholds, which are shown in Table 5. From the citation thresholds selected, VOSviewer calculates the link strength for each item from higher to lower. The user can choose how many items to select based on this metric. Then, the software provides a list of all items to be shown in the maps. There is the possibility to exclude items before generating the maps using a thesaurus file, feature used to exclude repeated items in WoS co-citation and countries inconsistencies in Scopus co-authorship, and to harmonize keywords in WoS and Scopus co-occurrence. Some of the items in the network can be unconnected to each other. VOSviewer calculates the larger set of connected items and asks if it should show only this set, which was the choice in this study.

All the analyses were made using the 'full counting', which means that each bibliometric link has the weight of 1, as opposed to 'fractional counting', where the weight of a link is fractionalized between the N items in a unit of analysis. For an in-depth discussion about full and fractional counting, see Perianes-Rodriguez et al. (2016) and for discussions on citation minimum, see Rauchfleisch and Schäfer (2018) and Trujillo and Long (2018).

Table 5 – Inputs and thresholds set in VOSviewer, for each analysis used.

Inputs/thresholds					
Type of analysis	Co-citation	Bibliographic coupling	Direct citation	Co-authorship	Co-occurrence
Unit of analysis	Cited references	Documents	Journals Authors	Countries	Author keywords
Minimum number of citations of an item	3	3	0	0	N/A
Minimum number of documents/occurrences of an item	N/A	N/A	2	1	5
Show only connected items?	Yes	Yes	Yes	Yes	Yes

Source: results of the study.

Table 6 presents the results for each analysis and database after the inputs and thresholds from Table 5 were applied. The *Step 1* – Number of items after minimum number of citations/ documents/ occurrences – and *Step 2* – Items selected by total link strength –, are intermediate steps within VOSviewer set to generate the bibliographic networks. *Step 3* presents the final number of items that will appear in the maps in Section 3.

Table 6 – Number of items after the inputs and thresholds for each analysis and database.

Type of analysis	Co-citation	Bibliographic coupling			Direct citation			Co-authorship		Co-occurrence	
Database	WoS	WoS	Scopus	Lens	WoS	Scopus	Lens	WoS	Scopus	WoS	Scopus
Step 1. Number of items after minimum number of citations/ documents/ occurrences	1406	572	1151	8043	J* = 97 A* = 244	J* = 168 A* = 681	J* = 1754 A* = 4694	77	109	83	126
Step 2. Items selected by total link strength	250	250	250	250	J* = 50 A* = 100	J* = 50 A* = 100	J* = 50 A* = 100	77	109	83	126
Step 3. Final number of items in the network	250	250	250	250	J* = 50 A* = 73	J* = 50 A* = 100	J* = 50 A* = 96	77	97	83	126

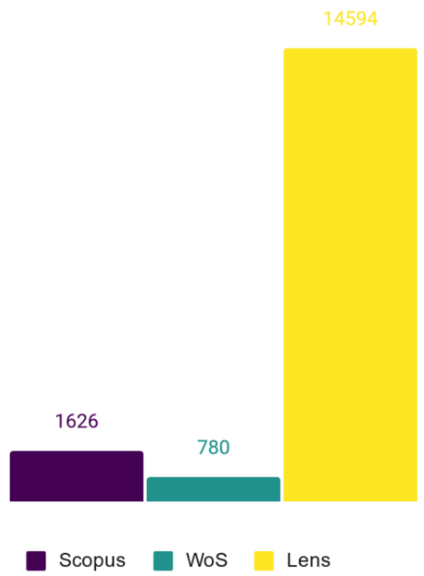
Source: results of the study.
*J = Journals, A = Authors.

The co-citation analysis was done only with WoS data since Lens metadata is not able to perform this analysis in VOSviewer. Scopus metadata, on the other hand, had inconsistencies within the cited references, which is common in this database. The Lens also do not provide consistent data to perform co-authorship and co-occurrence analysis.

3 Results and Discussion

Figure 1 shows the number of documents exported from WoS, Scopus and Lens. Lens, a free database, indexes a much higher number of documents than Scopus or WoS, which are paid databases. One of the reasons why Lens has such a high number of results is that it indexes more sources of documents (journals, conferences, books, etc.) and various types of documents other than those indexed by Scopus or WoS, such as dissertations and books.

Figure 1 – Number of documents exported from WoS, Scopus and Lens.

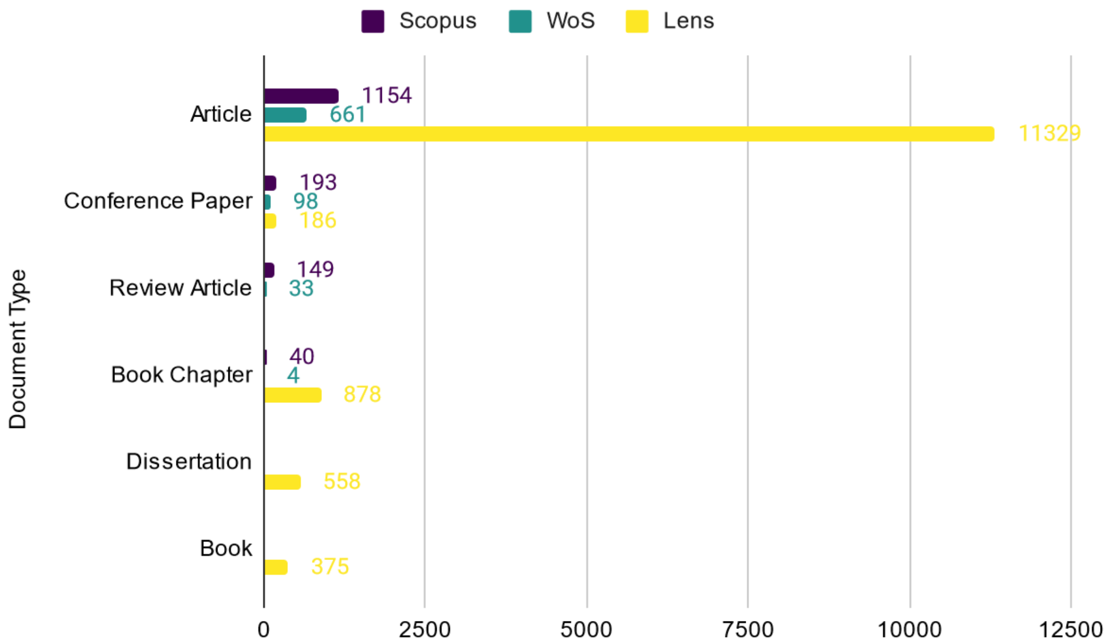


Source: results of the study.

Figure 2 shows the main types of documents from WoS, Scopus and Lens. The majority of documents in all databases are articles, followed by conference papers and book chapters (in Lens). Open access databases such as Lens and Dimensions tend to be less strict with the journals and other sources that are indexed. Web of Science is known for having less coverage of social sciences as well as a strict process of indexation of journals, which in turn reduces the number of documents found. One can argue that it is best to have numerous documents and not rely on the database to choose which ones are of higher quality. On the other hand, the criteria established by WoS and Scopus can guarantee standards for the academic community.

In Lens, the first entry is from 1891 with the article “Uruguay - A Financial Incident” by Ellis (1891). Records in Scopus start with the article by Thorndike (1928) “Sanitation, baths, and street-cleaning in the Middle Ages and renaissance”, that attempts to provide arguments regarding the poor conditions of sanitation in European cities during the medieval ages. WoS starts in 1990 with “Farming and nature conservation in the German Democratic Republic” by Schmidt (1990) describing the steadily increase in tensions between farming and nature conservation in the German Democratic Republic.

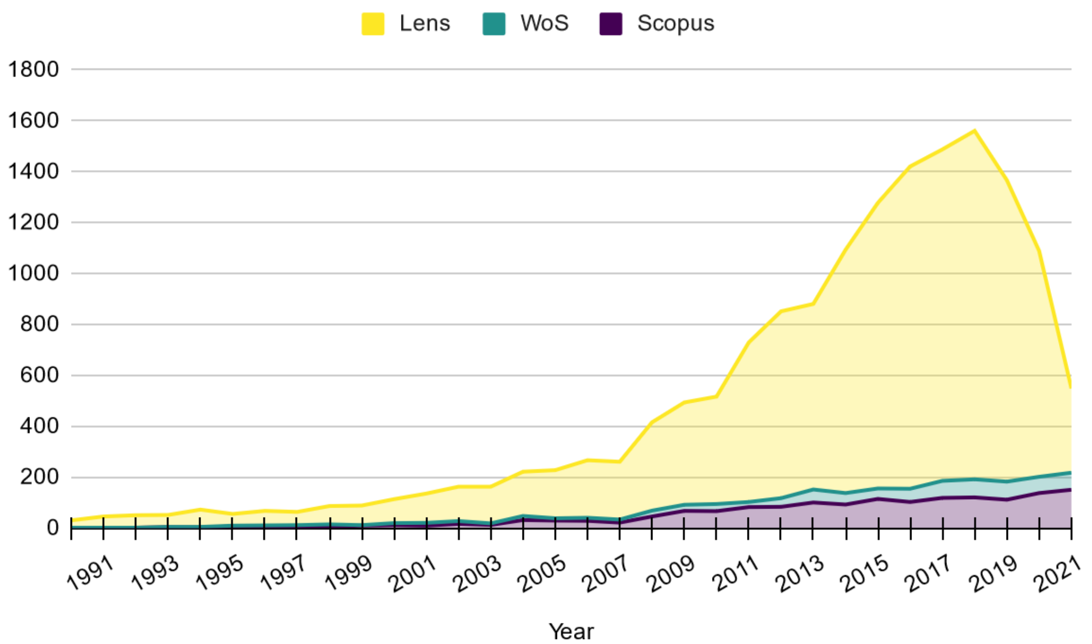
Figure 2 – Number and types of documents from WoS, Scopus and Lens.



Source: results of the study.

Figure 3 shows publications by year from the 1990s. We can observe an increase in the number of publications in the past fifteen years, which is an indicator of the novelty of the field of economics of restoration.

Figure 3 – Number of publications by year from the 1990s.



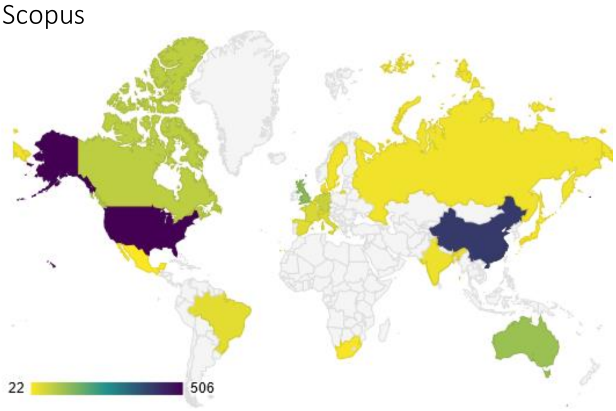
Source: results of the study.

3.1 Co-authorship and publications of countries

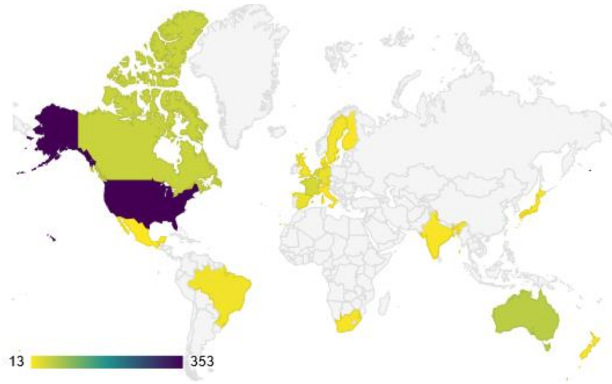
Figure 4 shows the number of publications by the top 20 countries in number of publications as indexed in each database. It is notable that the number of publications by the United States, Canada, United Kingdom, and China are prominent in all databases, alongside European countries, and Australia. Brazil also appears in the maps with a lower number of publications.

Figure 4 – Top 20 countries in number of publications.

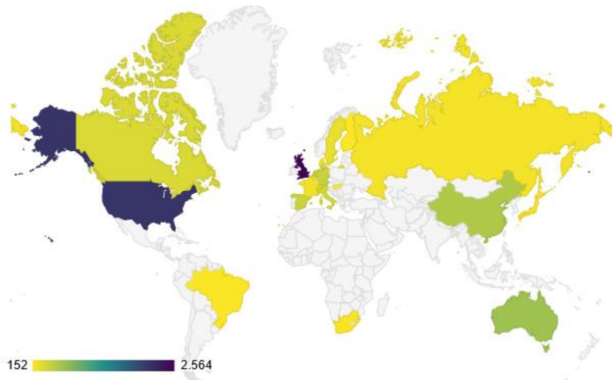
Scopus



WoS



Lens

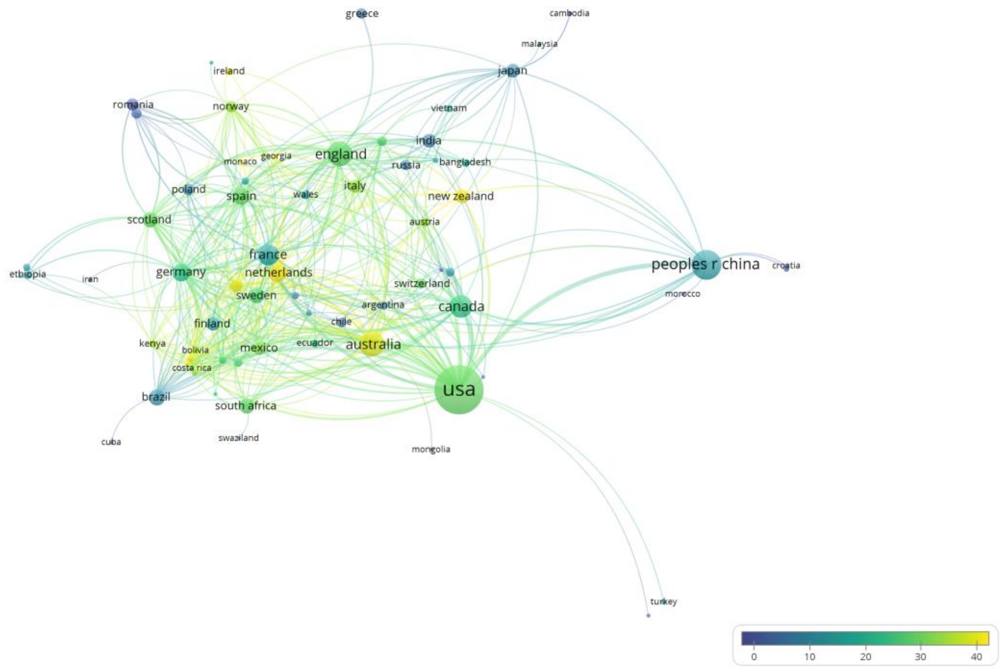


Source: results of the study.

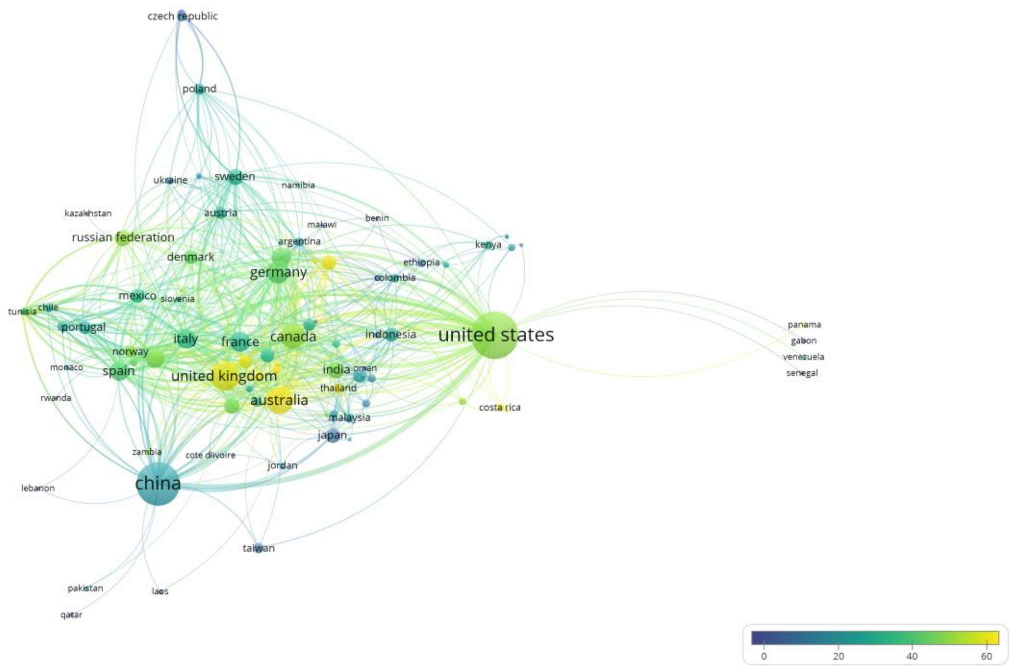
In Figure 5 it is possible to observe the co-authorship links between countries in WoS and Scopus. Co-authorship analysis of countries for Lens data is not possible in VOSviewer. The size of items reflects the number of documents published by countries, as in Figure 4. Countries close to each other are strongly related in co-authorship links, which means that authors from these countries tend to publish more together in comparison to those far from each other. The network from WoS and Scopus have similar patterns when it comes to countries relatedness and average citation. The United States is by far the country with more links with other countries. The prevalence of developed countries is notable in the center of the network, which indicates that they publish more in collaboration with others. The presence of developing countries mainly in the edges of the network indicates that they have few collaborations with other countries.

Figure 5 – Co-authorship of countries overlay maps.

A. WoS



B. Scopus



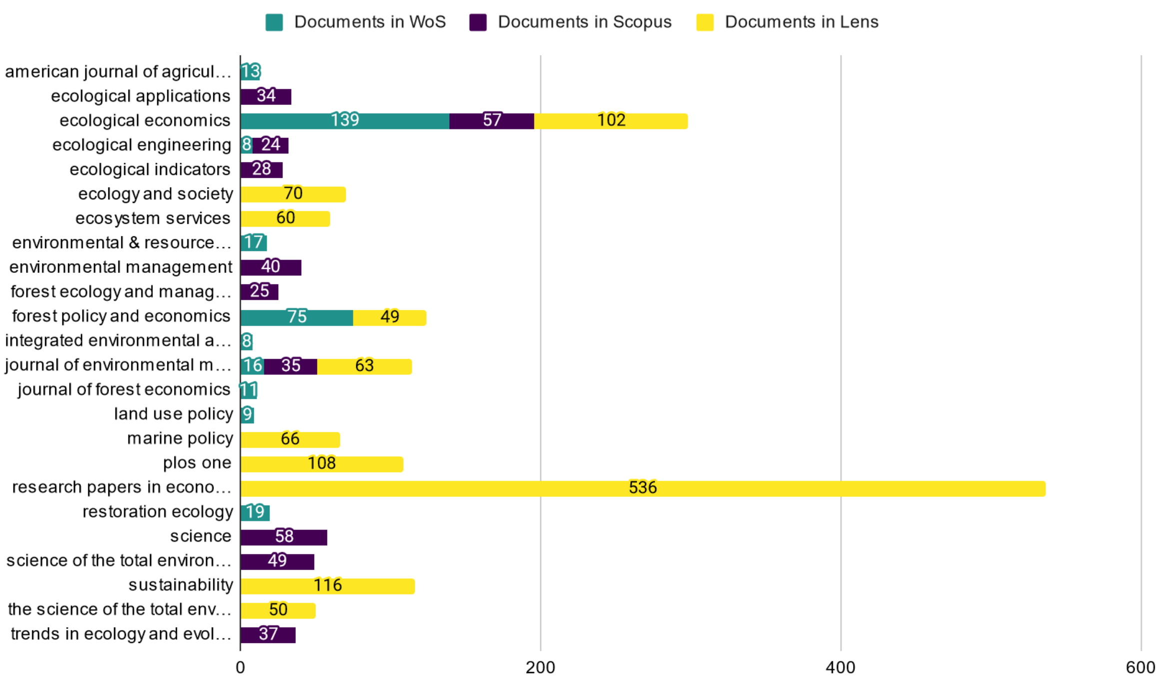
Source: results of the study. Observation: Weight attribute (size of items) by number of documents published. Score attribute (color range) by average of citations of the documents.

Some developing countries, for example, Brazil, Cuba, Argentina, and Malaysia received few citations in both databases (Fig. 5A and 5B), but others, such as Costa Rica, Bolivia, and Thailand, are colored yellow, which indicates that their documents receive more citations. China is notable for having a high number of documents, indicated by the size of the circle, in both databases. It has a strong link with the United States (indicated by the thickness of the line between them), but it has more collaborations with other countries as captured by Scopus (Fig. 5B) than in WoS (Fig. 5A).

3.2 Direct citation and the most productive journals

Figure 6 presents the top ten journals with more publications between databases. Only two journals ranked in the first ten positions are indexed in all three databases (Ecological Economics and the Journal of Environmental Management). A highlight is the Research Papers in Economics with 536 documents indexed in Lens.

Figure 6 – Top ten journals with more publications between WoS, Scopus, and Lens.

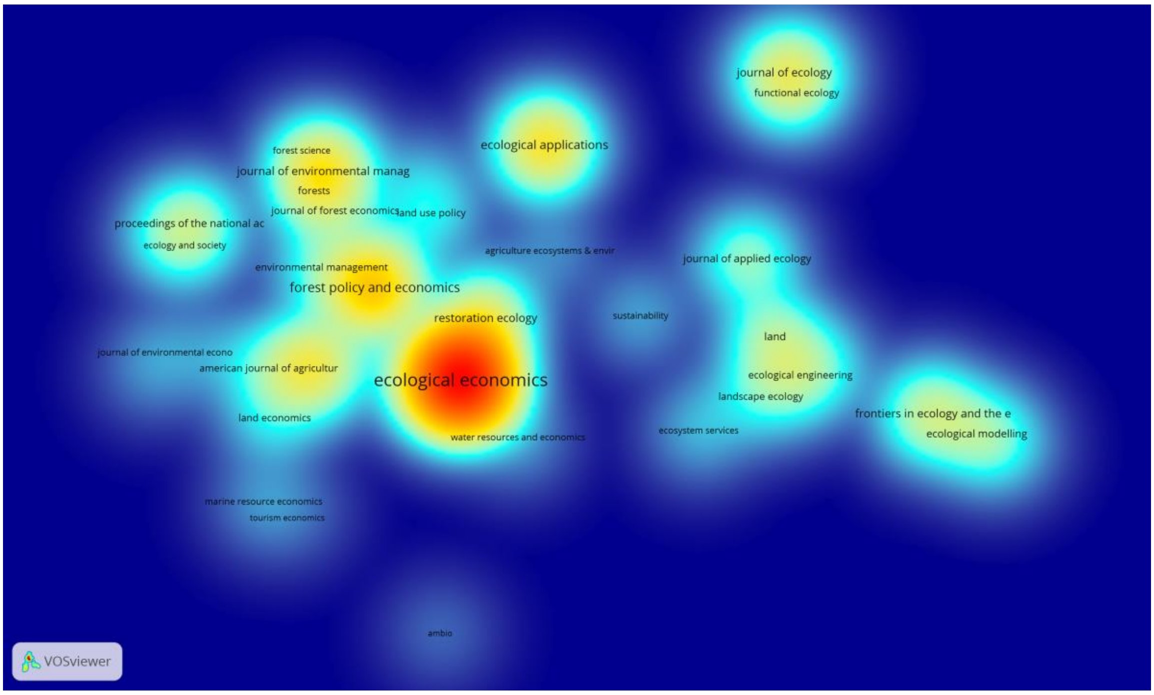


Source: results of the study.

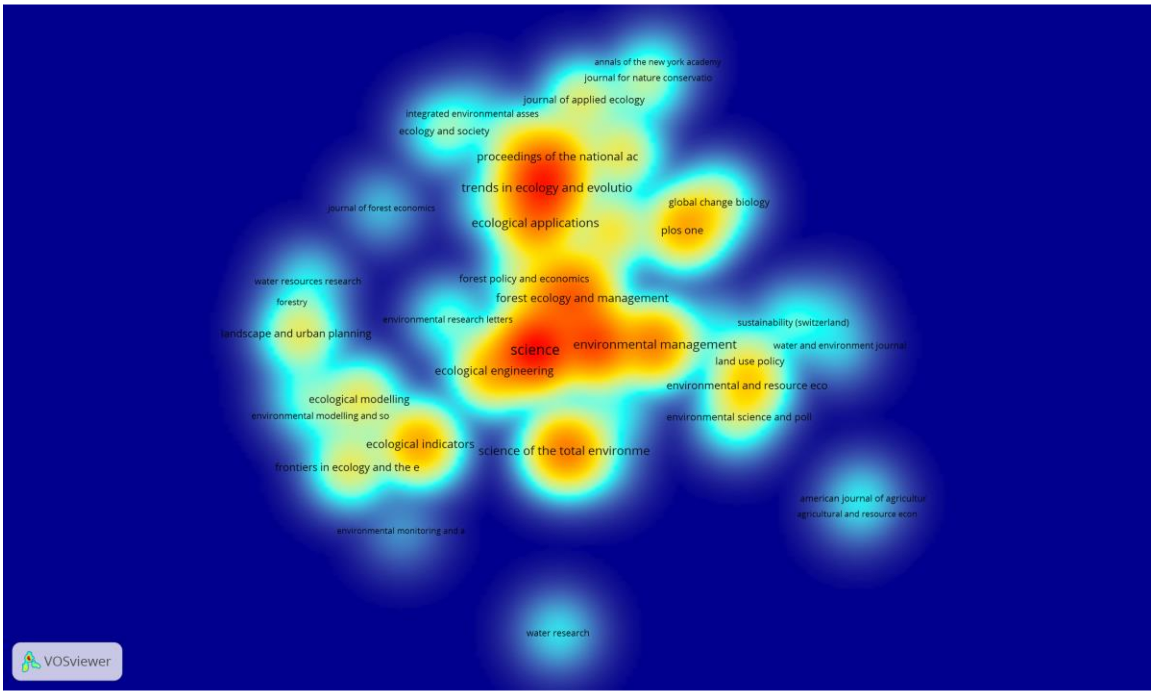
The direct citation of journals density map (WoS, Scopus, and Lens) is shown in Figure 7. The colors represent the weight attribute in terms of direct citations. We can observe that Ecological Economics maintains its prevalence as the most important item in WoS and Scopus, but other journals than those in Figure 6 are more prominent in terms of citations in these databases. The most important journals in WoS and Scopus address economic and ecological (i.e., forest, land, agriculture, water) topics, whereas in Lens, the most important journals focus on ecological and interdisciplinary themes.

Figure 7. Direct citation of journals density maps.

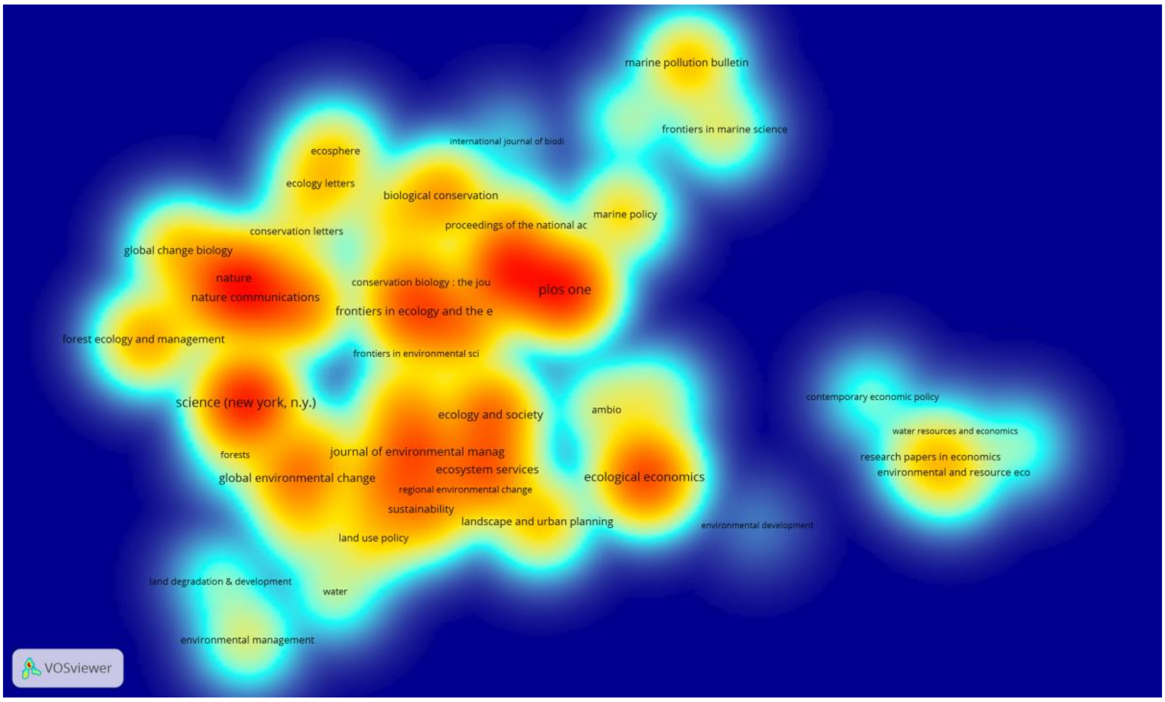
A. WoS



B. Scopus



C. Lens

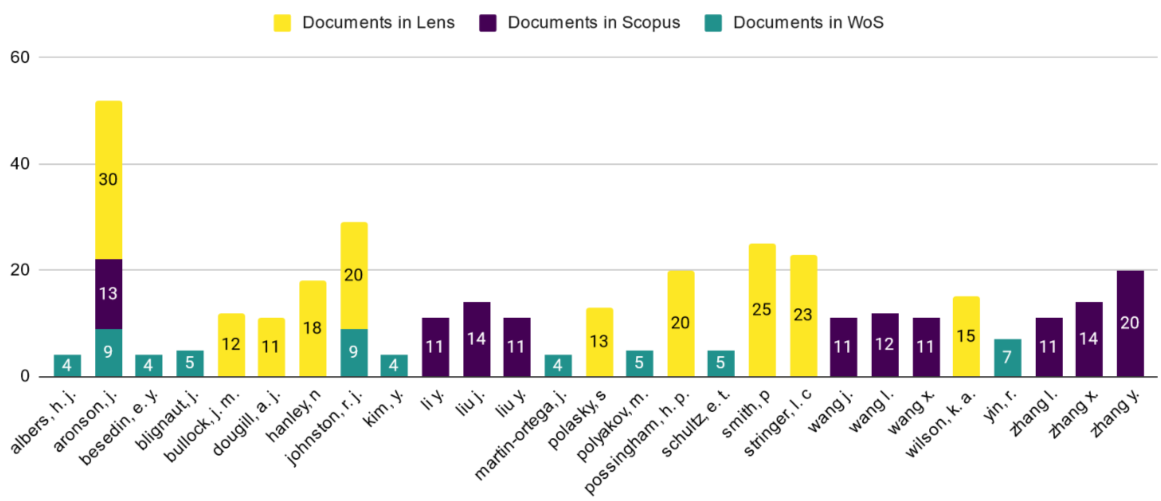


Source: results of the study. Observation: Weight attribute (colors) by number of citations of journals.

3.3 Direct citation and the most productive authors

Figure 8 presents the top ten authors with more publications between databases. James Aronson is the only author in the top ten ranking of all databases, followed by Robert Johnston, who appears in WoS and Lens. However, outside the top ten rank, several authors have documents indexed in more than one database. This shows in practice how databases index the documents very differently.

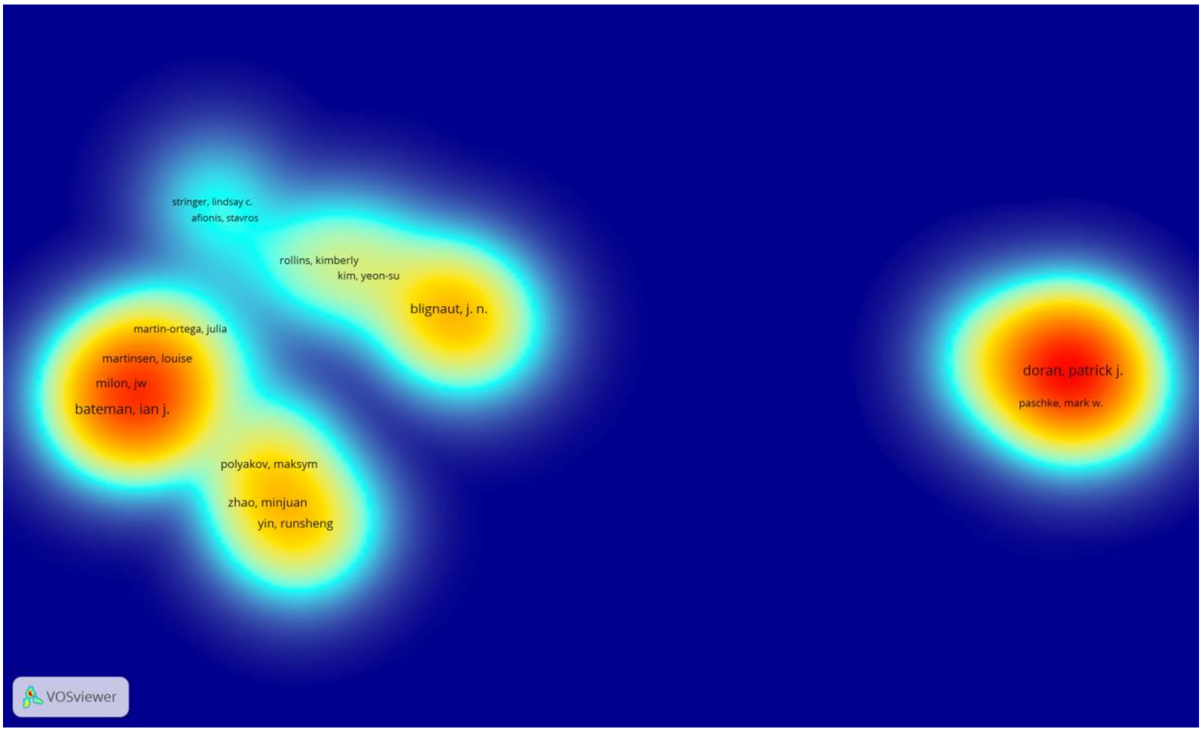
Figure 8 – Top ten authors with more publications in WoS, Scopus, and Lens.



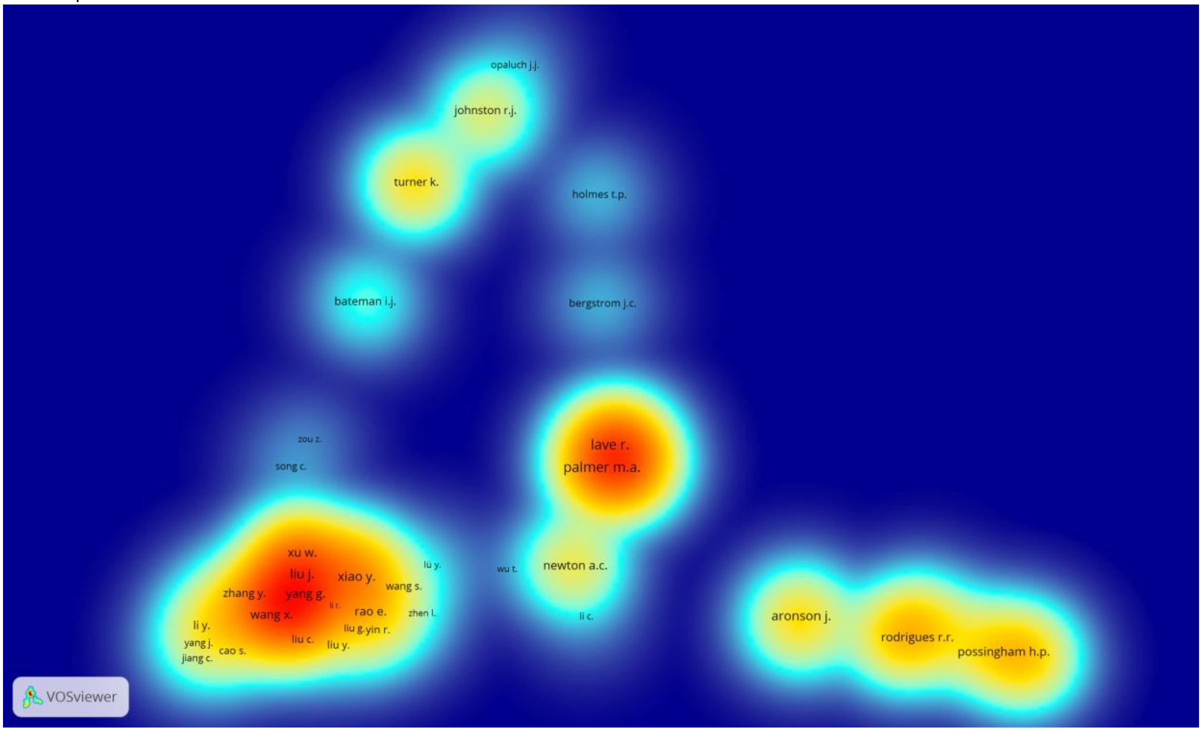
Source: results of the study.

The direct citation of authors density map (WoS, Scopus, and Lens) is shown in Figure 9. The colors represent the weight attribute in terms of direct citations. We can observe that the most important authors, as captured by citations in each database, are very different from Figure 8 and between each other. This indicates that the authors who receive more citations (Fig. 9) are not the ones that publish more in the topic (Fig. 8). Fig. 9 also shows how indexation of databases highlight different authors. For example, in WoS, Bateman, Milon, Martinsen, and Doran are the most cited authors. In Scopus, Wang, Yang, Liu, Lave and Palmer received more citations, whereas in Lens, Mace, Carpenter, and Biggs are more cited. Some authors shown in Fig. 8, such as Blignaut, Aronson, Possingham, and Johnston, appear in the maps in Fig. 9, but not among the most cited. A highlight is Scopus, that has an important cluster with only Chinese authors, indicating the importance of China as we saw in the co-authorship of countries analysis. Again, authors in WoS and Scopus are more focused on the economic aspects of restoration, while in Lens, authors publish more about its ecological aspects.

