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Compensação ambiental como mecanismo de conservação: dos métodos ao teste de cenários baseados no Novo Código Florestal

Environmental compensation as a mechanism for conservation: from methods to scenario testing based on the Brazilian new Forest Code

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São Paulo - SP
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Tese apresentada ao Programa de Pós-Graduação em Ecologia da Universidade de São Paulo para a obtenção do titulo de Doutora em Ecologia.

Orientador: Jean Paul Metzger

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Orientador

Dedicatória

À minha família,
meu alicerce e apoio incondicional,
especialmente aos meus queridos pais e irmã.

Epígrafe

Madrugada camponesa,
faz escuro ainda no chão,
mas é preciso plantar.
A noite já foi mais noite,
a manhã já vai chegar.
Não vale mais a canção
feita de medo e arremedo
para enganar solidão.
Agora vale a verdade
cantada simples e sempre,
agora vale a alegria
que se constrói dia-a-dia
feita de canto e de pão.
Breve há de ser (sinto no ar)
tempo de trigo maduro.
Vai ser tempo de ceifar.
Já se levantam prodígios,
chuva azul no milharal,
estala em flor o feijão,
um leite novo minando
no meu longe seringal.
Já é quase tempo de amor.
Colho um sol que arde no chão,
lavro a luz dentro da cana,
minha alma no seu pendão.
Madrugada camponesa.
Faz escuro (já nem tanto),
vale a pena trabalhar.
Faz escuro mas eu canto
porque a manhã vai chegar.
(Faz escuro, mas eu canto)

“Madrugada Camponesa” (1965)
poema de Thiago de Mello

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Índice

Resumo Geral **9**

Abstract **10**

Introdução Geral **11**

Capítulo 1: A review of condition metrics used in biodiversity offsetting. **15**

Capítulo 2: Including biodiversity, landscape, and ecosystem services in a Disaggregated Condition Metric for ecological compensation schemes **39**

Capítulo 3: Compensating Legal Reserve deficits with ecological equivalence **60**

Discussão Geral e Conclusões **77**

Referências Bibliográficas **80**

Apêndice A: Material Suplementar – Capítulo 1 .... **90**

Apêndice B: Material Suplementar – Capítulo 2 .... **92**

Apêndice C: Material Supplementar – Capítulo 3 .... **98**

Resumo Geral

Considerando-se a importância para a conservação e o crescente uso em todo o mundo das compensações ambientais e dos *offsets* de biodiversidade (*i.e.* compensações sem perdas líquidas de biodiversidade), é fundamental compreender e melhorar esses mecanismos. Neste trabalho, buscamos justamente ampliar nossa compreensão e dar sugestões de melhora com enfoque nas formas de medir e alcançar equivalência ecológica nas trocas de compensação. Primeiro, fizemos uma revisão bibliográfica da literatura acadêmica sobre as métricas de condição ambiental utilizadas nos *offsets*. Destrinchamos e entendemos as principais limitações das métricas: a frequente falha na incorporação das três dimensões da equivalência (biodiversidade, paisagem e serviços ecossistêmicos), a inclusão de muitos atributos ecológicos altamente agregados em uma só fórmula, gerando um único valor como resultado final, e o fato de terem sido desenvolvidas em poucos países, principalmente do Norte Global – porém, sendo comumente aplicadas em outros países, inclusive do Sul Global. Assim, nosso próximo passo foi tentar sanar essas limitações desenvolvendo uma nova métrica. Criamos a Métrica de Condição Ambiental Desagregada, que apresenta flexibilidade no número e na identidade dos atributos incluídos, sempre de forma desagregada. Para tornar a métrica mais simples, testamos as relações de sinergias e *trade-offs* dos atributos e identificamos aqueles mais redundantes que poderiam ser dispensados, sem deixar de incluir as três dimensões da equivalência. As trocas de compensação só são permitidas dentro de unidades espaciais (hexágonos de 5 a 10 mil hectares) que sejam da mesma classe de valores para os três atributos que foram selecionados ao final dos testes. Usando como área de estudo o bioma tropical Mata Atlântica dentro do estado de São Paulo, esses atributos foram riqueza de aves, conectividade da paisagem e serviço de polinização potencial. A Métrica de Condição Ambiental Desagregada apresenta alto potencial de ser transposta para outras regiões, em especial as do Sul Global. Nosso passo final foi testar a aplicação da métrica em uma situação real. Para isso, utilizamos o esquema de compensação de Reserva Legal proposto no Novo Código Florestal. Para a mesma área de estudo em São Paulo e para cada hexágono, calculamos valores de déficit e excedente de Reserva Legal, de áreas possivelmente disponíveis para restauração da vegetação nativa, de áreas privadas em situação irregular dentro de Unidades de Conservações públicas, onde a compensação poderia ser realizada, e dos custos para realizar essas estratégias de compensação. Criamos seis cenários para testar o desempenho dessas estratégias, sempre usando a Métrica de Condição Ambiental Desagregada e incluindo equivalência ecológica nas trocas. Mostramos que praticamente todo o déficit da Mata Atlântica de São Paulo pode ser compensado por uma combinação de proteção de excedentes de Reserva Legal com restauração, sendo este o cenário de melhor custo-benefício, considerando os custos, a resolução do déficit e também o aumento da cobertura florestal (considerado aqui como "adicionalidade"). Com isto, não só contribuímos para melhor entender o funcionamento e as lacunas das métricas de condição ambiental usadas em *offset* e compensação, como mostramos que é possível criar uma métrica que sane essas lacunas. Ainda mais relevante, mostramos que é possível incluir equivalência ecológica em um sistema real de compensação, mantendo uma alta oferta de áreas potenciais para compensação e com bom custo-benefício. Esperamos que nossos resultados possam ser aplicados e incorporados em regulamentos e políticas públicas ambientais referentes a esta temática.

Palavras-Chave: *Offset* de biodiversidade; Equivalência ecológica; Métricas de biodiversidade; Restauração de vegetação nativa; Políticas públicas ambientais; Governança.

Abstract

Given the importance of environmental compensations and biodiversity offsets (*i.e.* compensations with no net loss of biodiversity) for conservation and their increasing use worldwide, it is critical to understand and improve these mechanisms. In this work, we sought to broaden our understanding and make suggestions for improvement, focusing on ways to measure and achieve ecological equivalence in compensation trades. First, we reviewed the academic literature on the condition metrics used in offsets. We unraveled and understood the main limitations of the metrics: the frequent lack of incorporation of the three dimensions of equivalence (biodiversity, landscape and ecosystem services), the inclusion of many ecological attributes highly aggregated in a single formula, generating a single value as a final result, and the fact they were developed in few countries, primarily from the Global North – yet, they are commonly applied in other countries, inclusive from the Global South. Thus, our next step was trying to overcome these limitations by developing a new metric. We created the Disaggregated Condition Metric, which presents flexibility in the number and identity of the attributes included, always in a disaggregated way. To make the metric simpler, we tested the synergy and trade-off relationships of the attributes and identified those most redundant that could be dismissed, always including the three dimensions of equivalence. Compensation trades are only allowed within spatial units (hexagons from 5 to 10 thousand hectares) of the same value for the three attributes selected at the end of the tests. Using the tropical biome Atlantic Forest within the state of São Paulo as our study system, these attributes were: bird richness, landscape connectivity, and potential pollination service. The Disaggregated Condition Metric has a high potential to be successfully transposed to other regions, especially those from the Global South. Our final step was to test the metric application in a real situation. For this, we used the Legal Reserve compensation scheme proposed in the Brazilian New Forest Code. Considering the same study area in São Paulo, we calculated for each hexagon values of deficit and surplus of Legal Reserve, areas possibly available for restoration of native vegetation, private areas in an irregular situation within public protected areas, where the compensation could be carried out, and the costs for employing these compensation strategies. We created six scenarios to test the performance of these strategies, always using the Disaggregated Environmental Condition Metric and including ecological equivalence in the trades. We showed that practically the entire deficit of the Atlantic Forest of São Paulo can be compensated by a combination of protection of Legal Reserve surplus with restoration, which is the scenario with the best cost-efficiency, considering the costs, deficit resolution and increase in forest cover (considered here as "additionality"). Therefore, we not only contributed to a better understanding of the functioning and the gaps of condition metrics used in offset and compensation, but we also showed it is possible to create a metric that fills these gaps. Even more relevant, we showed it is possible to include ecological equivalence in a real compensation scheme, maintaining a high supply of potential areas for compensation with good cost-efficiency. We expect our results can be applied and incorporated into environmental regulations and public policies related to this theme.