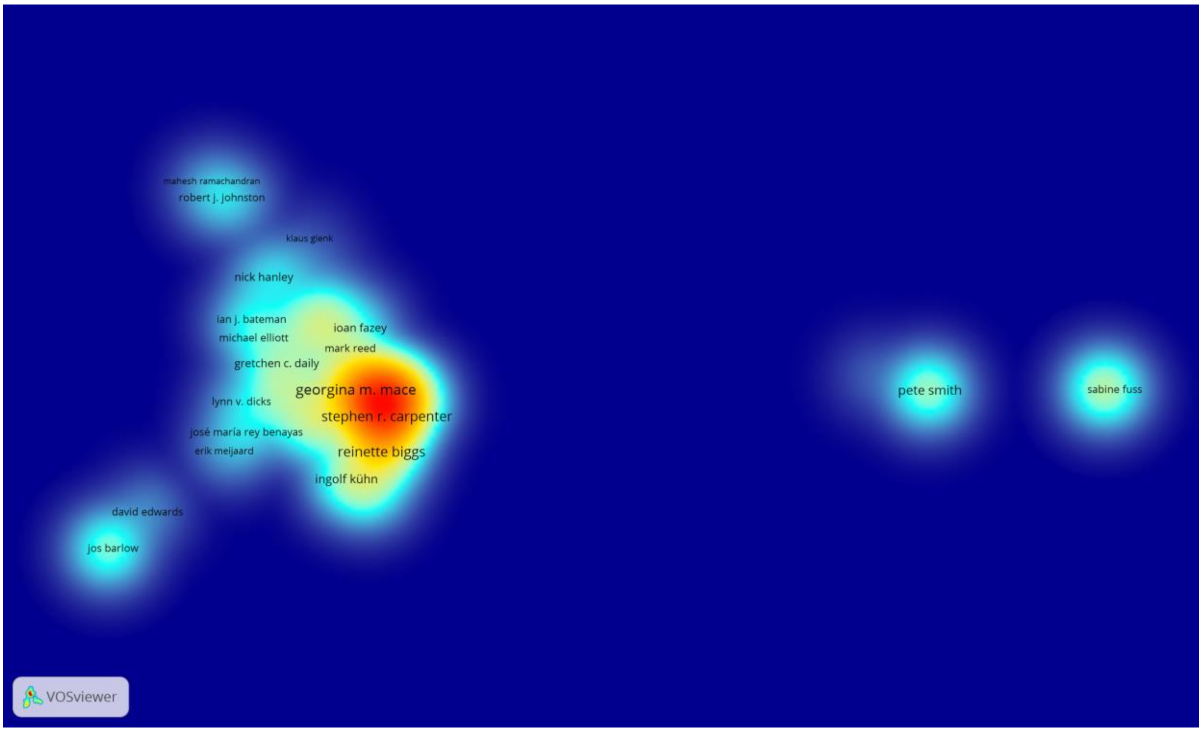
Figure 9 – Direct citation of authors density maps.
A. WoS



B. Scopus



C. Lens



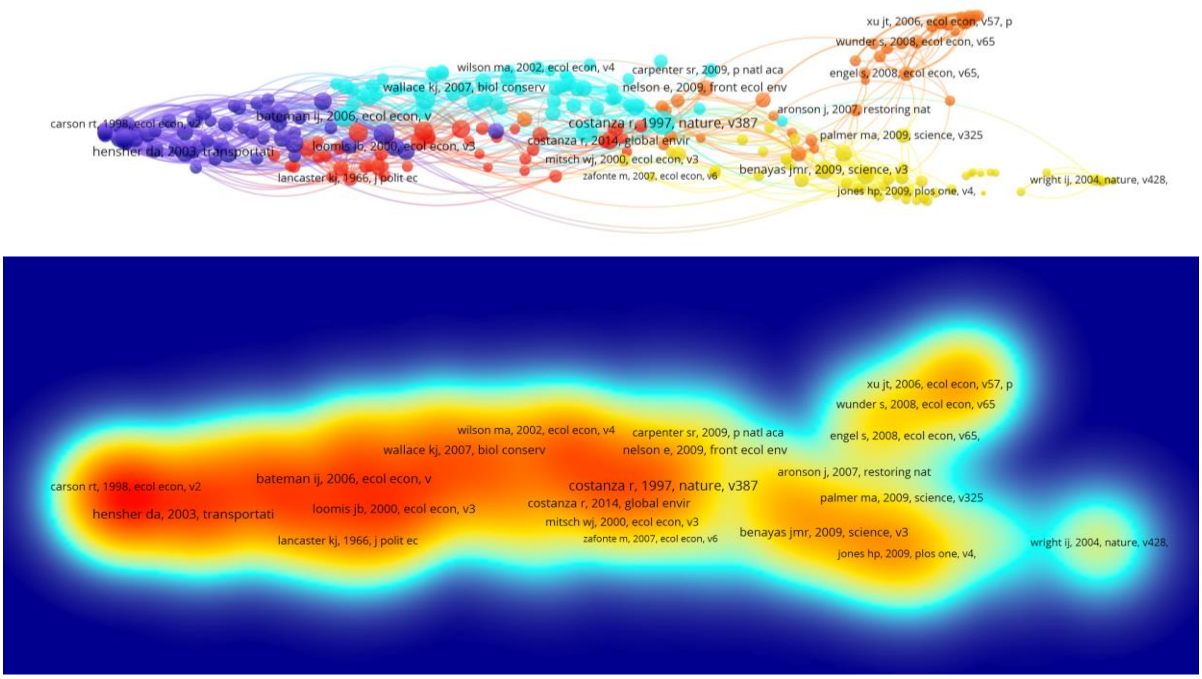
Source: results of the study. Observation: Weight (colors) by number of citations of authors.

3.4 Co-citation analysis

Network and density maps of WoS co-citation analysis are presented in Figure 10. The 5 clusters identified by WoS as the documents which provide the theoretical foundation of the early developments of the Economics of Restoration field and their description are as follows:

- Cluster 1 (blue): early developments of economic valuation methods, especially contingent valuation methods.
- Cluster 2 (light blue): economic valuation studies, classifications of ecosystem services and economic perspectives of ecosystem services.
- Cluster 3 (yellow): interrelations between ecological restoration and socio-economic aspects, costs and benefits of ecological and ecosystem restoration, including two meta-analyses within the ten most important cited references (by total link strength) of the cluster.
- Cluster 4 (red): updates on ecosystem services definitions and values, wetland, river, and coastal economic valuations.
- Cluster 5 (orange): economic and ecological aspects of biodiversity, conservation, and restoration, but with a more theoretical approach.

Figure 10 – Co-citation analysis of cited references in WoS.



Source: results of the study. Observation: Weight attribute (size of items) by total link strength of cited references. The colors in the network map (top) represent clusters of strongly related cited references. The color in the density map (bottom) represents the total link strength of cited references.

Clusters 1, 2, and 4 are concentrated in the center and left side of the map, and from the network map we can observe that their items are very close to each other, which is reflected by their common theme around different aspects of economic valuations. The density map shows that these clusters are the most important ones in this analysis. Clusters 3 and 5 are slightly separated on the right side of the map. Cluster 3 is the cluster focused on economic aspects of ecological restoration, and it is closer to cluster 5, that has relatively new documents (around 2008 - 2013) and is focused on theoretical aspects.

The density map confirms that the most important core documents, those that form the basis of the field of economics of restoration, come from clusters 1, 2, and 4, with the earliest studies of economic aspects of ecosystem services and economic valuations of different ecological subjects. The items with the strongest link strength (Table 7), that is, that are more cited together, also belong to these clusters, and focus on different valuation studies, which are the mainstream method of measuring the value of natural capital and ecosystem services. As we will see later in this thesis (Chapter 2), measuring benefits is still a challenge among restoration studies, and there is a lack of communication between practitioners and society about the benefits of restoration actions.

On the other hand, the clusters focused on the economics of restoration (3 and 5) are the less important among the other clusters, which is expected, given the newness of the field. The concept of less importance here is in terms of link strength that items have with each other. These are, for instance, documents on benefits of restoration (ARONSON et al., 2010; DE GROOT et al., 2013), costs and who pays for restoration (BIRCH et al., 2010; HOLL; HOWARTH, 2000; NAIDOO et al., 2006). It is worth noting that most of these documents were published from the 2000's. Given that co-citation reveals the documents that helped in the development of the field, the economics of restoration is indeed in its early stages.

The top 20 most important cited references by link strength in WoS are presented in Table 7.

Table 7 – Top 20 most important cited references in co-citation analysis by link strength in WoS.

Cited Reference	Total link strength	Citations	Cluster
Costanza et al., 1997. The value of the world's ecosystem services and natural capital. Nature.	389	57	2
de Groot et al., 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecological Economics.	296	26	2
Bateman et al., 2006. The aggregation of environmental benefit values: Welfare measures, distance decay and total WTP. Ecological Economics.	264	15	2
Bateman et al., 2004. Economic Valuation with Stated Preference Techniques: A Manual. Ecological Economics.	259	18	1
Boyd and Banzhaf, 2007. What are ecosystem services? The need for standardized environmental accounting units. Ecological Economics.	252	16	2
Hensher and Greene, 2003. The Mixed Logit model: The state of practice. Transportation.	220	10	1
Christie et al., 2006. Valuing the diversity of biodiversity. Ecological Economics.	219	9	1
Carlsson et al., 2003. Valuing wetland attributes: an application of choice experiments. Ecological Economics.	215	12	4
Freeman et al., 2014. The measurement of environmental and resource values: theory and methods.	213	21	4
Krinsky and Robb, 1986. On Approximating the Statistical Properties of Elasticities. The Review of Economics and Statistics.	209	17	1
Brander et al., 2006. The Empirics of Wetland Valuation: A Comprehensive Summary and a Meta-Analysis of the Literature.	207	21	4
Mitchell and Carson, 1989. Using Surveys to Value Public Goods: The Contingent Valuation Method. Using Surveys to Value Public Goods: The Contingent Valuation Method.	205	20	1
Benayas et al., 2009. Enhancement of Biodiversity and Ecosystem Services by Ecological Restoration: A Meta-Analysis. Science.	199	25	3
Loomis et al., 2000. Measuring the total economic value of restoring ecosystem services in an impaired river basin: results from a contingent valuation survey. Ecological Economics.	191	22	1
Johnston et al., 2002. Combining Economic and Ecological Indicators to Prioritize Salt Marsh Restoration Actions. American Journal of Agricultural Economics.	185	9	1
Milon and Scrogin, 2006. Latent preferences and valuation of wetland ecosystem restoration. Ecological Economics.	183	12	1
Bateman et al., 2011. Economic Analysis for Ecosystem Service Assessments. Environ Resource Economics.	172	13	1
Alcamo et al., 2003 Eds., 2003. Ecosystems and human well-being: a framework for assessment.	170	19	2
Balmford et al., 2002, Economic Reasons for Conserving Wild Nature. Science.	168	16	2
Poe et al., 2005. Computational Methods for Measuring the Difference of Empirical Distributions. American Journal of Agricultural Economics.	168	8	1

Source: results of the study.

3.5 Bibliographic coupling

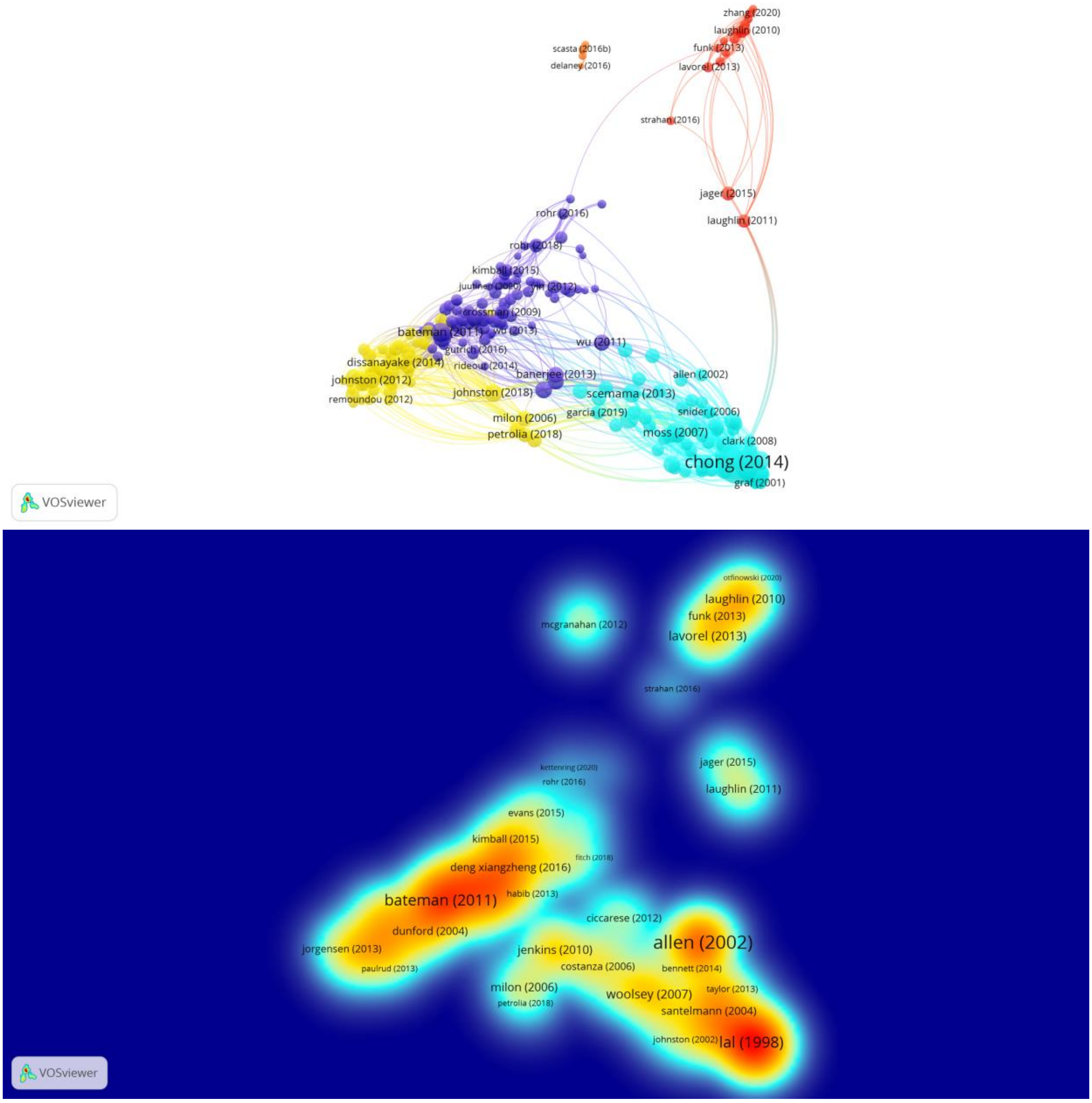
The bibliographic coupling analysis was done for all three databases. The network and density maps, as well as the description of clusters of each database, are presented below.

In WoS bibliographic coupling analysis (Figure 11), there are 5 clusters, and their description is as follows:

- Cluster 1 (blue): ecosystems services valuation; economic and cost-benefit assessments of restoration.
- Cluster 2 (light blue): ecological aspects of restoration in several ecosystems, policy, and economic implications of ecosystems management.
- Cluster 3 (yellow): economic valuations, especially stated preference, and the role of substitutes and indicators in trade-off values.
- Cluster 4 (red): soil and plant ecological aspects, functional traits of ecosystems and its ecological implications.
- Cluster 5 (orange): ecological aspects of restoration in fire-prone lands.

From the network map in Figure 11 we can observe that clusters 4 and 5, that focus on ecological aspects only, are distant from the others, but have links with clusters 1 and 2, which present themes regarding economics of restoration, such as investment, cost-effectiveness, and ecosystems management. Clusters 1 and 3 are closer to each other, and they both address economic valuation studies and other economic analysis of different ecosystems, for example coastal, wetlands, and grasslands. Cluster 2, that mixes ecological restoration and ecosystems management, has items close to clusters 1 and 3, which indicates the interdisciplinarity of the documents (documents in the bibliographic coupling analysis cite other documents together). The density map points that the clusters 4 and 5 are the less important ones among clusters, which indicates that the core documents of emerging topics are in clusters 1, 2, and 3.

Figure 11 – Bibliographic coupling of documents in WoS.
WoS



Source: results of the study. Observation: Weight attribute (size of items) by total link strength of documents. Colors in the network map (top) represents clusters of strongly linked documents. Colors in the density map (bottom) represent the total link strength of documents.

The top 10 most important documents by link strength in WoS are presented in Table 8.

Table 8 – Top 10 most important documents by link strength in WoS.

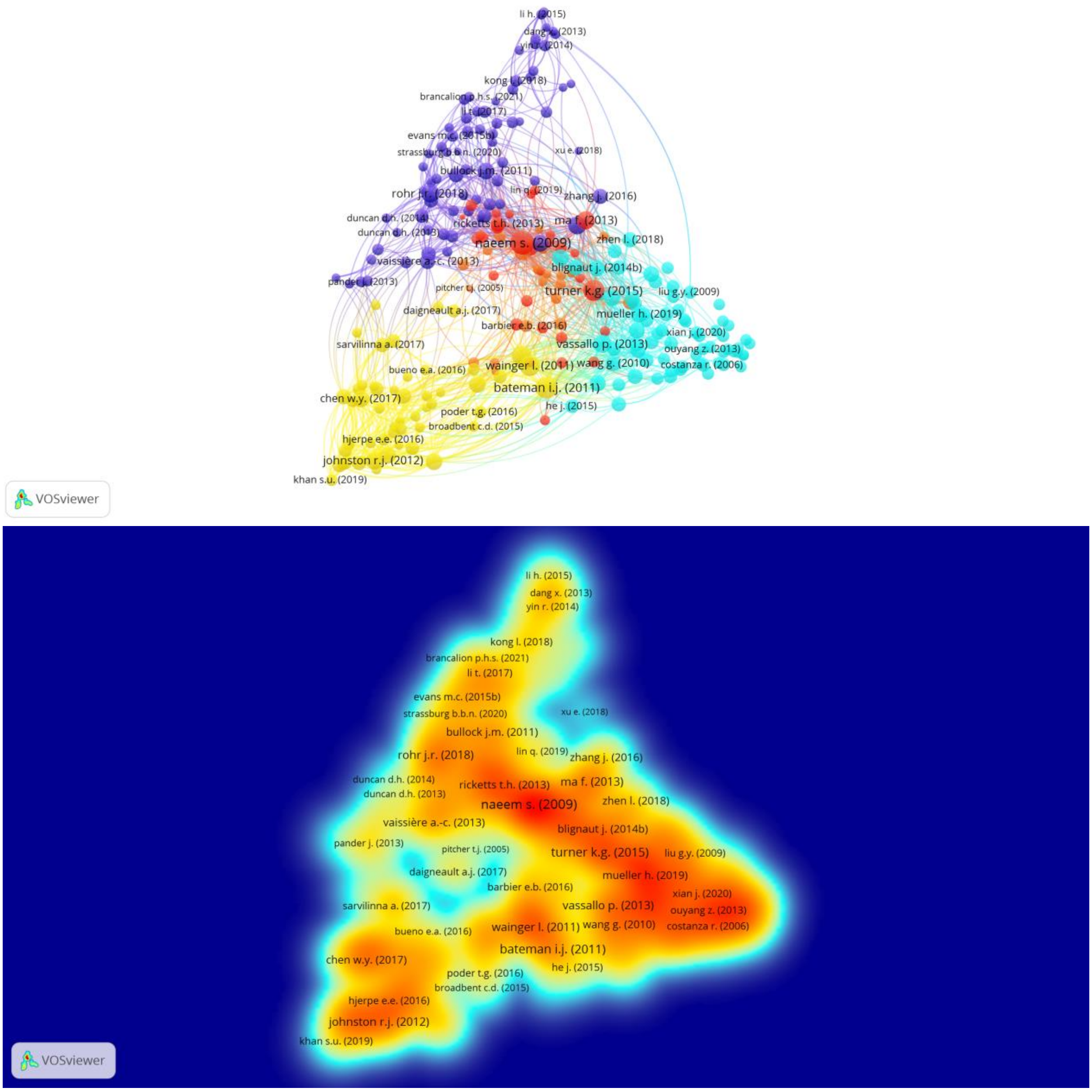
Document	Total link strength	Citations	Cluster
Ecosystem-based approaches to climate change adaptation: progress and challenges. (CHONG, 2014).	2937	44	2
Lakes and society: mirrors to our past, present and future (MOSS, 2007).	453	3	2
Soil erosion impact on agronomic productivity and environment quality (LAL, 1998).	390	362	2
Species choice and the risk of disease and insect attack: evaluating two methods of choosing between longleaf and other pines (MOSER; TREIMAN; JOHNSON, 2003).	389	5	2
Integrated emergy, energy and economic evaluation of rice and vegetable production systems in alluvial paddy fields: implications for agricultural policy in China (LU et al., 2010).	387	89	2
Economic analysis for ecosystem service assessments (BATEMAN et al., 2011).	386	348	1
The emergence of mitigation banking in the united states: impacts on the modes of organization and the characteristics of transactions (SCEMAMA; LEVREL, 2013).	352	6	2
Paying for restoration (HOLL; HOWARTH, 2000).	348	103	2
Realizing the potential of ecosystem services: a framework for relating ecological changes to economic benefits (WAINGER; MAZZOTTA, 2011).	322	60	1
Using ecosystem service values to evaluate tradeoffs in coastal hazard adaptation (JOHNSTON; MAKRIYANNIS; WHELCHEL, 2018).	321	7	3

Source: results of the study.

In Scopus bibliographic coupling analysis (Figure 12), there are 5 clusters, and their description is as follows:

- Cluster 1 (blue): economic and cost-benefit assessments of restoration, incorporating economic aspects into restoration.
- Cluster 2 (light blue): ecosystem services economic analysis and ecological management of ecosystems with policy and socioeconomic implications.
- Cluster 3 (yellow): economic valuation of restoration applied to different ecosystems but with a focus on ecosystem services, especially choice experiments.
- Cluster 4 (red): focus on economic analysis of ecological and economic aspects of restoration and management activities.
- Cluster 5 (orange): economic analysis and valuation of coastal, mangrove and other marine related ecosystems and ecosystem services.

Figure 12 – Bibliographic coupling of documents in Scopus.



Source: results of the study. Observation: Weight attribute (size of items) by total link strength of documents. The colors in the network map represent clusters of strongly linked documents. The color in the density map represents the total link strength of documents.

All clusters in Scopus bibliographic coupling address different aspects of economic analysis and valuations, with changes in approaches, valuation methods and subject of analysis. The network map (Fig. 12) reflects the relatedness of all clusters together, and the density map shows that all clusters are of relatively high importance among each other. We can see that regions of clusters 2, 4, and 5 have a weight (intense red areas) slightly higher than clusters 1 and 3. This indicates that ecological and economic aspects of restoration and ecosystem services are more prominent among economic analyses. The management aspects and their implications to governance is also an important topic of projects. Scopus also highlights the attention the aquatic ecosystems are receiving, which is interesting, since the mainstream international commitments look towards terrestrial ecosystems (as indicated by the major recent initiatives such as the Bonn Challenge and the UN Decade on Restoration). On the other hand, valuation studies are concentrated in cluster 3 with a focus on the method of choice experiments, which is a shift from the prevalence of contingent valuation studies captured by the co-citation analysis (Section 3.4).

Scopus documents given by bibliographic coupling analysis reveal that the economic analysis is a prominent research topic in restoration of different ecological subjects, which highlights the lower prevalence of studies that focus only on ecological aspects. The top 10 most important documents by link strength in Scopus are presented in Table 9.

Table 9 – Top 10 most important documents by link strength in Scopus.

Document	Total link strength	Citations	Cluster
Biodiversity, ecosystem functioning, and human wellbeing: an ecological and economic perspective (NAEEM et al., 2009)	523	264	4
Economic analysis for ecosystem service assessments (BATEMAN et al., 2011)	406	391	3
Review of methods, data, and models to assess changes in the value of ecosystem services from land degradation and restoration (TURNER et al., 2016).	380	180	4
Realizing the potential of ecosystem services: a framework for relating ecological changes to economic benefits (WAINGER; MAZZOTTA, 2011).	340	74	3
Public attitudes, preferences and willingness to pay for river ecosystem services (KHAN et al., 2019).	323	14	3
A review of ecosystem services and research perspectives (MA; LIU; EGRINYA ENEJI, 2013).	279	12	4
The value of the seagrass posidonia oceanica: a natural capital assessment (VASSALLO et al., 2013).	265	106	2
The ecology and economics of restoration: when, what, where, and how to restore ecosystems (ROHR et al., 2018).	260	32	1
The net ecosystem services value in mainland China (CAO et al., 2018).	256	18	1
Enhancing the content validity of stated preference valuation: the structure and function of ecological indicators (JOHNSTON et al., 2012).	247	55	3

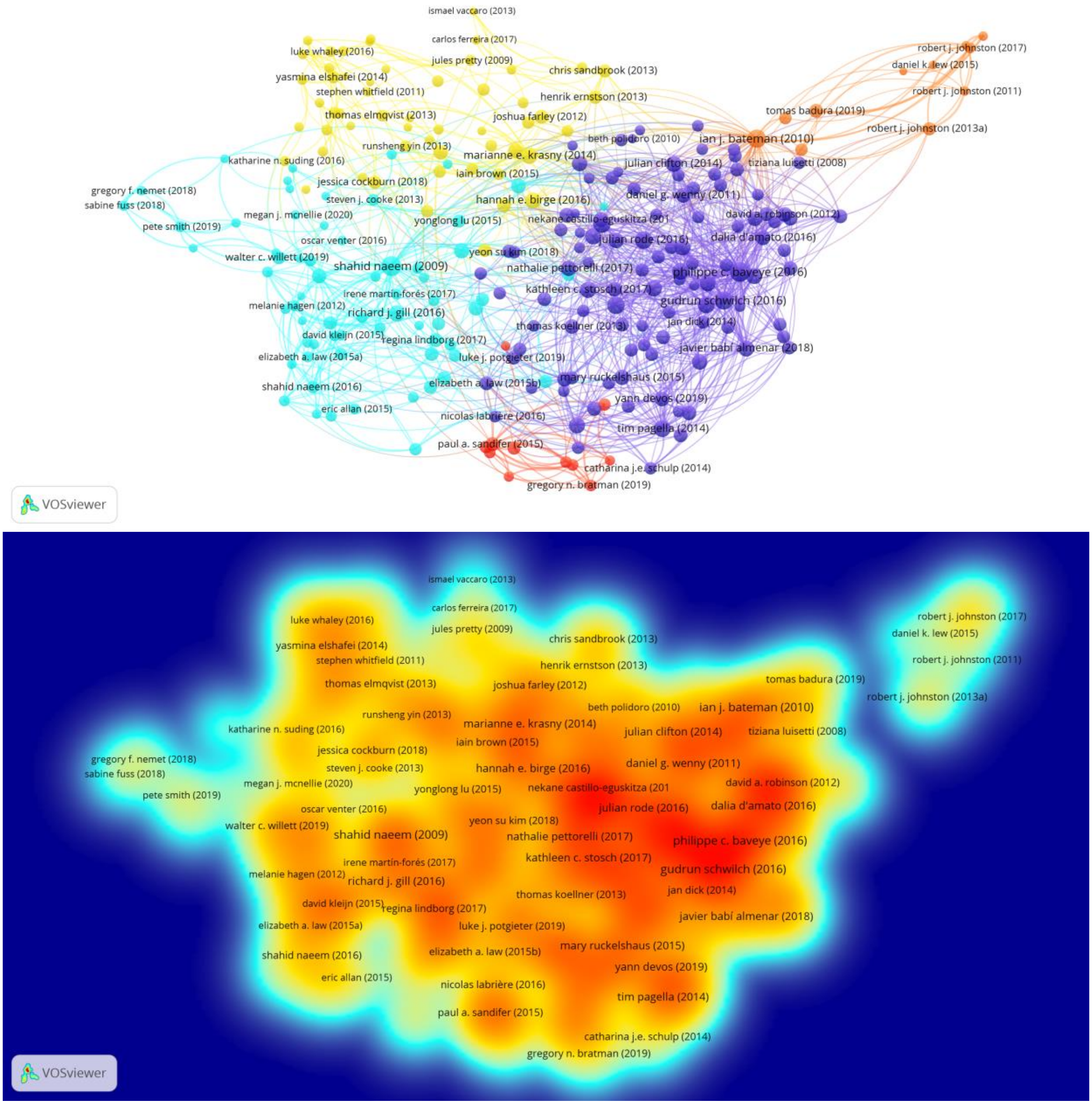
Source: results of the study.

In Lens bibliographic coupling analysis (Figure 13, p. 52), the cluster resolution was adjusted to 0.8 (from the standard 1) to reduce the number of clusters from 6 to 5. The clusters and their description are as follows:

- Cluster 1 (blue): economic analysis of ecosystem services.
- Cluster 2 (light blue): governance and management focused on ecological aspects of ecosystem services.
- Cluster 3 (yellow): economic analysis and socio-ecological aspects of ecosystem services.
- Cluster 4 (red): focus on connections between human-health, nature and well-being derived from green spaces and ecosystem services.
- Cluster 5 (orange): economic valuation of ecosystem services, ecological indicators, and other ecological aspects.

All clusters from Lens bibliographic coupling address different aspects of ecosystem services, such as economic analysis, governance, and economic and ecological management. Cluster 5, which addresses topics of economic valuation, indicators and ecological aspects, is slightly distant from the other clusters. It is interesting to observe that valuation receive less attention in this particular database that captures more documents, since valuation methods are the most used to capture value of ecological and ecosystem goods and services in general, and these values can be used to communicate the importance of the outcomes from restoration to society. As we will see in chapter 2 of this thesis, this communication is lacking from restoration practitioners and the scientific community to those that are or will be directly involved in restoration. Lens also has a cluster (cluster 4) that addresses issues of human-health and well-being from green spaces and ecosystem services, which indicates a different emerging topic not found in WoS and Scopus bibliographic coupling analysis. The density map shows that overall, all clusters are important, but cluster 1 is slightly more important than the others. This cluster is focused on ecosystem services, which is a good indicative that restoration actions can be going towards the resilience of these services.

Figure 13 – Bibliographic coupling of documents in Lens. Weight attribute (size of items) by total link strength of documents.



Source: results of the study. Observation: The colors in the network map represent clusters of strongly linked documents. The color in the density map represents the total link strength of documents.

The top 10 most important documents by link strength in Lens are presented in Table 10 (p. 53).

Chapter 2 of this thesis will focus on a literature review of cost and benefit aspects of economics of restoration as captured by co-citation and bibliographic coupling analysis. For now, we want to highlight the challenges of the field identified in the literature that we mapped.

On the economic side, incomplete or absent markets (BRANCALION et al., 2017) – for example, seed and seedling supply chains – or even qualified human resources are a setback. Market failures such as public good beneficiaries that benefit from restoration even not contributing directly with the efforts (GROOT et al., 2013), difficulties in estimating social benefits of restoration (IFTEKHAR et al., 2017) and even the lack of long-term studies that access restoration costs and benefits are also a problem (NUNES et al., 2017).

Table 10 – Top 10 most important documents by link strength in Lens.

Documents	Total link strength	Citations	Cluster
Soil "ecosystem" services and natural capital: critical appraisal of research on uncertain ground (BAVEYE; BAVEYE; GOWDY, 2016).	878	171	1
Biodiversity, ecosystem functioning, and human wellbeing - biodiversity, ecosystem functioning, and human wellbeing: an ecological and economic perspective (NAEEM et al., 2009).	877	438	2
Economic analysis for ecosystem service assessments (BATEMAN et al., 2011).	725	478	5
Operationalizing ecosystem services for the mitigation of soil threats: a proposed framework. (SCHWILCH et al., 2016).	690	49	1
'Ecosystem service opportunities': a practice-oriented framework for identifying economic instruments to enhance biodiversity and human livelihoods (RODE et al., 2016).	622	55	1
Operationalising ecosystem service approaches for governance: do measuring, mapping and valuing integrate sector-specific knowledge systems? (PRIMMER; FURMAN, 2012).	619	136	1
Ecosystem service trends in basin-scale restoration initiatives: a review (TRABUCCHI et al., 2012).	604	56	1
Development and use of a typology of mapping tools to assess their fitness for supporting management of ecosystem service provision (PAGELLA; SINCLAIR, 2014).	588	55	1
Current status and future prospects for the assessment of marine and coastal ecosystem services: a systematic review (LIQUETE et al., 2013).	579	339	1
How coastal strategic planning reflects interrelationships between ecosystem services: a four-step method (LI et al., 2016).	554	3	1

Source: results of the study.

In the ecological aspect, the main conclusion is that restoration is ecosystem and site specific (NUNES et al., 2017; GROOT et al., 2013) which increases the complexity of planning of projects especially because with large upfront costs, ecological and economic frameworks that work in an area frequently cannot be replicated in other areas, even in the same region. If there are no projects to address the causes of degradation, restoration actions cannot be sufficient to improve ecological conditions in the long term (KUMAR, 2017).

And in the governance and political aspects, the complexity of managing funding for restoration, that often comes from various sources and involves complex legal requirements (BENDOR et al., 2015b) and largescale governance (NUNES et al., 2017) may impact the large-scale restoration programs required for countries to commit with international initiatives such as the UN Decade on Restoration or the Bonn Challenge.

3.6 Co-occurrence analysis of author keywords

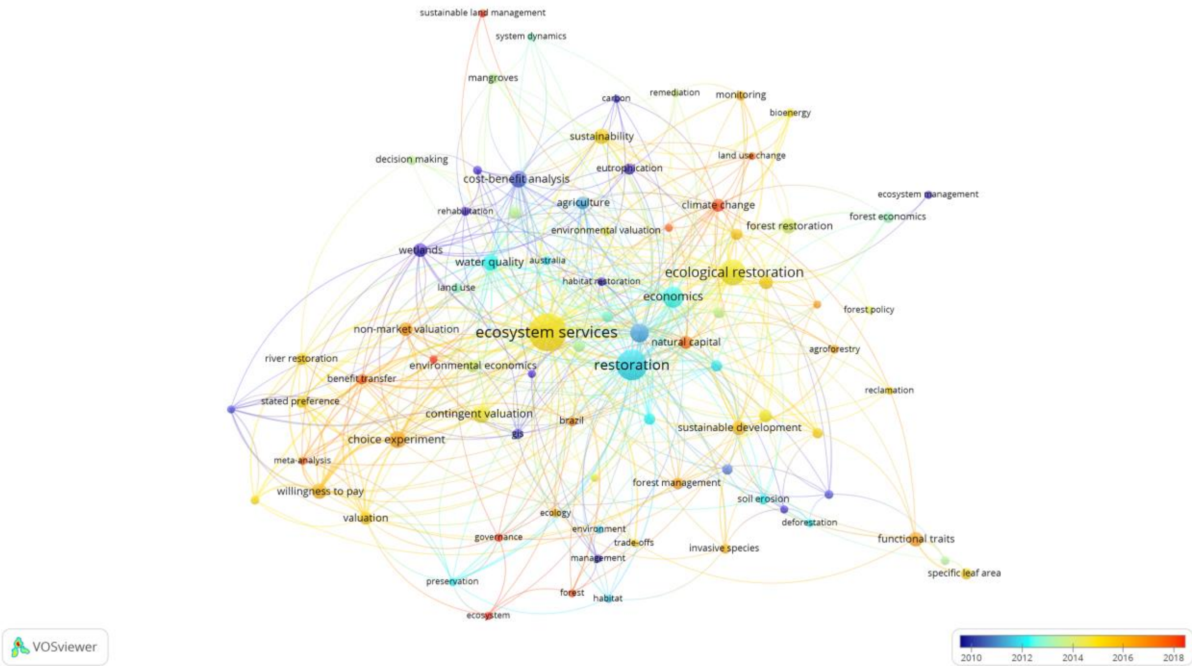
The co-occurrence analysis shows important themes of the economics of restoration field. The unit of analysis for the networks were author keywords. This is a good choice to reveal how authors classify their own work. The network maps in Figure 14 show author keywords with the higher number of occurrences and the average publication year of the documents in which the keywords appear.

Ecosystem services, restoration, ecological restoration, biodiversity, and economics are the most important keywords in terms of occurrences. These keywords have an average publication year from 2012 to 2016, which indicates a high number of publications with these topics in those years. This shows a relatively recent increase in studies that focus on these themes. Ecosystem services related topics are very important within economics of restoration, as shown in co-citation, bibliographic coupling, and co-occurrence analysis. They are given attention in terms of restoration projects that focus on improving their resilience and increasing services that could be used in payments for ecosystem services to fund restoration.

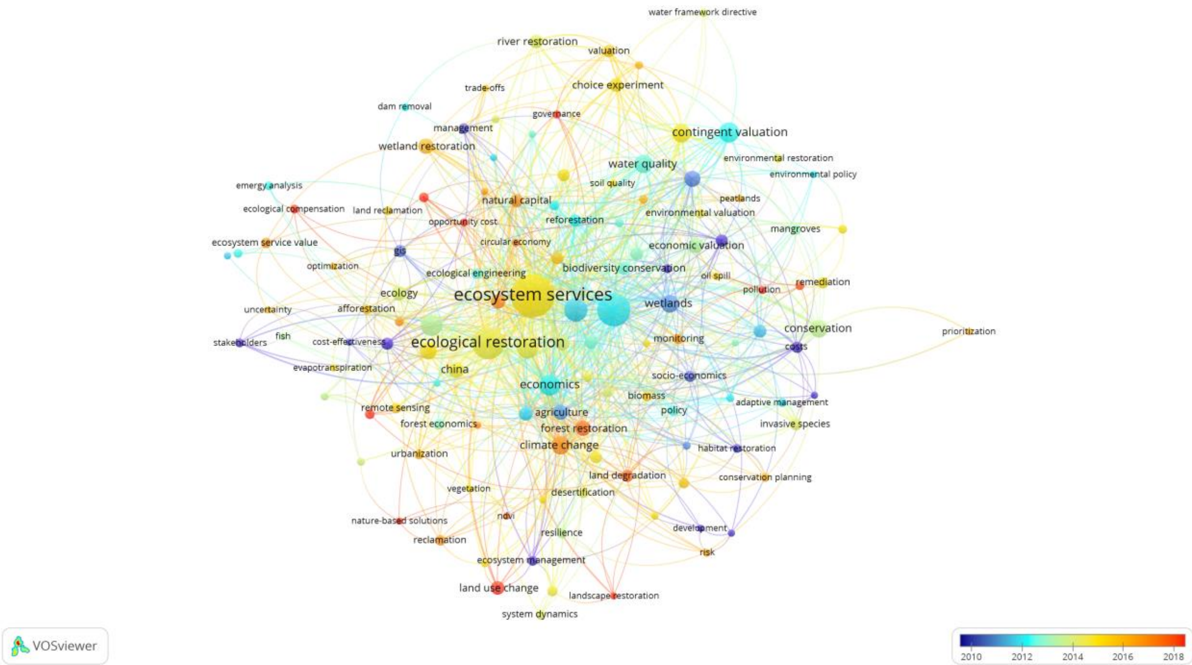
Smaller items, which have fewer occurrences, tend to have a more recent average publication year (Fig. 14). Within WoS, forest, governance, sustainable land management, and economic valuation methods occur in recent years. For Scopus, wetland, landscape and forest restoration, climate change, land use change, and ecological compensation are among the latest keywords.

Figure 14 – Co-occurrence of author keywords overlay maps for WoS and Scopus.

A. WoS



B. Scopus



Source: results of the study. Observation: Weight attribute (size of items) by occurrences of a keyword and Score attribute (color range) by average publication year of the documents in which keywords appear.

The top 20 most important author keywords by occurrences in WoS and Scopus are presented in Table 11. The keywords used in the database search were economics of restoration, forest, landscape, ecosystem, ecological, and savannah. Forest, ecosystem, and ecological restoration appear among the most used author keywords. On the other hand, landscape and savannah do not appear among keywords used by authors. As we will see in Chapter 2 of this thesis, landscape restoration is being acknowledged as a crucial shift in how we plan restoration projects if we are to scale-up restoration and achieve the goals proposed by international commitments such as the UN Decade on Restoration and the Bonn Challenge.

Table 11 – Top 20 keywords in WoS and Scopus, ranked by occurrences. Highlighted keywords occur in both WoS and Scopus.

Keywords WoS	Occurrences WoS	Ranking WoS		Keywords Scopus	Occurrences Scopus	Ranking Scopus
ecosystem services	104	1		ecosystem services	158	1
restoration	67	2		restoration	93	2
ecological restoration	49	3		ecological restoration	87	3
economics	31	4		biodiversity	46	4
biodiversity	25	5		land use	40	5
contingent valuation	22	6		sustainability	40	6
cost-benefit analysis	21	7		economics	36	7
choice experiment	20	8		contingent valuation	35	8
water quality	19	9		water quality	30	9
forest restoration	18	10		climate change	29	10
sustainability	18	11		willingness to pay	29	11
willingness to pay	17	12		wetlands	28	12
functional traits	16	13		conservation	26	13
sustainable development	15	14		sustainable development	24	14
china	14	15		cost-benefit analysis	23	15
non-market valuation	14	16		china	22	16
wetlands	14	17		economic valuation	21	17
climate change	13	18		agriculture	20	18
ecological economics	13	19		forest restoration	20	19
environmental economics	13	20		wetland restoration	20	20

Source: results of the study.

It is interesting to note that wetlands were not used in the search, but appear in the keywords list and in several documents within the search, highlighting the attention these ecosystems receive in the international literature as captured by WoS, Scopus and Lens.

Savannahs, on the other hand, are not receiving the proper attention despite being heavily degraded, especially in Brazil, where cattle and soy are expanding into the Cerrado biome as an externality of efforts of conservation in the Amazon biome. However, it is quite interesting that the expression “economics of restoration” was not found among any group of keywords in any database (“restoration economy” was not found either). After around 30 years since the concept started to be used (BLIGNAUT et al., 2014), authors do not seem to have incorporated these phrases to signal their economics of restoration studies.

4 Conclusion

We conducted a comprehensive bibliometric analysis of the economics of restoration field in Web of Science, Scopus, and Lens databases. The bibliometric indicators used were co-authorship, co-occurrence, direct citation, co-citation, and bibliographic coupling. The bibliographic maps highlight patterns of collaboration between countries, co-occurrence links between author keywords, and different citation relations and links as given by direct citation of journals and authors, co-citation of cited references, and bibliographic coupling of documents.

All the bibliometric analyses highlighted documents, references, and keywords relatively new, with most results being published from the 2000s. The co-occurrence analysis shows that ecological restoration is more prominent than the other keywords used in the databases search, which were forest, landscape, and savannah. Forest and landscape do appear in the co-citation, bibliographic coupling, and co-occurrence analysis. In its turn, savannah was not found in the maps. Wetland was not used in the search, but appeared in all analyses, which indicates the attention this ecosystem is receiving around the world.

The bibliometric maps show that the economics of restoration is shifting from conceptual and methodological developments to address pressing topics, such as forest and landscape restoration challenges, climate change and land use change. There are also advances in improving economic valuations and cost-benefit analysis, with a focus on the measurement of benefits. We will focus on a detailed review of costs and benefits of restoration in the next chapter of this thesis, Chapter 2, that was constructed from the reading and the analysis of documents identified by this bibliometric analysis.

One of the challenges of this study came from the metadata of the databases, which made some of the analysis impossible for Scopus and Lens. The choice of three databases in a bibliometric analysis is not common in the literature, with most studies focusing on Web of Science. However, we believe that using more than one database and including Lens, an open access database, resulted in a more comprehensive picture of the field of economics of restoration. The sum of all analysis illustrates how the field came from early topics, such as economic valuation use, to governance, policy, and management of important issues regarding restoration and conservation.

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Chapter 2 – The costs and benefits of restoration: current status and the way forward

> Theodore Roosevelt (1910) said, "To waste, to destroy our natural resources, to skin and exhaust the land instead of using it so as to increase its usefulness, will result in undermining in the days of our children the very prosperity which we ought by right to hand down to them amplified and developed." Roosevelt articulates a desire for the "wise use" or "sustainable" management of natural resources such that their "usefulness" increases through time. (MAHER et al., 2020).

1 Introduction

A decade ago, Ciccarese et al. (2012) affirmed that the 20th century observed significant progress in conservation, but that the twenty-first century would be a time of forest restoration. Restoration is recognized as being required to reduce the economic and socioeconomic disruptions that came along with the ecological degradation, particularly in developing countries (ARONSON et al., 2010), and to achieve sustainable development goals (BIRCH et al., 2010; GROOT et al., 2013; WORTLEY; HERO; HOWES, 2013; BLIGNAUT; ARONSON, 2020).

It is also a strategy for reversing biodiversity losses and increasing the provision of ecosystem services (BULLOCK et al., 2011; WORTLEY; HERO; HOWES, 2013), mitigating climate change (BRANCALION et al., 2021) recovering lost ecosystem goods and services and contributing to economic development (BLIGNAUT; ARONSON; WIT, 2014; BULLOCK et al., 2011; BLIGNAUT; ARONSON, 2020), among other benefits (BLIGNAUT; ARONSON; GROOT, 2014). It is becoming a mainstream research topic and a framework for policy-makers and managers (MAZÓN et al., 2019).

The economics of restoration is the overlap between restoration ecology and ecological and environmental economics (BLIGNAUT; ARONSON; WIT, 2014). It has been said that the restoration success in providing economic benefits worldwide is linked with its use along with ecosystem services, biodiversity conservation, and nonmarket services (MENZ; DIXON; HOBBS, 2013), thus making it embedded within an economic framework (BENDOR et al., 2015).

We believe that the integration of economics into restoration practices still needs much effort, both in conceptual and empirical matters. This article is a literature review derived from the bibliometric analysis of this thesis (Chapter 1). The aim here is to contribute to the science of economics of restoration by identifying the state of the art around benefits, costs and financing methods, frameworks, challenges, and future developments of restoration. If conservation of natural capital can be made economically beneficial (GROOT et al., 2013; BLIGNAUT et al., 2014), ecological restoration also may yield excellent returns on investment, provided a mid to long-term perspective is adopted and that the full range of known benefits is considered (GROOT et al., 2013; BLIGNAUT et al., 2014; ROHR et al., 2018).

This article is divided in six sections. After this introduction, Section 2 will briefly discuss the reasons why we need economics of restoration and the challenges yet to overcome. This section also introduces how the concepts of cost-benefit (CBA) and cost-effectiveness (CEA) analysis are important to guide success in restoration by identifying what is lacking regarding benefits and costs of restoration. Section 3 presents the restoration benefits already identified in the literature and the methods and the frameworks used for the estimation and the analysis of benefits. Section 4 identifies the types of costs reported in the literature, and the several methods that are used to determine these costs. Thus, we also discuss the implications of not having a cost database and a standardized framework for determining costs that could be replicated by different stakeholders in different regions. Since restoration demands a large amount of investment, Section 5 addresses the potential sources for financing restoration and presents a discussion of who should be responsible for paying for restoration. Concluding remarks follow in Section 6.

2 Why do we need the economics of restoration?

For many years, the science and practice of restoration has been based primarily on ecological considerations. Only recently, restoration scientists and practitioners have begun to include economic aspects in the design of restoration projects (BLIGNAUT et al. 2014; IFTEKHAR et al., 2017). However, there is clear evidence that restoration practitioners are not properly signaling the evidence of the benefits of restoration as a good investment to society, and the links between ecological restoration, policy and society (ARONSON et al., 2010; KUMAR, 2017).

For example, The Economics of Ecosystems and Biodiversity (TEEB) project reviewed over 2000 restoration case studies. Only 96 studies (less than 5%) provided meaningful cost data (BULLOCK et al., 2011) and none provided analysis of both costs and benefits (BIRCH et al., 2010; KUMAR, 2017). Based on 225 case studies from around the world with respect to benefits and 94 with respect to costs, Groot et al. (2013) state that they are confident in their economic analysis and its sensitivity analysis scenario, which shows that restoration provides financial profit. However, Matzek (2018) states that the study from Groot et al. (2013) had to rely on coarse assumptions when showing that restoration returns more in benefits than it incurs in costs, since published studies quantifying the benefits were simply unavailable. Wortley et al. (2013) found that only 2.5% of published restoration studies reported both ecological and economic data.

In a review by Mazón et al. (2019), 84 of 91 publications measured ecological attributes, seven evaluated socioeconomic attributes, and none included both ecological and socioeconomic attributes. Among socioeconomic attributes, economic benefits were the most frequently evaluated (four articles); both community engagement and cultural values were evaluated in two publications each. And in a recent review of eight meta-analysis by Blignaut and Aronson (2020), among 1401 restoration studies, only three provide actual benefit-cost ratio, because there is no standard formula or format to communicate the costs and benefits of restoration.

Given the scarcity of restoration funding, and of conservation in general, restoration projects need to achieve their ecological, social and economic objectives with the least-cost strategy. Aronson (2010) adapted from Jackson et al. (1995) the five elements of restoration: the ecological, economic, social, cultural, and political elements. Later, Rohr et al. (2016), added four aspects within these elements: goals and objectives realistically set, adequate funding, all stakeholders involved, and careful consideration of the costs and benefits (Figure 1).

In this sense, efficient allocation of funds is one of the premises of a well implemented restoration project, program, or plan. There are several tools and frameworks to select the best restoration strategy (BLIGNAUT; ARONSON; WIT, 2014), but cost-benefit (CBA) and cost-effectiveness (CEA) analyses are the most prominent ones.

Cost-benefit analysis (CBA) attributes monetary values to benefits derived from restoration projects, to compare them with the costs of the project or plan, which can be then compared against other projects or plans. CBA has emerged as a prominent approach, both for assessing the success rates of restoration and to investigate whether restoration is a viable investment in the long run (KUMAR, 2017).

Figure 1 – Elements of an ideal restoration.

Source: Adapted from Aronson (2010) and Rohr et al. (2016).

Most applications of benefit-cost models accept linearity concerning time, but restoration occurs within the context of dynamic, complex ecosystems that often respond to large and unpredictable changes at various scales in space and time (KIMBALL et al., 2015; BLIGNAUT; ARONSON; WIT, 2014). A time-based intervention makes sense from an economic analysis standpoint, but if events such as fires, droughts, floods, and other events that result in changes at spatial scales well beyond the specific ecosystem or landscape targeted are ignored, restoration efforts are likely to fail (BLIGNAUT; ARONSON; WIT, 2014).

Indirect consumption, option, existence and bequest values for ecosystem services also need to be considered, which can capture the possible future use of services (BULLOCK et al., 2011). And in some cases social CBA is important to decide whether a restoration action is socially desirable, a private cost-benefit analysis often can drive the success of a restoration project (SCHIAPPACASSE et al., 2012).

Cost-effectiveness analysis (CEA) is a form of Return on Investment in which benefits are measured in nonmonetary units. Managers explicitly specify what outcomes they want to achieve, define the benefits they expect from conservation action, and estimate the costs it would take to achieve them. It provides guidance to managers and practitioners by clarifying where the highest rate of conservation return is (AUERBACH; TULLOCH; POSSINGHAM, 2014).

It is also important to note that with CEA, the most cost-effective methods are not necessarily the methods that result in the highest cover regardless of cost (KIMBALL et al., 2015). To understand whether the recovery of ecosystem services coincides with the recovery of biodiversity, it is crucial to calculate its cost-effectiveness and to consider the success of a restoration project (BULLOCK et al., 2011).

Among costs and benefits, the methods to determine the benefits of restoration have been steadily better developed and reported on in peer-reviewed journals over the past two decades (BLIGNAUT; ARONSON; WIT, 2014), while the quality and quantity of information on costs varies among studies (BULLOCK et al., 2011; ROBBINS; DANIELS, 2011). In the following section, we will focus on specific aspects of benefits (Section 3) and costs (Section 4) of restoration.

3 The benefits of restoration

There is a clear need for definition and valuation of the socioeconomic outcomes of restoration projects (ARONSON et al. 2010), especially because this is needed to identify the benefits of restoration (BULLOCK et al., 2011). On the other hand, the financial attractiveness of a restoration project needs to include information, not only on costs, but also on the environmental, social and economic benefits, short, medium and long term, marketed and non-marketed (GITZ et al. 2020; NEESON et al., 2016). Even if the benefits cannot be monetized, benefit indicators developed from conceptual models that incorporate economic concepts can improve decision-making on restoration (WAINGER et al., 2010).

Similar to costs, benefits also face difficulties in ecological restoration research, starting from the claim that restoration benefits to society are not often examined in detail (BULLOCK et al., 2011; KUMAR, 2017). Benefits also depend dramatically on the restoration site selection (KNOCHE; LUPI; SUITER, 2015).

Context-specific modelling of environmental and social benefits may be needed to understand their causal relationship with restoration interventions in a field of study and over a period of time (BODIN et al., 2021). To improve the use of modelled benefits of an ecosystem as proxy, Bodin et al. (2021) included in The Economics of Ecosystem Restoration (TEER) framework a benefit module that aims to collect empirical data on the full range of benefits of restoration interventions, consistently and continuously, over long periods of time. The TEER benefit module collects information on two categories of benefits: 1) benefits with market value (the net increase in benefits from restoration efforts that have a market value); 2) other environmental and social benefits (the improvement of ecosystem functionality and the associated safety net, health benefit, and job opportunities that are not directly exchangeable in the market). The TEER framework is a promising tool for the future, for standardizing both costs and benefits.

Although the analysis of benefits of restoration is relatively new (ARONSON et al., 2010), there have been several advances in this matter and the literature reports many benefits of restoration, already identified and quantified. Among these are:

- Waste treatment, watershed protection, carbon sequestration, secondary productivity of use to people (REY BENAYAS et al. 2009; ARONSON et al., 2010);
- Improvements or enhancements in the supply and quality of ecosystem services to society perceivable in the short term, and locally, such as increased productivity of farmland and rangelands (GEERKEN; ILAIWI 2004; ARONSON et al., 2010);
- Reduced soil erosion and mudslides, and greater protection against floods and offshore storms (CLEWELL; ARONSON 2006, 2007; ARONSON et al., 2010);
- Reducing extinction risk, improving water supplies, and increasing food security (BRANCALION et al., 2021);
- Restitution from damage to coastal fisheries after oil spills and prevention of natural disasters (MATZEK, 2018);
- Job creation (MATZEK, 2018; BLIGNAUT; ARONSON, 2020);
- Regulation compliance and carbon sequestration (NUNES et al., 2017);
- Reduction in storm damage and the linked avoided cost, direct recreational benefits, indirect benefits such as the increase of property values (PAOLI; GASTAUDO; VASSALLO, 2013);
- Livelihood opportunities and public health benefits (BLIGNAUT; ARONSON, 2020);

- Retention of soil and water, movement, cycling, and sequestration of elements, and the trophic complexity of the area (COSTANZA et al. 1997; KIMBALL et al., 2015);
- Water supply, sandstorm prevention, and carbon sequestration (OUYANG et al., 2020);
- Provisioning services (water availability, wood materials, wood fuels and electricity, and grazing capacity) and a regulating service (ecosystem carbon) (STAFFORD et al., 2017);
- “Insurance” from disturbances such as wildfire (STEPHENS et al. 2010; WU; KIM; HURTEAU, 2011).

Based on a comprehensive literature review, BenDor et al. (2015) also cite the following long-term economic benefits: (i) increased property values and local tax revenue; (ii) increased revenues associated with tourism and outdoor recreation; (iii) increased fish and game revenues; and (iv) increased ecosystem services (erosion control, stormwater management, groundwater recharge, surface water availability, water quality, flood control, carbon sequestration).

The analysis of the benefits of restoration to people was in its infancy in the beginning of the last decade (BULLOCK et al., 2011) and, since then, several methods and frameworks were developed. Table 1 lists the most frequent cited in the literature, and further information of these methods can be found on the references listed in the right column of the table. A highlight is the benefit transfer method, that estimates benefits of the site of interest in comparison to other sites where valuation studies were performed, and a habitat equivalence analysis that can be used to select restoration projects that will best compensate for habitat injuries.

Not all methods require monetary estimates. Indicators and ranking methods incorporate intrinsic restoration values without monetizing benefits (ROBBINS; DANIELS, 2011). Although sometimes it is simply not possible to attribute a value to benefit at all (BENDOR et al., 2015), in today’s fiscal climate, it is more important than ever to demonstrate the multiple ways that conservation work benefits not just the environment but also our economy (KELLON; HESSELGRAVE, 2014). On top of that, unless the costs of restoration are made equitably distributed in relation to the benefits provided (BULLOCK et al., 2011) and restoration can be made financially viable for landowners, scaling up and connecting restored lands together, as biodiversity conservation interest require, will never be achieved (BLIGNAUT; ARONSON; WIT, 2014; BRANCALION et al., 2021).

Table 1 – Methods and frameworks for the analysis of the benefits of restoration.	
Method	References
Non-market valuation such as: hedonic method, travel cost method, contingent valuation, choice experiments	(ROBBINS; DANIELS, 2011) (BENDOR et al., 2015)
Total Economic Valuation (TEV) framework	(KELLON; HESSELGRAVE, 2014)
Cost methods	(ROBBINS; DANIELS, 2011) (BENDOR et al., 2015)
Benefit transfer	(MATZEK, 2018) (IFTEKHAR et al., 2017) (ROBBINS; DANIELS, 2011) (BENDOR et al., 2015)
Economic valuation of ecosystem services	(KIMBALL et al., 2015) (OUYANG et al., 2020) (BULLOCK et al., 2011) (COSTANZA et al., 1997)
Habitat equivalency analysis (especially for damaged habitats)	(KIMBALL et al., 2015)
Value of marginal product (the increase in the market value of marketed goods generated by input of the ecosystem service)	(OUYANG et al., 2020)
Value of the marketed good, net of the value of inputs other than ecosystem services (e.g., labor, machinery, commercial fertilizer, and so forth).	(OUYANG et al., 2020)
Source: results of the study.	

4 The costs of restoration

Restoration is indeed costly, but part of this conclusion came from an incomplete accounting of benefits. Cost-benefit analyses tend to be done based on financial values only, without reflecting the nonmarket benefits restoration would create (BARBIER 2007; DE GROOT et al. 2013; VERDONE; SEIDL, 2017). The effect of human activities on ecosystem goods and services is often excluded in conventional cost-benefit analyses (GROOT et al., 2013).

Traditionally, restoration has been considered simply a cost to be paid (BULLOCK et al., 2011; GROOT et al., 2013; KUMAR, 2017; BLIGNAUT; ARONSON; DE GROOT, 2014; IFTEKHAR et al., 2017) but Blignaut et al. (2014) point out that there is already a framework to consider restoration a value-generating option and not just a cost item in budgets. The link between conservation of biological diversity and natural ecosystems with the maintenance of ecosystem goods and services (EGS) to support sustainable local economic development and reduce poverty was clearly demonstrated by major international initiatives, including the Convention on Biological Diversity (CBD), the Millennium Development Goals, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (TEEB 2010;

GROOT et al., 2013), and the Millennium Ecosystem Assessment (MA) (BLIGNAUT; ARONSON; WIT, 2014).

On the other hand, focusing only on estimating benefits can mislead decision-making (KUMAR, 2017). However, the cost–benefit analysis (CBA) (BIRCH et al., 2010; BULLOCK et al., 2011); and the cost-effectiveness analysis (GROOT et al., 2013; KUMAR, 2017) of restoration projects were very few among the literature gathered by the bibliometric analysis in Chapter 1.

In face of the scarce resources for funding, information on cost is important, as it allows decisions to be made on whether to conserve or to restore, which restoration methods to use, and which restoration projects to select (IFTEKHAR et al., 2017). When under-budgeted, projects are likely to fail and overestimate restoration efforts. When over-budgeted, inefficient allocation of scarce resources may occur, within or/and across projects (BODIN et al., 2021).

Restoration processes must avoid costly and simplistic plantings while achieving the greatest value for money (MENZ; DIXON; HOBBS, 2013). Better information can help in different ways. Data on costs can identify how interventions end depending on context, better choices of development, funding, and prioritization of projects (BODIN et al., 2021).

However, the overall lack of information on restoration effectiveness and even how to access its effectiveness, poorly specified metrics, and insufficient knowledge of human impacts is a challenge to up-scale projects from local to landscape or regional levels and limits the incorporation of ecological restoration in land-use planning and decision-making (LI et al., 2017; KIMBALL et al., 2015; KNOCHE; LUPI; SUITER, 2015). Poorly defined targets and a lack of quality (or any) monitoring greatly inhibits the overall understanding of restoration (WORTLEY; HERO; HOWES, 2013; KIMBALL et al., 2015; KNOCHE; LUPI; SUITER, 2015).

For example, the lack of reliable information that goes beyond projects lifespan, such as data on costs, is harming cost-benefit and cost-effectiveness analysis of restoration projects. (BODIN et al., 2021; BULLOCK et al., 2011; KIMBALL et al., 2015; ROBBINS; DANIELS, 2011; KUMAR, 2017; NEESON et al., 2016; ANSELL et al., 2016; ROHR et al., 2018). Regarding costs, there is also limited availability of spatially explicit costs (ANSELL et al., 2016), lack of spatial distribution of economic indicators in the landscape such as opportunity cost (BRYAN; KING; WARD, 2011; KNOCHE; LUPI; SUITER, 2015), and many restoration projects are performed by consultants who view cost data as proprietary or publish infrequently (ROBBINS; DANIELS, 2011).

Several literature reviews also point to the lack of time to develop appropriate models (WAINGER; MAZZOTTA, 2011), the lack of comparability across contexts, the lack of comparability of categories of restoration interventions, the lack of systematic and a common standard for reporting, and the lack of data in general, especially in tropical regions (BODIN et al., 2021; BLIGNAUT et al. 2014; ROBBINS; DANIELS, 2011; KUMAR, 2017; IFTEKHAR et al., 2017).

Table 2 shows various types of costs identified in the literature, which exemplifies how reporting on costs lack systematic and common standards. A highlight is the use of opportunity costs and the lack of mentions on the use of total costs of a project.

Table 2 – Types of costs of restoration reported in the literature.

Type of cost	References
Total cost	(BLIGNAUT; ARONSON; WIT, 2014)
Total cost summing implementation and accumulated land opportunity costs	(BRANCALION et al., 2021)
Private and public costs	(NUNES et al., 2017)
Average cost	(BLIGNAUT; ARONSON; WIT, 2014)
Only private financial cost	(BLIGNAUT; ARONSON; WIT, 2014)
Aggregate costs	(BULLOCK et al., 2011)
Only capital or labor costs	(BULLOCK et al., 2011)
Wages paid to laborers	(BULLOCK et al., 2011)
Direct costs of construction costs and operation and maintenance costs	(ROBBINS; DANIELS, 2011)
Hidden costs of restoration (planning, permitting, overhead, facilities, volunteer time, and monitoring)	(ROBBINS; DANIELS, 2011)
Opportunity costs in terms of foregone revenue	(ROBBINS; DANIELS, 2011) (ANSELL et al., 2016)
Opportunity costs of compliance	(NUNES et al., 2017) (BUDIHARTA et al., 2014)
Annual land opportunity cost	(BRANCALION et al., 2021) (BUDIHARTA et al., 2014)
Acquisition, establishment, maintenance, and transaction costs	(IFTEKHAR et al., 2017)
Area-based approaches	(ANSELL et al., 2016)
Cost per number of surviving individuals, per growth of seedlings, or per probability of meeting specific thresholds of success	(KIMBALL et al., 2015)

Source: results of the study.

Several authors also point how the differences in determination of costs is harming advances in the economics of restoration, for example, it makes comparisons very difficult (BLIGNAUT; ARONSON; WIT, 2014; BULLOCK et al., 2011), it makes it difficult to build a track record of reference cases that could be used as benchmarks (BLIGNAUT; ARONSON; WIT, 2014), and results in overall wastage of public funds, selection of wrong projects, and failure to achieve restoration targets (IFTEKHAR et al., 2017).

Ansell et al. (2016) advocate that if evaluation objectives are to identify the most cost-effective intervention from a range of potential options, using standardized costs across interventions will enable comparisons of the relative cost-effectiveness than the use of actual data. However, existing databases of restoration projects are often specific for a given local or ecosystem, and cannot be replicable for future restoration projects or other regions (BODIN et al., 2021). This may be due to the following factors:

- Local economic, social and biophysical contexts intrinsically affect the cost of restoration (BENDOR et al., 2015; BODIN et al., 2021). For example, the following variations of project costs between ecosystem type were: several hundreds to thousands of US$ ha^{-1} (grasslands, rangelands and forests); several tens of thousands (inland waters); or millions of US$ ha^{-1} for coral reefs (BULLOCK et al., 2011; KUMAR, 2017);
- Each intervention category is likely to lead to different planning, implementations and monitoring activities (BODIN et al., 2021);
- Categories of costs are reported in various formats, if recorded at all. For example, the cost of compensating or purchasing land was rarely recorded (BODIN et al., 2021);
- Different degrees of degradation affect restoration costs (GAERTNER et al., 2012; BODIN et al., 2021);
- Costs differ according to timescales for success and the methods used (BULLOCK et al., 2011). For example, small-scale restoration that is often done for research purposes tends to be much more expensive than the large-scale operations (GROOT et al., 2013);
- Scaling up to the global level requires multiplicative and additional costs relating to social and political requirements (MENZ; DIXON; HOBBS, 2013);
- Restoration can generate costs at locations different from the ones where the restoration takes place (BULLOCK et al., 2011).

In face of these issues, standardizing data gathering and improving data sharing would be greatly beneficial (ROBBINS; DANIELS, 2011) for policy, planning, and design of ecosystem restoration projects (BODIN et al., 2021; ROHR et al., 2018). A way of doing that is developing protocols for gathering and reporting the direct costs of restoration activities. The TEER (BODIN et al., 2021) has a standard framework with pre-defined expenditure categories and a closed list of interventions or set of interventions. They claim it would limit the variability in the reporting of costs as well as making it standardized across data points. Information on the social and biophysical context are also required within the TEER framework.

5 Financing restoration

Suppose we have identified the costs of a given restoration project or plan. The next question is the one made by (HOLL; HOWARTH, 2000) twenty years ago: “Who will pay for restoration?”. Ecological restoration costs are a long-term burden for both residents and governments. Therefore, an appropriate policy would increase the efficiency of the program by minimizing both government expenditures and the burden on those affected by the program (GONG et al., 2012).

Several authors have been contributing with ways to integrate ecological and socioeconomic objectives in restoration projects (ARONSON et al., 2010). Economics cannot provide the sole motivation for restoration per se (BLIGNAUT; ARONSON; WIT, 2014) as markets provide partial information to what society wants (ARONSON et al., 2010). Since markets treat as externalities the costs and benefits of degradation and restoration, largely ignoring them (TREVISAN et al., 2016), restoration activities continue to suffer from chronic underfinancing (PISTORIUS; FREIBERG, 2014). Nevertheless, it is imperative to find financial resources for new investments for restoration (BLIGNAUT; ARONSON; WIT, 2014).

In Table 3, we have put together several financial sources identified in the literature that give an overview of the financing landscape of restoration. We have sources from ecological options (ex.: biobanking, wood products, agroecology) to policies, public funding, and economic instruments (where payments for ecosystem services are heavily studied and used).

Table 3 – Financing sources for restoration identified in the literature.

Financing source	Reference
Government funding, laws, and associated litigation	(BULLOCK et al., 2011) (ROHR et al., 2018) (BENDOR et al., 2015)
Companies restoring ecosystems degraded by their activities	(BULLOCK et al., 2011)
Biobanking and biodiversity offsetting initiatives	(BULLOCK et al., 2011)
Payments for ecosystem services that help to pay or reward ecological restoration	(ARONSON et al., 2010) (BULLOCK et al., 2011) (GROOT et al., 2013) (ROHR et al., 2016) (LONG et al., 2018) (MATZEK, 2018) (SCHIAPPACASSE et al., 2012) (BLIGNAUT; ARONSON; DE GROOT, 2014) (BRANCALION et al., 2017) (ROHR et al., 2018)
REDD+	(GROOT et al., 2013) (SCHIAPPACASSE et al., 2012) (STICKLER et al., 2009)
Interagency collaborations and public–private partnerships	(BENDOR et al., 2015)
Private investments (foundations, non-profits, corporations, and institutions to increase sustainability or meet corporate social responsibility goals)	(BENDOR et al., 2015)
Wood products, including firewood, timber, pulp, resins, and others forest products	(BRANCALION et al., 2017) (NUNES et al., 2017) (VOGLER et al., 2015)
Carbon farming	(EVANS et al., 2015)
Environmental assurance bonding	(BULLOCK et al. 2011) (ROHR et al., 2018)
Agroecology	(TREVISAN et al., 2016)

Source: results of the study.

However, relying on just a type of funding source is not the way forward. All sectors of the economy are responsible for the costs of restoration, because restoration is an economic development concern (BLIGNAUT; ARONSON, 2020). The actors involved in market-oriented governance may include communities, NGOs, individuals, and governments. Although market actors play an important role, governments around the world organize and fund forest landscape restoration programs in practice (LONG et al., 2018; PISTORIUS; FREIBERG, 2014; BLIGNAUT; ARONSON; DE GROOT, 2014; KIMBALL et al., 2015). Government investment is often needed because many returns from restoration will be realized only in the long term and in the realm of broader public interests (BULLOCK et al., 2011). But once most of the restoration is or will be undertaken in private lands, legal requirements for compliance are not sufficient. Legislation should include direct compensation, incentives and disincentives, and straight-up economic benefits (BLIGNAUT; ARONSON; WIT, 2014; CROSSMAN; BRYAN; SUMMERS, 2011; SCHIAPPACASSE et al., 2012).

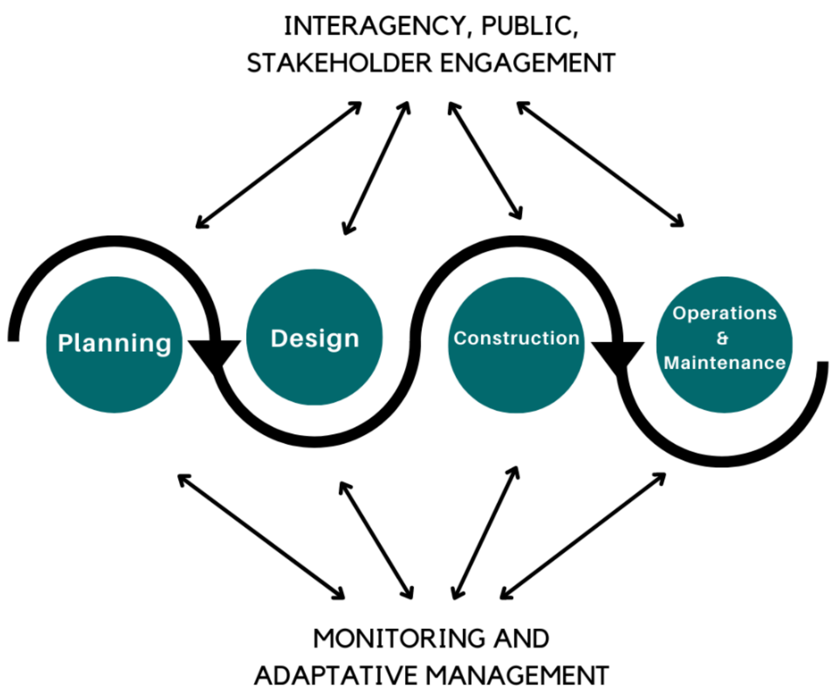
To participate voluntarily in restoration, socio-economic overview and justification is necessary to motivate landowners (RODRIGUES et al., 2011; SCHIAPPACASSE et al., 2012; TREVISAN et al., 2016; VERDONE; SEIDL, 2017; VOGLER et al., 2015; WU; KIM; HURTEAU, 2011). Conservation agencies looking for cooperation from a private landowner can make use of determining the social and economic benefits of restoration (IFTEKHAR et al., 2017). In theory, individual farmers would restore their forest if the cost of remaining non-compliant is greater than the land-use opportunity cost, but there is evidence from non-profit groups of significant conservation investments by landowners without direct compensation (NUNES et al., 2017).

Given the several challenges that comprise ecological and economic aspects of restoration, the framework called forest landscape restoration (FLR) moves restoration beyond sectoral and site-based activities toward an integrated approach at landscape level (Reed et al. 2016; (LONG et al., 2018). It includes large, contiguous, or fragmented areas (equal to or greater than several km2) (MENZ; DIXON; HOBBS, 2013) and its objectives are not only to restore the ecological integrity of degraded or damaged forests, but also to improve the sustainability of livelihoods. It is also an emerging and effective approach to address the negative impacts associated with forest restoration programs (LONG et al., 2018).

Groot et al. (2013) and Menz et al. (2013) suggest that restoration projects must be implemented with a landscape or bioregional perspective, because the effectiveness of forest restoration and its chances of sustainability are both much greater on a large scale (VERDONE; SEIDL, 2017; CICCARESE; MATTSSON; PETTENELLA, 2012). A diverse set of forest definitions is needed to capture the forest concept in all its dimensions, which will not be discussed in depth here for the purposes of this article, but a comprehensive discussion about this topic can be found in (CHAZDON et al., 2016).

The adoption of forest landscape restoration requires a significant shift from state-controlled to polycentric governance, which is characterized by multiple governing authorities at multiple levels (OSTROM, 2010). Although more empirical attention is still needed for this matter (LONG et al., 2018; PISTORIUS; FREIBERG, 2014), the dynamic nature of socio-economic context should always be considered in the planning, monitoring, and adaptive management of large scale ecological restoration programs for developing and promoting effective and flexible restoration interventions (LI et al., 2017; MENZ; DIXON; HOBBS, 2013). Within the project itself, (ROHR et al., 2016) stress that adaptive management and monitoring, and stakeholder engagement, should occur throughout all five stages of restoration projects (Figure 2), and it's a crucial factor in the learning curve for the success of restoration implementation (ROHR et al., 2018).

Figure 2 – The four stages of a restoration project by Rohr et al (2016).



Source: adapted from Rohr et al (2016).

In planning for implementation, multi-year funding should be accounted for to ensure the maintenance of sites after planting, including fire prevention and management (BUDIHARTA et al., 2014; BLIGNAUT; ARONSON; DE GROOT, 2014; IFTEKHAR et al., 2017). Monitoring of costs and benefits over time is needed to determine the best conceptual and technological approaches to ecosystem restoration and the best cost-benefit ratio for each ecosystem type.

6 Concluding remarks

A fundamental principle of forest and landscape restoration (FLR) is the enhancement of rural livelihoods (CHAZDON et al., 2016) and for farmers, monetary income is among the most important economic factors (TREVISAN et al., 2016). Rural communities in different regions around the world are often highly dependent on forest resources to support their livelihoods (BIRCH et al., 2010; VOGLER et al., 2015), and without economic sustainability, most landowners will be forced by their need to survive to return to the old practices that created the original environmental problems (GONG et al., 2012). These communities need to be active in FLR projects because if they ignore how these projects are helping to revert degradation, long-term restoration will be seriously compromised (MAZÓN et al., 2019).

Because restoration can improve human livelihoods and enhance biodiversity, it has a role in global environmental policy (BULLOCK et al., 2011; WORTLEY; HERO; HOWES, 2013; LI et al., 2017; ROHR et al., 2018) and its success needs to encompass the effects that ecological and socioeconomic outcomes and benefits have on welfare and community development (WORTLEY; HERO; HOWES, 2013; LI et al., 2017; KNOCHE; LUPI; SUITER, 2015; TURNER et al., 2015). To solve the gaps among society, researchers, policymakers, restoration and payment systems is an urgency since more than a decade ago (ARONSON et al., 2010; ROHR et al., 2016). However, several studies indicate that there is still poor communication between those who benefit from restoration and those who conduct research (BLIGNAUT; ARONSON; WIT, 2014; IFTEKHAR et al., 2017; KUMAR, 2017).

In order to reduce this gap, the restoration outcomes and the implications to society, as well as the links with agriculture and other systems, need to be highlighted wherever possible. The obvious, potential and direct impact of benefits to people need to be explicit (MENZ; DIXON; HOBBS, 2013; ARONSON et al. 2010). Financing and policy should always be discussed in papers and reports (ARONSON et al. 2010). Luckily, these have been increasingly incorporated in restoration plans and goals by both researches and managers (MAZÓN et al., 2019).

As a final comment, there are some concerns regarding the major international commitments over the last decade, because few targets have been achieved by countries. Yet, the UN General Assembly declared the UN Decade on Ecosystem Restoration (UNDER) from 2021 to 2030. With the Bonn Challenge already on its way, they represent bold global challenges. Verdone and Seidl (2017) state that accounting for costs and benefits can make these targets being met efficiently, and advances in frameworks such as the TEER presented by Bodin et al. (2021) can facilitate the way forward.

This study presented a comprehensive view of the challenges, opportunities and critical aspects that need to be solved to advance in the economics of restoration research and its application, especially regarding the methods and frameworks needed to estimate costs and benefits. It is clear from the evidence that there is much work to do to fully integrate the ecological practices in restoration with economic concepts and methods. However, this article shows that much progress has been made and, by identifying and systematizing the current challenges, we provide a path for future improvements and developments in the economics of restoration science. We also believe that our work will make it easier for readers to identify up to date information about their issues of interest, helping them with the state of the art of the main challenges of economics of restoration.

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Chapter 3 – Is economics of restoration helping with decision-making challenges? Insights guided by bibliometrics

1 Introduction

The many functional interactions triggered by the multifactorial interdependence of ecosystem processes lead to uncertainties about possible responses given by different habitats under restoration management (HODGE; ADAMS, 2016; KANGAS; OLLIKAINEN, 2019; SCEMAMA; LEVREL, 2019). When these natural responses are unclear, it is difficult to calculate the resilience of natural environments (BARBIER, 2016), anticipate the outcome of restoration actions (SCEMAMA; LEVREL, 2019) and, ultimately, design natural capital markets (TEYTELBOYM, 2019). On top of that, restoration activities can take decades or even centuries (ARONSON; BLIGNAUT; ARONSON, 2017), and even after decades, ecosystems such as wetlands and grasslands will not fully recover (BLIGNAUT; ARONSON, 2020). As stressed by Kangas and Ollikainen (2019), there is no compensation for irreplaceable habitats, vulnerable ecosystems, or endangered species.

Although there is evidence of the ecological and economic effectiveness of restoration (GROOT et al., 2013; MORENO-MATEOS et al., 2012; SCEMAMA; LEVREL, 2019), studies that go beyond costs are still rare (BLIGNAUT; ARONSON, 2020). Restoration can alleviate poverty, generate employment and income, and provide environmental goods and services to society, and it is likely to fail if merely understood as a narrowly focused environmental activity (BRANCALION et al., 2017). According to Iftekhar et al. (2016) a better use of economic instruments, tools, and principles can help with restoration challenges. To assist with the paradigm shift that is needed towards a 'restoration narrative' (BLIGNAUT; ARONSON, 2020), a bibliometric analysis of the field of economics of restoration was done in this study.