Key words: Biodiversity offset; Ecological equivalence; Biodiversity metrics; Native vegetation restoration; Environmental public policy; Governance.

Introdução Geral

No mundo contemporâneo, a exploração dos recursos naturais pelas atividades humanas vem causando grande impacto sobre o meio ambiente e mesmo sobre a disponibilidade dos próprios recursos (Steffen et al., 2015; Wiedmann et al., 2015). De um modo geral, essas atividades são representadas pela agropecuária e por grandes empreendimentos (como construções de hidrelétricas e exploração minerária). Consequências recorrentes dessas atividades são perda e fragmentação de habitat nativo (Tilman et al., 2017), diminuição da heterogeneidade em paisagens agrícolas (Tscharntke et al., 2005), aumento do efeito estufa (IPCC, 2021) e consequente intensificação das mudanças climáticas (Foden et al., 2013). Em especial, a perda de habitat e as mudanças climáticas constituem ameaças à biodiversidade em nível global (Cardinale et al., 2012; IPBES, 2019). Os grandes empreendimentos frequentemente causam grande impacto, mas em escala mais pontual, ao passo que a agropecuária, devido a sua distribuição capilar nas diversas paisagens, é apontada como a maior responsável pela perda de biodiversidade em ambientes terrestres (Pilling et al., 2020).

As compensações ambientais e os *offsets* de biodiversidade foram criados justamente para contrapor essa perda ecológica (BBOP, 2012a). Essas medidas constituem o último passo da chamada "hierarquia de mitigação", em que primeiro procura-se evitar o impacto ambiental causado pela atividade humana, em seguida minimiza-se o impacto considerado inevitável, quando possível reabilita-se a área impactada *in loco* e, por fim, realiza-se a compensação do "impacto residual" (aquele que se manteve após seguir toda a hierarquia) (Ekstrom, et al., 2015). Como o próprio nome diz, a ideia é compensar as perdas pelos impactos com ganhos ecológicos. Os tipos de ganho variam amplamente, podendo ir desde um simples pagamento para investimento em educação ambiental nas comunidades atingidas pelo impacto, até trocas muito precisas entre espécies ou funções ecológicas (BBOP, 2012a). Estas últimas são baseadas em cálculos de complexidade diversa e podem variar no grau de "equivalência ecológica" empregada, que é a busca, na comparação entre perdas e ganhos, por equivalência no tipo (elementos ecológicos a serem trocados e como serão comparados numericamente) e na quantidade (quantificação de perdas e ganhos e cálculos da equivalência entre eles) (BBOP, 2012a).

"Compensações ambientais" é um termo geral que abarca todo tipo de compensação, com mais ou menos equivalência ecológica. Os *offsets* de biodiversidade são um tipo de compensação mais estrita (BBOP, 2012a), pois a meta é chegar à perda líquida ecológica zero (denominada "no net loss" em Inglês), ou mesmo a um ganho ecológico, o que exige precisão na medição de equivalência e trocas com alto grau de equivalências em tipo e quantidade. *Offsets* são usados no mundo todo, principalmente em grandes empreendimentos (Bull and Strange, 2018) (*e.g.* mineração). Compensações, por seu caráter flexível, são usadas em qualquer situação em que haja um impacto negativo das atividades humanas. Um exemplo são as compensações de Áreas de Proteção Permanente (APP) e de Reserva Legal previstas na Lei de Proteção à Vegetação Nativa, mais conhecida como Novo Código Florestal Brasileiro (Brasil, 2012). Segundo esta lei, proprietários de terras com déficit em APP ou Reserva Legal devem necessariamente realizar a compensação. No Código constam algumas estratégias para se compensar e a exigência em termos de equivalência é que déficit e área compensada devem ter área igual e estar localizados no mesmo bioma.

As compensações e os offsets têm sido amplamente utilizados nos últimos anos por um número crescente de países (GIBOP, 2019; Gonçalves et al., 2015) e esta tendência não deve mudar (Maron et al., 2016b). Contudo, essa promissora estratégia de conservação vem enfrentando desafios em sua implementação e diversas críticas quanto à sua efetividade (E. Apostolopoulou and Adams, 2017; Bull et al., 2013; Robinson, 2009; Walker et al., 2009; zu Ermgassen et al., 2019). Um questionamento frequente é sobre o real alcance da equivalência ecológica nas trocas de compensação (Gonçalves et al., 2015), bem como sobre a forma de medir equivalência e a transparência na medição (Bull et al., 2013; Gardner et al., 2013; Maron et al., 2016b; Quétier and Lavorel, 2011). Por exemplo, algumas métricas utilizadas são simples e de fácil entendimento, mas contém pouca informação (Quétier and Lavorel, 2011). Outras métricas são informativas, porém muito complexas e podem unificar diversas variáveis ambientais em um só valor final, diminuindo a transparência nas trocas (Gibbons and Lindenmayer, 2007; Hanford et al., 2017; Maseyk et al., 2016). Ademais, o conceito de equivalência ecológica definido em BBOP (2012b) inclui aspectos da biodiversidade, de paisagem e de serviços ecossistêmicos. Sendo assim, ao se buscar equivalência nas trocas de compensação é importante que essas três "dimensões da equivalência" estejam presentes nas medidas, mas isto não acontece na prática (Apostolopoulou and Adams, 2017; Bidaud et al., 2017; Jacob et al., 2016).

Dessa forma, falta clareza no entendimento das métricas utilizadas em compensação e *offset*, inclusive para compreender em quê elas atendem ou não às necessidades dos esquemas de compensação em que são empregadas. A partir deste entendimento, seria possível mapear as fraquezas dessas métricas para então propor adaptações às métricas já existentes, ou mesmo novas métricas. Para melhor compreender o funcionamento de novas métricas, o ideal seria testá-las em um esquema de *offset* ou compensação real, com regras e condições ambientais concretas. Isto poderia ser feito, por exemplo, em um sistema de licenciamento ambiental de uma hidrelétrica, ou em um sistema de compensação ambiental compulsória, como o presente no novo Código Florestal.

Esta tese buscou justamente responder a essas demandas, primeiro aprofundando os mencionados problemas e limitações relativos a *offsets* e compensações, para então criar ferramentas que ajudem na solução desses problemas. No primeiro capítulo, fizemos uma revisão bibliográfica para analisar as "métricas de condição ambiental" amplamente utilizadas em *offsets* de biodiversidade, segundo a literatura acadêmica. As métricas de condição ambiental são usadas na buscar pela "equivalência de tipo", supracitada. Escolhemos trabalhar com essas métricas porque são as primeiras a serem calculadas em um *offset* – por vezes as únicas – estando, portanto, na base do processo de trocas por compensação. Vimos que as métricas de condição ambiental quase sempre incluem a dimensão de equivalência biodiversidade, cerca de metade inclui a dimensão paisagem, mas raramente métricas incluem a dimensão serviços ecossistêmicos. As métricas em geral utilizam muitos atributos ecológicos que frequentemente vêm agregados na fórmula da métrica, *i.e.,* atributos variados são colapsados para gerar um único valor final de resultado, e as trocas serão baseadas neste valor final. Além disso, vimos que quase todas as métricas foram desenvolvidas em alguns poucos países do Norte Global. Isto é uma limitação para sua aplicação em outros países, principalmente países megadiversos do Sul Global, já que métricas desenvolvidas em um contexto podem ser específicas e não captar características importantes de outros contextos (Bull et al., 2014b).