Bibliometrics is a method for measuring, monitoring, and studying all kinds of bibliographic data (GLÄNZEL, 2003; JOSÉ DE OLIVEIRA et al., 2019; LIU et al., 2019). The visualization of bibliometric networks, or 'science mapping' (VAN ECK; WALTMAN, 2014), is used to quantitatively analyze a given field of interest. It is possible to obtain detailed information about past, present and trends in academic literature (GLÄNZEL, 2003; LIU et al., 2019). This study will be conducted using co-citation and bibliographic coupling networks. A co-citation occurs when two papers are cited together by a third one (SMALL, 1973), and a bibliographic coupling occurs when two papers cite one (or more) papers together (KESSLER, 1963).

Co-citation and bibliographic coupling complement each other. They can be used for information retrieval, as was done in this study, and for research evaluation. Results from bibliometrics can also be used to help subsidize decisions on research policy and funds (JOSÉ DE OLIVEIRA et al., 2019). Although not without controversy (AKSNES; LANGFELDT; WOUTERS, 2019), citation is assumed as a measure of relevance of documents, authors, or journals. Co-citation is more influenced by citation metrics, where heavily co-cited documents tend to be very cited as well (GLÄNZEL, 2003; SMALL, 1973). It can be interpreted that co-citation reveals the structure of core documents that form the basis of a discipline, the important documents that helped in the development of that science, and on the other hand, bibliographic coupling reflects the documents that cite together, being less influenced by citation and due to that it can identify core documents that represent emerging research topics (AKSNES; LANGFELDT; WOUTERS, 2019; GLÄNZEL, 2003; MARIANO; SANTOS, 2017; TRUJILLO; LONG, 2018).

Bibliometric analysis is being used in different topics related to environmental sciences and economics. To cite a few, there are studies related to ecosystem services (DRAGOS; DRAGOS, 2013; LIU et al., 2019; VALENTINA et al., 2018; VANDERWILDE; NEWELL, 2021), research in deforestation (ALEIXANDRE-BENAVENT et al., 2018), forest fires in tropical forests (JUÁREZ-OROZCO; SIEBE; FERNÁNDEZ Y FERNÁNDEZ, 2017), sustainable development (DU et al., 2021), environmental taxes (BASHIR et al., 2021), circular economy (MARTINHO; MOURÃO, 2020; RUIZ-REAL et al., 2018), bioeconomy (BAMBO; POURIS, 2020), Environmental Kuznets Curve (SARKODIE; STREZOV, 2019), carbon tax (ZHANG et al., 2016) and climate change adaptation (WANG, 2018).

Romanelli et al. (2018) and Guan et al. (2019) conducted bibliometric analysis on ecological restoration as a research field, but they have only used co-authorship, co-occurrence and/or co-word in their analysis, and none have focused nor identified economic aspects in their analysis. Specifically for the Economics of Restoration there are the literature reviews from BenDor et al. (2015), Blignaut et al. (2014) and Iftekhar et al. (2016), but no bibliometric analysis was identified. Most studies only use Web of Science (WoS) and a few use co-citation and/or bibliographic coupling.

The present study is a bibliometric analysis of Economics of Restoration using co-citation and bibliographic coupling networks. The aim of this study is to identify the research themes which are important and influential for the field of economics of restoration, and to present the key topics of these research themes that need to be further addressed to strengthen the decision-making processes when it comes to restoration actions.

Following this introduction, the second section of this paper presents the methods, tools and materials used. The third section presents the results with the bibliometric maps and research themes identified. The fourth section is a discussion with the key topics of the research themes, and the fifth section presents the conclusion.

2 Methods and materials

2.1 Co-citation and bibliographic coupling maps

A bibliometric map visually represents the connection between items in a bibliometric network. In this study, the items in the co-citation maps are the cited references in the documents selected in Scopus and WoS, and the items in the bibliographic coupling maps are the documents themselves. The connection between items is known as a link, in the present case a co-citation link or a bibliographic coupling link, and the strength of a link can be measured by a positive numerical value. The higher this numerical value is, the stronger the link strength. There can be no more than one link between any pair of items (VAN ECK; WALTMAN, 2021).

The software used in this study, VOSviewer (*Section 2.3*), calculates two standard weight attributes: the links and the total link strength. In the co-citation maps, the link attribute indicates the number of co-citation links of a given cited reference with other cited references, and the total link strength indicates the total strength of the co-citation links of a given cited reference with other cited references. In the bibliographic coupling maps, the link attribute indicates the number of bibliographic coupling links of a given document with other documents, and the total link strength indicates the total strength of the bibliographic coupling links of a given document with other documents (VAN ECK; WALTMAN, 2014, 2021).

In this study, two visualizations of a map will be used for each co-citation and bibliographic coupling analysis: the item density and the network visualizations. In the item density visualization, items are represented by their label and the color of a given point in the map indicates the density of items at that point. The 'rainbow' palette provided by VOSviewer was selected to illustrate the density. The colors range from light blue to green and from yellow to red. The closer the color of the point is to red, the larger the number of items in the neighborhood of that point and the higher the weights of the items in the neighborhood. Thus, the closer the color of the point is to light blue, the smaller the number of items in the neighborhood of that point and the lower the weights of the items in the neighborhood. The item density visualization does not show the link between items.

The network visualization represents the items by their label and a circle. The size of the label and the circle of each item is determined by the standard weight attributes. The higher the weight is, the larger the label and circle of an item. The link is represented by a line between two items. In the network visualization it is possible to observe that each item is attributed to a unique cluster. A cluster is a group of items that can be potentially close to each other and the number of clusters is calculated by an arbitrary resolution parameter set by the user. The default resolution of 1 worked well for all co-citation and bibliographic coupling analysis of this study. Each cluster has its own color, and the color of an item represents the cluster which it belongs to.

Following the color sequence light blue – green – yellow – orange – red in the item density visualization, the light blue points in a map are interpreted as less important and the red points as more important. In the network visualization, the size of an item in relation to other items related to its importance, with bigger items being more important. This is not a classification of the quality of the content of the items, but an indicator of the importance of items in the cluster they belong to and for the research-field topics highlighted by the bibliometric analysis.

The distance between the items approximately indicates the relatedness of the items in terms of co-citation or bibliographic coupling links. In general, the closer two items are to each other, the stronger is their relatedness. This is calculated using a Visualization of Similarities (VOS) technique. The clustering of items will often reflect this relationship, but sometimes an item can belong to one cluster and have a stronger link with an item from another cluster. Since VOSviewer uses a distance-based approach to place the items in the maps, the distance between items is more important than the cluster they belong to when it comes to assess the structure of the science field of interest. We refer to van Eck and Waltman (2014; 2010) for more details about the VOS and clustering technique adopted by VOSviewer.

2.2 Data Sources

Scopus and WoS databases were used as bibliographic sources. As shown in Figure 1, the keywords “economics of restoration” were used as search parameters in the Scopus “Article title, abstract, keyword” and WoS “Topic” fields. In both databases, the first filter was to select “Article” from the “document types”. The second filter was to select “Environmental Science” from Scopus “Subject area” and “WoS Categories” fields. The date range for the search was from 2011 to 2021. After filtering, 753 articles from Scopus and 89 articles from WoS were selected. The search took place on April 5, 2021.

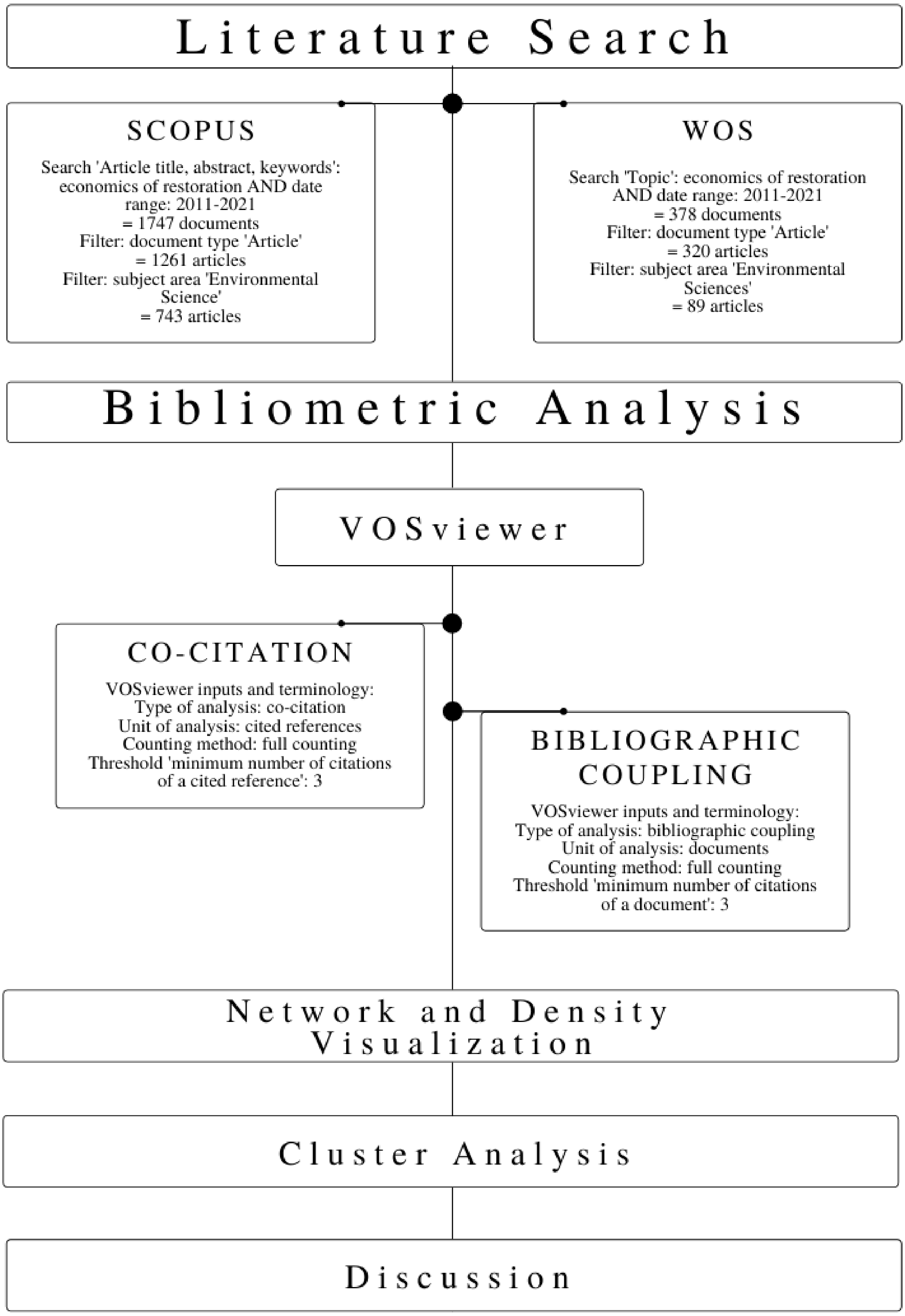
The citation information provided by the databases is exported in different formats: *.csv* from Scopus and *.txt* from WoS. Hence, since VOSviewer creates networks and maps for each database separately, duplicates between databases are not excluded.

For co-citation, the unit of analysis was “cited references” and a minimum of 3 citations of a “cited reference” was set as threshold, from now on referred as citation threshold for both analysis. For bibliographic coupling, the unit of analysis was “documents” and a minimum of 3 citations of a “document” was set as citation threshold (see Fig. 1 for VOSviewer terminology).

In the final maps, VOSviewer refers as ‘items’ all cited references and documents. In every analysis, the ‘full counting’ method was selected, meaning that each co-citation or bibliographic coupling link has the same weight of 1, as opposed to ‘fractional counting’, where the weight of a link is fractionalized between the N items in an unit of analysis. For an in-depth discussion about full and fractional counting, see Perianes-Rodriguez et al. (2016) and for discussions on citation minimum, see Rauchfleisch and Schäfer (2018) and Trujillo and Long (2018).

From the citation thresholds selected, VOSviewer calculates the link strength for each item from higher to lower. The user can choose how many items to select based on this metric. Then, the software provides a list of all items that will be shown in the maps. There is the possibility to exclude items before generating the maps, feature that was used to exclude repeated references that occurred only for the Scopus co-citation analysis. Finally, some of the items in the network can be unconnected to each other. VOSviewer calculates the larger set of connected items and asks if it should show only this set, which was the choice for the present analysis.

Figure 1 – Literature search, bibliometric analysis and VOSviewer terminology diagram.



Source: results of the study.

Table 1 shows the initial number of items from the first citation threshold and the final number of items in the maps. The number of documents from the citation threshold of co-citation of Scopus and WoS was used as a reference to choose the quantity of items in the subsequent selection of items based on the link strength for bibliographic coupling of each database.

Table 1 – Inputs and thresholds to calculate the number of items in the bibliometric network maps based on Scopus and WoS bibliographic data.

Bibliometric networks	Co-citation		Bibliographic Coupling	
Bibliographic sources	Scopus	WoS	Scopus	WoS
Citation threshold	118	64	553	67
Cited references based on link strength	118	64	118	64
After excluding repeated items (only occurred in Scopus co-citation)	96	64	118	64
Set of connected items in the maps	**81**	**62**	**118**	**57**

Source: results of the study.

2.3 Softwares

VOSviewer (version 1.6.15) is a free software tool developed by van Eck and Waltman (2010) that intends to analyze bibliometric networks using maps based on network data. VOSviewer can use bibliographic databases to construct networks of scientific publications, researchers, keywords, scientific journals, countries, research organizations, or terms. The items in these networks can be connected by co-citation, bibliographic coupling, co-occurrence, co-authorship, or citation links. To visualize and explore the maps, the software provides three visualization options: network and density visualizations, that will be used in this study, and the overlay visualization. For more information about VOSviewer please refer to the website https://www.vosviewer.com/. Zotero (version 5.0.96) is an open-source reference manager software. Within a bibliometric analysis, a reference manager helps locating and retrieving information on the items in a bibliometric network. More information about Zotero can be found at https://www.zotero.org/. Supporting tables were made with Microsoft Excel 2016.

3 Results

The results are divided into two sections. The first section is a primary analysis that presents the most important items in each co-citation and bibliographic coupling map, the relationships between clusters as seen in the network visualization, and the focus of each cluster. The second section organizes the clusters in Research Theme groups based on clusters focus similarity and density of items as seen in the item density visualization.

3.1 Primary Analysis of Clusters

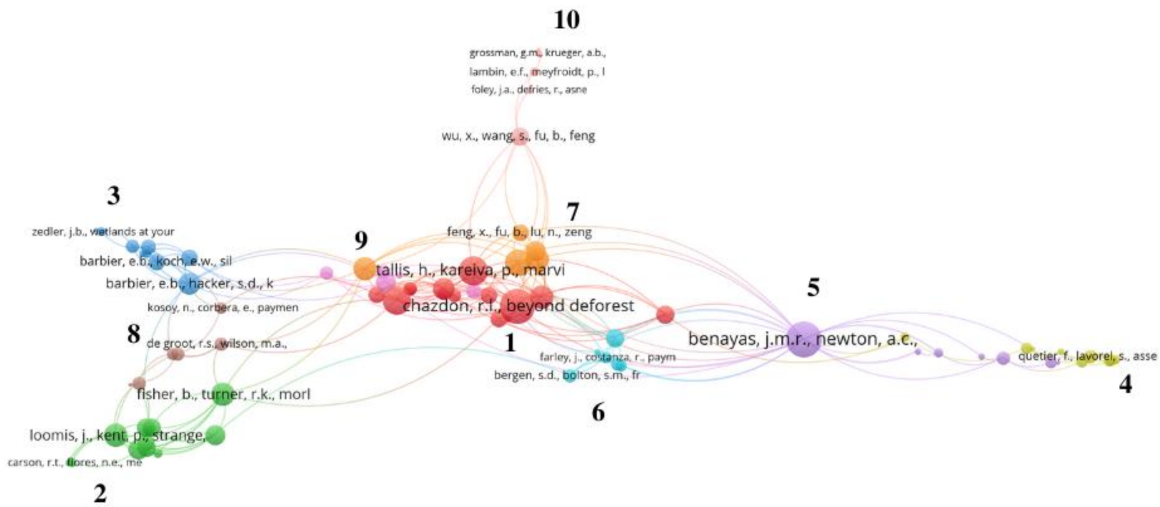
3.1.1 Co-citation maps

The co-citation network visualization for Scopus and WoS is presented in Figure 2 and Figure 3. Items are classified by link weight, which means that the items with more links with other items will be shown more prominently than the others.

In the Scopus map (Fig. 2) it is possible to immediately identify the two most important items in the map. The first being the study from (BENAYAS et al., 2009), from cluster 5, titled "Enhancement of Biodiversity and Ecosystem Services by Ecological Restoration: A Meta-Analysis". It is not only the item with more links with other items, but it's linked with other five different clusters from the map. The second is the study from (CHAZDON, 2008), from cluster 1, titled "Beyond Deforestation: Restoring Forests and Ecosystem Services on Degraded Lands".

There is a total of ten clusters, and it is possible to notice that the clusters in the center of the map often share links with all other clusters, which is not the case for clusters 10 and 4, for instance, that only share links with one or two other clusters. This indicates a distant connection of the items in these clusters, especially for cluster 10, distant from all others.

Figure 2 – Co-citation map: network visualization for Scopus.



Source: results of the study. Observation: The numbers in the figure refer to the clusters.

A closer look into the main topic of each Scopus cluster:

- Cluster 1 focuses on early definitions of ecosystem services (ES) and their relationships and interactions with drivers of ES. Important items include Bennett et al., (2009); Chazdon, (2008); Lamb et al., (2005); Liu and Yang (2012); Tallis et al., (2008).
- Cluster 2 focuses on water ecosystems and wetlands, the methods include economic and contingent valuations, choice experiments and management and decision-making discussions. Important items include Birol et al., (2006); Carlsson et al., (2003); Carson et al., (2001); Daily et al., (2009); Fisher et al., (2009); Loomis et al., (2000).
- Cluster 3 focuses on economic valuation of coastal ecosystem services and covers blue carbon related issues. Important items include Barbier et al., (2008, 2011); Engle (2011); Kirwan and Megonigal (2013); Mcleod et al., (2011).
- Cluster 4 focuses on biodiversity offsetting, ecological equivalence, and the economic and ecologic relations regarding these topics. Important items are Bull et al., 2013; Calvet et al., 2015; Costanza et al., 1997; Quétier and Lavorel, 2011; van Teeffelen et al., 2014.
- Cluster 5 focuses on conceptual frameworks for ecological restoration, conservation planning and success measures. A highlight of this cluster is the already cited meta-analysis on ecological restoration made by Benayas et al. (2009). Important items are Hobbs and Norton, 1996; Margules and Pressey, 2000; Ruiz-Jaen and Mitchell Aide, 2005.

- Cluster 6 covers payments for ecosystem services, economic costs and ecosystem recovering, and the role of ecological engineering. Important items include Bergen et al., 2001; Engel et al., 2008; Farley and Costanza, 2010; Jones and Schmitz, 2009; Naidoo et al., 2006.
- Cluster 7 focuses on the aspects of economic development and restoration, ecological and socioeconomic factors and effects of restoration, the relations between ecological restoration and ES. Mostly are China related studies. Important items are Cao et al., 2014; Feng et al., 2013; Liu et al., 2008; Vitousek et al., 1997; Wang et al., 2011.
- Cluster 8 focuses on economic valuation of ecosystem goods and services and threatened species. It also includes discussions on valuation to help with decision making processes and commodification of ES. Important items include Costanza et al., 2014; de Groot et al., 2002; Kosoy and Corbera, 2010; Laurans et al., 2013; Richardson and Loomis, 2009.
- Cluster 9 covers the interface between restoration and biodiversity and land use, including food productions and carbon from forest regeneration. Important items include Bullock et al., 2011; Foley et al., 2005; Gilroy et al., 2014; Phalan et al., 2011; Suding, 2011.
- Cluster 10 focuses on economic growth and non-market benefits. Important items include Brouwer et al., 2016; Foley et al., 2005; Grossman and Krueger, 1995; Lambin and Meyfroidt, 2010; Wu et al., 2019.

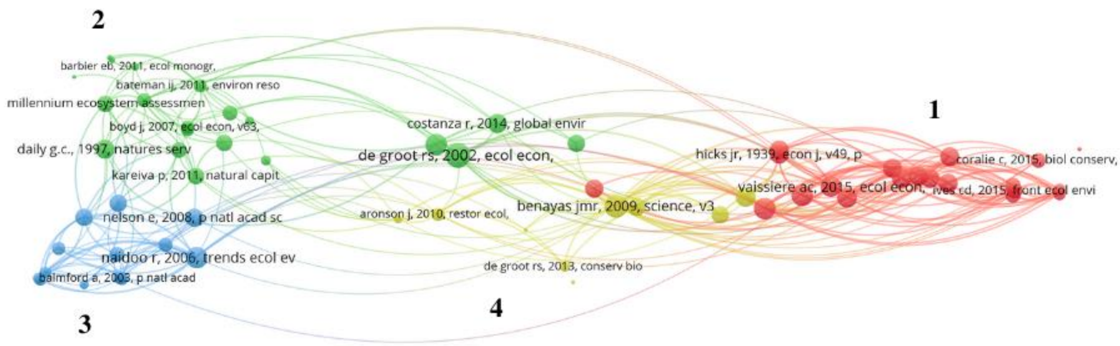
In the WoS map (Fig. 3), there are four clusters, all connected with each other. The most important item is the one from cluster 2, the study from de Groot et al. (2002) titled "*A typology for the classification, description and valuation of ecosystem functions, goods and services*", followed by Benayas et al. (2009), also the main one from the Scopus map.

A closer look into the main topic of each WoS cluster:

- Cluster 1 covers biodiversity offsets, perverse incentives, and policy development. Important items include Coggan et al., 2013; Gordon et al., 2015; McKenney and Kiesecker, 2010; Vaissière and Levrel, 2015; Walker et al., 2009.
- Cluster 2 focuses on all issues related to ES, from classification to economic analysis and valuation. A highlight from this cluster is the 1997 global valuation of ES, from Costanza et al. (1997). Other important items include Bateman et al., 2011; Costanza et al., 2014; de Groot et al., 2002.

- Cluster 3 focuses on economic costs, benefits and return on investment in conservation. Important items include Balmford et al., 2003; Murdoch et al., 2007; Naidoo et al., 2006; Naidoo and Ricketts, 2006; Nelson et al., 2008.
- Cluster 4 is a mix cluster covering evaluation of restored habitats and the importance of scale in restoration. Important items include Aronson et al., 2010; Benayas et al., 2009; De Groot et al., 2013; Mitsch and Gosselink, 2000; Moreno-Mateos et al., 2012.

Figure 3 – Co-citation map: network visualization for WoS.



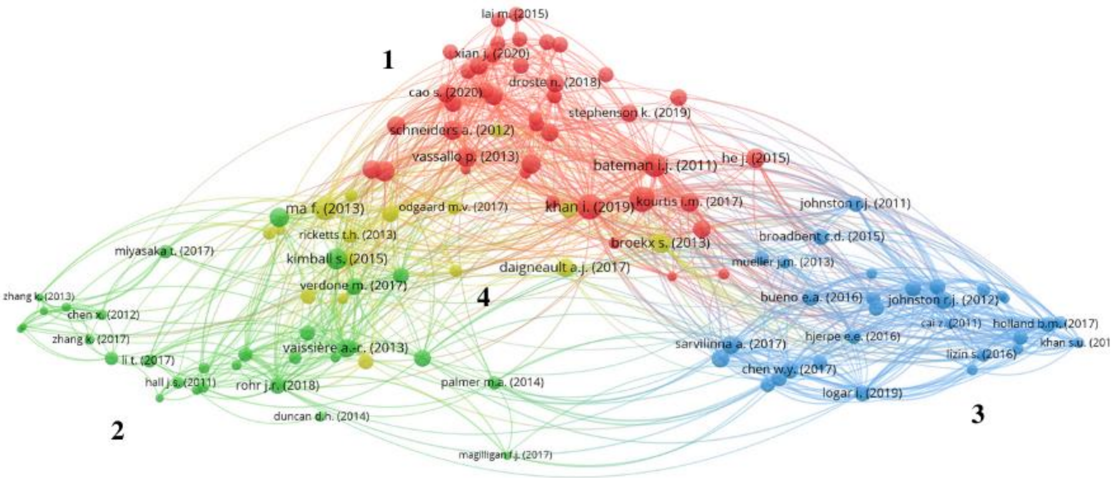
Source: results of the study. Observation: The numbers in the figure refer to the clusters.

3.1.2 Bibliographic coupling maps

The Scopus and WoS network visualizations for bibliographic coupling are presented in Figure 4 and Figure 5. Items are classified by link weight, meaning that the items with more links with other items will be shown more prominently that the others.

In the Scopus map (Fig. 4), there are four large clusters, all connected with each other. Cluster 3 is the only one that do not overlap with another cluster. An interesting observation in this map is that most of the circles have a similar size, which indicates that the items have a similar link weight. If, in a bibliographic coupling, links between items indicate similarity between their reference list, this network visualization suggests that this group of items is largely influenced by the same articles. The most important items of the map are all from cluster 1, the first being the study from Wainger and Mazzotta (2011), "*Realizing the potential of ecosystem services: A framework for relating ecological changes to economic benefits*", followed by Khan et al. (2019), "*Public attitudes, preferences and willingness to pay for river ecosystem services*", and then Bateman et al. (2011), "*Economic analysis for ecosystem service assessments*".

Figure 4 – Bibliographic coupling map: network visualization for Scopus.



Source: results of the study. Observation: The numbers in the figure refer to the clusters.

A closer look into the main topic of each Scopus cluster:

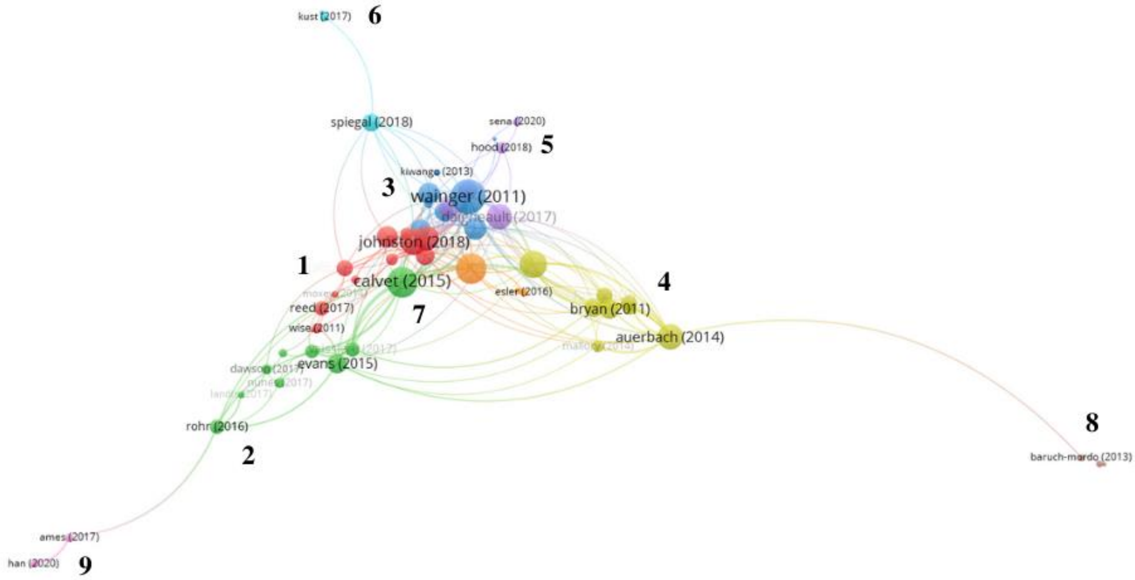
- Cluster 1 focuses on economic analysis for ES and biodiversity, including natural capital assessment, ecosystem management, and restoration of natural capital studies. Important items include Adame et al., 2015; Bakshi et al., 2015; Banerjee et al., 2013; Bateman et al., 2011; Blignaut et al., 2014; Li et al., 2011; Schneiders et al., 2012; Vassallo et al., 2013; Wainger and Mazzotta, 2011; Winn and Pogutz, 2013.
- Cluster 2 focuses on payments for ecosystem services (PES) and carbon payments, agent-based modelling, and cost effectiveness analysis of restoration. Important items include Bayraktarov et al., 2016; Chen et al., 2012; Crossman et al., 2011; Dang and Liu, 2012; Evans et al., 2015; Kimball et al., 2015; Palmer et al., 2014; Rodrigues et al., 2011; Yin et al., 2014.
- Cluster 3 focuses on economic valuation, mainly applied to water ecosystems: rivers, urban rivers, and watersheds. Important items include Almansa et al., 2012; Bergstrom

and Loomis, 2017; Hjerpe et al., 2015; Johnston et al., 2012, 2011; Johnston and Ramachandran, 2014; Kenney et al., 2012; Martin-Ortega et al., 2011; Mueller et al., 2013; Zhao et al., 2013.

- Cluster 4 is a mix of studies of cultural ES, spatial analysis applied to ES and internet-based valuation surveys. Important items include Allan et al., 2015; Broekx et al., 2013; Daigneault et al., 2017; Labiosa et al., 2013; Newton et al., 2012; Obeng and Aguilar, 2018; Ricketts and Lonsdorf, 2013; Rogers et al., 2015; Spiegal et al., 2018; Van Berkel and Verburg, 2014.

In the WoS map (Fig. 5), there are nine small clusters, six of them concentrated in the center of the map. Although these clusters are very close, there is a clear pattern between them: clusters 2, 4, and 7 are located at the bottom of the group, and clusters 1, 3, and 5, at the top (1, 3, and 5). The other three clusters in the map are of small importance. The most important item is the study from Wainger and Mazzotta (2011), the same from the Scopus map (Fig. 3A), followed by Calvet et al. (2015), "*The Biodiversity Offsetting Dilemma: Between Economic Rationales and Ecological Dynamics*", and Blignaut et al. (2014), "*Restoration of natural capital: A key strategy on the path to sustainability*".

Figure 5 – Bibliographic coupling map: network visualization for WoS.



Source: results of the study. Observation: The numbers in the figure refer to the clusters.

A closer look into the main topic of each WoS cluster:

- Cluster 1 include habitat and resource equivalence analysis, PES and ES analysis. Important items include Becker et al., 2014; Desvousges et al., 2018; Nicolette et al., 2013; Reed et al., 2017; Stafford et al., 2017.

- Cluster 2 focuses on governance and management of restoration, including biodiversity restoration and biodiversity offset. Important items include Calvet et al., 2015; Dawson et al., 2017; Evans et al., 2015; Landis et al., 2017; Rohr et al., 2016.
- Cluster 3 focuses on the topics of economic benefits from ecological changes, enhancing ecosystems, and risk management. Important items include Baumber, 2017; Deacon et al., 2015; Everard et al., 2014; Van Passel et al., 2013; Wainger and Mazzotta, 2011).
- Cluster 4 focuses on the topics of opportunity costs, cost effective management, return on investment, and economic and ecological outcomes. Important items include Auerbach et al., 2014; Bryan et al., 2011; Habib et al., 2013; Ricketts and Lonsdorf, 2013; Wang et al., 2016.
- Cluster 5 is a mix of economic valuation, cost-effectiveness and nexus analysis all related to water ES, and case studies related with hard science, sediments, infrastructure. Important items include Daigneault et al., 2017; Garcia et al., 2019; Hood et al., 2018; Lee and Khim, 2017; Mitchell and Casman, 2011.
- Cluster 6 focuses on land use, land degradation and climate ES. Important items include Kust et al., 2017; Nost, 2019; Qadir et al., 2014; Spiegal et al., 2018.
- Cluster 7 focuses on investment and restoration of natural capital, including discussions about the use of interdisciplinarity to overcome complex social-ecological problems. Important items include Blignaut et al., 2014; Blignaut, 2019; Esler et al., 2016.
- Cluster 8 focuses on economic studies of fuel reduction treatment and conservation investment options. Important items include Baruch-Mordo et al., 2013; Huang et al., 2013; Taylor et al., 2013.
- Cluster 9 focuses on ecological aspects about leaf traits and adaptability and forest succession. Important items include Ames et al., 2017; Han et al., 2020; Tiantian et al., 2011.

3.2 Research Themes

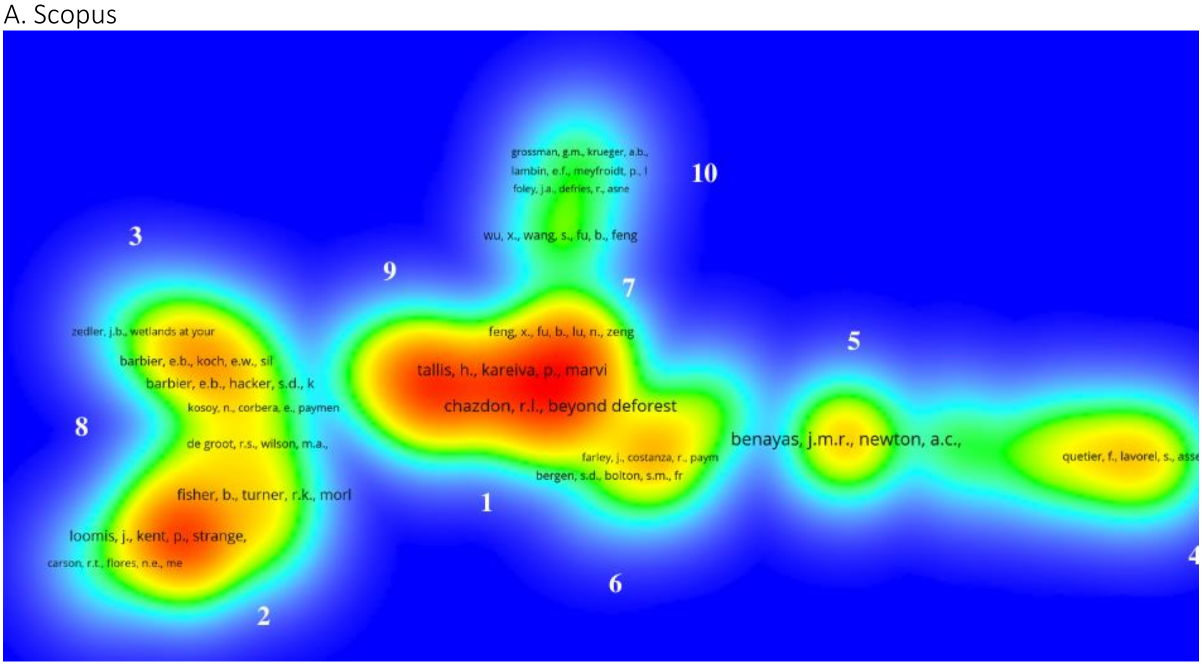
The item density visualization provides a more intuitive map of dense areas than the network visualization. Recalling *Section 2.3,* that defined dense areas as the sum of both number of items closer to a point and the weights of the items, it is possible to come to a final classification of the research themes highlighted by the bibliometric analysis.

For this purpose and using the rainbow classification of importance of items described in *Section 2.3.1*, orange and red areas are automatically selected as more important, the light blue and green areas are considered not important and discarded, and the yellow areas are evaluated individually, based on the weight classification of the specific items in each map.

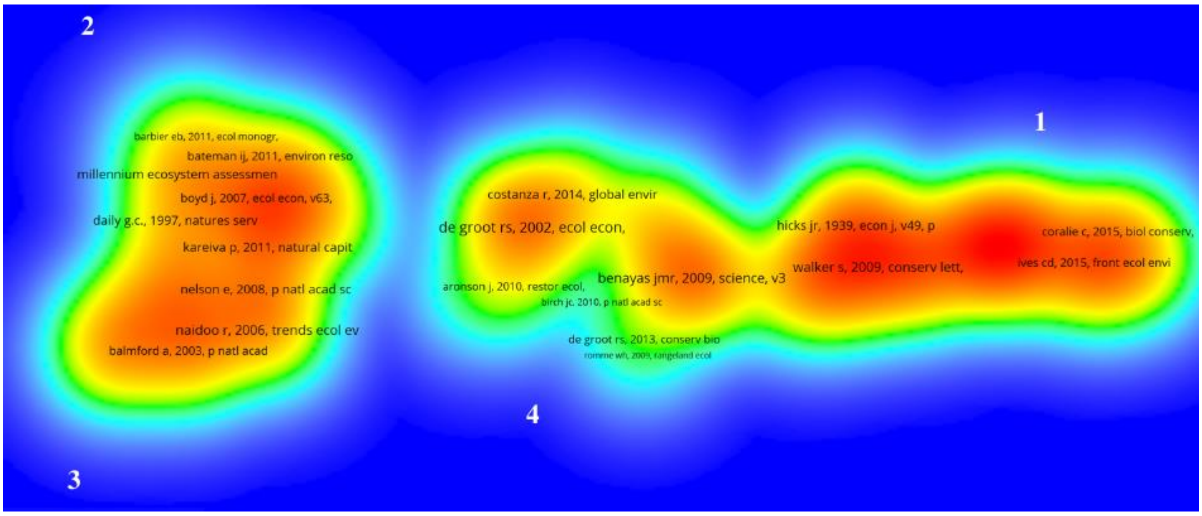
The Scopus and WoS item density visualizations for co-citation are presented in Figure 6. For Scopus, the density view (Fig. 6A) is similar to the network view (Fig. 2) and it is possible to identify more precisely that the cluster 10 is the least important, whereas clusters 1, 7 and 9 are the most important. Cluster 5 and 4 are colored yellow because there are few items in those areas, especially cluster 5, which have the item with the strongest link weight of the map but is isolated from other items.

On the other hand, the WoS density view (Fig. 6B), show the clear separation of the four items in the center of the map that belong to cluster 2 but are closer to cluster 4. The rest of the map is similar to the network view (Fig. 3). The most important item of this map in terms of link weight is in an orange point of the map, once again because of the low density of items in the area.

Figure 6 – Co-citation maps: item density visualization for Scopus (A) and WoS (B).
A. Scopus



B. WoS



Observation: The numbers in the figure refer to the clusters. Source: results of the study.

From these observations and the content description of the clusters in *Section 3.1.1* there were organized four scholarly themes grouping together Scopus and WoS results:

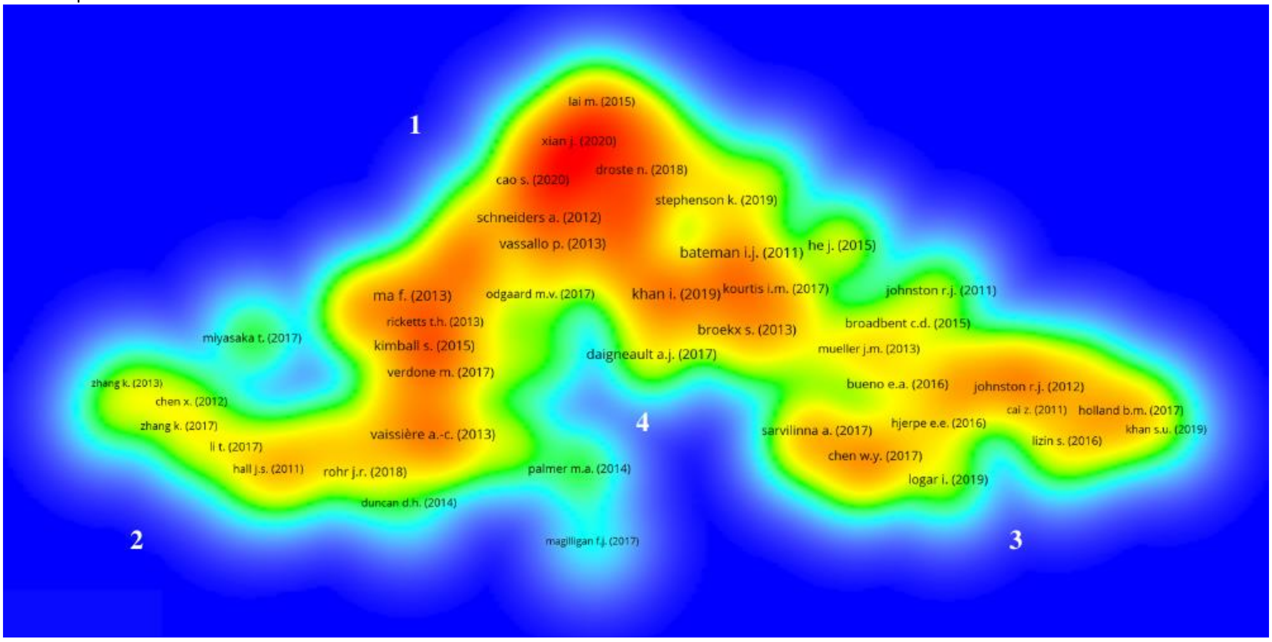
1. The Economic Analysis Theme: economic valuation, cost-benefit analysis and several analytic methods are heavily cited both in Scopus and WoS. It is not a surprise that these methods appear to be so important in the co-citation analysis. Since they are one of the foundations of environmental economics and lately incorporated into ecological economics studies as well, it is expected that they also play an important role in the economics of restoration, especially when it comes to decision-making processes in early studies that deal with environmental problems.
2. The Ecosystem Services Theme: all aspects related to ES were covered, from PES, cost-benefit analysis, valuation, management, decision-making processes, to cultural and social aspects. Although all ecosystems receive attention, big emphasis is given to ES provided by water resources.
3. The Biodiversity and Conservation Theme: the topic of biodiversity offset receives less attention than ES but is present too, as well as the challenges of conservation. Policy and investment are cross-cutting topics.
4. The Ecological Restoration Theme: articles about ecological restoration are the majority in the co-citation networks. From early conceptual frameworks to monitoring and success measures, and the relations between restoration, ES, and biodiversity. The

interface of restoration and economic development, cultural and socioeconomic factors are also discussed. Ecological equivalence and scale in restoration can also be found.

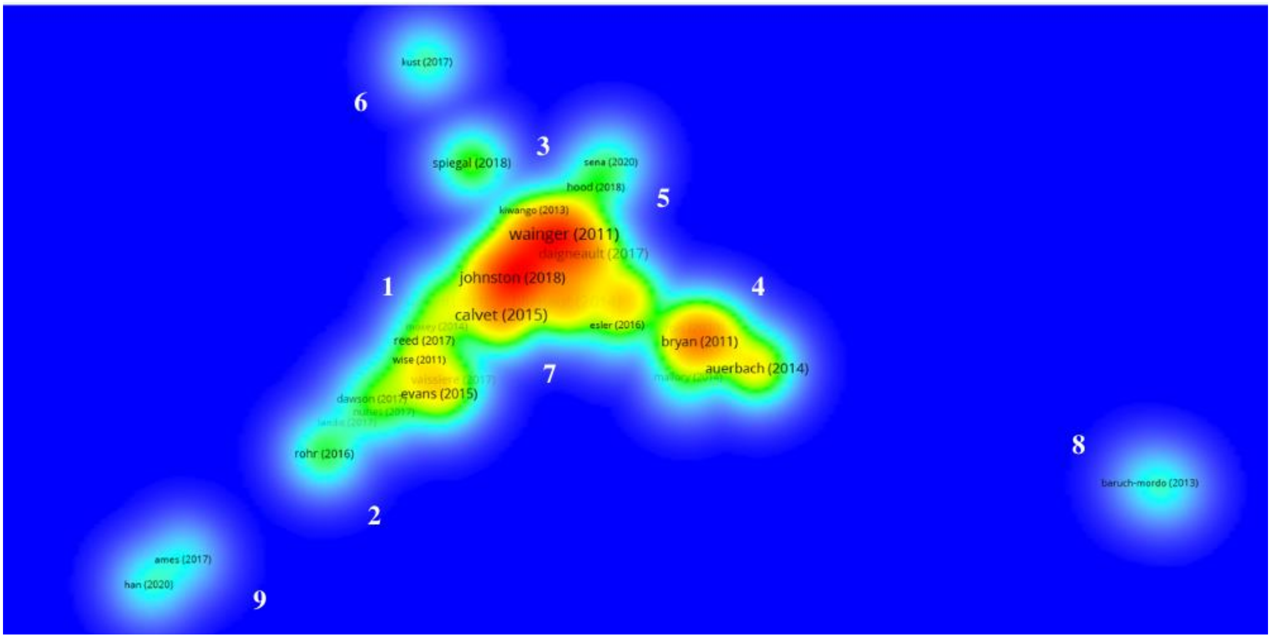
The Scopus and WoS item density visualizations for bibliographic coupling are presented in Figure 7.

Figure 7 – Bibliographic coupling maps: item density visualization for Scopus (A) and WoS (B).

A. Scopus



B. WoS



Source: results of the study. The numbers in the figure refer to the clusters.

The Scopus item density view (Fig. 7A) illustrates the connectedness between all clusters, as discussed with the network view (Fig. 4). Besides three items, all others are important in the network (yellow, orange, and red colors), and the map highlights cluster 1 as the most important one.

The WoS item density view (Fig. 7B) identifies the items in the center of the map as the most important ones. As seen in more details in the network visualization (Fig. 5), there are items from clusters 1, 2, 3, 5, and 7 in this region, a pattern of connectedness similar to the previous Scopus analysis (Fig. 7A).

From these observations and the content description of the clusters in *Section 3.1.12* there were organized three scholarly themes grouping together Scopus and WoS results:

1. ES, PES and Carbon Payments Theme: ES is present in bibliographic coupling in a similar way as in the co-citation analysis, but in this case, PES and carbon payments are more frequent topics.
2. Economic Valuation Theme: as in the co-citation analysis, economic valuation is present in the bibliographic coupling. Spatial analysis, agent-based modelling and nexus analysis are some of the methods that appear more in the bibliographic coupling.
3. The Economics of Restoration Theme: governance, management, and cost-effectiveness of restoration are more evident in the bibliographic coupling analysis. Opportunity costs, investment, risk management, and the ecological-social interface are prominent topics.

4 Discussion

The economics of restoration comprises a set of activities that include planning, coordination, financing, monitoring, and implementing restoration projects and plans (BLIGNAUT et al., 2014; ARONSON et al., 2017; BLIGNAUT; ARONSON, 2020) and this bibliometric analysis highlights the interconnectedness of disciplines that come together to form the grounds of the 'Economics of Restoration' research field as it appears in Scopus and Web of Science.

Much progress has been made when it comes to, for instance, cost-benefit and cost-effectiveness analysis (ADAME et al., 2015; BAYRAKTAROV et al., 2016; BECKER et al., 2014; DAIGNEAULT et al., 2017; KENNEY et al., 2012; KIMBALL et al., 2015; QADIR et al., 2014; STAFFORD et al., 2017), economic analysis and valuation (LOOMIS et al., 2000; BERGSTROM;

LOOMIS, 2017; CARLSSON et al., 2003; CARSON et al., 2001; COSTANZA et al., 2008, 1997; ZHAO et al., 2013), success measures (BENAYAS et al., 2009; GROOT et al., 2013; RUIZ-JAEN; MITCHELL AIDE, 2005; DAWSON et al., 2017; MORENO-MATEOS et al., 2012; SUDING, 2011), and frameworks for ecological restoration (DANG; LIU, 2012; GANN et al., 2019; HOBBS; NORTON, 1996; ROHR et al., 2016).

However, most restoration studies don’t go beyond project costs (BLIGNAUT; ARONSON, 2020; IFTEKHAR et al., 2016), and there is a need to further develop concepts and applications regarding ecological equivalence (DESVOUSGES et al., 2018; QUÉTIER; LAVOREL, 2011), economic development, social and cultural factors related to restoration (WANG et al., 2011; CAO et al., 2014), non-market benefits and non-use values (BROUWER et al., 2016; WAINGER et al., 2018), prioritization and investment in restoration (BLIGNAUT, 2019; ALLAN et al., 2015). The literature disclosed by this bibliometric analysis has brought into light key topics that will potentially help in future economics of restoration discussions and decision-making processes. They are briefly discussed here.

4.1 Uncertainty, public goods, and specificity of natural capital

The need to further address economic concepts that have a big impact on restoration projects was the first topic that drew awareness. These concepts are the specificity of natural capital and the public good quality of environmental resources, and the uncertainty driven from these aspects into restoration projects. The specificity of natural capital is a well-known challenge for the ecological restoration but recalling the need to conserve the aggregate stock of capital (Mueller, 2007), the natural-human-manufactured trio does not stand alone if only one aspect receives attention (CALVET et al., 2015; SCEMAMA; LEVREL, 2019).

Hence, a careful look into the human capital is needed. Every step of a restoration project requires proper training and capacities and, the more endemic the restoration target is, the more specific the required knowledge of best practices to be used will be (Dawson et al., 2017). Specificity also affects the behavior of investment actors, since these are specialized, long-term investments that will lose its value if redeployed to other uses. When protecting the investment so no one benefits from breaking the relationship, or simply because not all restoration projects will be successful, transaction costs increase, which in turn limits investment incentives (SCEMAMA; LEVREL, 2019). Searching for an environment of trust and mutual values not only reduces the behavioral uncertainty but is also a factor that can increase social capital, which has been recognized as an important factor for landowner participation and community acceptance in environmental programs (BUCKINGHAM et al., 2020; MORRISON et al., 2011).

Lastly, a discussion around ecological restoration that wish to receive the benefits from economic analysis cannot forget or ignore the public good characteristic of the environment. The distinction between local, national, and even global public goods is directly related to the appropriate level of government funding and intervention (LOOMIS et al., 2000). For example, if the intergenerational equity is a concern within a project, the discount rate to be used should be decided on the basis of the local environmental context (DESVOUSGES et al., 2018), whereas a clear picture of who bear the costs and who enjoy the benefits will help minimizing the free rider problem, which is especially observed in restoration projects (BRANCALION et al., 2017).

4.2 The role of governments and markets

Understanding of the appropriate role of a government is still conflicting because some authors advocate that public support could be withdrawn as soon as the project is underway and risks are better known (BRANCALION et al., 2017), while others claim that a public fund is needed for the entire duration of the restoration project or program precisely because of the market failures attributed to environmental goods and services (HODGE; ADAMS, 2016). A hybrid organization seems to be the best approach, complemented by an adaptive management that, in the face of uncertainties, makes it possible to readjust project aspects along the way (DAWSON et al., 2017; SCEMAMA; LEVREL, 2019).

The arguments for the success of restoration projects relying not only on market or government action itself were numerous among the articles in this literature review. For example, without specific regulations, markets tend to make the most financially profitable decisions at the expense of ecological needs (BLIGNAUT, 2019), either aiming on short-term rather than long-term benefits/gains or choosing the lower opportunity costs areas with safe land tenure locations that are usually scattered among small property owners (BRANCALION et al., 2017; BLIGNAUT, 2019). Careful planning needs to be conducted to avoid inefficient allocation of property rights, and an outside incentive or some form of coercion to participate in the market is necessary, otherwise even the most sophisticated market design is subject to fail (TEYTELBOYM, 2019). In this sense, governments can improve monitoring technologies and databases, and the structure required to enforce the law (OTTONI SANTIAGO et al., 2018). Certification can also lead markets towards ecologically better restoration decisions (BRANCALION et al., 2017). On the other hand, governments around the world have been failing major international agreements related to environmental targets for decades (BUTCHART et al., 2010; ROSEN, 2015; SECRETARIAT OF THE CONVENTION ON BIOLOGICAL DIVERSITY, 2010), being the most iconic one the Aichi Targets in which none of the 20 targets were fully met by any party of the Convention on Biological Diversity according to the Global Biodiversity Outlook 5 - GBO 5 (SECRETARIAT OF THE CONVENTION ON BIOLOGICAL DIVERSITY, 2020, p. 10).

From 2021 to 2030, United Nations declared the Decade on Ecosystem Restoration (UNDER), a global effort to scale up restoration. What can we expect for the upcoming years? Blignaut (2019), FAO (2017), and UNDP (2020) provide evidence that governments alone cannot leverage enough funds to cover all of the restoration (or even conservation) activities they need to engage in but can get involved in both public and private partnerships to unlock financial resources. The UNDER Strategy[2] does mention a series of financial changes needed to scale up the investments to achieve the goals, and they point to the same direction as other recent reports that promote major financial changes, such as the Moving Mountains (UNDP, 2020) and the Financing Nature (DEUTZ et al., 2020).

Albeit the suggestions, the Strategy doesn't have – or even plan to have – specific targets to be tracked along the way. Better long-term monitoring of projects and in-depth acknowledgment of uncertainties of restoration activities are missing, and this observation has drawn the attention of both critiques and enthusiasts of UNDER (ARONSON et al., 2020; COOKE et al., 2019; YOUNG and SCHWARTZ, 2019), also going in the opposite direction of what has been identified as important for restoration projects in this study (see also *Sections 4.1 and 4.3*). The Strategy expects that governments will undertake "fast and fair changes to national investments, subsidy regimes, taxation regimes and the regulatory environment such that finance is made available for ecosystem restoration". The private sector, on the other hand, is expected "to develop bankable business plans for restoration initiatives that take into account the full range of benefits expected over the long-term and adhere to rigorous social and

[2] Full document available at <https://www.decadeonrestoration.org/strategy>.

environmental standards”. These are bold expectations that seem to ignore past experiences such as the ones highlighted in the cited GBOs, that point that leveraging financial resources are one of the main causes of failure of the CBD targets in the past 20 years.

In addition, the UNDER starts without a restoration-tailored plan to implement the Strategy’s call for “shifts in financial flows, subsidies and taxes towards sustainable production, trade and consumption of commercial goods and services”. If we are in any way seriously considering any level of success of this Decade, it is fair to say that these *shifts* will not happen without an assessment of what can be truly expected from governments and the private sector, and what are the real possibilities that governments have to implement these radical changes.

4.3 Scale, communities, and investment

Restoration should be understood as an investment in ecosystems similar to other investments in the economy (BARBIER, 2016; DESVOUSGES et al., 2018). People value the flow of services provided by natural resources in the same way as they value the financial assets for the flow of money they produce over time (DESVOUSGES et al., 2018) and this understanding can help with the ongoing efforts to assess the intrinsic value of cultural benefits and ecosystem services that are still difficult to capture by current economic approaches (BARBIER, 2016), generally remaining unaccounted for in market transactions (HOLMES et al., 2004).

Regardless the time required to do a substantial ecosystem recovery, this is the primary desire for ecological restoration projects (GANN et al., 2019). However, it is a challenge to persuade multiple actors and landowners in a landscape to obtain sufficient restoration to generate economies of scale (BLIGNAUT et al., 2014). Especially because there is a lack of markets for biodiversity (HUNT, 2008), and even when there is a market, it can be eliminated if an ecosystem-specific service takes too long to be generated by market-driven restoration projects (BRANCALION et al., 2017). An option to circumvent these obstacles is to target results that could bring immediate and direct benefits for people (Silva et al., 2016), e.g., working with landowners on a smaller scale to find fast-growing native species that give faster returns, while increasing the diversity of restored land. Morrison et al. (2011) stress that understanding and increasing landowner participation in incentive programs for environmental improvement is crucial from an ecological point of view, as well as important to achieve the economic goals of efficiency and equity of the project.

Planning for a project to deliver economic returns quickly enough to sustain the market not only strengthens the participation of landowners but can be a way to reconcile the debate between the long term needed for restoration activities and the financial mainstream of short-term contracts. According to Hodge (2019), not only the long term, but also the uncertainty of investments in natural capital still challenge the conventional logic of projects with predefined time span and goals. Hodge also stresses the importance of an environment of trust between actors for the success of investments, an aspect already discussed in Section 4.1.

In defining priority areas for investment, (DE VALCK et al., 2017) propose that the eligibility of substitute sites should be evaluated based on the full spectrum of direct, indirect, use and non-use of nature, as well as the local individuals knowledge and perception. Combining ecological attributes and relevance to affected people can increase the attractiveness in an investment decision (DE VALCK et al., 2017) and social and cultural contexts must also be taken into account when adapting the restoration project to its place of implementation (HODGE; ADAMS, 2016; SCEMAMA; LEVREL, 2019). As reinforced by Buckingham et al. (2020) the success of restoration relies on people and how they relate to their surrounding ecosystem. In this sense, adjusting project goals and people's priorities in the same direction increases the positive results of restoration.

5 Conclusions

The bibliometric analysis of this article used co-citation and bibliographic coupling maps to identify important and influential economics of restoration research themes. Furthermore, a brief discussion of key topics within these research themes was presented. Co-citation reveals most documents being within the Ecological Restoration theme. Early concepts, frameworks, and discussions about the relationship between restoration, biodiversity, ecosystem services, socioeconomic factors, economic development, and scale are addressed. Other relevant research themes that form the intellectual structure of economics of restoration are the Economic Analysis, Ecosystem Services, Biodiversity and Conservation. Bibliographic coupling shows that management, cost-effectiveness, governance, investment, and risk management are the most prominent research-front topics within the economics of restoration. Economic analysis and ecosystem services and are also present in the bibliographic coupling, but the emphasis is given to agent-based modelling, spatial analysis, carbon, and ecosystem services payments, to cite a few.

This study concludes that the economics of ecological restoration has a solid background in ecological and economic science, being an intrinsic interdisciplinary field with contributions from different disciplines. However, there were identified key topics to bring economic aspects and decision-making processes together. The first key topic that comes to light in the literature review was the need to better understand the implications of the specificity of natural capital and public goods in behavioral uncertainties among agents. Another key finding was that the role of governments and markets is not clearly defined or structured yet. Although there is an indicative that a hybrid solution will work the best, there is a need for more studies to investigate the relationships between ecological restoration and different policies and programs, economic instruments, and market regulations. The last key topic that arose in this study was the interconnectedness of communities and investments to scale-up restoration worldwide. We need better investment solutions in the same way that we need to improve our knowledge on how to better engage landowners and to adjust society priorities and restoration projects to scale-up restoration worldwide.

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Chapter 4 – Trade-offs in restoration areas for carbon and koala conservation

1 Introduction

Worldwide, changes to natural ecosystems as a result of land clearing have been increasing at an alarming rate (RUS et al., 2021) to the point that the majority of the world's species are threatened by a range of risks which include climate change, habitat loss, fragmentation, disease, invasive species, to cite a few (NG et al., 2014). There is a strong case for conserving the remaining pristine and undisturbed areas (CRISTESCU et al., 2013), but with 6 billion hectares of degraded land (OECD, 2019) restoration will continue to play an important part.

Restoration can deliver multiple benefits and offer new economic and business opportunities. At a landscape scale, it can help maximize synergies and manage potential trade-offs between ecosystem services, as well as balancing competing demands for land or ocean resources (OECD, 2019). At the same time, limited resources mean that restoration projects and plans should include actions that can mitigate multiple threats (NG et al., 2014), and use decision tools and methods to prioritize areas for restoration (SANTIKA et al., 2015).

The use of fauna as an indicator to declare the restoration of a site is a good parameter in conjunction with flora to assure that all components that maintain biodiversity have returned to the site. Iconic fauna is a good candidate for this purpose. These are well-known animal species that gain a disproportionate share of the public's attention and are often used to anchor an environmental campaign. They draw attention to the generic issues of conserving biodiversity, with the potential to benefit all wildlife suffering similar problems and occupying similar geographical areas (MCALPINE et al., 2015).

The koala (*Phascolarctos cinereus*) is an iconic arboreal folivorous marsupial found in eucalypt forests and woodlands in eastern Australia, within a 1.5 million km² range covering the states of New South Wales, the Australian Capital Territory, Queensland, South Australia and Victoria (TRUEMAN et al., 2017; MITCHELL et al., 2021). In 1992, the koala was listed as a threatened species under the NSW legislation, and in 2012, it was classified as a nationally vulnerable species in Australia under the Commonwealth Government's Environment Protection and Biodiversity Conservation (EPBC) Act 1999, as well as listed as 'Vulnerable' by the International Union for the Conservation of Nature (IUCN) (LUNNEY et al., 2004; IUCN, 2012; CRISTESCU et al., 2013; SANTIKA et al., 2015; MATTHEWS et al., 2016; MITCHELL et al., 2021). According to Lam et al. (2020), to help the koala population, the current IUCN listing of koalas as Vulnerable should be immediately upgraded to Critically Endangered. In February 2022, the EPCB Act changed the status of the koalas from vulnerable to endangered[3]. The koala also continues to play an important role in Australian tourism, both symbolically and materially, and it has played a significant part in the marketing of Australia overseas (MARKWELL, 2020b).

Habitat loss has been identified as the key cause of the decline of Koalas in NSW, but fire, habitat fragmentation, urban development, car strikes, dog attacks, drought, disease, and predation by exotic canids have exacerbated their decline (LUNNEY et al., 2004; LUNNEY et al., 2007; KAVANAGH; STANTON, 2012; SANTIKA et al., 2015; TISDELL et al., 2017; TRUEMAN et al., 2017; MARKWELL, 2020a; MARKWELL, 2020b). As the area of habitat diminishes and the remaining area becomes fragmented, other threats to koalas will rise proportionally, particularly dogs, cars and fires (LUNNEY et al., 2007; ADAMS-HOSKING et al., 2012; MATTHEWS et al., 2016).

Important gaps in knowledge regarding restoration for koala conservation include the age at which replanted habitat can support koalas, whether vegetation planted under proposed carbon storage schemes contributes to the re-establishment of Koala habitat, and options for revegetating priority areas in the context of landscape configuration and climate change (KAVANAGH; STANTON, 2012). There is a pressing need to identify priority recovery actions for this species across NSW (SANTIKA et al., 2015). In addition, Australia needs to increase forestation in its key habitat areas. This will not only help the koalas but also reduce the carbon footprint and the climate change currently threatening so many other species and the region overall (LAM et al., 2020). Climate change affects koalas through excessive temperatures; reduced nutritional status and moisture content of eucalypt leaves; and high intensity fires. Climate change is also acknowledged as a factor in these unprecedented fires (MARKWELL, 2020a).

Human activities can enhance or reduce forest carbon storage. Land use, land use change, and forestry activities (LULUCF) are one of the economic sectors in the Kyoto Protocol that needs to be considered regarding sources and sinks of greenhouse gas (GHG) emissions. The important role of forests in climate change mitigation was recognized in 2016 by the Paris Agreement. Voluntary Carbon Markets (VCMs) can promote the transition into low-carbon

[3] <https://www.environment.nsw.gov.au/threatenedspeciesapp/profile.aspx?id=10616>

emission economies. VCMs are undergoing a strong expansion in quantities of carbon credits traded and in the number of operators in recent years. Simple procedures and an absence of specific legislation give VCMs greater flexibility and an easier access to carbon credit exchanges. In the context of VCMs, improved forest management, afforestation, reforestation, and urban forestry are some of the activities that can produce carbon credits (NONINI; FIALA, 2019). Integrating ecological and socioeconomic aspects into forest management to capture revenues from VCMs offers opportunities to expand restoration areas. An interdisciplinary approach to forest management can support decision-making processes in this context.

Due to limited resources, providing economic opportunities while meeting socio-ecological objectives is one of the challenges when deciding on priority areas for restoration. The trade-offs between ecological and economic outcomes need to be assessed to better design prioritization frameworks and to understand the relationships among socioeconomic goals and the profit (if any) that could be generated from restoration activities. The goal of this study is to spatially analyze trade-offs between ecological and economic management objectives to restore habitats for koala conservation. Production possibility frontiers (PPF) and attainment levels were derived for various restoration scenarios and prioritization objectives, including potential profit that could be generated with carbon credits from forest biomass.

2 Methods

2.1 Study area description

The Brigalow Belt South Bioregion (BBS) lies in northern NSW and southern Queensland with a total area of 27,196,933 ha, of which 5,333,469 ha (19.61%) fall within NSW, occupying 6.7% of the state. The bioregion is located within the eastern subhumid region of Australia (NSW NATIONAL PARKS AND WILDLIFE SERVICE, 2000). A subhumid climate, with no dry season and hot summers, characterizes the southeastern section of the bioregion, while a generally dry subtropical climate dominates in the northwest. Minor patches to the southeast of the bioregion fall within the temperate zone, with no dry season and warm summer. To the far west of the bioregion and in the outlier enclosed within the Darling Riverine Plains Bioregion, the climate can be described as hot and semi-arid. Mean annual rainfall is between 449-1015 mm and the mean annual temperature is between 10-19 ºC. The bioregion landscapes are derived from both extensive basalt flows and quartz sandstones and consequently have variable soils and vegetation depending on the local rock type or sediment source.

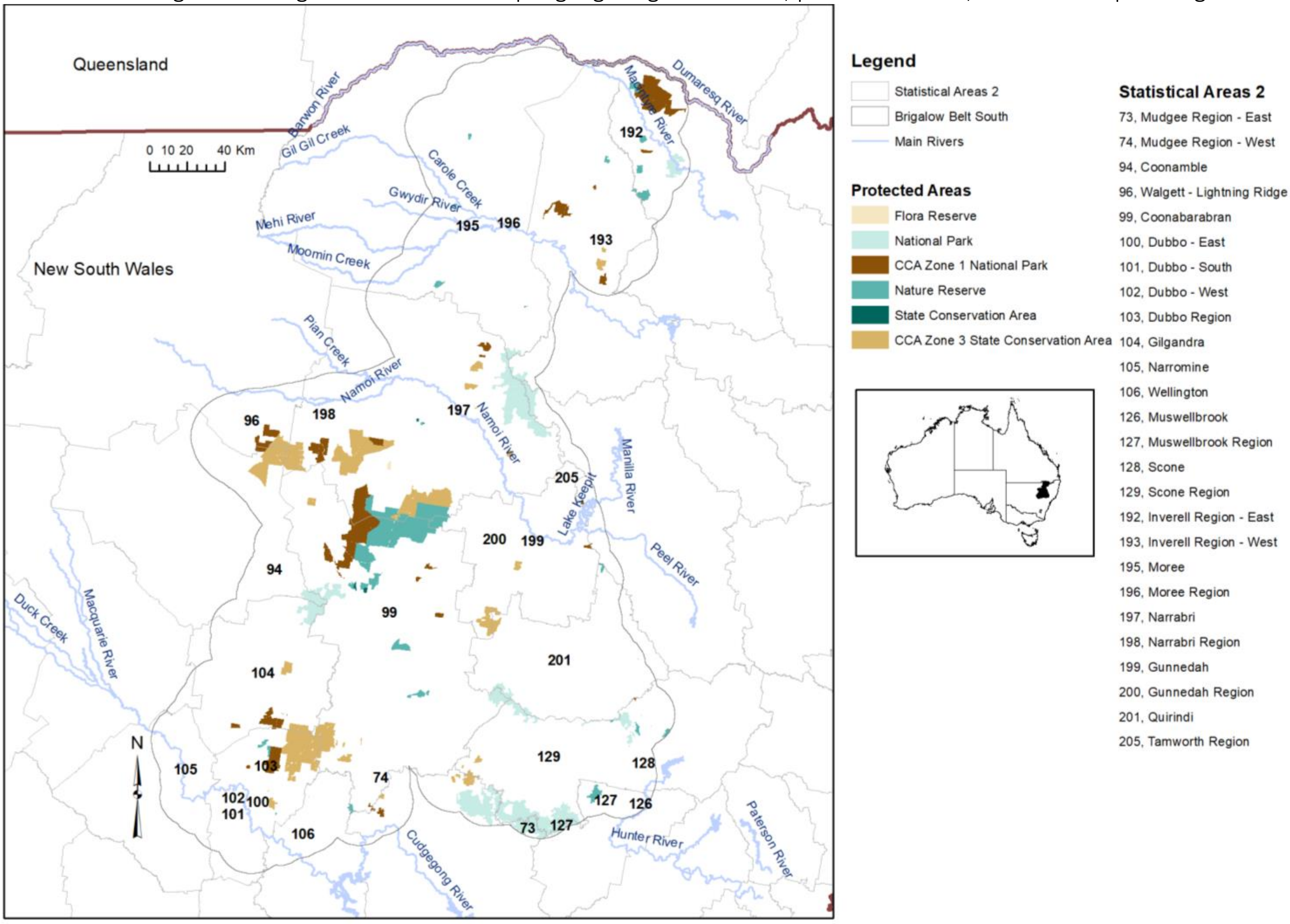
Few systematic surveys have been conducted in the bioregion, but records from various surveys can illustrate the vertebrate fauna of the bioregion, which consists of 18 amphibian species, 68 reptiles, 281 birds, and 82 mammal species. Many of these species are considered threatened, including the endangered malleefowl (*Leipoa ocellata*), for which the bioregion represents an important habitat, and the vulnerable koala (*Phascolarctos cinereus*) which has important populations in the Warrumbungles, the Pilliga and the area around Gunnedah (NSW NATIONAL PARKS AND WILDLIFE SERVICE, 2000). In this bioregion, the tree species often selected by koalas include the Blakely's red gum (*Eucalyptus blakelyi*), the river red gum (*Eucalyptus camaldulensis*) and the white box (*Eucalyptus albens*), while the pilliga box (*Eucalyptus pilligaensis*), the poplar box (*Eucalyptus populnea*), the narrow-leaved ironbark (*Eucalyptus crebra*) and the rough-barked apple (*Angophora floribunda*) are occasionally used for food in Gunnedah (NSW NATIONAL PARKS AND WILDLIFE SERVICE, 2000, 2003).

The north coast and its immediate west on the tablelands and plains, such as around Gunnedah, represent one of the most important areas for Koala conservation in NSW (MATTHEWS et al., 2016). This area was one of the few places in NSW with an increasing population of koalas (ELLIS et al., 2017). The population neighboring the Gunnedah township has been increasing since the 1980s but has declined in 2009 due to drought and a severe heatwave. The Pilliga Forest (Nature Reserve at the west of Gunnedah), the largest area of native forest in inland NSW, supported more than 15,000 koalas at the end of the 1990s, but its population has declined since then (MCALPINE et al., 2015). Lunney et al. (2017) found that this decline can be as high as 80% in the Pilliga forests.

Much of the surrounding Liverpool Plains region (south of Gunnedah) has been substantially cleared (<10% woodland cover remaining) for intensive cropping and grazing (KAVANAGH; STANTON, 2012) and the extreme pressures faced by koalas are unlikely to allow them to recover without management intervention (LUNNEY et al., 2017).

Figure 1 shows the BBS main rivers, protected areas and the Statistical Areas 2 (SA2) regions that were set as planning areas in this study. Each SA2 region is built to "represent a community that interacts together socially and economically" (AUSTRALIAN BUREAU OF STATISTICS, 2016). This justifies our partition of the study area into planning regions.

Figure 1 – Brigalow Belt South map highlighting main rivers, protected areas, and the SA2 planning areas.



Source: results of the study.

2.2 Optimization model

We followed the methodology of Ager et al. (2016, 2017) to model potential restoration priorities in the Brigalow Belt South and to identify tradeoffs among three key variables: Koala Habitat Suitability (KHS), Bushfire Risk to Dwellings (BFR), Maximum Above Ground Biomass (AGB). In addition, Profit was used as an alternative objective associated with AGB. Modeling was done by combining all layers of information into a single shapefile.

We used ForSysX version 2, formerly the Landscape Treatment Designer (AGER et al., 2012), a program designed to solve the problem of treating landscapes to decide on forest restoration projects. It uses a unique stand polygon attributed with the variables metrics. A restoration scenario can be set in terms of objectives (KHS, BFR, AGB, Profit), constraints (area treated), and treatment thresholds (e.g., additional conditions of any variable, not set in this study). ForSysX will identify one or more sites within the planning areas that maximize the objective:

$$Max\sum_{j=1}^{k}\left(Z_j * \sum\left(W_i N_{ij}\right)\right) \qquad \text{Eq. 1}$$

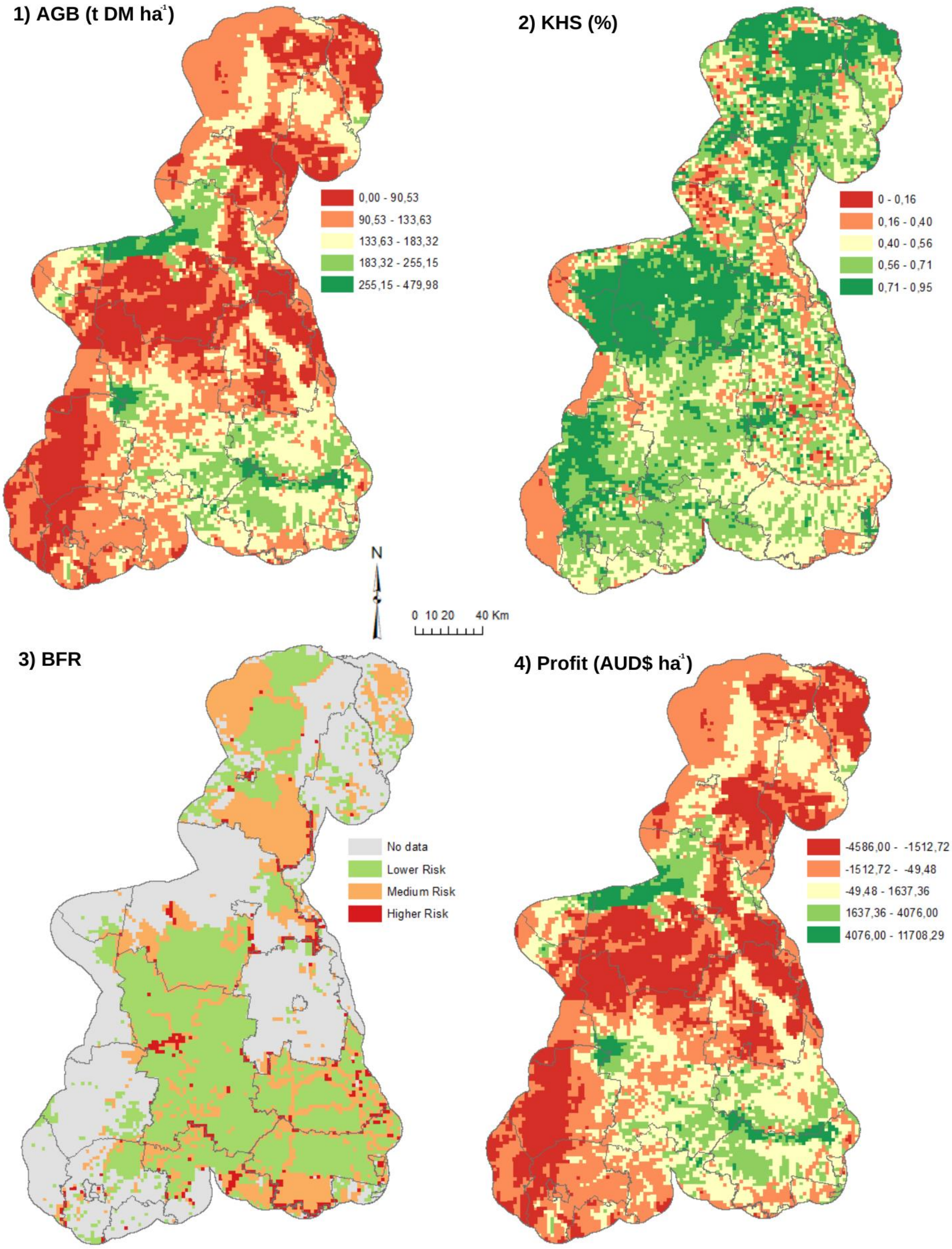
Subject to:

$$\sum_{j=1}^{k}\left(Z_j A_j\right) \leq C \qquad \text{Eq. 2}$$

Where C is a global constraint on activity per planning area, Z is a vector of binary variables indicating whether the jth site is treated (e.g., Zj=1 for treated sites and 0 for untreated sites), Nij is the contribution to objective i in stand j if treated, and Aj is the area of the jth treated site. Wi is a weighting coefficient that can be used to prioritize one objective versus another. Given multiple planning areas, the program iterates through each one, then reports the maximum objective value and the selected treatment sites. Treatment here refers to the act of selecting a site to iterate into the model.

The sites to be included in the model (vector Z in Eq. 1) were obtained by downscaling the Koala Likelihood Map (KLM) from the Koala Habitat Information Base (Department of Planning, Industry, and Environment, 2019), from the original 10 km^2 grid to a 2.5 km^2 grid, resulting in 12,620 sites. From these, only sites with attributed KLM values were set as available to the model, resulting in 8,278 sites (65.59% of total sites). Most of the sites have an area of 650 ha, with only 774 sites at the perimeter ranging from 0.007 to 624.96 ha. To each site was assigned the metrics of KHS, BFR, AGB, and Profit, as shown in Figure 2 (see data sources in Section 2.3).

Figure 2 – Management Priorities mapped into the 2.5 km² grid.



Source: results of the study.

Trade-offs were analyzed between the objectives. It was assumed that the objectives KHS, BFR, and AGB would be addressed by the restoration activities described in Section 2.4. The focus was to compare AGB and Profit with KHS and BFR by changing the relative weights of each objective (Eq. 2). Integer weights were varied in all combinations from 0 to 10 in increments of 1 in pairwise fashion. For instance, weights of 10 and 0 for objectives A and B, respectively, generated the maximum production for A, whereas equal weights for each objective generated a balanced production for both. Once the treatment constraint *C* of 10,000 ha was met, the total objective value was summed for each stand in the planning area. Outputs were used to generate production possibility frontiers between the different objectives. To standardize reporting of different metrics, ForSysX calculates the percentage contribution of attainment of each site to the study area (BBS) and sums these values for each planning area (SA2), thus providing a standardized metric to compare different objectives. We performed additional analyses by prioritizing each objective individually as a "restoration priority" and deriving cumulative attainment of each priority given an increasing number of planning areas under different restoration priorities.

Sensitivity analysis was done changing the constraint C to 15,000, 20,000 and 25,000 ha in the single prioritization scenarios and comparing the percent change in the cumulative attainment and in the maximum attainment.