A partir destes resultados, seguimos para o desenvolvimento de uma nova métrica de condição ambiental, no segundo capítulo. Devido às restrições envolvidas no *offset*, consideramos compensação em um contexto mais amplo para o desenvolvimento da métrica. Baseamo-nos em uma série de dados de biodiversidade, paisagem e serviços ecossistêmicos disponíveis para a Mata Atlântica do estado de São Paulo, região que usamos como sistema de estudo. Testamos correlações, sinergias e trocas (*trade-off*) entre os diferentes atributos ecológicos incluídos, sempre de forma desagregada, com o objetivo de reter a maior informação com a menor redundância. Criamos assim a Métrica de Condição Ambiental Desagregada, que inclui um atributo de cada dimensão da equivalência, baseada em dados de um bioma tropical e de um país do Sul Global, mas que pode ser facilmente adaptada a outras regiões, já que deixamos registrado o procedimento de escolha dos atributos para composição final da métrica. Também explicamos o passo-a-passo para a implementação da métrica, que garante a equivalência ecológica nas trocas de compensação ambiental.

Em nosso terceiro capítulo, aplicamos a Métrica de Condição Ambiental Desagregada a um esquema de compensação real. Escolhemos o esquema de compensação de Reserva Legal proposto pelo novo Código Florestal no Brasil, devido às suas diversas estratégias de compensação, bem como sua grande importância em termos de conservação, pois mais de 50% da vegetação nativa existente no Brasil está dentro de propriedades privadas (Sparovek et al., 2015). Nossa escolha também teve origem na polêmica em relação à inclusão de equivalência ecológica nesse esquema de compensação, determinada pelo Supremo Tribunal Federal - STF em 2019 (Brasil, 2018), mas bastante criticada pelos setores envolvidos com a temática. Parte da crítica foi por não haver clareza em como essa equivalência seria medida e aplicada e se sua aplicação seria factível. Usamos novamente a Mata Atlântica de São Paulo como sistema de estudo e geramos cenários para testar quais são as melhores estratégias ou combinações de estratégias de compensação. Para isto, incluímos a premissa de equivalência ecológica, os déficits e excedentes de Reserva Legal, os custos para compensar através de proteção de vegetação existente e de restauração, e o potencial de adicionalidade em termos de cobertura (vegetação nativa adicionada em relação à situação inicial) de cada estratégia. O resultado com melhor custo-benefício indicou uma combinação de estratégias, iniciando pela compensação por proteção de excedentes de Reserva Legal, passando então para a restauração dos déficits restantes.

Esperamos que os resultados desta tese melhorem o entendimento das métricas de condição ambiental e aumentem a inclusão de equivalência ecológica nos esquemas de *offset* e compensação. A Métrica de Condição Ambiental Desagregada poderá e deverá ser melhorada, inclusive ao longo de sua implementação, mas representa um importante primeiro passo em direção a métricas mais completas e eficazes, e também com mais flexibilidade para contemplar contextos de regiões diferentes, em especial as pertencentes ao Sul Global. Por fim, o teste que fizemos utilizando nossa métrica em compensação de Reserva Legal mostrou que é possível compensar com equivalência ecológica, obtendo um bom custo-benefício e ainda dentro do estado de São Paulo. Essas informações devem ser de grande relevância no debate atual sobre a implementação do Novo Código Florestal, tanto no estado de São Paulo como em outros estados. Esperamos, assim, que esta tese seja uma contribuição relevante para impulsionar a prática da compensação ambiental no Brasil.

Capítulo 1: A review of condition metrics used in biodiversity offsetting

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Abstract

Biodiversity offsets are commonly used to compensate for environmental impacts, but their effectiveness is often questioned. Measurements of losses and gains often rely on Condition Metrics, which measure the sites' ecological attributes to form the 'currency' in which expected losses and gains are estimated. Condition metrics are central to most offset policies, but their attributes and calculations vary substantially. We reviewed the academic literature to draw a profile of existing condition metrics used in the offsetting context. Of the 17 we found, 15 include biodiversity attributes, 10 include landscape, and five include ecosystem services attributes, the three "dimensions of equivalence". Most metrics include many ecological attributes and require fieldwork and GIS data to be calculated, but few use modeling and expert opinion. Generally, metrics aggregate the attributes into a single value and were created in Global North countries. To favor more transparent and ecologically equivalent offset trades worldwide, we suggest condition metrics should include the three dimensions of equivalence in a disaggregated way, *i.e.* measurements done separately and analyzed in conjunction. The use of modeling, expert opinion and GIS may facilitate the inclusion of the dimensions and reduce the need for intensive (and expensive) fieldwork. Testing synergies and trade-offs among attributes could indicate if metrics might diminish their elevated number of attributes without losing information. Finally, adaptations when using condition metrics in places other than where they were created – and even creating new ones – is especially important in Global South countries.

Key-words: Biodiversity Conservation; Biodiversity Metrics; Ecological Compensation; Public Policy; Ecological Equivalence.

1. Introduction

Biodiversity offsets have been increasingly adopted in environmental policies and the private sector in recent years (Gonçalves et al., 2015), and their popularity with governments appears unlikely to change (Maron et al., 2016b). They are a strict type of environmental compensation for biodiversity losses (BBOP, 2012a) that aims to achieve no net loss (NNL) of biodiversity, seeking ecological equivalence between losses and gains in impacted and offset areas, respectively (BBOP, 2012b). However, the effectiveness of offsets has often been questioned and their implementation faces important challenges (Robinson, 2009; Walker et al., 2009; Bull et al., 2013; E. Apostolopoulou and Adams, 2017; zu Ermgassen et al., 2019), particularly with respect to achieving their goals (*e.g.* NNL) and to the transparency in their implementation and mensuration methods (Maron et al., 2016b).

Part of this mistrust comes from the premise that is frequently possible to achieve ecological equivalence between impacted areas and compensation areas (Gonçalves et al., 2015). Ecological equivalence means that both the type and the amount of gains are the same as the losses (BBOP, 2012a). *Equivalence of type* is usually achieved through a combination of the *currency* – the kinds of ecological elements that will be traded in an offset process (*e.g.* species, landscape or ecosystem types) and how these kinds will be numerically compared – and the *rules* that regulate the trading (*e.g.* trades must happen within the same vegetation type and within the same sub-region). Ecological elements that are not in the currency calculation may be included in a rule. The rules of an offset policy set the parameters of what can be considered ecologically equivalent and therefore traded, and may vary from place to place and across time.

Equivalence of amount is the quantification of biodiversity losses and gains in offset processes and the calculations needed to perform trades, based on the estimated losses and gains, time lags and other factors (BBOP, 2012a). Calculation approaches that account for equivalence of amount are sometimes called “loss-gain metrics”. They require as a first step the identification of a currency for use in the calculation. This currency is often comprised of one or more measures of the quality or condition of a vegetation or habitat type. With this ‘ecological condition’ value, loss-gain metrics can calculate how much will be lost in the impact site and how many units of that currency will be necessary in the offset site to adequately offset the impact (Maron et al., 2018).