2.3 Objectives and Data Sources

The data sources for the three priorities are described below.

2.3.1 Koalas

Information on koalas was obtained from the Koala Habitat Information Base (KHIB), a statewide database with spatial data on koalas provided by the New South Wales (NSW) Government under the Koala Strategy (Department of Planning, Industry, and Environment, 2019). The KHIB provides seven statewide datasets: 1) Koala Habitat Suitability Model (KHS), 2) Koala Tree Index (KTI), 3) Koala preferred-tree species model, 4) Koala Likelihood Map (KLM) and Koala Likelihood Confidence Map, 5) high-resolution map of tree cover and water bodies, 6) areas of regional koala significance (ARKS), and 7) all BioNet[4] koala sightings.

Two of these datasets were used in this study: the Koala Habitat Suitability Model (KHS) as one of the management priorities, and the Koala Likelihood Map (KLM) as a base to determine the availability of the stands for treatment. The Areas of Regional Koala Significance (ARKS) were used for supporting information. These datasets are described in Table 1. The

[4] NSW BioNet: <https://www.environment.nsw.gov.au/topics/animals-and-plants/biodiversity/nsw-bionet>

original high-resolution KHS raster was resampled to a 2.5 km^2 pixel raster with the mean values of model variables for each new pixel.

Table 1 – Koala Habitat Information Base (KHIB) datasets used in this study.

Dataset	Description
Koala Habitat Suitability Model (KHS)	A high-resolution raster that relates environmental factors (e.g. soil, topography, vegetation) to sites occupied by koalas in order to predict the distribution and suitability of potential habitat for koalas, compared to other available areas.
Koala Likelihood Map (KLM)	The dataset predicts the likelihood of finding a koala in relation to other arboreal mammals across a 10-km grid covering NSW, built using existing arboreal mammal records from the past 20 years (currently 1999 to 2019). To each grid cell is assigned a value for the likelihood of koalas (p) based on a binomial distribution, with each record being a koala (K) or another arboreal mammal. The proportion of all records within a cell (N) (all subject species, including koalas) that are koalas represents the likelihood: p = K/N. This provides the relative likelihood of koalas being recorded, with a value between 0 (no koalas) and 1; i.e., a higher value represents a higher relative likelihood.

Source: adapted from Department of Planning, Industry and Environment (2019).

2.3.2 Maximum Above Ground Biomass

The Maximum Above Ground Biomass (AGB) is a spatial layer embedded within the Emissions Reduction Fund's Full Carbon Accounting Model (FullCAM) (DEPARTMENT OF INDUSTRY, SCIENCE, ENERGY AND RESOURCES, 2017). It was developed to estimate greenhouse gas emissions and removals from the land sector, for inclusion in Australia's annual national greenhouse gas inventory. Computationally, the AGB exerts a strong influence on forest growth, affecting the rate of above-ground biomass accumulation, as well as defining the upper above-ground biomass limit, or site potential. As this layer represents biomass at forest maturity, it depicts the potential vegetation density that an area could support, not the current vegetation distribution which reflects past land management, such as clearing and regrowth of woody vegetation. The layer used in this study is the second version of the dataset, published in March 2020. The values were reported as tonnes of dry matter per hectare (t DM ha^{-1}).

2.3.3 Bushfire Risk

The NSW Bush Fire Prone Land (BFPL) dataset is a map prepared under the Guide for Bush Fire Prone Land Mapping (NSW RURAL FIRE SERVICE, 2015). It is mapped within a local government area, which becomes the trigger for planning for bush fire protection. BFPL mapping is intended to designate areas of the State that are at higher bush fire risk for development control purposes. BFPL is an area of land that can support a bush fire or is likely to be subject to a bush fire attack, as designated on a bushfire-prone land map. The original definitions of bushfire vegetation categories under the version used in this study are:

- Vegetation Category 1: areas of forest, woodlands, heaths (tall and short), forested wetlands, and timber plantations.
- Vegetation Category 2: Rainforests. Lower risk vegetation parcels. These vegetation parcels represent a lower bush fire risk to surrounding development and consist of: Remnant vegetation; Land with ongoing land management practices that actively reduce bush fire risk.
- Vegetation Category 3: Grasslands, freshwater wetlands, semi-arid woodlands, alpine complex, and arid shrublands.

In order to be used in the model, these categories were rearranged into bushfire risk categories as described in Table 2.

Table 2 – Bushfire risk categories from the NSW Bush Fire Prone Land Vegetation Categories.

Original BFPL Vegetation Categories	Bushfire Risk Categories
0 – no data	0 – no data
Vegetation Category 2	1
Vegetation Category 1	2
Vegetation Category 3	3

Source: adapted from NSW Rural Fire Service (2015).

An index (BFR) was created by multiplying the bushfire risk categories by the number of dwellings intersecting the BFPL map. The number of dwellings was obtained from the 2016 Australian Bureau of Statistics Census data (AUSTRALIAN BUREAU OF STATISTICS, 2016). This index was created as a proxy to include the human perspective in the model since all other variables, including BFPL, were constructed under environmental factors. Under this index, an area with high bushfire risk and a high number of dwellings will have a higher priority than an area with the same bushfire risk but a lower number of dwellings, since the presence of humans can alter patterns of ignitions in a landscape (BENTLEY; PENMAN, 2017).

2.4 Restoration activities cost and profit

Costs of restoration activities were obtained from the Investment Framework for Environmental Resources (INFFER) report of March 2020 (PARK; ROBERTS, 2020). This report was prepared to guide the Australian government's investment in the Environment Restoration Fund project “Protecting Koalas of South-east Queensland and Northern New South Wales”.

Park and Roberts (2020) designed the INFFER framework specifically to help integrate economic, sociopolitical, and biophysical factors into decision-making and is based on benefit-cost analysis principles. A package of restoration actions was defined, with activities that would address koala threats in the ARKS. These threats were identified by KHIB, and include: i) habitat loss, fragmentation, and degradation; ii) urbanization (assessed as part of habitat loss, fragmentation, and degradation); iii) collisions with motor vehicles; iv) predation by wild or domestic dogs; v) wildfire and intense prescribed burns; vi) heatwave; vii) disease, and viii) reduction in the suitability of habitat from the effects of climate change.

The package of actions is composed of habitat enhancement, weed management, ecological burning, and grazing management. These actions need to be defined according to the needs of each site (a detailed description of each action can be found in Park and Roberts, (2020)). The proposed cost of restoration (*CR*) per hectare is AUD$4,586. Assumptions in this study are that these actions would improve habitat resilience, having an impact on reducing bushfire risk and increasing habitat suitability for koalas, as well as above-ground biomass. This is possible because prioritizing one objective will result in co-benefits if restoration is done sustainably and effective. Multiple dimensions will be addressed, such as increasing biodiversity protection, supporting climate change mitigation and contributing to resilience and adaptation (GANN et al., 2019; ZHOU et al., 2022).

We estimated the profit for each site by subtracting the costs of restoration activities from the potential revenue of carbon credit units sold in voluntary markets. The profit for each site was defined as:

$$R_j = (N_{AGBj} \times 0.5 \times 3.67)P_C - CR_j \qquad \text{Eq. 3}$$

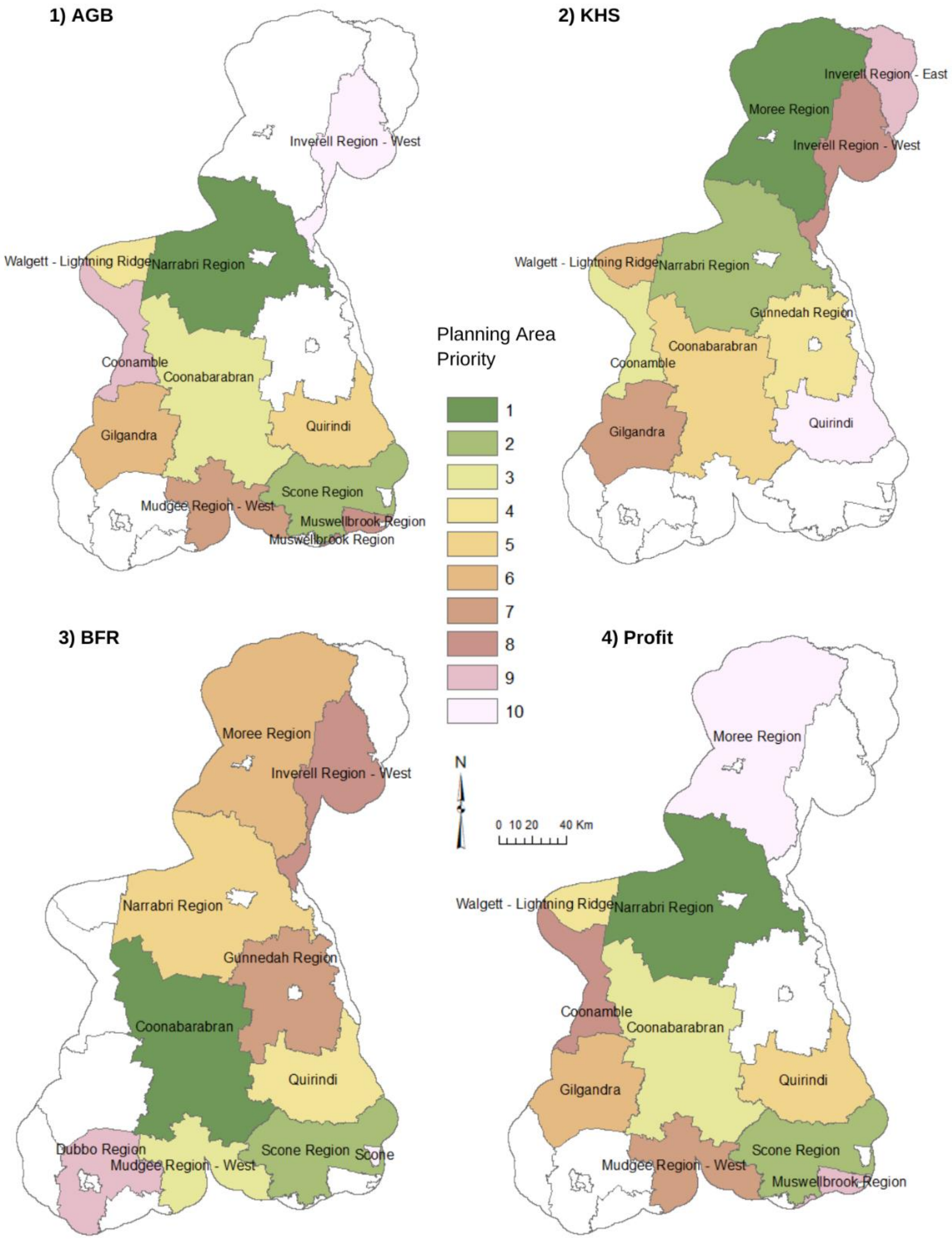
The 0.5 factor converts AGB to carbon equivalents, and the 3.67 factor converts biomass carbon to carbon dioxide equivalents (CO^2). Initially, we used the carbon price P_C = AUD$18.50 per Australian Carbon Credit Unit (ACCU) from the Quarterly Carbon Market Report of March 2021). This profit (Profit in Fig. 2) was used in the trade-off analysis along with the ecological priorities previously described. We also simulated the carbon prices of AUD$30.00 and AUD$50.00 in the KHS-AGB trade-off. The cost of restoration was kept constant at CR_j = AUD$4,586/ha.

3 Results

3.1 Planning Area Priority

The top ten priority planning areas for each objective are presented in Figure 3.

Figure 3 – Planning areas priority for the single prioritization scenario.



Source: results of the study.

The planning area with the highest priority is different for each objective. The main areas for KHS are in the north and west regions (Moree, Narrabri, Coonamble), while for BFR they are in the central and south-east regions (Coonabarabran, Scone, and Mudgee West). For AGB and Profit, the main areas are also in the central and south-east regions (Narrabri, Scone, and Coonabarabran). As expected, (Eq.3), the maps for AGB and Profit are almost the same, only differing in the last three positions. These maps illustrate that, if we are to prioritize one objective over another, the choices will be different.

3.2 Cumulative Attainment for Prioritization Scenarios

Attainment is measured as the percentage of the total restoration objective in the study area treated in a particular scenario. Figure 4 and Table 3 show cumulative attainment for scenarios when each objective is prioritized with the weight of 1, while all other objectives have weights of 0. Figure 4A shows that the highest attainment between ecological objectives is achieved when prioritizing BFR (10.17%), followed by AGB (4.84%), and KHS (3.87%). When each of these variables is prioritized, cumulative attainment in profit is positive only in the AGB scenario (21.35%) and negative for BFR (-2.74%) and KHS (-5.98). There were strong trade-offs between BFR and the other two objectives when it was prioritized (Figure 4D), meaning that increasing efforts towards reducing BFR (dwellings at risk of bushfires) can compete with efforts to increase AGB (above ground biomass) and KHS (koala habitat suitability).

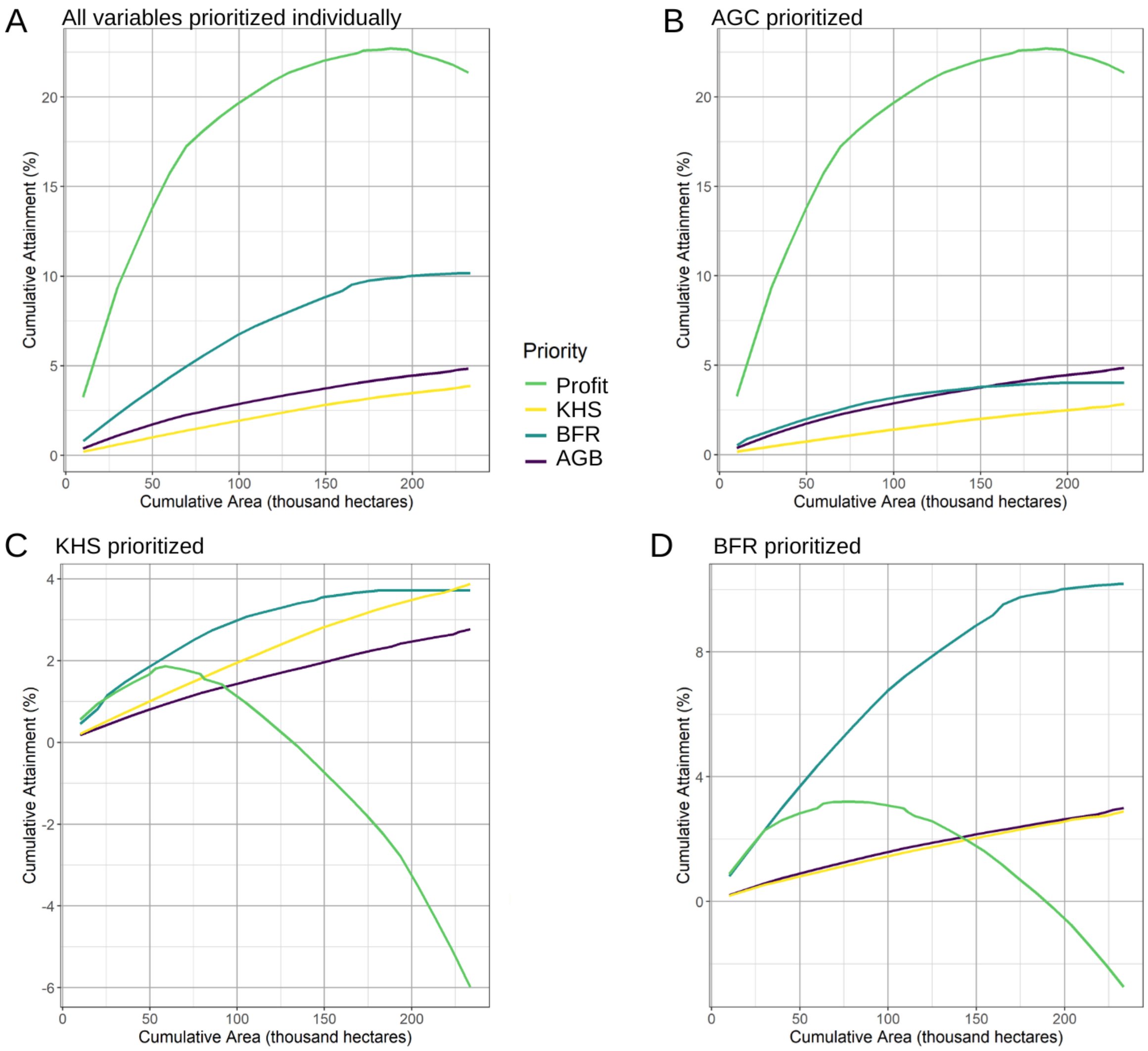
Table 3 – Cumulative attainment (%), area treated (thousand ha), and profit (million AUD$) in the single prioritization scenario for biomass, habitat suitability, bushfire risk, and profit.

	Cumulative Attainment (%)					
Prioritization	**AGB**	**KHS**	**BFR**	**Profit**	**Area treated (thousand ha)**	**Profit (million AUD$)**
AGB	4.84	2.82	4.01	21.35*	232.37	536.14
KHS	2.76	3.87	3.71	-5.98	233.49	-151.93
BFR	2.99	2.88	10.17	-2.74	233.48	-69.29

Source: results of the study. Attainment in profit when biomass is prioritized is 21.35%. Attainment in profit when profit is prioritized is 21.36%.

On the other hand, AGB and KHS were positively correlated in all scenarios (they are both monotonically increasing in all cases in Fig. 4). Figure 4(C and D) shows that there is more flexibility in BFR than in KHS to aggregate more areas into treatment before profit decreases to zero (approximately 125,000 ha for KHS and 180,000 ha for BFR). When prioritized, profit increases with the other objectives up to the point where sites with negative profits were incorporated into the model. The comparison between Figure 4A and Fig. 4B shows that, when Profit is prioritized, the attainment in BFR decreased by 6.16% and in KHS it decreased by 1.05%, compared with the scenario when each of these variables is prioritized. The attainment of the other priorities is the same when Profit or AGB are prioritized (Figure B).

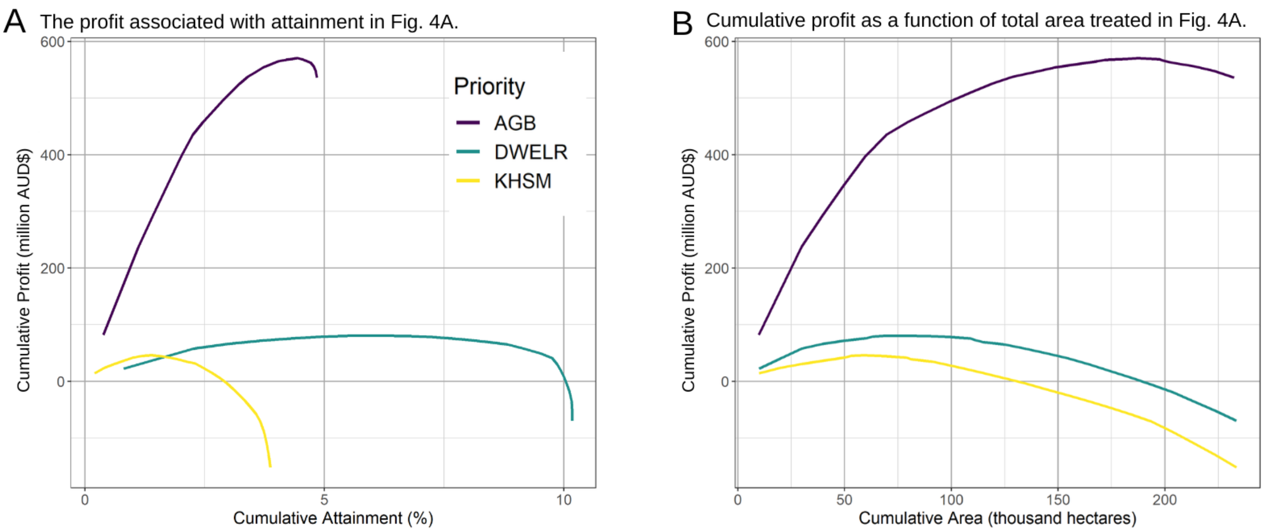
Figure 4 – Cumulative attainment for different single prioritization scenarios of the variables habitat suitability (KHS), bushfire risk (BFR), above ground biomass (AGB), and Profit.



Source: results of the study.

Figure 5 shows attainment versus profit (Fig. 5A) and area treated versus profit (Figure 5B) for each prioritization scenario. These figures highlight the costs and benefits of each restoration priority. For example, prioritizing KHS would cost AUD$151.93 million to treat 233,495 ha, treating up to 3.87% of the suitable Koala habitat in the study area (the percentages here refer to the cumulative attainment in x-axis in figure 5A). Prioritizing BFR would reach a similar area of habitat suitability, but at a cost of AUD$69.29 million and representing 10.17% of the bushfire risk in the study area. However, both objectives can be treated at no cost or even with profit for levels of restoration areas below 125,000 ha for KHS and 180,000 ha for BFR. Prioritizing AGB would return a profit of AUD$536.14 million, with 4.84% attainment for AGB in the study area.

Figure 5 – Cumulative profit versus attainment and area for Habitat Suitability, Bushfire Risk and Above Ground Biomass.



Source: results of the study.

3.3 The equal weight scenarios between the objectives

Instead of prioritizing one objective at a time, it is also possible to give equal weights between pairs of objectives (Eq. 2). Table 4 shows that the trade-off scenarios with equal weights between KHS, BFR and AGB decrease the attainment of all variables when compared with the single prioritization scenarios. However, when prioritized alone, KHS and BFR had negative profits, and when prioritized with equal weights with AGB, profit occurs for both KHS and AGB and BFR and AGB.

Table 4 – Attainment (%) in the trade-off scenarios with equal weights between priorities.

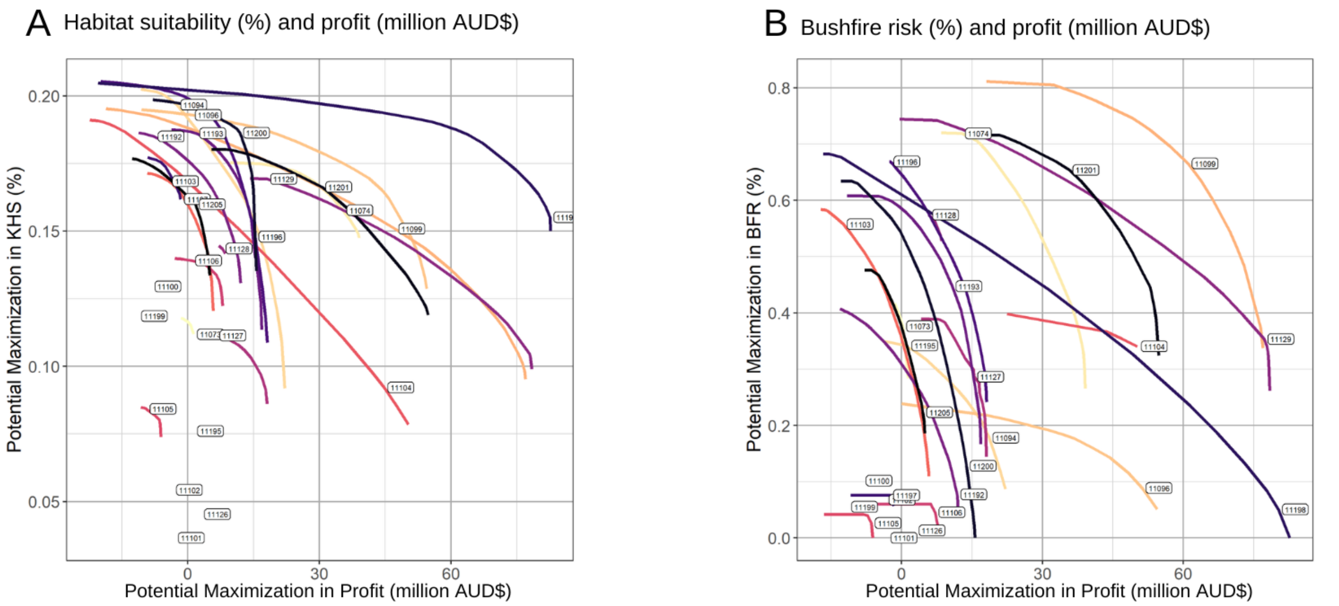
Weights	AGB	KHS	BFR	Profit (million AUD$)
AGB and KHS = 1	4.08	3.62	-	288.23
AGB and BFR = 1	4.35	-	8.08	378.38

Source: results of the study.

3.4 Production possibility frontiers

Figure 6 shows trade-off scenarios between potential maximization in Profit (in a thousand AUD$) and the other two objectives. Production possibility frontiers show that few areas have a high potential for maximizing two objectives together. In general, improving profit in both scenarios reduces the attainment of the other variables, highlighting the trade-off between economic and ecological objectives. In Figure 6A, the highest attainment level for KHS implies the higher costs in the trade-off, but several areas can reach zero profit without a severe impact on attainment. For BFR (Figure 6B), four of the areas with the highest attainment for bushfire risk have zero or positive values for profit. On the other hand, the impact on reduction in bushfire risk is high towards a positive value in profit for planning areas that started with negative values for profit.

Figure 6 – Trade-off scenarios between the ecological management priorities and Profit (thousand AUD$). Each line represents an SA2 zone.



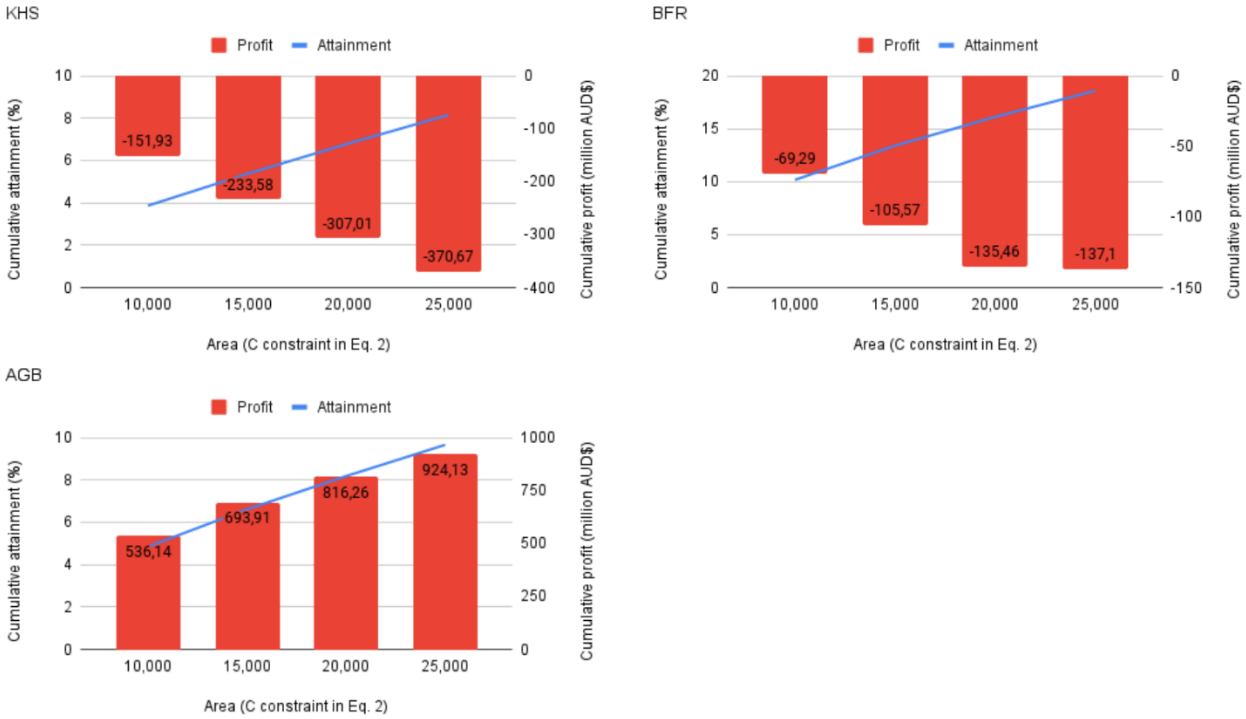
Source: results of the study.

3.5 Sensitivity Analysis

3.5.1 Impact of changes in the area treated in attainment and profit

Figure 7 shows that when the total area that can be treated (C in Eq. 2) increases (budget constraint is relaxed), cumulative attainment for all variables increases. This means that the larger the area treated in the planning areas, the larger the maximization in habitat suitability for koalas (KHS) and the reduction in bushfire risk to dwellings (BFR). In this sense, since BFR is a combination of human population density and fire threats, it can be prioritized in the areas where dwellings are at a higher risk of bushfires. On the other hand, profit decreases for KHS and BFR when more sites with negative profits come into solution.

Figure 7 – Individual prioritization scenarios when the area constraint C is changed in Eq. 2.



Source: results of the study.

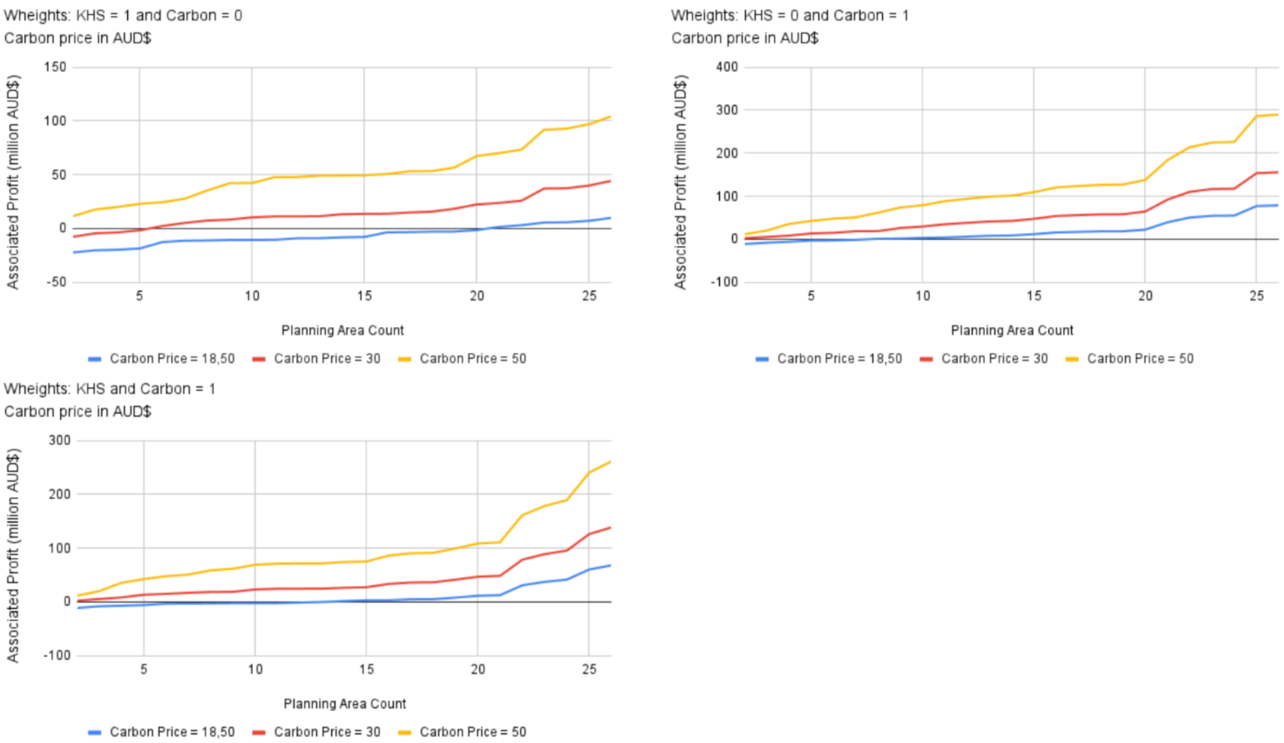
We tested scenarios with changes in the area C constraint in Eq. 2 from 10,000 ha to 15,000 ha, 20,000 ha and 25,000 ha respectively. The changes in area constraint led to lower changes in the attainment and profit for almost all objectives except for KHS profit and BFR profit in the 15,000 ha constraint (Table 5).

Table 5 – Percent changes in maximum attainment and profit as a function of changes in the area constraint C in Eq. 2.						
	AGB		KHS		BFR	
Percent change in the area constraint (C in Eq. 2)	Attainment (%)	Profit (%)	Attainment (%)	Profit (%)	Attainment (%)	Profit (%)
50 (15,000 ha)	36.6	29.4	39.0	53.7	31.8	52.4
33 (20,000 ha)	23.8	17.6	26.4	31.4	20.3	28.3
25 (25,000 ha)	18.1	13.2	19.9	20.7	15.3	1.2
Source: results of the study.						

3.5.2 Koala conservation and carbon under different scenarios

Figure 8 shows the associated profit when the carbon price increases from AUD$18.50, the baseline previously used to AUD$30.00 and AUD$50.00. The trade-off scenario when KHS is prioritized over carbon achieves the lowest profits, whereas when carbon is prioritized over KHS or they receive the same weight, profit is higher and with values close to each other in both scenarios. This goes in the same direction as the baseline scenario (when the price is AUD$18.50): opting for a balanced use of ecological and economic activities is a better choice for restoration programs.

Figure 8 – Associated profit in scenarios where the carbon price is increased from AUD$18.50 to AUD30.00 and AUD$50.00.



Source: results of the study.

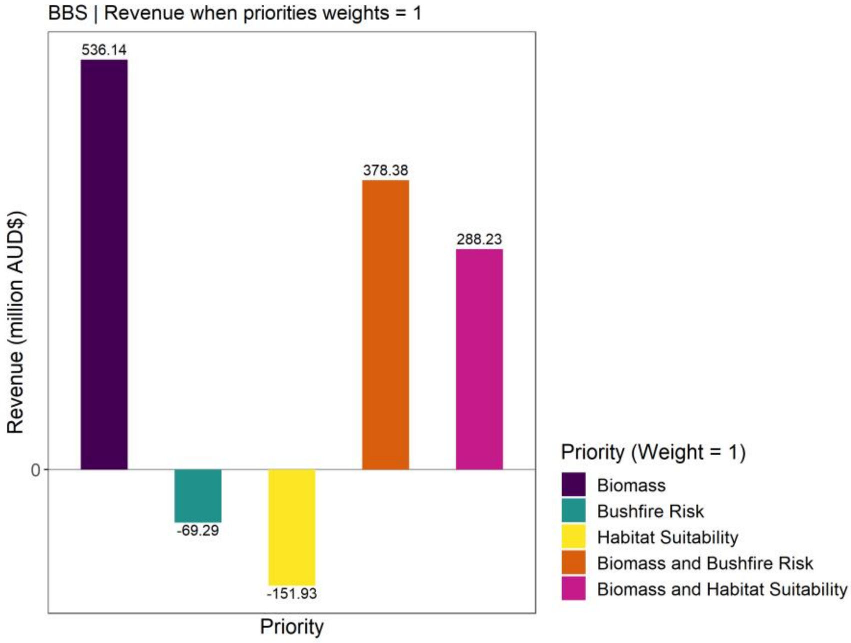
4 Discussion and Conclusion

The analysis of tradeoffs between different restoration goals and the attainment of these goals can help prioritize restoration actions and improve management of limited budgets. This is the first application of the ForSysX model in Australia and, as far as we know, outside the US. This model was developed by Ager et al. (2012) within the US Forest Service, and we have adapted it to our study area and variables. In the US, the model has been used for several National Forests to prioritize planning areas and identify high-priority landscapes to improve the effectiveness of restoration programs of the US Forest Service (AGER et al., 2017; AGER; DAY; VOGLER, 2016; VOGLER et al., 2015). The authors have been successful in using spatial planning tools to help guide decisions among different restoration goals. In our study, we adapted the model to a macro-level situation, using the best available information for each one of the variables. Our results are consistent with the data and show that it is possible to adopt the same principles of the original model in the Australian case. Each management objective has its priority restoration areas, which demonstrates the complexity of making several management objectives compatible.

Our economic analyses corroborate earlier studies that show how economic opportunities for restoration programs are a challenge (IFTEKHAR et al., 2017; SAMUEL, 2020). Our results show that the economic viability of restoration projects is tenuous under the scenarios modelled, and that optimizing profit from carbon leads to a sharp reduction in the attainment of other objectives. Production possibility frontiers and attainment were highly variable among planning areas, and point to local priorities and opportunities to achieve restoration goals within the study area. The single prioritization scenarios for ecological objectives lead to few opportunities with no-cost restoration activities. But, if ecological and economic objectives are prioritized with equal weights, there is an economic return to balance the costs of restoration. This emphasizes the importance of project designs which incorporate economic activities instead of projects that just focus on the ecological outcomes.

In Figure 9, profits from the trade-off scenarios when each priority receives equal weight are compared with the single prioritization scenarios. It can be observed that profit decreased in the trade-offs when compared with the single prioritization scenario for biomass but increased when compared with bushfire risk and habitat suitability prioritization scenarios.

Figure 9 – Profit (million AUD$) in the trade-off scenarios with equal weights between priorities.

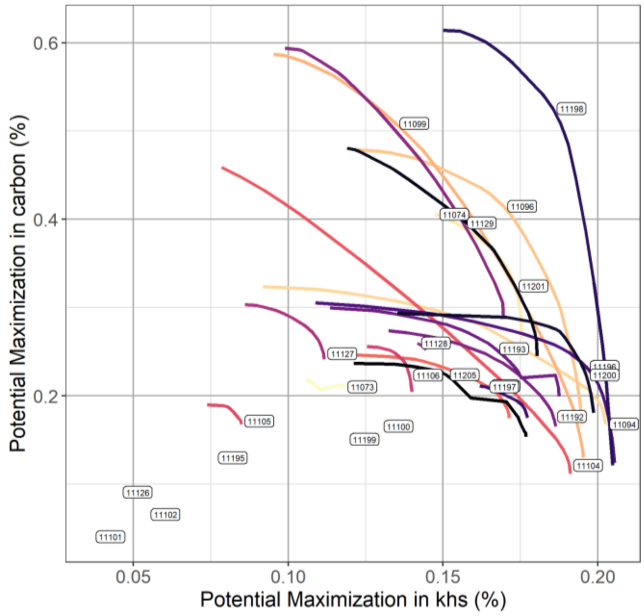


Source: results of the study.

The conservation of koalas is becoming increasingly urgent. Such conservation includes restoring areas previously degraded, as well as areas recently affected by fires. Our results suggest that public spending will be required to cover the opportunity costs of koala conservation. The use of carbon markets as an incentive to landowners to restore or conserve their land is an interesting option, however not without its challenges. As the production possibility frontiers show (Fig. 10), planning areas show sharp tradeoffs between maximizing KHS (habitats suitable for koalas) and maximizing potential carbon that could generate profit to fund restoration in the planning areas.

We show that prioritization decisions are strongly dependent on stand and planning area attributes, as demonstrated by other studies (LI et al., 2020; VOGLER et al., 2015). For instance, one can have a set of prioritization decisions among planning areas that can help decide restoration plans and programs. On the other hand, specific stands also have their trade-off scenarios that can guide local restoration projects. As noted by Ager (2017), trade-off decisions are a multiscale and scale-dependent problem, and there can be several trade-off relationships among the spatial scale.

Figure 10 – Production possibility frontiers between maximization in carbon and habitat suitability for koalas of the 26 planning areas.



Source: results of the study.

Since there are few opportunities to achieve various management objectives within the same stand, the need for a careful selection of stands to meet the restoration goals is emphasized. To achieve long-term restoration success, the various management objectives need to be balanced. However, areas that present sharp tradeoffs as the areas observed in this study can benefit from a restoration strategy focused on the management objective with more potential of having positive outcomes. To be able to identify those areas and their potential in the prioritization process of restoration programs with limited budgets is crucial.

Several assumptions were made in this study, for example, that restoration treatments would address each management objective, and that restoration costs and profit would not vary among areas. The proposed cost of the restoration is based on actions that will address common threats in the study area, such as habitat loss, fragmentation, degradation, wildfire and intense prescribed burns, and effects of climate change (Section 2.4). As noted in Section 2.4, co-benefits are generated from a restoration priority. These co-benefits can be environmental and socio-economic, and First Nations people are well placed to contribute to these efforts. Also, these co-benefits are especially important for carbon markets because they can increase the carbon credit attached to them[5]. We also acknowledge that the transaction costs of selling carbon, not included in the model, will affect profits. However, these assumptions do not compromise the ability of the model to provide an insightful picture of the capabilities of the study area at a macro level.

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Chapter 5 – Carbon and conservation trade-offs in the Brazilian Savannah

1 Introduction

Worldwide, changes to natural ecosystems as a result of land clearing have been increasing at an alarming rate (RUS et al., 2021) to the point that the majority of the world's species are threatened by a range of risks which include climate change, habitat loss, fragmentation, disease, invasive species, to cite a few (NG et al., 2014).

The Cerrado – the Brazilian savannah – is particularly sensitive and has been threatened by deforestation, agricultural expansion and land use change. It is the second largest biome both in Brazil and in South America, and it occupies about 24% of the national territory, or about 2 million square-kilometers (REIS et al., 2017). The Cerrado is a global biodiversity hotspot, with 0,4% of the vertebrates and 1,5% of the plants of the world being endemic to the biome (MYERS et al., 2000). Within Brazil, 30% of the species of fauna and flora of the country occur in the Cerrado (WWF-BRASIL, 2015). The Cerrado also contributes, in water volume, to eight of the twelve most important Brazilian catchments (LIMA; SILVA, 2005).

It is estimated that 72% of the carbon emissions of Brazil originate from deforestation of the Cerrado and the Atlantic Forest. From 1940 to 1995, the land use change started in the south of the biome, but is now more intense in the northern region (DIAS et al., 2016; LEITE et al., 2012; PARENTE; FERREIRA, 2018). At present, agriculture occupies 12% of the area, and planted pastureland 29%, with grazing being the main land use in the biome (BRASIL, 2015). It is estimated that 43% of Cerrado's original vegetation has already been lost (MAPBIOMAS, 2022) and it is predicted that 34% of the remaining areas will be lost by 2050 if the current land use pattern remains the same. A further 40 million hectares can be legally deforested, and on top of that, only 8,21% of the biome is under protected areas (ICMBio, 2021). There is still a knowledge gap regarding the tropical savannah restoration (SILVEIRA et al., 2020), and the same time, there is a demand for restoring 5 million hectares (MMA, 2007).

There is a strong case for conserving the remaining pristine and undisturbed areas (CRISTESCU et al., 2013), but with 6 billion hectares of degraded land worldwide (OECD, 2019), restoration will continue to play an important part. Restoration can deliver multiple benefits and offer new economic and business opportunities. At a landscape scale, it can help maximize synergies and manage potential trade-offs between ecosystem services, as well as balance competing demands for land or ocean resources (OECD, 2019). At the same time, limited resources mean that restoration projects and plans should include actions able to mitigate multiple threats (NG et al., 2014), and use decision tools and methods to prioritize areas for restoration (SANTIKA et al., 2015).

In this study, an ecoregion will be used as a unit of analysis at a landscape level. An ecoregion is a biogeographic unit for the analysis and planning of biodiversity conservation which encompasses all its dimensions (SANO et al., 2008). According to Ferreira and Arruda (2001) adopting an ecoregion as the unit of analysis of the landscape have the advantages of assessing different biogeographic scales for the long-term biodiversity conservation planning, and addressing species, communities, and the habitat with the biodiversity management at the same time.

The ecoregion concept has evolved alongside with solutions for biodiversity conservation, which aims to help reach the conservation targets from the various biodiversity targets signed by the country in the past decades. However, the direct interventions in the local communities which are required to lead to environmental and socioeconomic sustainability demand higher investments, and have a greater complexity than other interventions (SANO et al., 2008).

Human activities can enhance or reduce forest carbon storage. Land use, land use change, and forestry activities (LULUCF) is one of the economic sectors that need to be considered regarding sources and sinks of greenhouse gas (GHG) emissions, and the role of forests in climate change mitigation was recognized in 2016 by the Paris Agreement. Voluntary Carbon Markets (VCMs) can promote the transition into low-carbon emission economies, integrating ecological and socioeconomic aspects into forest management, and an interdisciplinary approach to forest management can support decision-making processes. In recent years, VCMs have been undergoing a strong expansion in quantities of carbon credits traded and in the number of operators. Simple procedures and an absence of specific legislation give the VCMs greater flexibility and easier access to carbon credit exchanges. In the context of VCMs, improved forest management, afforestation, reforestation, and urban forestry are some of the activities that can produce carbon credits (NONINI; FIALA, 2019).

Due to limited resources, providing economic opportunities while meeting socio-ecological objectives is one of the challenges when deciding on priority areas for restoration. The trade-offs between ecological and economic outcomes need to be accessed to better design prioritization frameworks and to understand the relationships among socioeconomic goals and the revenue, if any, that could be generated from restoration activities. The goal of this study is to spatially analyze trade-offs between ecological and economic management objectives to restore habitats to reduce deforestation susceptibility of the Cerrado biome. Production possibility frontiers (PPF) and attainment levels were derived for various restoration scenarios and prioritization objectives, including potential revenue that could be generated with carbon credits from forest biomass.

This article is organized as follows: section 2 presents the methods, study area, optimization model and the description of objectives and data sources used. Section 3 presents the results, including planning area priority, cumulative attainment for prioritization scenarios, profit and attainment under different restoration methods, and the production possibility frontiers. Section 4 presents the discussion and conclusion.

2 Methods

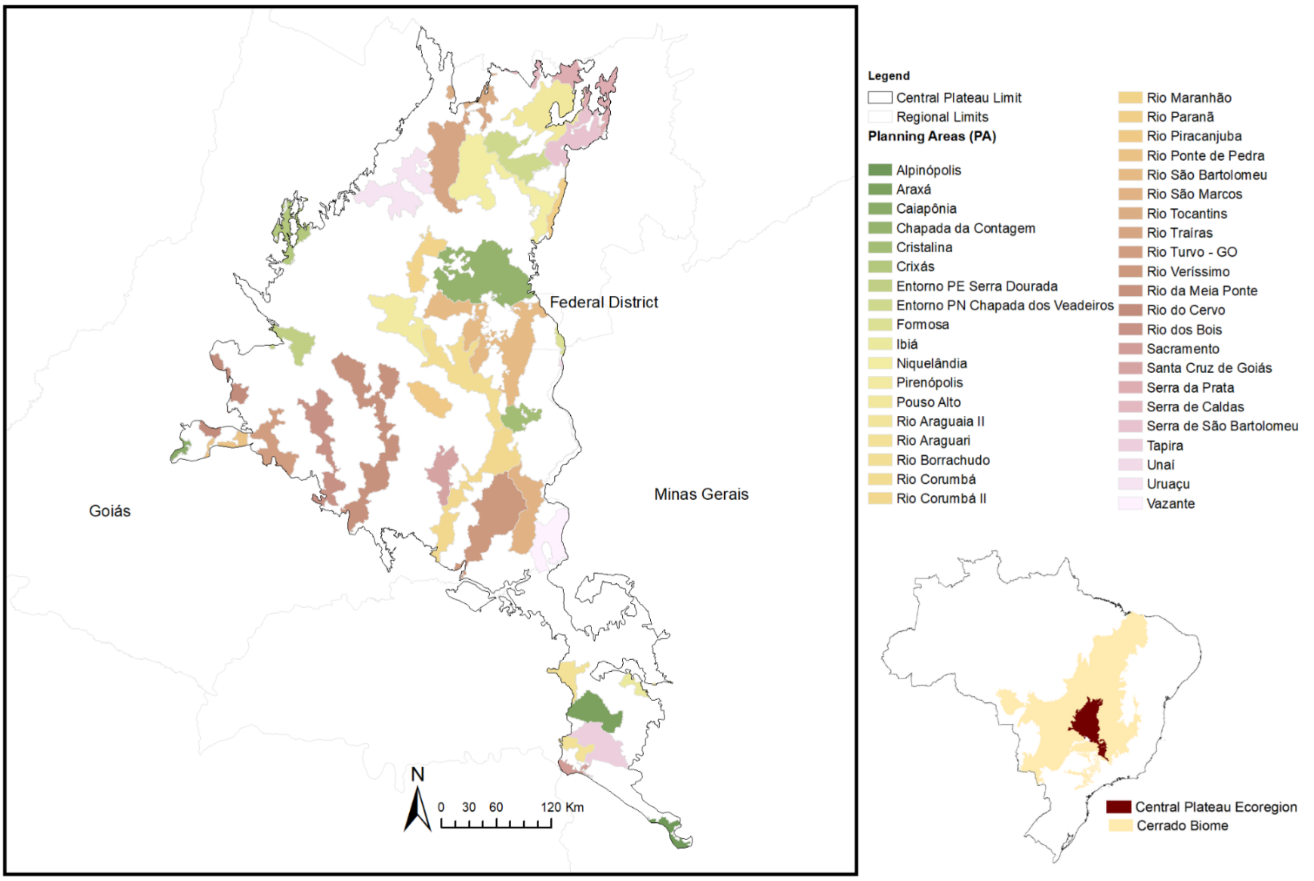
2.1 Description of the study area

The study area is the portion of the Cerrado's Central Plateau Ecoregion that occurs in the States of Goiás, Minas Gerais, and the Federal District of Brazil (Figure 1). The Central Plateau (henceforth CPE) covers an area of 157,160.8 km² (7.84% of the biome) and is known as the nuclear ecoregion of that same biome. The altimetry range is from 350 to 1200 meters, with a great morphological complexity. The main types of soils, depending on the relief and the source materials, are Red-Yellow Latosol, Red Latosol, Cambisol and Litholic Neosol. The main catchments are Corumbá, Maranhão, Meia Ponte, Paranaíba, Tocantins, and Turvo. There are 49 endemic species of flora found in this ecoregion, and only 1,9% of the CPE is assigned to protected areas (SANO et al., 2008).

The planning areas used in this study were based on the Priority Areas for Conservation, Sustainable Use and Benefit Sharing of Biodiversity that occur in the CPE. These areas are defined as a public policy instrument with the goal to help with decision-making related to the planning and implementation of adequate measures for the sustainable use, recovery, and conservation of ecosystems. To define these areas, spatial information on the occurrence of species and ecosystems are processed at the same time as the costs and opportunities of conservation. The Priority Areas are defined for all major six Brazilian biomes: (i) Cerrado (Brazilian savannah); (ii) Atlantic Forest; (iii) Caatinga (scrubland); (iv) Pantanal (wetlands); (v) Pampa (southern fields); (vi) Amazon Forest, and the Coastal and Marine Zones (MMA, 2018). There are 900 Priority Areas in Brazil, with 431 occurring in the Cerrado, which represents 47,8% of the priority areas of the country (WWF-Brasil, 2015).

Figure 1 shows the CPE area used in this study and the forty (40) Planning Areas (PA) set for this study. The management priorities used to model scenarios are described in the following sections.

Figure 1 – The Central Plateau Ecoregion (CPE).



Source: results of the study. The portion that occurs in the states of Goiás, Minas Gerais, and the Federal District was used in the study. The 40 Planning Areas (PA) of the study are based on the Priority Areas for Conservation, Sustainable Use and Benefit Sharing of Biodiversity that occur in the study area.

2.2 Optimization model

We followed the methodology of Ager et al. (2016; 2017) to model potential restoration priorities in the CPE and to identify tradeoffs among five variables: Above Ground Carbon (AGC), Below Ground Carbon (BGC), Deforestation Susceptibility Probability (DSP), Weight Vulnerability of Fauna (WVF), and Fire Risk Probability (FRP). In addition, carbon Revenue (R) from AGC and BGC were used as an alternative objective.

We used ForSysX version 2, formerly the Landscape Treatment Designer (AGER et al., 2012), a program designed to solve the problem of treating landscapes to decide on forest restoration projects. It uses a unique site polygon attributed with the priority metrics. A restoration scenario can be set in terms of the objectives (AGC, BGC, DSP, WVF, FRP, Revenue), constraints (area treated), and treatment thresholds (eg. additional conditions of any variable, not set in this study). ForSysX will identify one or more sites within the planning areas that maximize the objective:

$$Max \sum_{j=1}^{k} \left(Z_j * \sum (W_i N_{ij})\right) \qquad \text{Eq. 1}$$

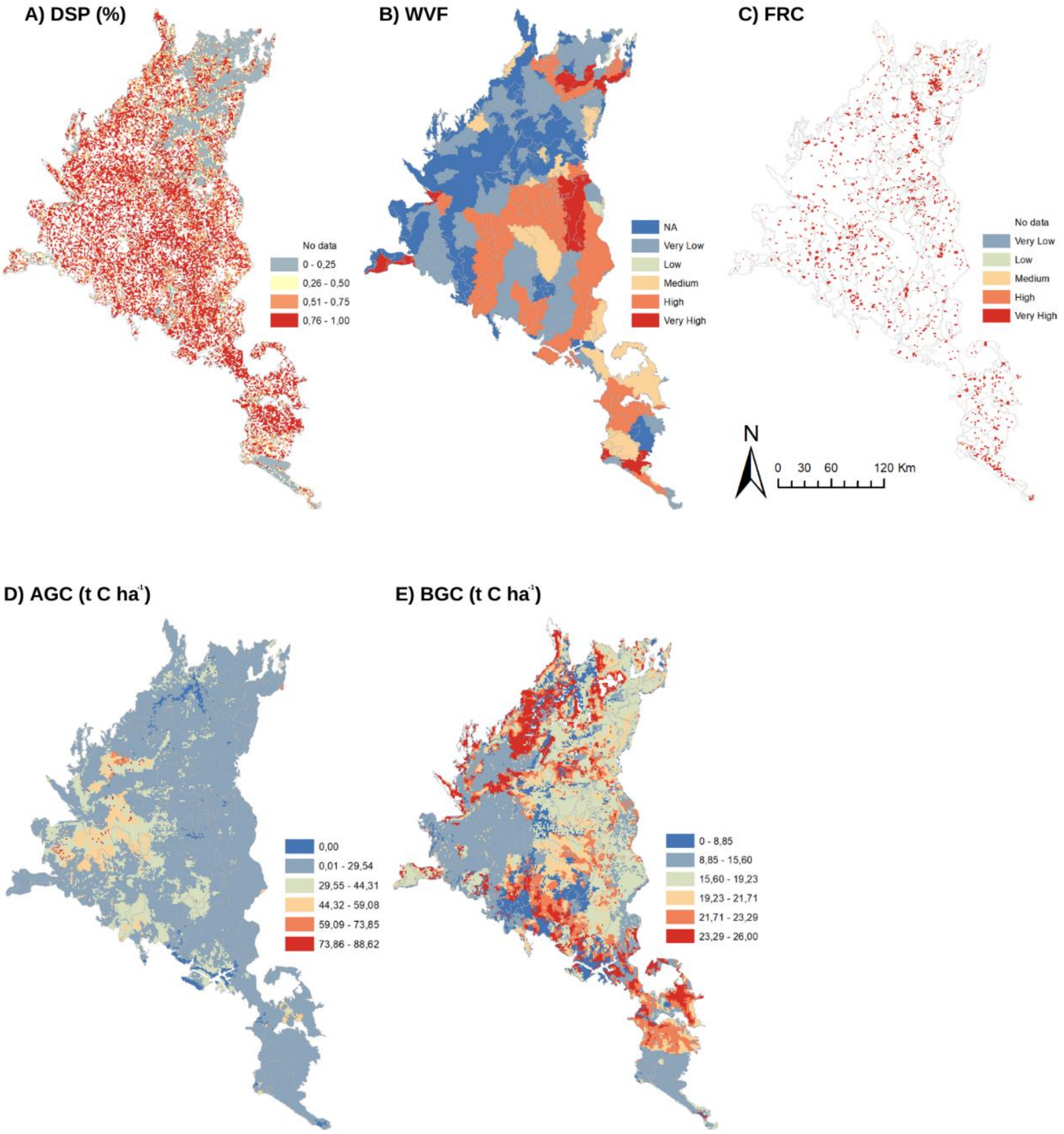
Subject to:

$$\sum_{j=1}^{k} (Z_j A_j) \leq C \qquad \text{Eq. 2}$$

Where C is a global constraint on activity per planning area, Z is a vector of binary variables indicating whether the jth site is treated (e.g., Zj=1 for treated sites and 0 for untreated sites), Nij is the contribution to objective i in site j if treated, and A is the area of the jth treated site. Wi is a weighting coefficient that can be used to emphasize one objective versus another. Given multiple planning areas, the program iterates through each one of them, and subsequently reports the maximum objective value and the selected treatment sites. Treatment here refers to the act of selecting a site to iterate into the model.

We created a square grid in the study area, which resulted in 30,589 potential sites to be included in the model (vector Z in Eq. 1). The average area of the sites is 591.69 ha, with the smallest having 579.25 ha and the biggest 602.07 ha. Only the sites that occur inside the forty planning areas were set as available to the model, resulting in 13,679 sites (44.71% of total sites). Each site was assigned the metrics of AGC, BGC, DSP, WVF, FPR as shown in Figure 2, and Revenues from AGC and BGC (see data sources in Section 2.3).

Figure 2 – Management Priorities mapped into the CPE grid



Source: results of the study. Above Ground Carbon (AGC), Below Ground Carbon (BGC), Deforestation Susceptibility Probability (DSP), Weight Vulnerability of Fauna (WVF), and Fire Risk Probability (FRP).

Trade-offs were analyzed between the priorities. It was assumed that the objectives AGC, BGC, DSP, WVF, and FPR would be addressed by the restoration activities described in Section 2.3.5. The focus was to compare carbon from above and below ground (revenue and profit) with the other variables by changing the relative weights of each priority (Eq. 2). Integer weights were varied in all combinations from 0 to 10 in increments of 1 in a pairwise fashion. For instance, weights of 10 and 0 for priorities A and B, respectively, generated the maximum production for A, whereas equal weights for each priority generated a balanced production for both. Once the treatment constraint *C* of 10,000 ha was met, the total objective value was summed for each site in the planning area. Outputs were used to generate production possibility frontiers between the different objectives. To standardize reporting of different metrics, ForSysX calculates the percentage contribution of attainment of each site to the study area (CPE) and sums these values for each planning area (PA), thus providing a standardized metric to compare different objectives. We performed additional analyses by prioritizing each objective individually as a "restoration priority" and deriving cumulative attainment of each priority given an increasing number of planning areas under different restoration priorities.

2.3 Objectives and Data Sources

The data sources for the five priorities are described below.

2.3.1 Above and Below Ground Carbon

The Above Ground (AGC) and Below Ground (BGC) Carbon are two spatial layers embedded within the Fourth National Inventory of Anthropogenic Emissions and Removals of Greenhouse Gases – Land Use Sector, Land Use Change and Forests. It was developed under the Fourth National Communication and the Brazilian Biennial Update Reports to the United Nations Framework Convention on Climate Change (UNFCCC), published in 2020 (MCTI, 2020). The estimation was done considering forty phytophisiognomies of the Cerrado biome and reported in five different layers of carbon stocks: total carbon, above ground, below ground, dead wood, and litter. For more information on all variables used, please refer to the report (MCTI, 2020). The layers used in this study refers to the above ground (AGC) and below ground (BGC) carbon. Values were reported as tonnes of carbon per hectare (t C ha^{-1}).

2.3.2 Deforestation Susceptibility Probability

The Deforestation Susceptibility Probability (DSP) was obtained from the Cerrado Deforestation Polygon Assessment Tool (DPAT), developed by the Laboratory of Image Processing and Geoprocessing (Lapig in the original) from the Federal University of Goiás (UFG). Cerrado DPAT (https://cerradodpat.ufg.br/) is an online and free tool for managers, researchers, and society to obtain information regarding the Cerrado biome. Deforestation and susceptibility of natural areas to deforestation are among the main information of this tool. DPAT produces two high-resolution rasters with pixels attributed with the susceptibility (or probability) of a native area being anthropized through clear-cutting, according to the patterns observed between the years 2010 and 2015. The two rasters represent two scenarios, with deforestation polygons higher and lower than 0.5 square-kilometers, respectively, named as small and large deforestation. Small deforestation is associated with land with low agricultural suitability, whereas large deforestation is associated with land with high agricultural suitability (CERRADO-DPAT, 2022). In this study, the layer with polygons lower than 0.5 square-kilometers was used. A point shapefile with the pixels values was extracted from the raster and intersected with the CPE grid to be used in ForSysX. The maximum value of the points intersecting each site was used.

2.3.3 Weight Vulnerability of Fauna

We used the Brazilian National RedList vulnerability weight classes calculated from the status of threatened species (vulnerable, endangered, critically endangered). These weight classes were used as one of the criteria of the Biological Dimension to prioritize the Key Biodiversity Areas (KBA) in terms of the threat they face. The biological criteria that include information of irreplaceability and vulnerability of fauna and flora species is the most important factor when it comes to the prioritization process of biological importance of KBAs. KBAs also include metrics such as alignment with national priorities, civil society capacity, ecosystem services, level of threat, and original vegetation cover. For more information on how the KBAs are prioritized, please see the Appendix at CEPF-CERRADO (2018).

Table 1 shows the five weight classes of vulnerability attributed to each site in the study area. As explained in the CEPT-CERRADO (2018) document, the weight is the relative importance of a relevant category over another, and the weighting factor is the result of the decision maker preferences. It is important to note that this weighting factor cannot be perfectly modeled since they are based on concrete facts but are subjective to human choice. It is, however, a good indicator to access the fauna vulnerability in the areas of choice.

Table 1 – Weights and classes of vulnerability of fauna.	
Vulnerability Class	**Weight**
Very Low	0.034
Low	0.065
Medium	0.146
High	0.295
Very High	0.460
Source: CEPF-CERRADO (2018).	

2.3.4 Fire Risk Classes

The Fire Risk Classes (FRC) are produced everyday by the National Institute of Spatial Research (INPE in the original), under the Platform of Monitoring and Warning of Forest Fires in the Cerrado (ProCerrado - INPE) Project. This project is part of the Cerrado Program, a joint initiative between Brazil and the United Kingdom with support from the World Bank. The aim of the program is to improve the management of natural resources in the biome and to contribute to the mitigation of climate change through the improvement of public policies and the practices undertaken by rural producers.

The data is publicly available at <queimadas.dgi.inpe.br /queimadas/bdqueimadas>. We exported a point shapefile with all focus fires that occurred in the year of 2020. To each of the points it is attributed a fire risk class which is calculated using the parameters of rainfall history for the last 120 days, the maximum air temperature, the minimum relative humidity, the type of vegetation and the occurrence of fire outbreaks. Please refer to Setzer, Sismanoglu and Santos (2019) for more information. Table 2 presents the range of the fire risk classes.

Table 2 – Fire Risk Classes.	
Risk	**Fire Risk (FR) Values**
Very Low	FR < 0.15
Low	0.15 < FR ≤ 0.40
Medium	0.40 < FR ≤ 0.70
High	0.70 < FR ≤ 0.95
Very High	FR > 0.95
Source: from Setzer, Sismanoglu and Santos (2019).	

2.3.5 Restoration activities costs and carbon revenue

Revenues from AGC (R_{AGC}) and BGC (R_{BGC}) were used in the trade-offs with the other variables to compare the scenarios between the production of above and below ground carbon. The Revenue for each site was defined as:

$R_{AGCj} = (N_{AGCj} \times 3.67)P_C$ Eq. 3

$R_{BGCj} = (N_{BGCj} \times 3.67)P_C$ Eq. 4

The 3.67 factor converts biomass carbon to carbon dioxide equivalents (CO^2). We used a carbon price P_C = US$4.30 per credit reported by Forest Trends' Ecosystem Marketplace (2021). According to the Ecosystem Marketplace Forest Trends report (2021), most of the credits coming from Latin America and the Caribbean are from the Forestry and Land Use category. In 2020, 85% of the credits came from this category at an average price of US$4.46 per tonne, and in 2021, 80% of credits came from this category at an average price of US$4.30. Brazil (4.6 MtCO2e in 2020 and 3.1 MtCO2e in 2021) and Peru (7.7 MtCO2e in 2020 and 23.5 MtCO2e 2021) are the main sources of those credits (Forest Trends' Ecosystem Marketplace, 2021).

Data on costs of restoration (CR) were obtained from TNC (2018) for three types of restoration practices: Total Planting (TP), Assisted Natural Regeneration (ANR) and Natural Regeneration (NR), under unfavorable environmental conditions. We did the money restatement using IPCA index, following a conversion to US$ dollars using the price of R$5.04 per USD, that was effective in 15 July 2018. Table 3 shows the final costs used. Assumptions in this study are that these restoration practices would improve habitat resilience, having an impact on increasing above and below ground carbon stocks, and reducing deforestation susceptibility, vulnerability of fauna and fire risk. This is possible because prioritizing one objective will result in co-benefits if restoration is done sustainably and effective. Multiple dimensions will be addressed, such as increasing biodiversity protection, supporting climate change mitigation and contributing to resilience and adaptation (GANN et al., 2019; ZHOU et al., 2022).

Table 3 – Restoration costs of three types of restoration practices (S): Total Planting (TP), Assisted Natural Regeneration (ANR) and Natural Regeneration (NR).		
Restoration practice	**Cost (US$)**	**Description**
Total Planting (seedlings)	4362.67	Planting of seedlings in total area. Variations in the distribution of individuals (e.g., spacing) can occur.
Assisted Natural Regeneration	465.14	Assisting the natural processes of vegetation regeneration, optimizing desirable processes (e.g.: increased diversity) and controlling undesirable processes (e.g.: ants and invasive species).
Natural Regeneration	40.89	Isolating the degraded area from its stressors (e.g.: fire, livestock, human traffic, rainwater discharge, etc.).
Source: description adapted from TNC (2018).		

We estimated the profit for each site by subtracting the costs of restoration activities from the potential revenue of carbon credit units sold in voluntary markets. The Profit for each site was defined as:

$PR_{AGCj} = R_{AGCj} - CR_j$ Eq. 5

$PR_{BGCj} = R_{BGCj} - CR_j$ Eq. 6

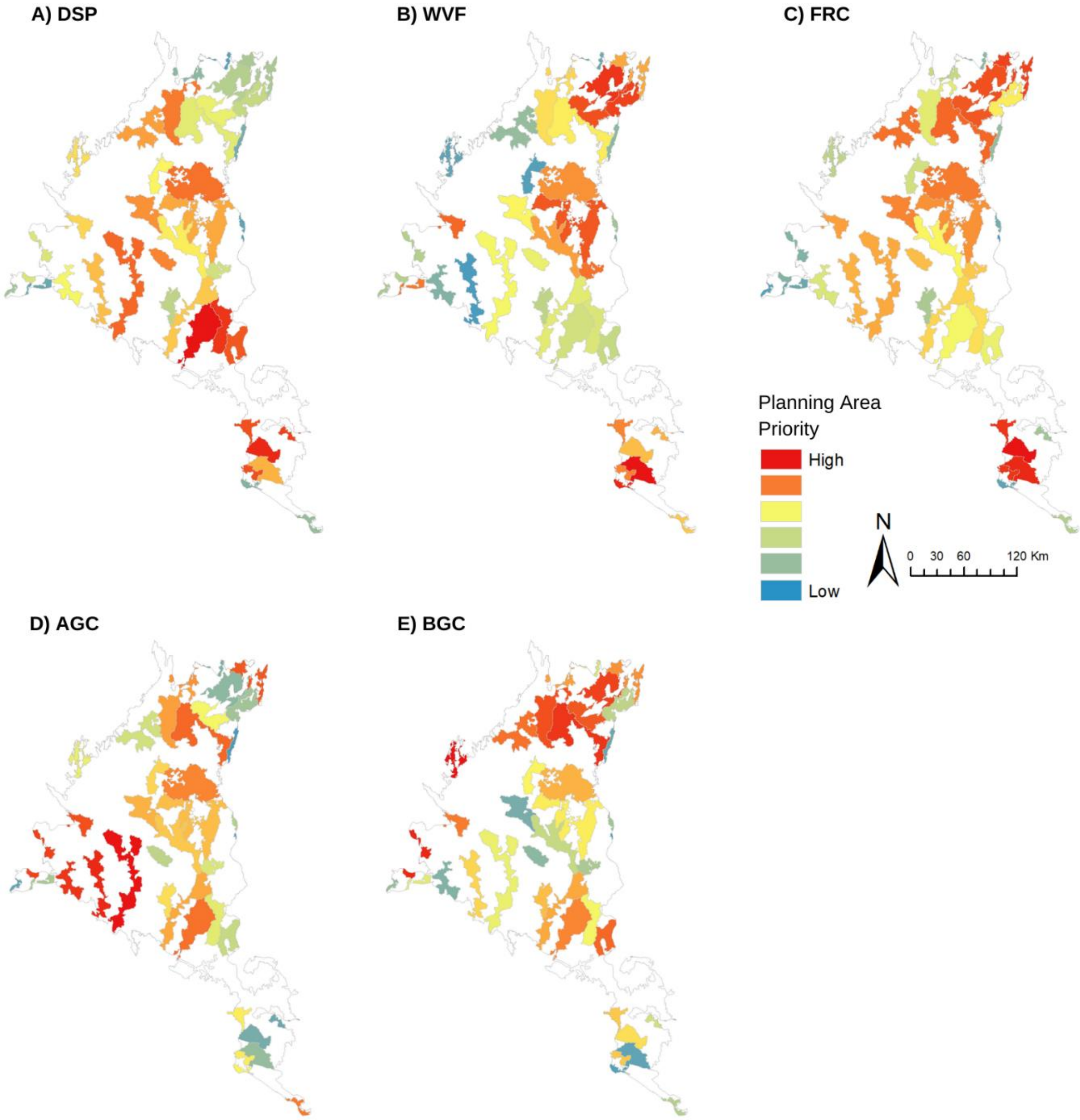
The Profit from AGC and BGC was calculated for the three types of costs when the other variables (AGC, BGC, DSP, WVF, FRC) were prioritized individually, and then the attainment was calculated for each scenario.

3 Results

3.1 Planning Area Priority

Figure 3 shows the planning area priority for each variable when they are prioritized individually. We can observe that the priority areas for AGC are in the west region of CPE, whereas the north region concentrates the priority areas for BGC. The south region of the CPE is of low priority for AGB and BGC, but is of high priority for DSP, WVF and FRC. WVF and FRC have similar patterns of priority areas while DSP concentrates the areas, with high priority in the central-south regions.

Figure 3 – Planning area priority for each variable.



Source: results of the study. Above Ground Carbon (AGC), Below Ground Carbon (BGC), Deforestation Susceptibility Probability (DSP), Weight Vulnerability of Fauna (WVF), and Fire Risk Probability (FRP).

3.2 Cumulative Attainment for Prioritization Scenarios

Attainment is measured as the percentage of the total restoration objective in the study area that is treated in a particular scenario. Figure 4 and Table 4 show cumulative attainment when each objective is prioritized individually, that is, one is attributed the weight of 1 while the others are attributed the weight of 0. Figure 4A groups all variables prioritized individually and shows that FRC (24.81%) is the objective that achieve the highest attainment, followed by AGC (10.64%), WVF (4.62%), DSP (4.67%) and BGC (2.98%). In terms of revenue when variables are prioritized individually (Table 4), AGC achieves the highest revenue (US$173.27 million), followed by BGC (US$136.78 million).

As showed in Fig. 2 (Section 2.2), this is explained by the fact that BGC quantities in the area have a maximum of 26 $tCha^{-1}$ (Fig. 2E), while the majority of AGC areas reach up to 29.54 $tCha^{-1}$, with higher quantities reaching up to 88.62 $tCha^{-1}$ (Fig. 2D). It is interesting, though, that when the ecological variables are prioritized, revenue from BGC is slightly higher than revenue from AGC (Table 4). This can be explained because there is a greater overlap between the high priority areas for the ecological variables (Fig. 3) with areas with more BGC storage (Fig. 2E) than AGC (Fig. 2D). This indicates that high attainment for DSP, WVF, or FRC is the goal for the area, defining restoration practices that enhance BGC is a good strategy to obtain more revenue to fund restoration activities (also adding the AGC that can be sold at the same time).

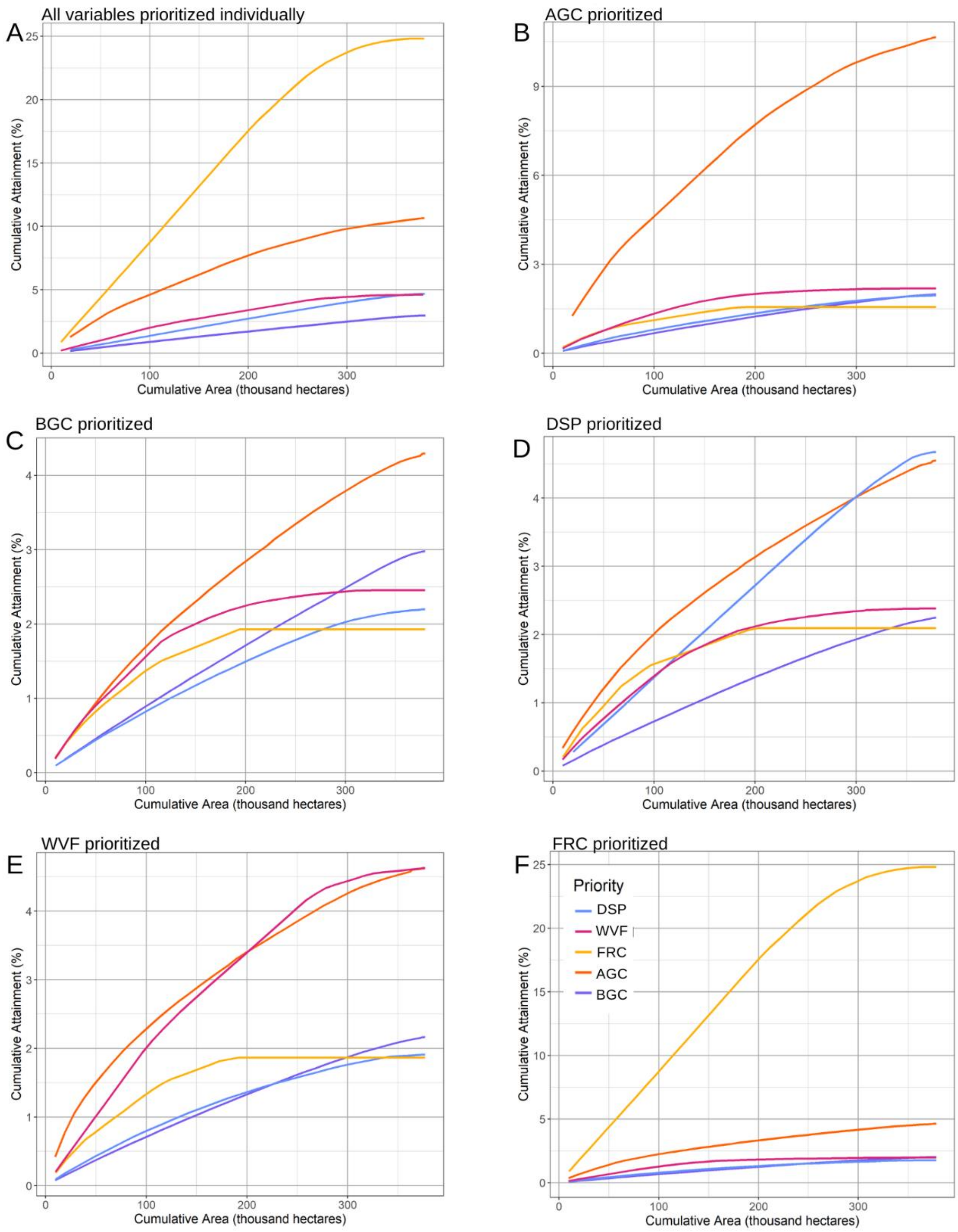
Table 4 - Cumulative attainment (%), area treated (thousand ha), and revenue (million US$) in the single prioritization scenario for AGC, BGC, DSP, WVF, and FRC.

Prioritization	Cumulative attainment (%)					Area treated (thousand ha)	Revenue (million US$)	
	AGC	BGC	DSP	WVF	FRC		AGC	BGC
AGC	**10.64**	1.99	1.95	2.19	1.56	369.17	173.27	-
BGC	4.29	**2.98**	2.19	2.45	1.92	370.22	-	136.78
DSP	4.55	2.24	**4.67**	2.38	2.09	369.12	76.47	103.94
WVF	4.62	2.16	1.90	**4.62**	1.86	367.55	80.02	99.83
FRC	4.65	2.02	1.77	1.98	**24.81**	368.69	80.06	93.48

Source: results of the study. Numbers in bold highlight when the attainment of that variable, whilst the other attainments in the same line shows the behavior for the other variables.

The other panels in Figure 4 show the behavior of the other objectives when each is prioritized. When DSP (Fig. 4D), WVF (Fig. 4E), FRC (Fig. 4F) and AGB (Fig. 4B) were prioritized, they achieved the highest attainment (same as in Fig. 4A) in their scenarios compared to the other variables. Only BGC (Fig. 4C) does not achieve the highest attainment in its single prioritization scenario, with the attainment of 2.98% while AGC attains 4.29%.

Figure 4 – Cumulative attainment for different single prioritization scenarios.



Source: results of the study. Above Ground Carbon (AGC), Below Ground Carbon (BGC), Deforestation Susceptibility Probability (DSP), Weight Vulnerability of Fauna (WVF), and Fire Risk Probability (FRP).

In general, objectives show similar patterns when they're not prioritized, changing the patterns when they're attributed the weight of 1. For example, when FRC and WVF are not prioritized, they show similar pattern increasing attainment up to 200,000 ha and maintaining that level of attainment when more areas are added to the model. This is in accordance with these two variables having the same priority areas in Section 3.1. On the other hand, DSP, AGC, and BGC increase monotonically in all scenarios, including when each is prioritized.