Here, we focus on condition metrics – those used to generate a currency to calculate losses and gains. Condition metrics quantify the condition or quality of a site based on one or more ecological elements and are commonly used when the target of an offset trade is an ecosystem or vegetation type. Many condition metrics have been developed, studied and applied (McKenney and Kiesecker, 2010; Quétier and Lavorel, 2011; Bezombes et al., 2017; Gamarra et al., 2018). Such metrics can require large amounts of data to be calculated (*e.g.* Pöll et al., 2016; Drobnik et al., 2020) and can be highly complex, or narrowly applicable to particular biodiversity targets, which diminishes their breadth of application, but improves like-for-like outcomes (Hanford et al., 2017; Quétier and Lavorel, 2011). These data may be aggregated, resulting in a single value representing all the ecological elements targeted. This means that substitutions among these elements can occur, often in an unclear way (Gibbons and Lindenmayer, 2007; Maseyk et al., 2016; Hanford et al., 2017). These implicit substitutions may bring undesirable outcomes to biodiversity (Maron et al., 2016b), such as exchanging an element of higher conservation value by another of lower value (Walker et al., 2009; Bull et al., 2015), or falling to reflect important but more subtle differences between sites (Hanford et al., 2017). On the other hand, simpler and easy-to-understand metrics may be too simplistic to reflect complex entities (Quétier and Lavorel, 2011). Moreover, condition metrics developed for a certain region may not adapt well to other regions, at least not without careful adjustments (Bull et al., 2014b). Thus, it seems important to understand the regional context in which each metric was developed before applying it.

According to BBOP (2012b), ecological equivalence in offsetting schemes refers to 'like-for-like' trades of losses and gains - *i.e.* the elements traded are equivalent in both their type and their amount. Achieving a like for like trade ideally requires consideration of biological diversity and functionality, ecological condition, landscape context and ecosystem services (ES) (BBOP, 2012b). Thus, these general aspects are important to the concept of ecological equivalence and should be included in offset trades. A transparent measurement of sites' conditions for these aspects should enhance the ecological equivalence in trades. Here, we grouped these general aspects into three categories: biodiversity, landscape, and ecosystem services, which we called "dimensions of equivalence". Biodiversity is important to include in offset exchanges, but landscape and ES inclusion are also relevant, because offsets typically occur in contexts of human-driven degradation and landscape fragmentation, factors that affect both biodiversity processes and ecosystem services (Mitchell et al., 2015; Sonter et al., 2020). Also, understanding the link between social and ecological factors is important to ensure offset implementation and effectiveness (Habib et al., 2013). However, many offset metrics have been criticized for not capturing landscape and social-environmental aspects (Jacob et al., 2016; Apostolopoulou and Adams, 2017; Bidaud et al., 2017) and it has been recommended the metrics should not include biodiversity features alone (Bull et al., 2013).

Our goal in this work was to understand how the condition metrics (CMs) used in offsetting function according to their original conceptualization and how they incorporate the different dimensions of equivalence. Therefore, we did not focus on whether the metrics are currently in place, how they are applied via different policies around the world, nor on the policies' rules. Given the importance and also the challenges related to condition metrics used in offsetting, we conducted a review of the peer-reviewed literature to understand (1) how they are calculated, (2) what dimensions of equivalence (*i.e.* biodiversity, landscape and ecosystem services) CMs measure, (3) how data demanding they are, (4) how data are aggregated, and (5) under what regional and ecological context they were developed. Based on our findings, we profiled existing CMs, examined their strengths and weaknesses and suggested how they can become more efficient and transparently implemented in offsetting.

2. Methods

An increasing number of countries are using offset schemes (Gonçalves et al., 2015; GIBOP, 2019), but often the metrics they use are documented only in the grey literature. Accessing a range of grey literature in several languages is challenging (Theis et al., 2020), especially when the goal is to make a detailed review. The Global Inventory of Biodiversity Offsets Policy (GIBOP, 2019) provides summarized information on policies from around the world, including translated non-English versions when possible. However, our search was restricted to the academic peer-reviewed literature to capture the more widely known condition metrics used in offsets that have been through peer-review processes, which are therefore likely to be more sophisticated and robust. If a condition metric was cited in the papers we reviewed, but not described in them, this means the metric is probably widely known, so it was included as well. To understand these metrics in detail, we searched for the original documents that described them, whether they were academic or grey-literature documents.

On 21st May 2018, we conducted a search on online literature databases (Science Direct, JSTOR, Scopus, Web of Science) in English, Spanish, and Portuguese, and we updated the search on 13th November 2020. We used a compound search term that combined the general ideas of "biodiversity offset", "metric", and "ecological equivalence": *("ecolog* offset*" OR "biological offset*" OR "environmental offset*" OR "biodiversity offset*") AND (metric* OR measure* OR index OR indices OR* *calculation* OR variabl*)*. We screened all papers to select those that discussed condition metrics (Figure 1): metrics that calculate sites' ecological quality or condition and are used to compare the condition of losses and gains of two or more sites in an offset scheme.

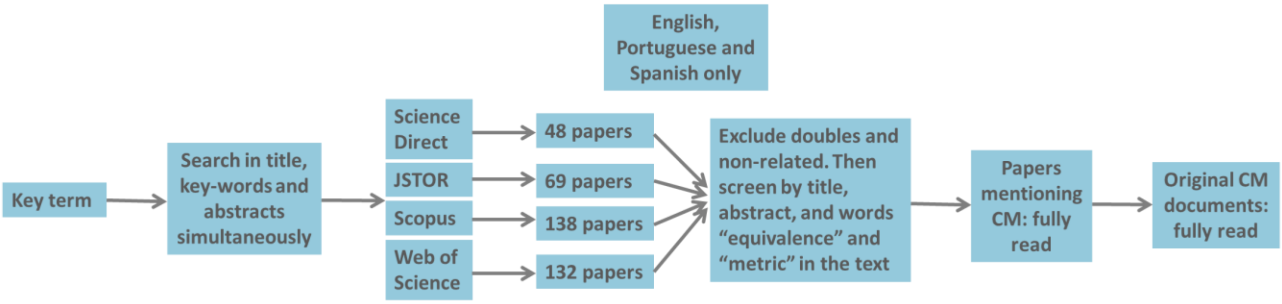

Figure 1: Step-by-step scheme of our online literature search.

To answer the five questions we proposed, we collected a large set of information on ecological and calculation characteristics of each CM, summarized in Table 1. We also created a specific scheme, shown in Figure 2 and further explained below, to extract information on how each CM included ecological attributes related to each of the three dimensions of equivalence. By "ecological attributes" we mean all the ecological variables that are directly measured in each metric (Table 1).

Table 1: Items used to extract information from the condition metrics reviewed and the questions to which each item is related.

Item	Definition and categories	Answers to which question (Q)
Ecological attributes	The ecological variables specifically measured and included in the CM formula. These attributes were used to assess which dimensions of equivalence were included in each metric (see text below).	Q1, Q2, Q3
Mathematical formula	General mathematical expression of each metric according to the ecological attributes it measures and the mathematical relationships among them.	Q1, Q4
Original instructions	Instructions found in CMs original papers that defined how the metric should be calculated and/or how its results should be compared. Later local offset policies may have changed them when applying the metric, but here we attained to what was planned in the CM origins. Calculations were made in population, assemblage, ecosystem or landscape level. These instructions were used to assess which dimensions of equivalence were included in each metric (see text below).	Q1, Q2, Q3, Q4
Institution and country that developed the CM	The type of institution (government, company, academy or NGO) responsible for the development of the CM and its original country.	Q5
Broad currency groups	The CMs were grouped according to broad characteristics they represent, such as habitat suitability, vegetation structure and composition, aquatic-ecosystem structure, landscape measurements, etc.	Q5
Benchmark	A reference state reflecting good condition for a given ecological attribute with which the value of the attribute at the site in question can be compared to (BBOP, 2012b). We evaluated whether the metric used benchmarks and what reference state they consider.	Q1, Q3
Metric aggregation level	Whether metrics accounted for ecological attributes individually (one attribute type in a simple formula), in aggregate (many attributes in one complex formula, resulting in a single value), or in disaggregated measures (many attributes in separate formulas, whose results are analyzed in conjunction) (adapted from Maseyk et al., 2016).	Q1, Q4
Method and data requirements	The methodological procedure and type of data the metric demand to be calculated: fieldwork, database (consolidated on field and/or laboratory work), GIS (mapping data), expert opinion (opinion of specialists on a given subject), modeling (analysis to generalize different types of data).	Q1, Q3