3.3 Profit and attainment under different types of restoration methods

We will now look at the prioritization scenarios in terms of the profits they achieve under the three restoration costs used (Total Planting, Assisted Natural Regeneration, and Natural Regeneration). Figure 5 shows attainment of priorities when they are prioritized individually as in Figure 5A and the profit that could be generated from carbon credits. AGC (left) and BGC (right) scenarios are shown for each restoration method. Objectives will achieve the same attainment level in all scenarios, but at different profits and/or costs depending on the restoration method. Fig. 5 (A and B) show that Natural Regeneration is the only method in which profit and attainment increase for all variables, both for AGC and BGC.

Fig 5C shows a different scenario for AGC and Assisted Natural Regeneration. All variables started with revenues higher than costs, DSP and WVF return revenue until approximately 1% attainment, and FRC until approximately 7% attainment, when costs start to increase, and losses are around US$90 million. AGC, on the other hand, has increasing revenue and attainment up to 7.5% attainment, when costs start to increase. But it manages to return US$1.56 (Table 5) million profits at the maximum attainment possible for AGC (10.64%).

Table 5 - Cumulative attainment (%), revenue (million US$), and profit (million US$) from the single prioritization scenarios.

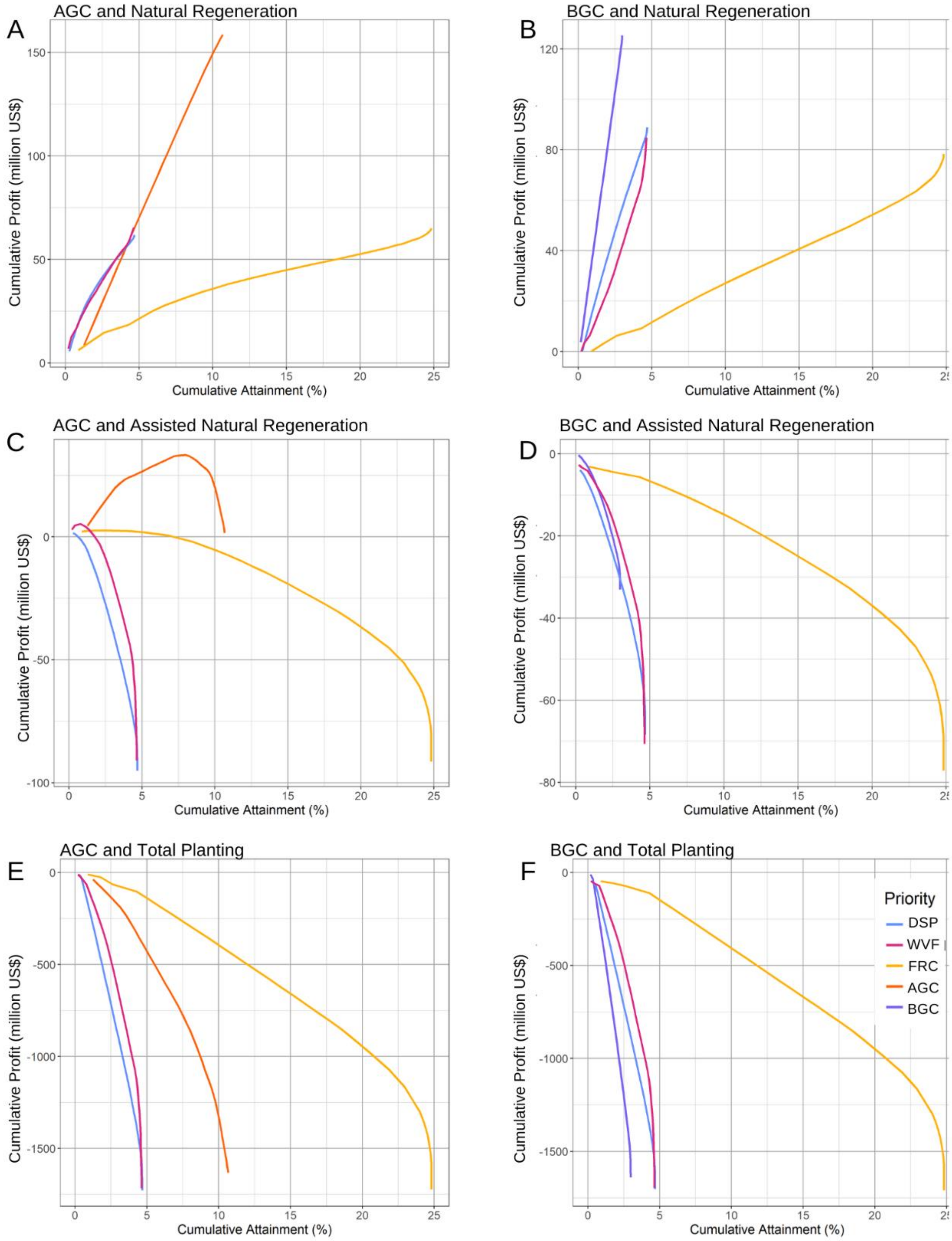
Prioritization	Cumulative attainment (%)	Revenue (million US$)		Profit (million US$)					
				RN		ANR		TP	
		AGC	BGC	AGC	BGC	AGC	BGC	AGC	BGC
AGC	10.64	173.27	-	158.18	-	1.56	-	-1,632.45	-
BGC	2.98	-	136.78	-	125.31	-	-33.05	-	-1,639.50
DSP	4.67	76.47	103.94	61.37	88.85	-95.23	-68.47	-1,729.04	-1,702.13
WVF	4.62	80.02	99.83	64.99	84.80	-90.95	-70.66	-1,717.85	-1,697.29
FRC	24.81	80.06	93.48	64.98	78.40	-91.44	-77.23	-1,723.37	-1,709.84

Source: results of the study. Above Ground Carbon (AGB), Below Ground Carbon (BGC), Total Planting (seedlings) (TP), Assisted Natural Regeneration (ANR), and Natural Regeneration (NR).

For the other scenarios, BGC with Assisted Natural Regeneration (Fig. 5D), and AGC and BGC with Total Planting (Fig. E and F, respectively), all areas don't have negative profits right from the beginning, with increasing costs reaching up to US$77.24 million in the Assisted

Natural Regeneration case, and more than US$1.5 billion for Total Planting. This indicates that in our case, the production of carbon credits is not enough to fund for restoration under Total Planting or Assisted Natural Regeneration methods. Therefore, public, or other types of investments would be needed to achieve the highest attainment possible.

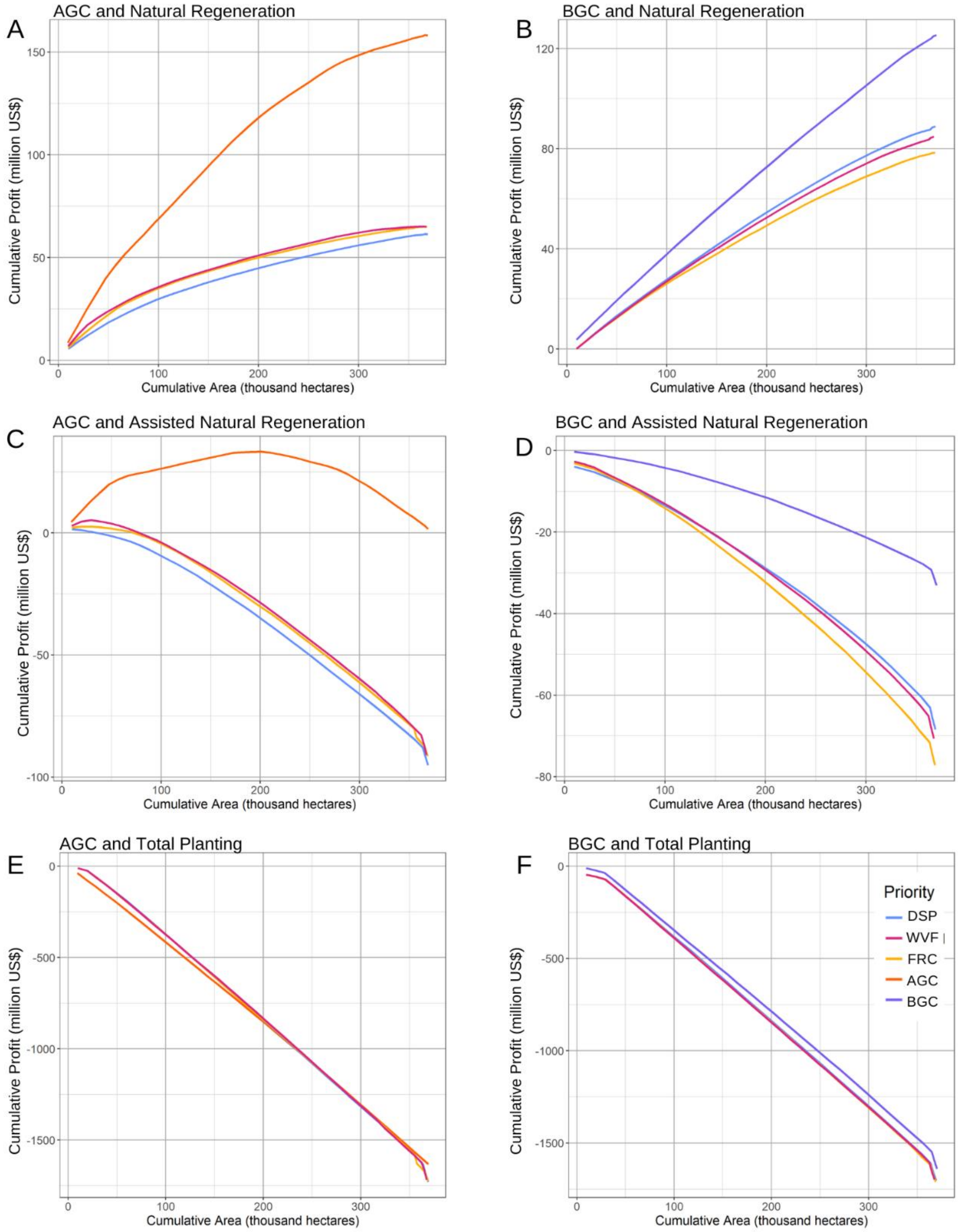
Figure 5 – Cumulative attainment of the objectives and the profit from AGB and BGC revenue under three types of restoration costs.



Source: results of the study.

Figure 6 shows the area treated, and the profit related for the variables.

Figure 6 – Area treated within the objectives and the profit from AGB and BGC revenue under three types of restoration costs.



Source: results of the study.

We can observe similar patterns in Fig. 5. With the natural regeneration method, profit from AGC and BGC could be used to fund restoration activities while the other objectives are prioritized. In the Assisted Natural Regeneration method, profit will increase for AGC up to 200 thousand hectares, when it starts to decrease. Also, in the AGC scenario, there is flexibility to have profit and prioritize WVF or FRC in areas below 70,000 ha. With the total planting method, profit decreases linearly with increasing area treated, with the same losses from Fig. 5 if the maximum area is to be treated.

3.4 Production possibility frontiers

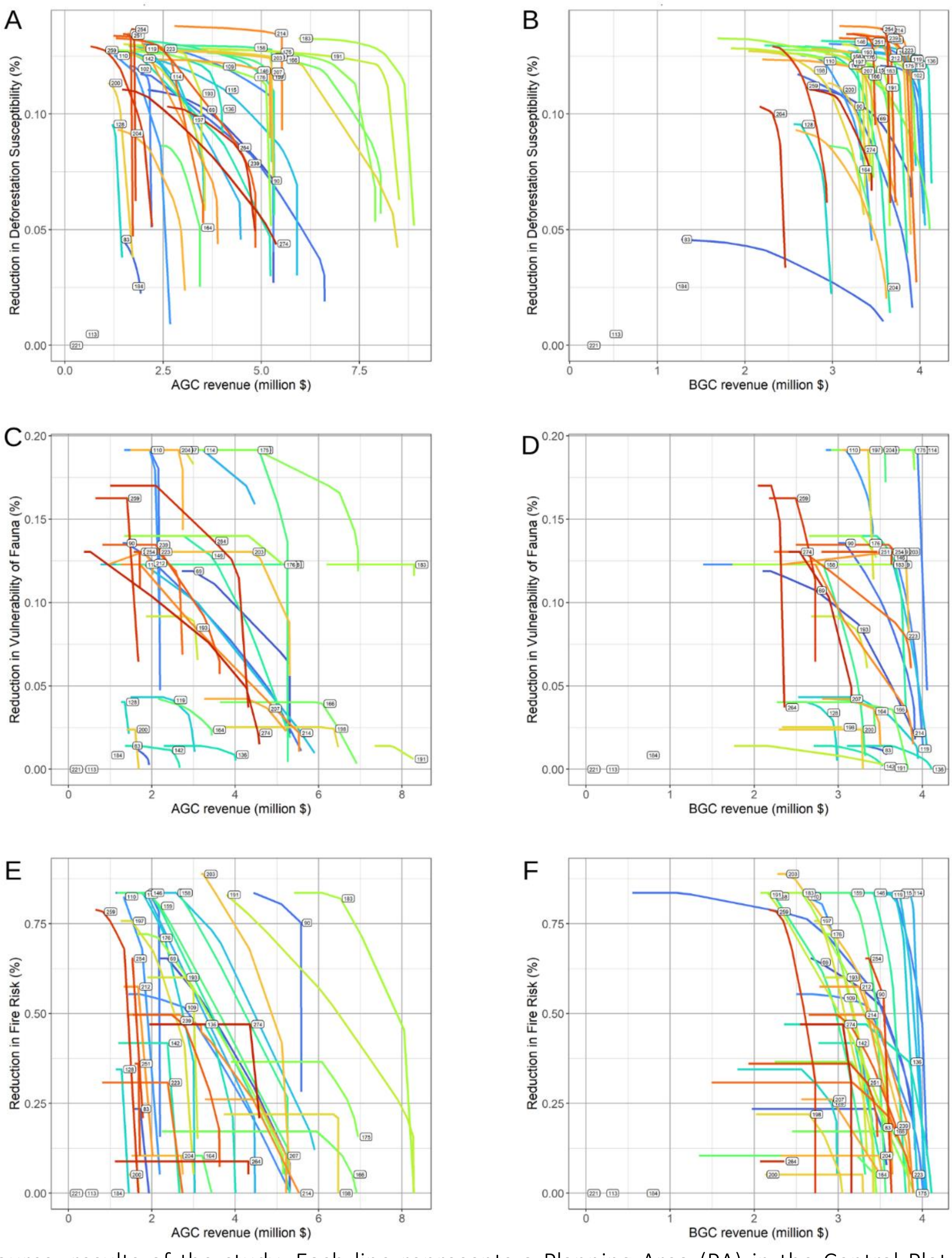
Figure 7 (p. 162) shows trade-off scenarios between potential maximization in Revenue for AGC and BGC (in a million US$) and DSP, WVF, and FRC. Production possibility frontiers show that few areas have a high potential for maximizing two objectives together, especially when maximizing BGC. Only a few areas in panels 7A (DSP) and 7C (WVF) have a more balanced trade-off with AGC revenue. In general, ecological, and economic variables have sharp trade-offs, meaning that improving revenue from carbon will reduce attainment of the ecological variables.

4 Discussion and Conclusion

Prioritization of restoration actions and management of limited budgets can be improved by analyzing attainment of various restoration goals and the trade-offs between these goals. As far as we know, this is the second application of the ForSysX model outside the US, the first being the Australian case presented in this thesis (Chapter 4). Developed by Ager et al. (2012), these spatial planning tools have been successfully used by the US Forest Service. Their model is used to help guide decisions among different restoration goals, identify high-priority landscapes and prioritize planning areas (AGER et al., 2017; AGER; DAY; VOGLER, 2016; VOGLER et al., 2015).

We have adapted it to a macro-level situation, using the best available information for each of the variables within our study area. Our results are consistent with the data and show that it is possible to adopt the same principles of the original model to the Brazilian case. Each management objective has its priority restoration areas, which demonstrates the complexity of making several management objectives compatible. Chapter 4 also points to the same conclusion.

Figure 7 – Trade-off scenarios between DSP, WVF, and FRC and Revenue from AGC and BGC (million US$).



Source: results of the study. Each line represents a Planning Area (PA) in the Central Plateau Ecoregion (CPE). Above Ground Carbon (AGC), Below Ground Carbon (BGC), Deforestation Susceptibility Probability (DSP), Weight Vulnerability of Fauna (WVF), and Fire Risk Probability (FRP).

Our economic analyses show that high attainment for economic and ecological objectives at the same time in the same area does not happen, highlighting the challenge of economic opportunities in restoration programs, which is corroborated by other studies

(Iftekhar et al., 2017; Samuel, 2020; Chapter 4, this thesis). Production possibility frontiers and attainment were highly variable among planning areas, which indicates that priorities and opportunities to achieve restoration goals would have better results if planned locally instead of in a landscape area.When we look at revenue, we can observe that increasing revenue leads to a sharp trade-off for most areas in all scenarios. Few areas show a more rounded/concave trade-off that have the potential to increase carbon revenue without a large reduction of the attainment in the ecological variable. This scenario was found in the cases of AGC versus reduction in deforestation susceptibility and AGC versus vulnerability of fauna. These results are similar to the ones found in chapter 4 of this thesis. In the two cases, it shows how important it is to look carefully at the potential of each site when designing a restoration project. Areas that have a balanced trade-off between variables can aim at having more than one restoration goal at the same site, whereas areas with sharp trade-offs can have a restoration strategy focusing on the objective that they would benefit most from.

Our results show that the economic viability of restoration projects is tenuous under the scenarios modelled, and that optimizing revenue from carbon leads to a sharp reduction in the attainment of other objectives.

This emphasizes the importance of project designs that incorporate economic activities instead of projects that just focus on the ecological outcomes. In addition, our results show that ecological attainment is achieved even when economic variables are prioritized. We suggest that at a landscape level, ecological priorities could be targeted, while specific sites with high economic potential can be selected for local projects. To be able to identify those areas and their potential is crucial in the prioritization process of restoration programs with limited budgets.

4.1 Profit of restoration methods and stakeholders' choices

As we presented in the introduction (Section 1) of this article, deforestation is a pressing issue in the Cerrado biome. In 2017, the government established the National Plan for Native Vegetation Recovery (PLANAVEG in the Portuguese abbreviation), aiming to restore 5 million ha in the Cerrado (MMA, 2007). Hence, attention could be given to reducing the susceptibility of deforestation (DSP), because this variable is positively correlated with increasing above and below-ground carbon (AGC and BGC). Therefore, profit from carbon credits can be used to fund restoration efforts to reduce deforestation while achieving increasing attainment from these variables (DSP, AGC, and BGC).

Focusing on DSP can also benefit from the natural regeneration method, which is the only profitable method for this study. According to Durigan et al. (2011), when an area in the Cerrado biome is disturbed by deforestation, natural regeneration has a very high potential to recover savannah formations, and high potential to recover forest formations. However, this method requires a period longer than the other methods of restoration. From the same TNC (2018) study from where the costs used in this study were obtained, Table 6 compares the period in months for implementation, maintenance, and total period for the restoration methods we used. We can observe that while the average period for total planting with seedlings is 3 years, assisted natural regeneration takes 4.9 years, and natural regeneration can take 5.3 years.

Table 6 – Period in months for implementation, maintenance, and total period for the restoration methods we used.

Restoration method	Implementation (months)	Maintenance (months)	Total (months)	Years
Total Planting (seedlings)	10	26	36	3.0
Assisted Natural Regeneration	24	35	59	4.9
Natural Regeneration	31	34	64	5.3

Source: adapted from TNC (2018)

The focus of this study was to investigate the potential of selling carbon credits to fund restoration activities. We discovered that between the restoration methods analyzed, only Natural Regeneration returns profit, but it is also the method that requires a longer time. Assisted Natural Regeneration and Total Planting are faster methods, but they require additional investments, since relying on carbon credits is not enough to return profits that could fund restoration activities. We suggest that, at a local level, projects should target actions that would increase economic benefits to help fund the restoration together with the carbon revenue. For example, choosing native species with more commercial potential even if they are not the ones that would be chosen from an ecological standpoint. This decision can also be easily explained to investors and receive higher community support.

This points to the fact that restoration projects need to consider not only the feasibility of methods, but also stakeholders' objectives and demands. We recall chapter 2 of this thesis, where we concluded with the importance of communication between restoration practitioners, researchers, and society. An informed decision could then be made by comparing the required time of investments, the costs that would be spent throughout the project, and the returns expected. We show that prioritization decisions are strongly dependent on site and planning area attributes, as demonstrated by other studies (Li et al., 2020; Vogler et al., 2015, chapter 4 of this thesis). As noted by Ager (2017), trade-off decisions are a multiscale and scale-dependent problem, and there can be several trade-off relationships among the spatial scale.

Several assumptions were made in this study, for example, that restoration treatments would address each management objective, and that restoration costs and revenue would not vary among areas. The proposed cost of the restoration is based on actions that will address common threats in the study area, such as deforestation susceptibility, vulnerability of fauna and fire risk (Section 2.3.5). As noted in Section 2.3.5, co-benefits are generated from the restoration priorities, and they can be environmental and socio-economic. They are especially important for carbon markets because they can increase the carbon credit attached to them[6]. We also acknowledge that the transaction costs of selling carbon, not included in the model, will affect profits. However, these assumptions do not compromise the ability of the model to provide an insightful picture of the capabilities of the study area at a macro level.

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Thesis Conclusion

The contribution of this thesis to the field of Economics of Restoration started, in Chapter 1, with a comprehensive bibliometric analysis of three major scientific databases: Web of Science, Scopus, and Lens. As bibliometric indicators we used co-authorship, co-occurrence, direct citation, co-citation, and bibliographic coupling. The evidence clearly shows the newness of the field: all indicators highlight most documents from the 2000s, followed by the 1990s. And this also includes co-citation, an indicator that aims to identify older documents important to the basis of the science of interest. The Economics of Restoration studies started with the adaptation of economic concepts and methods to the science of restoration ecology. The collaboration between ecologists and economists made it possible to advance economic valuations and cost-benefit analysis to improve restoration projects and programs. Although there is much uncertainty on the functioning of ecosystems, restoration economists were able to shift the focus to pressing issues related to land use change and climate change, to respond to demands coming from the international commitment that countries need to achieve to up-scale landscape and forest restoration.

The use of bibliometric analysis to map the scientific landscape of a field and identify how it is developing through time is increasing in the literature (Chapter 1). This bibliometric analysis of the Economics of Restoration is the first that applied five bibliometric indicators and used three databases. One benefit of bibliometrics is that it reduced the researcher's selection bias when identifying the important documents in its analysis. We took advantage of this feature to develop a literature review on challenges, opportunities, and critical aspects regarding costs, benefits, and investments that need to be solved to advance in the economics of restoration research.

The aforementioned literature review (Chapter 2) highlights that the methods and the frameworks for the analysis of benefits had great developments in the last decade. Critical aspects identified are the fact that benefits are highly dependent on the site selection, and the benefits to society are not yet analyzed in detail. Regarding costs, there is a lack of information in general, especially on opportunity costs and spatially explicit costs. Standardized data gathering, reporting on data, and data sharing were identified as important actions a decade ago and have received little attention to date, especially regarding costs. It was only in 2021, within The Economics of Ecosystem Restoration (TEER) initiative, that a standardized framework and database for costs and benefits was developed and proposed. These data will help policy, programs, and projects by providing proxies of costs and benefits. However, a new challenge arrives, since this recording of data requires long periods, and it needs to be consistent and continuous.

The main challenge identified by this review is the fact that the gap between society, researchers, and policymakers was identified more than a decade ago, but there is still poor communication between those who benefit from restoration and those who conduct research. The recommendations to solve this gap focus on making the implications of the restoration outcomes explicit to society, increasing the number of reports and articles that discuss financing and costs, and highlighting the potential and direct impacts of benefits to people. Human-related challenges were also found in Chapter 3, where for decision-making purposes, better investment solutions are interconnected with engaged landowners and local communities, and the priorities of society need to be adjusted to scale-up restoration projects.

The two final chapters of this thesis (Chapters 4 and 5) were an application of a spatial optimization model, which uses trade-offs and attainment between management goals to guide prioritization decisions in large-scale areas. Following the findings from Chapter 2, which indicate large-scale areas as more effective for restoration, our areas of study were a Bioregion in the Australian case and an Ecoregion in the Brazilian case. The two articles tested economic and ecological management objectives. The economic variable is the use of carbon credits for their potential to fund restoration. Ecological variables included koala conservation and fire resilience (Chapter 4); fauna vulnerability, deforestation susceptibility, and fire risk (Chapter 5). To the best of our knowledge, these were the first two applications of this model outside the US, where it was developed by the US Forest Service to be used within their National Forests.

The results from the two articles follow similar patterns and exemplify the complexity of making several management objectives compatible. For example, all management objectives have different priority restoration areas, and a high attainment for economic and ecological objectives in the same area does not happen. In Chapter 4, we focused on the question of whether prioritization with an equal weight between variables would be a better practice. In the single prioritization scenarios for ecological objectives, there are few profit opportunities. But, if ecological and economic objectives are prioritized with equal weights, there is an economic return to balance the costs of restoration. This emphasizes the importance of project designs that incorporate economic activities instead of projects that focus exclusively on the ecological outcomes.

In Chapter 5, we tested the costs of three methods of restoration (Natural Regeneration, Assisted Natural Regeneration, and Total Planting with Seedlings). Only natural regeneration is profitable given the revenue available to fund the restoration costs, but this is also the method that requires a longer period than the other two methods. However, this method also has a high potential to recover the Cerrado (savannah) formations disturbed by deforestation, which is the most pressing issue among the environmental variables we tested for this area. Our data show that relying on a single source of income (in our case, carbon credits) is not the best option and that external funding will be needed when the area demands a specific type of restoration method that can be costly. If it is urgent in the project area to increase the resilience of ecological aspects, and the activities required for this objective are not compatible with economic activities, extra funding will also be needed.

We suggest that, at a landscape level, prioritization could be driven by ecological objectives and demands of the area. In its turn, at a local level, projects should prioritize actions that would bring financial returns to fund for restoration, and economic benefits for the local people affected by the project. Given our findings and recommendations, it is evident how important it is to identify the attributes of the area of study, and how decisions will be impacted by these attributes. Restoration projects need to consider the feasibility of methods, but also stakeholders' objectives and demands. We recall Chapter 2 of this thesis, in which we concluded with the importance of communication between restoration practitioners, researchers, and society. An informed decision could, then, be made by comparing the required time of investments, that is, the costs that would be spent throughout the project, with the returns and benefits expected from the project. Also, the more information those involved with restoration have, the more equipped they are to deal with the uncertainties from the specificity of the natural capital and the aspect of public goods related to restoration outcomes, a challenge addressed in Chapter 3.

An important change that needs to take place was identified in Chapter 2, which is the need to plan and develop restoration not in small regions or individual disconnected sites. Considering that the higher effectiveness and sustainability of restoration occur at a large-scale, projects must be developed from the perspective of the landscape or bioregional projects, which has been called as Forest Landscape Restoration, or FLR. This perspective comes embedded with a fundamental principle that rural communities need to be active in projects. Long-term restoration is impacted by how these communities understand that restoration projects are helping to revert degradation.

We are now entering the third year of the United Nations Decade on Ecosystem Restoration (UNDER), declared by the UN General Assembly to run from 2021 to 2030. The Bonn Challenge, with worldwide commitments as bold as the ones presented by UNDER, is already on its way. In order not to reproduce the failures from the past (such as the Aichi Targets), two aspects need to advance at a faster rate than what has been done. The first is the inclusion of rural communities and landowners in the decision-making process, since the long-term restoration goals must comply with society's needs. The second is that researchers and practitioners need to commit themselves to the use of the frameworks that would help the information sharing between projects.

Throughout its five chapters, this thesis accomplished its purpose by comprehensively investigating the evolution of the Economics of Restoration field, and then systematizing and identifying the challenges faced by all of those involved with restoration. From the literature selection, reviewing and discussing key topics, to the decision-making aspects and then modelling, each article provides a path for future improvements, research, and outcomes. Each chapter is based on the best up-to-date and relevant literature and data, and we believe that this work provides quality resources for future research.

The robust model used in this thesis is an instrument to be applied at the macro level, by state and federal governments. It should be used so that the Brazilian government understands the potential of regions and biomes and achieves better synergy between policies and programs for landscape-scale restoration. The two applications presented here also demonstrate the difficulties that are faced in large-scale data collection. For example, there is no large-scale database of fauna in Brazil to use with the model to compare with the Australian scenario with koalas. This study points out these deficiencies to help to mitigate the bottlenecks that prevent the advancement of Brazilian environmental agendas.

For the decade of restoration, this macro understanding of the country and its potential is of crucial importance, because there must be a synergy of actions at the federal level. The application of this model guides the decision-making of what should receive more investment and what needs to be left aside, given the scenario of interest. When trade-offs are properly analyzed at a macro level, where funding is more available to conduct this type of model, resources can be allocated efficiently to local projects, thus bringing greater benefits to local communities.

On the other hand, the application of bibliometrics to the economics of restoration, using international databases to identify the advances of this science that interconnects the economic sciences and the science of ecological restoration demonstrates the importance of this tool so that the studies are aligned with the scientific state-of-the-art. Bibliometrics needs to be incorporated as an instrument in institutions and project teams because the theoretical aspect should not be left out. This technique is the method of survey and literature review that has been growing the most in the academy and have the strong advantage of applying quantitative indicators even to identify qualitative aspects of the research topics.

Especially for economic sciences, which makes few applications of bibliometrics in their research, this thesis is a good example of how this survey and indicators such as co-citation and bibliographic coupling manage to map, efficiently and scientifically, how economics has been incorporated into other disciplines.

It should be noted that the use of bibliometrics extends beyond the themes of this thesis. Scholars of other topics cannot give up a robust tool for bibliographic research such as this one. The difficulty of doing a quality literature review still pervades researchers at various levels, especially post-graduate candidates. There is a demand among new academics to be more confident of what is important to their research amongst the scientific production, what are the best databases, and which articles and other documents are most relevant. This thesis demonstrates this instrument and shows the path of possibilities for the use of bibliometrics in scientific writing.

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APPENDIX A – Proof of publication

As mentioned in the Thesis Introduction, Chapter 3 consists of an article published in 2021 in the journal Environmental Development, entitled "Is Economics of Restoration helping with decision-making challenges? Insights guided by Bibliometrics". Here is a snapshot at the editor's website. Article DOI is: https://doi.org/10.1016/j.envdev.2021.100674.

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Is economics of restoration helping with decision-making challenges? Insights guided by bibliometrics

Maria Luiza Almeida Luz

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Abstract

Society is already seeing the ecological and economic benefits from restoration projects. However, the challenge is much bigger than the current efforts from ecologists and economists around the world. The Economics of Restoration is the interdisciplinary research field that is believed to have the necessary tools and instruments to solve this restoration gap, yet a better use and understanding of economic aspects and concepts are still needed. A bibliometric analysis of the field of economics of restoration was done in this study. Bibliometrics can offer insights on the intellectual structure of a discipline and thus indicate future paths for research development. The goal of this study was to identify important and influential economics of restoration research themes and key topics that will strengthen decision-making processes for restoration actions if better addressed in the future. The analysis reveals that few studies go beyond costs, lacking a full estimation of benefits. Economic concepts of uncertainty, public goods and specificity of natural capital are not well incorporated yet, and the relationship between governments and markets, as well as the one between communities and investments, require more attention to scale-up restoration worldwide. This study is believed to be the first one using bibliometrics to guide a discussion around economics of restoration and can be subsequentially replicated in other disciplines.

APPENDIX B – Glossary

Aggregate stock of capital: the total quantity of capital used in the production of services and goods. This includes equipment, factories, tools, machinery, and buildings.

Agroecology: considered a holistic and integrated approach that applies ecological and social concepts and principles to the management and design of food systems and sustainable agriculture. It seeks to create socially equitable food systems where people can have a choice over what they eat and how and where it is produced.

Aichi Targets: the 20 targets included in the Strategic Plan for Biodiversity for the 2011-2020 period. It was adopted in the tenth meeting of the Conference of the Parties, held from 18 to 29 October 2010, in Nagoya, Aichi Prefecture, Japan.

Assessment: the process to evaluate the merits of a proposal or project that includes identifying, calculating, and comparing the costs and benefits. It can be evaluated in comparison with alternatives or absolute values.

Biobanking: or Biodiversity Banking, is the measurement and commodification of biodiversity as part of a conservation and land management scheme. Biodiversity credits are calculated based on a range of values of a particular land and landowners can generate those credits by protecting the biodiversity. Companies and organizations, including government agencies, can buy these credits to offset their negative environmental impacts.

Biodiversity hotspot: introduced in 1988 by Norman Myers, a biodiversity hotspot is a region with a high level of endemic species and a high rate of habitat loss.

Biodiversity: also known for biological diversity, comprise the variety of all life on Earth, including genetic variability, species diversity, and ecosystem diversity.

Bioeconomy: the sustainable and innovative use of natural resources and biological knowledge to provide services, food, bioenergy, and industrial products to the people and all economic sectors, seeking a sustainable economy.

Bonn Challenge: is a global goal to restore 150 million hectares of degraded and deforested landscapes by 2020 and 350 million hectares by 2030. Launched by the Government of Germany and IUCN in 2011, it surpassed the 150-million-hectare milestone for pledges in 2017.

Carbon farming: is a farm approach to implement practices to improve the rate of carbon capture on working landscapes, removing CO_2 from the atmosphere and storing it in plant material and/or soil organic matter.

Carbon sequestration: the process of capturing and storing atmospheric carbon dioxide, with the goal of reducing global climate change.

Circular economy: is a model that aims to extend the life cycle of products and materials through leasing, sharing, reusing, refurbishing, repairing, and recycling as long as possible. Three principles are required for a circular economy: the regeneration of nature, eliminating waste and pollution, and circulating products and materials.

Climate change: is the long-term shifts in temperatures and weather patterns. It can be natural, but human activities are the main drivers of climate change since the 1800s. The activities that impact the most are the burning of fossil fuels like gas, oil, and coal.

Compliance: the act of abiding by the applicable rules and laws, including internal company directives, country-specific laws, and requirements from the regulatory authorities.

Contingent Valuation Method (CVM): a method to estimate economic values for all kinds of the ecosystem and environmental services. The "contingent" means the specific hypothetical scenario and environmental services that people are asked to state their willingness to pay.

Convention on Biological Diversity (CBD): started in 1992 at the Rio Conference, it is the first global agreement on the sustainable use and conservation of biological diversity, now ratified by more than 175 countries.

Critically endangered species: a species that is classified as facing an extremely high risk of extinction in the wild. The International Union for Conservation of Nature (IUCN) classifies the species to incorporate the IUCN Red List.

Discount rate: the rate of interest that reflects the present value of future cash flows.

Ecological Economics: founded in the 1980s, it is an interdisciplinary and transdisciplinary field that treats the economy as a subsystem of the Earth's ecosystem.

Ecosystem service: a service provided by the natural environment that benefits humans. For example clean air, crop pollination, and weather regulation.

Environmental assurance bonding: also known as e-bond, it is a compulsory deposit that must be paid by anyone that intends to undertake any activity that may damage the environment.

Environmental economic valuation: is an attempt to measure the monetary or quantitative value of goods and services provided by the natural environment to people. It is a utilitarian account of the contribution of environmental goods and services to human preferences.

Environmental Economics: starting in the 1960s, it is a subfield of neoclassical economics that concerns environmental issues.

Environmental Kuznets Curve: a hypothesis that economic growth leads to environmental degradation up to a certain level of income, from where economic growth will then lead to environmental remediation.

Externality: it is generated when an action of a person affects other people and is not accounted for in the market price. It can be positive or negative.

FAO: is the United Nations Food and Agriculture Organization that aims to improve nutrition and food security and defeat hunger worldwide.

Fragmentation: occurs when habitats are divided into smaller and isolated patches, generally from harmful activities such as deforestation.

Governance: is the political interactions and processes between the institutions of an organized society. It follows laws and norms and can be at the local, regional, national, international or in-company level.

Greenhouse Gas (GHG): a gas that, when in excess in the atmosphere prevents part of the heat from the sun to return to space, warming the planet and creating the greenhouse effect.

Habitat Equivalence Analysis (HEA): a method that assumes that equivalent habitats will provide equivalent services, which could be used to compensate for lost services from one habitat by another.

Intrinsic value: the concept that nature has value independent of the direct or indirect benefits to humans.

Invasive species: a species that was introduced in an area that it doesn't belong to, on purpose or accidentally. Often leads to negative impacts on the local species.

Market failure: is the process where markets fail to allocate resources efficiently. An externality is a type of market failure.

Millennium Development Goals (MDGs): these were 8 goals derived from the United Nations Millennium Declaration, signed in September 2000, that UN Member States had to agree to try to achieve by 2015. They have been superseded by the Sustainable Development Goals (SDGs).

Millennium Ecosystem Assessment (MA): a series of five technical volumes and six synthesis reports with the state-of-the-art conditions of the ecosystems worldwide and the proposed options to conserve, restore or enhance their services. Initiated in 2001 and concluded by 2005, it involved the collaboration of more than 1360 experts worldwide.

Natural capital: is defined as the world's stock of all natural resources, from species, air, soil, geology, etc.

NGO: a non-governmental organization is generally a nonprofit entity formed independently of the government. Most are related to environmental, social and humanitarian causes.

Nonmarket benefits: benefits from goods and services that are not traded in traditional markets but are valued by society.

Opportunity cost: the value or benefit of a choice compared to the value or benefit of alternatives.

Paris Agreement: is the international treaty on climate change that superseded the Kyoto Protocol. It was adopted in 2015 by 196 Parties at COP 21 in Paris and entered into force on November 2016. Its goal is to limit global warming compared to pre-industrial levels, preferably to 1.5 degrees Celsius.

Production Possibility Frontiers (PPF): a graph that shows different combinations of the output of two goods, services or scenarios produced using available resources and technology.

Public good: a good that is both free to use or access (non-excludable) and can be used by more than one person at the same time without reducing availability for others (non-rivalrous).

REDD+: stands for Reducing Emissions from Deforestation and forest Degradation, including the sustainable management of forests, and the conservation and enhancement of forest carbon stocks. It is a framework created by the United Nations Framework Convention on Climate Change (UNFCCC) and aims to implement activities by national governments to reduce human pressure on forests that can result in greenhouse gas emissions at the national level.

Sustainable Development Goals (SDGs): the 17 goals that superseded the Millenium Development Goals (MDGs) for the Agenda 2030. The aim is to work on the social, economic, and environmental dimensions to complete the MDGs that were not achieved.

Sustainable development: defined in the 1987 Brundtland Report as "Development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs".

Transaction costs: the costs involved in all kinds of market exchange, including the costs of discovering market prices and enforcing contracts.

UNDER: The United Nations Decade on Ecosystem Restoration (2021-2030) aims to prevent, halt and reverse the degradation of ecosystems and to foster landscape-scale restoration worldwide.

UNDP: The United Nations Development Programme works to eradicate poverty and reduce inequalities through the sustainable development of nations, in more than 170 countries and territories.

Voluntary Carbon Markets (VCMs): markets where carbon credits are purchased voluntarily, frequently by organizations seeking to offset their emissions, and are not related to compliance with legally binding emissions reduction obligations.

Vulnerable species: a species whose population has declined at least 50 percent by known causes or declined at least 30 percent by unknown causes.