Since each dimension of equivalence is broad, we subdivided each into a number of components (Figure 2), and each component is measured by one or more ecological attributes. After reviewing the original instructions and the ecological attributes measured in each CM formula, we searched for the components they belonged to, so we could understand which dimensions of equivalence were being incorporated by each metric. We considered numerical and categorical attributes for all components. *Biodiversity dimension* was subdivided into species features (*e.g.* species richness and composition) and structure, *i.e.* all the measurements made to understand habitat and population structures. *Landscape dimension* was subdivided into composition and configuration, *i.e.* the amount of landscape units and how these units are arranged in space, respectively (Fahrig, 2005). *Ecosystem services dimension* represents the inclusion of the social-environmental aspects involving ecological equivalence, as they are human benefits derived from ecosystems processes (TEEB, 2010), and were subdivided into provision, regulating and cultural services.

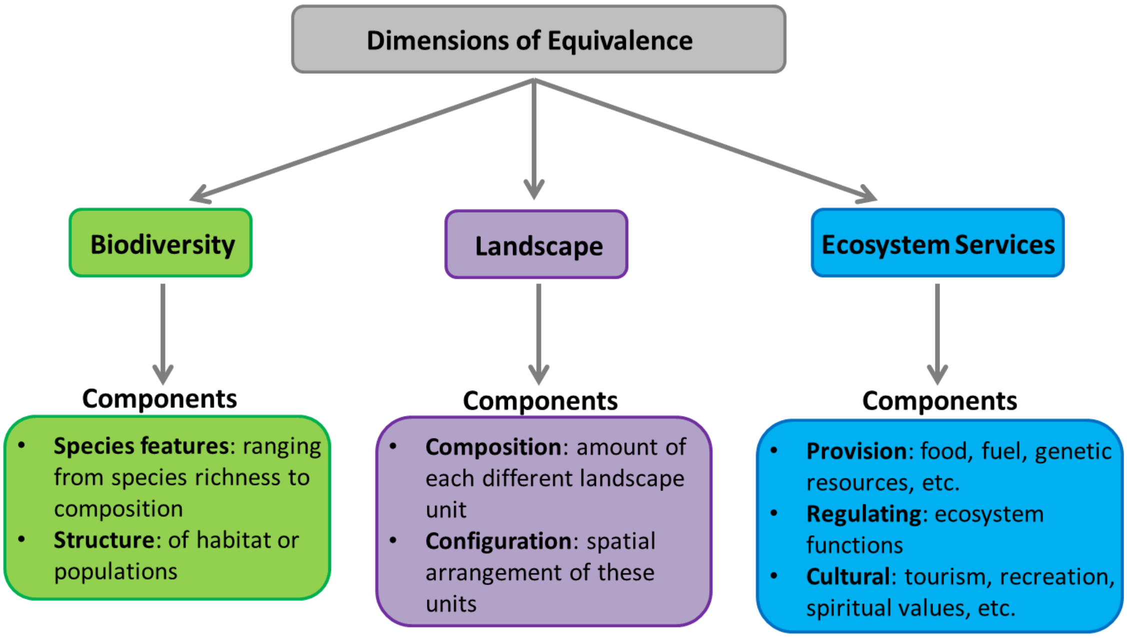

Figure 2: Dimensions of equivalence considered in this review and their respective components.

The similarity indices of Sorenson and Morisita-Horn used, for example, by Curran et al. (2014) to measure restoration success in offset context, comparing the species similarity of secondary-growth and old-growth communities, were not included in our CM list. This is because these metrics compare the similarity of two sites, whereas our review focuses on metrics that are used to measure condition at each site separately. Normally, the offset exchange has to be within a category or class deemed to be similar enough *a priori*, then the amounts of gain and loss are compared – using condition metrics – and the similarity comparison itself is not used.

3. Results

After excluding doubles and papers non-related to offset, our search returned a total of 170 papers. We screened these and found 31 papers that either described or mentioned one or more condition metrics (CMs), so these 31 papers were fully read. In these papers, we identified a total of 17 unique CMs. However, they were not all described in the 31 papers: six CMs were described in six of these papers, but two were described in two academic papers that were not captured by our search, and nine CMs were described either in some kind of policy or technical report (grey-literature documents). Thus, we fully read nine grey-literature documents and eight academic papers describing CMs, a total of 17 documents (one per CM). We fully read a total of 43 documents: the first 31 papers, which included six academic papers that described CMs, plus other two academic papers and nine grey-literature documents that also described CMs. In the Supplementary Material we provided information about the 31 papers included in this review (Sup. Mat. Table 1) and the raw data collected from the condition metrics (Sup. Mat. Table 2). The CMs general characteristics are described in Table 2.

Table 2: Presentation of the Condition Metrics (CMs), with their names and abbreviations, the bibliographic reference that originally created them and a short description of each. Names in quotation marks were given by the authors in the lack of an official original name. The CMs' formulas, ecological attributes included and original instructions are presented as well. These data help in answering questions 1, 2, 3 and 4. CMs are disposed in chronological order of creation.

CM and reference	Brief description of CM	Formulas	Ecological attributes	Original instructions
Habitat Evaluation Procedure (HEP) or Habitat Units (US) (Fish and Wildlife Service, 1980)	Measures the quality of a habitat, assuming the supporting needs of key-species are strongly correlated to environmental variables, so their presence is an indicator of habitat quality. Its units are Habitat Units: Habitat Suitability Index for species in the land-covers under study and the area of available habitat.	**HEP** = Habitat Suitability Index x area of habitat	Habitat variables (which will vary according to the species, *e.g.* food and reproductive resources, population dynamics, and especially easily measurable physical, chemical and vegetation variables).	Calculated to each species separately (population level); only comparable within the same species. Species are chosen based on public interest, economic and/or ecological value.
Habitat Hectares (HH) (Parkes et al., 2003)	Measures the quality of a vegetation type, expressed as a percentage of the benchmark for each attribute. It usually includes 10 attributes of quality: 7 of site condition, and 3 of landscape context, scored according to their relative importance.	**HH** = (sum of quality attributes in % scores) x area of vegetation sampled	Large trees, tree (canopy) cover, understory components, cover of weeds, recruitment, organic litter, logs, patch size, neighborhood, distance to core area.	Calculated to each vegetation type separately (assemblage level); comparisons are usually within the same vegetation type, but it allows comparison between different vegetation types.
Florida Wetland Condition Index (FWCI) (Reiss, 2006)	Measures the quality of wetlands, based on six attributes of macrophyte assemblage, each previously scored from 0 to 10. They are correlated with water and soil parameters and to the Landscape Development Intensity (LDI), a human-disturbance measure used to indicate wetlands with different disturbance levels.	**FWCI** = sum of scores of the six macrophyte attributes	Tolerant indicator species, sensitive indicator species, exotic species, floristic quality assessment index (FQAI), native perennial species and wetland status species. Scores range from 0 to 10 (10 = benchmark), which is done partly based on expert opinion.	Calculated to each wetland separately (ecosystem level); it can be grouped and calculated in local or regional scales. Attributes included in FWCI were chosen according to correlation with the two LDI categories (less or more developed). LDI is based on the use of nonrenewable energy in each land use within a 100 m buffer around a wetland (landscape level).
Stream Ecological Valuation Method (SEV) (Neale et al., 2011)	Measures the quality of streams, based on the 14 most important hydrological functions (attributes), that are also measured in a practical way, defined by authors. Each stream is sampled for the 14 attributes and each attribute generates a score through specific	**SEV** = mean of the 14 hydrological attribute scores	Natural flow regime, connectivity and complexity of floodplains, connectivity for species migrations, connectivity to groundwater, water temperature control, dissolved oxygen levels, organic matter input, in-stream particle retention,	Calculated to each stream separately (ecosystem level); comparable among streams of the same type, but it may be compared among different types, considering different benchmark values for each type.

	algorithms. Each stream receives one SEV score, the higher the better its condition.		decontamination of pollutants, substrate and riparian conditions, aquatic physical conditions, riparian vegetation intactness, evaluation of fish and of invertebrate communities.	
Biodiversity Offsetting Pilots (BOP) (DEFRA , 2012)	Measures the quality of a habitat based on its distinctiveness and condition. Each habitat is assigned a category of distinctiveness, low (2), medium (4) and high (6), and a category of poor (1), moderate (2) and good (3) condition (associated weights in parenthesis). These are multiplied by the habitat area to return the "biodiversity units", which translate the quality value of the impact or offset area.	**BOP =** habitat distinctiveness x habitat condition x area (hectares) If the area has >1 habitat type: **BOP =** BOP_hab1 + BOP_hab2 + BOP_hab3 + ...	Distinctiveness: all habitats of England are already categorized (DEFRA, 2012 - Appendix 1), based on attributes such as species richness, diversity, rarity and the degree to which a habitat supports rare species. Condition: attributes vary with habitat type, but they focus on vegetation structure and composition. The measurements adopted are described in the Higher Level Scheme (HLS) Farm Environment Plan handbook.	Calculated to each habitat type or group of habitats (ecosystem level); it allows various comparisons and out-of-kind trades, but it leaves clear that there should never be a trade-down and that high distinctiveness habitats should have like-for-like trades. Habitat distinctiveness levels may be reconsidered according to local characteristics.
Landscape Context Index (LCI) (MADS, 2012)	Measures the connectivity of a habitat patch in a local landscape, calculating the percentage of habitat within a buffer of 500 m radio drawn around the habitat patch. As it is a simple metric, it is usually combined with other metrics in searching offset sites (see Mandle et al., 2016).	**LCI =** (habitat total area x 100) / (500m buffer total area)	Total amount of habitat inside the buffer	Calculated to each habitat type separately (assemblage level) at the landscape scale; only comparable within the same habitat type. The LCI of any offset site must be equal to or greater than the LCI of the patches that were impacted (landscape level).
Quality Hectare (QH) (Temple et al., 2012)	Measures the quality of a vegetation type, expressed as a percentage of the benchmark for each attribute. We show here the attributes authors used in their case study, but they may vary according to context. As the vegetation area assessed is also considered, the metric is counted in "Quality hectares" units.	**QH =** % habitat quality (which is the sum of attributes' %) x area of vegetation assessed	General condition of the forest, signs of cutting, openings, agricultural areas, fires, observations of the vertical structure of the forest canopy level, % canopy cover.	Calculated to each vegetation type separately (assemblage level); comparable within the same vegetation type, but may also be used in non-equivalent trades.
Module Assessment	Measures the quality of an area before impact	**Sector 1 (S1) =** (QA1 x	Impact area: biotope age, environment	Sectors must be as similar as possible

Method (MAM) (Morandeau, D. & Vilaysack, D., 2012)	and its forecast scenario after offset. The area is divided in sectors, each evaluated based on a number of pre-established variables, the quality attributes (QA), scoring from 0.2 to 2. Then, sectors values are summed to give MAM final value for that area. Authors pre-establish 7 quality attributes for impact area and 6 for offset area, but there may be more.	QA2 x (…) x QA7) x sector area **MAM =** S1 + S2 + (...) + Sn	quality, net function, natural dynamic, conservation degree, quality of species composition, exigent species. Offset area: restoration feasibility, environment quality, net function, natural dynamic, necessary maintenance, regional representativeness of biotope.	in vegetation structure and composition; comparisons are made between areas that may include different vegetation or ecosystem types (ecosystem level).
California Rapid Assessment Method for Wetlands (CRAM) (CWMW, 2013)	Measures the quality of wetlands, based on submetrics (attributes) used to calculate 4 ecological classes: buffer and landscape context, hydrology, physical and biotic structure. The submetrics are scored in 4 classes of numerical value (12, 9, 6, 3); higher values represent better quality.	**CRAM =** mean of 4 ecological classes scores Class score = % the submetrics' score is of maximum possible score for that class	Buffer and Landscape: stream corridor continuity, % of wetland with buffer, average buffer width, buffer condition. Hydrology: water source, hydroperiod, hydrologic connectivity. Physical Structure: structural patch richness, topographic complexity. Biotic Structure: number of plant layers present, number of co-dominant species, % invasion, horizontal interspersion, vertical biotic structure (some of them based on expert opinion).	Calculated to each wetland separately (ecosystem level); the submetrics may vary slightly among wetland types, so comparisons must be made among wetlands of the same type. It may be compared among different wetland types, considering different benchmark values for each type.
Conservation Significance Index (CSI) (Virah-Sawmy et al., 2014)	Measures the conservation value of a site – its significance, by measuring endemic and/or threatened species in a site relative to their remaining habitat area, multiplied by the impact or the offset area. The higher the index, the more significant is the site. Authors suggest this metric be complementary to other habitat-quality metrics.	**CSI =** (number of endemic and/or threatened species / their remaining habitat area) x impacted area OR offset area	Number of endemic/threatened species in the region of interest and their remaining habitat area.	Calculated for endemic and/or threatened species (assemblage level), comparable among different regions.
Somerset Habitat Evaluation Procedure (SHEP) (Burrows, 2014)	Measures the quality of a habitat, based on Habitat Suitability Index and Habitat Units as HEP, but includes spatiality: the Density Bands are concentric zones, centered at a point where the species was recorded, with 3 radio sizes based on the species home range or dispersal capacity, a proxy for its density and functional	**SHEP =** (Habitat Suitability Index x Density Band value) x habitat area	Habitat variables (which will vary according to the focus species), quality of matrix, habitat formation and management, density band values.	Calculated to each species separately (population level); only comparable within the same species. Species are chosen based on public interest, economic and/or ecological value. Density Band values vary from 3 - closer to 1 - further from the species

	connectivity. The metric also considers habitat formation, management and surrounding matrix in HSI calculation.			record, defined based on expert opinion.
“Log response ratio of species richness” (LRR) (Spake et al., 2015)	Measures the quality (success) of restoration, by assessing the difference in richness of functional groups (among fungi, lichens and beetles) from secondary (restored) to old-growth forests in different succession stages. The old-growth richness is the benchmark for all groups, so the smaller the LRR, the better the quality.	**LRR** = (Ln mean richness in secondary forest) – (Ln mean richness in old-growth forest)	Richness of epiphytic lichens, ectomycorrhizal fungi, deadwood fungi, litter fungi, saproxylic beetles, non-saproxylic beetles (from coniferous and broadleaved forest).	Calculated to each functional group separately (assemblage level); only comparable within the same functional group; results are qualitatively analyzed in conjunction.
Composite Biotope Value (CBV) (Pöll et al., 2016)	Measures the quality (success) of restoration, how much of the old-growth area quality (the benchmark) has been reached by the restored area, accounting for gradients of equivalence. The study area is divided in polygons to which a biotope type is attributed. The metric is based on the basic biotope type value (BT) and on measures, in each polygon, of structural features, relevance attributes, management actions and current threats.	**CBV** = Biotope Type + (sum structural attributes) + (sum relevance attributes) + (sum managements) - (sum habitat threats)	BT is calculated on each biotope restorability, rareness, complexity and species diversity, all based on expert opinion. Structural: diversity indices for biotope type and plant community diversity, summarized % cover of a plant species, categories of connectivity among habitat patches. Relevance: number of plant species present in Red List. Manage: current and target management activities. Threats: current and potential 6 most abundant threats to habitat.	Calculated to each biotope type separately (ecosystem level), the final CBV value must be compared to the value of a Reference site (benchmark) to judge about the level of restoration. Also, an average of different CBVs may be calculated to compare areas with more than 1 biotope type.
NSW Vegetation Integrity Score (VIS) (OEH - NSW Government, 2017)	Measures the quality of a vegetation type based on the composition, structure and function of the "growth-form groups" (*e.g.* trees, shrubs, grass-like) present at one site. With little adaptations in the formula, it can predict the vegetation condition before and after impact and after offset implementation, either with or without management, so that these situations can also be compared.	**VIS** = cubic root (CCS x SCS x FCS) **CCS** = sum (composition score x weight of all growth-form groups) **SCS** = sum (structure score x weight of all growth-form groups**)** **FCS** = sum (function score x weight of all attributes measured)	Composition Condition Score (CCS): Mean species richness for the growth-form group. Structure Condition Score (SCS): Mean cover for the growth-form group. Function Condition Score (FCS): mean number of large trees, mean length of fallen logs, mean litter cover, mean tree regeneration, mean tree stem size class.	Calculated to a vegetation zone that may include different growth-form groups (ecosystem level), so it may allow comparisons of different vegetation types. Function Condition Score does not apply to open vegetation formation; to these, a shorter formula is applied: VIS = quadratic root (CCS x SCS).

Ecosystem Services - based Soil Quality Index (SQUID) (Drobnik et al., 2018)	Measures the quality of ecosystem services (ES), based on the quality of soil functions and their capacity to support and provide the ES. Information on soil functions comes from soil attributes assessments; functions are weighted according to their contribution to each ES. There are up to 16 soil-based ES, ranging from 0 (soil supports ES poorly) to 5 (soil supports all ES highly). The higher the SQUID score, the higher the ES quality.	**SQUID** = mean of soil-based ES **Soil-based ES** = sum (soil function quality x function weight of all functions measured)	The 16 ES belong to 4 categories: healthy/wellbeing, security, natural diversity and natural production factors (economic services). Soil functions (10) are calculated based on 10 soil attributes. For more details, see Drobnik et al. (2018).	Calculated to a region, which may include different vegetation, habitat and ecosystem service types (ecosystem level), so it allows out-of-kind trades. Soil-function weights are provided by expert opinion.
"Disaggregated Model - Reef Habitat" (DMRH) (Stone et al., 2019)	Measures the quality of reef habitats through assessments of a central species (*Sabellaria alveolata*). It is based on Maseyk and colleagues' Disaggregated Model (Maseyk et al., 2016), in which adequate components and attributes are chosen, measured and analyzed separately. This metric also seeks to evaluate the spatial-temporal influence on the condition of each site sampled.	**DMRH: C1 =** % species cover **C2 =** abundance of associated species **C3 =** % formation of the 5 categories **C4 =** % tube aperture of the 5 categories	C1 species distribution: cover of *S. alveolata*. C2 species composition: abundance of species associated with *S. alveolata*. C3 species age structure: 5 categories of *S. alveolata* formation: hummock, sheet, reef, patchy and encrusting. C4 reef health: 4 categories of *S. alveolata* tube aperture condition: newly settled, crispy, worn and dead.	Calculated to each *S. alveolata* habitat separately (ecosystem level), comparable within this type of habitat, but trading-up is possible. The study case presented brought very specific attributes, but attributes should be chosen according to the conservation policy that is most adequate to the environmental issue.
"Equivalent Connectivity Framework" (ECF) (Bergès et al., 2020)	Measures the quality of a landscape before and after impact and offset take place. Quality is measured in terms of functional connectivity using the Equivalent Connectivity index (*i.e.* ECA - Saura et al., 2011), with which scenarios are generated and compared. The ultimate goal is to achieve a NNL of connectivity, with after-offset landscape EC equal to pre-impact landscape EC.	**ECF =** variation in EC = ECafter - ECbefore **EC =** √sum of the dispersal probabilities between all pairs of patch in the landscape	Patch area, estimation of the focus species dispersal capacity (based on database and/or expert opinion). These attributes are multiplied for each pair of patch to result the dispersal probability.	Calculated to each species separately (population level); comparisons among landscape scenarios are possible only for the same species.

Most CMs have more than seven ecological attributes (Figure 3), with a mean of 8.8 attributes per metric. Three are single-attribute metrics (total area of habitat in the buffer, number of endemic/threatened species and species dispersal probability), two are measured in a disaggregated framework (LRR and DMRH) and the remaining are aggregated (12). This means that, for most metrics, the numerous attributes that enter the metrics are summarized in a single-value result. The majority of metrics were developed by academy, government or a cooperation of both, but some were developed by companies and NGOs as well (Figure 4). Most CMs were created in countries of the Global North: United States (3), England (3), Switzerland (3), Australia (3), Wales (1), Austria (1), France (1) and New Zealand (1); one CM was created in Colombia (LCI). Benchmarks are present in 11 metrics, either related to the metric's final score or to the attributes in the metric's formula. Most benchmarks (8) represented the quality of an undisturbed ecosystem, one represented the quality of a pre-impact habitat (ECF) and two were about the optimum carrying capacity for a given species (HEP and SHEP). The characteristics of the CMs reviewed related to their broad currency groups, method requirements and dimensions of equivalence incorporated are in Table 3.

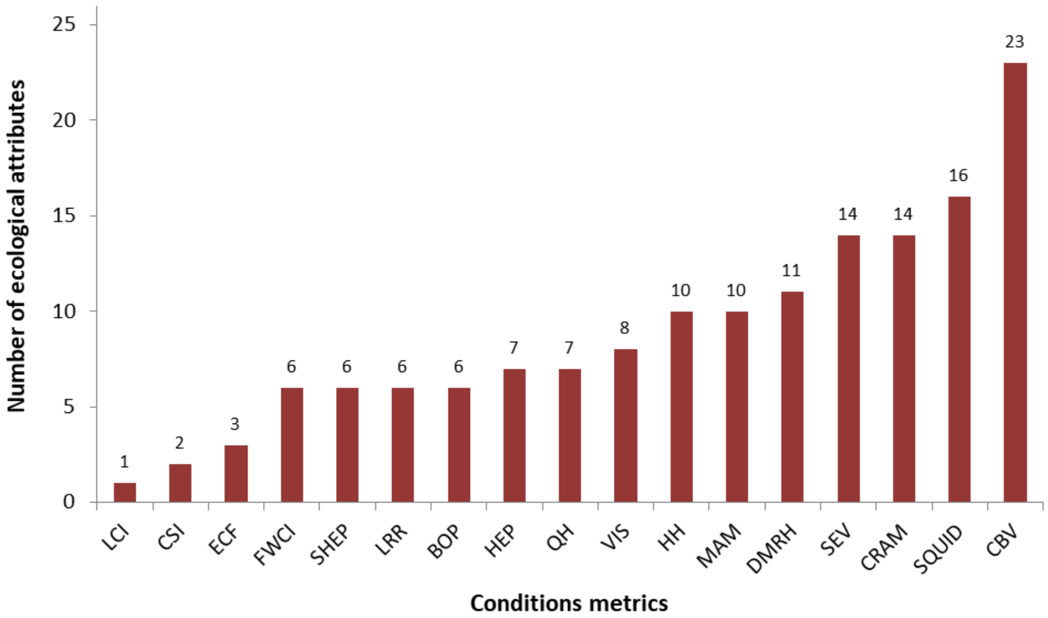

Figure 3: Number of ecological attributes demanded by each Condition Metric (CM). The number on each bar shows the exact number per metric. For CMs' abbreviation codes, see Table 2. We highlight that SHEP and HEP may demand a larger number of attributes, as they depend on the focus species on which the metric will be calculated, and BOP also may demand more attributes because it is originally presented with general attributes only (see Table 2). These data help in answering question 3.

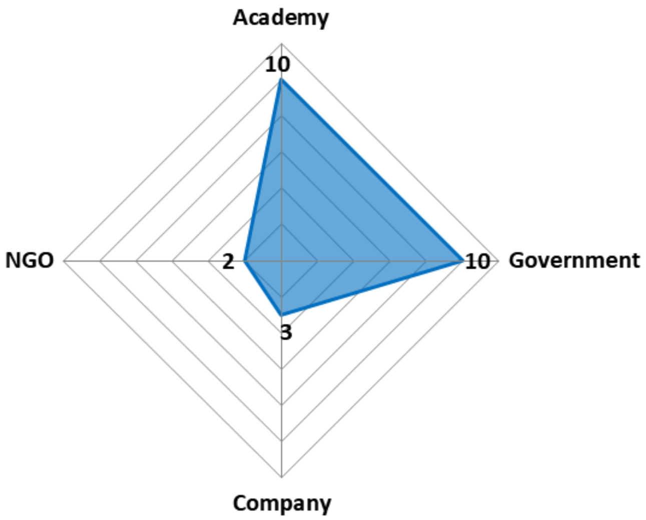

Figure 4: Types of institutions that developed the Condition Metrics (CMs) reviewed. The numbers at the vertices of the shaded polygon represent the number of CMs that were developed by each institution (Academy, NGO, Company and Government). We highlight that often CM development happened in cooperation of the institutions. These data help in answering question 5.

Table 3: Characteristics of the condition metrics reviewed related to their broad currency groups, method and data requirements and incorporation of equivalence dimensions, components and ecological attributes. The equivalence dimensions' components were evaluated according to the ecological attributes present in condition metrics' formulas and original instructions. These data help in answering questions 1, 2, 3 and 5.

Condition metric	**Broad currency group**	**Method and data requirements**	**Equivalence dimensions: components included and number and type of attributes per component**
Habitat Evaluation Procedure (HEP) or Habitat Units *	Habitat suitability	Field work, database, GIS	**Biodiversity:** composition (1 categorical attribute); structure (3 quantitative attributes) **Ecosystem Services:** regulating (2 quantitative attributes)
Habitat hectares (HH)	Vegetation structure and composition	Field work, database, GIS	**Biodiversity:** composition (2 categorical and 1 quantitative attribute); structure (2 categorical and 2 quantitative attributes) **Landscape:** composition (2 quantitative attributes); configuration (1 quantitative attribute)
Florida Wetland Condition Index (FWCI)	Aquatic-ecosystem structure	Field work, database, GIS, expert opinion	**Biodiversity:** composition (4 categorical and 3 quantitative attributes) **Landscape:** composition (1 quantitative attribute)
Stream Ecological Valuation Method (SEV)	Aquatic-ecosystem structure	Field work, database, GIS	**Biodiversity:** composition (2 quantitative attributes); structure (5 categorical and 4 quantitative attributes) **Landscape:** configuration (1 categorical and 1 quantitative attribute) **Ecosystem Services:** regulating (1 categorical attribute)
Biodiversity Offsetting Pilots (BOP) *	Conservation significance / Vegetation structure and composition	Field work, database, GIS	**Biodiversity:** composition (2 categorical and 2 quantitative attributes); structure (2 quantitative attributes)
Landscape Context Index (LCI)	Landscape measurements	GIS	**Landscape:** composition (1 categorical and 1 quantitative attribute)

Quality Hectare (QH)	Vegetation structure and composition	Field work, database, GIS	**Biodiversity:** composition (1 categorical attribute); structure (4 categorical and 3 quantitative attributes)
Module Assessment Method (MAM)	Vegetation structure and composition	Field work, database, GIS	**Biodiversity:** composition (1 categorical and 1 quantitative attribute); structure (5 categorical attributes) **Ecosystem Services:** regulating (1 categorical attribute)
California Rapid Assessment Method for Wetlands (CRAM)	Aquatic-ecosystem structure	Field work, database, GIS, expert opinion	**Biodiversity:** composition (3 quantitative attributes); structure (5 categorical and 2 quantitative attributes) **Landscape:** composition (2 quantitative attributes); configuration (2 categorical attributes) **Ecosystem Services:** provision (1 categorical attribute); regulating (1 categorical attribute)
Conservation Significance Index (CSI)	Conservation significance	Field work, database, GIS, modeling	**Biodiversity:** composition (1 categorical and 1 quantitative attribute) **Landscape:** composition (1 quantitative attribute)
Somerset Habitat Evaluation Procedure (SHEP) *	Habitat suitability	Field work, database, GIS, expert opinion	**Biodiversity:** composition (1 categorical attribute); structure (2 categorical and varying quantitative attributes) **Landscape:** composition (1 categorical attribute); configuration (1 categorical attribute)
Log response ratio of species richness (LRR)	Indicators of vegetation structure (restoration success)	Field work, database	**Biodiversity:** composition (1 categorical and 6 quantitative attributes)
Composite Biotope Value (CBV) **	Vegetation structure and composition (restoration success)	Field work, database, GIS, expert opinion	**Biodiversity:** composition (2 categorical and 3 quantitative attributes) **Landscape:** configuration (1 categorical attribute)
NSW Vegetation Integrity Score (VIS)	Vegetation structure and composition	Field work, database	**Biodiversity:** composition (1 quantitative attribute); structure (1 categorical and 6 quantitative attributes)
ES-based Soil Quality Index (SQUID)	Soil-based ecosystem services	Field work, database, GIS, expert opinion	**Ecosystem Services:** provision (7 quantitative attributes); regulating (5 quantitative attributes); cultural (4 quantitative attributes)
Disaggregated Model - Reef Habitat (DMRH)	Aquatic-ecosystem structure	Field work, GIS,	**Biodiversity:** composition (1 quantitative attribute); structure (10 quantitative attributes)
Equivalent Connectivity Framework (ECF)	Landscape measurements	Database, GIS, expert opinion, modeling	**Biodiversity:** composition (1 categorical attribute) **Landscape:** composition (1 quantitative attribute); configuration (1 quantitative attribute)

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* These metrics were described as having some flexibility about the number of attributes they may include; we assigned the minimum number indicated by authors.

** Management and threats attributes could not be properly fitted in any component of equivalence dimensions.

Nearly all metrics demand data from GIS and fieldwork and/or consolidated database (Figure 6). A few also demand data from modeling and expert opinion (*i.e.* data estimated by experts each time the metric is applied). GIS data are used to map study areas, define vegetation types and calculate area and landscape metrics. Data from fieldwork or a well-established database are usually the basis for site-level CM calculation of most ecological attributes considered in each metric, as remotely-sensed data are often insufficient to collect the necessary information at the fine resolution required. Six CMs were in the broad currency group of vegetation structure and/or composition, while four CMs focused on aquatic ecosystems (stream, wetland and intertidal habitat), two on habitat suitability (based on habitat area and habitat variables, *e.g.* food and reproductive resources, as related to the focal species) and other two on landscape measurements. The diversity of broad currency groups is a consequence of the specific local need in the moment each metric was created. All CMs incorporated at least one component from the biodiversity dimension of equivalence (Figure 7), except for LCI and SQUID, which incorporated solely landscape and ecosystem service components, respectively. The landscape dimension showed an intermediate level of inclusion (10 CMs) and the ecosystem services dimension was included in only five CMs.

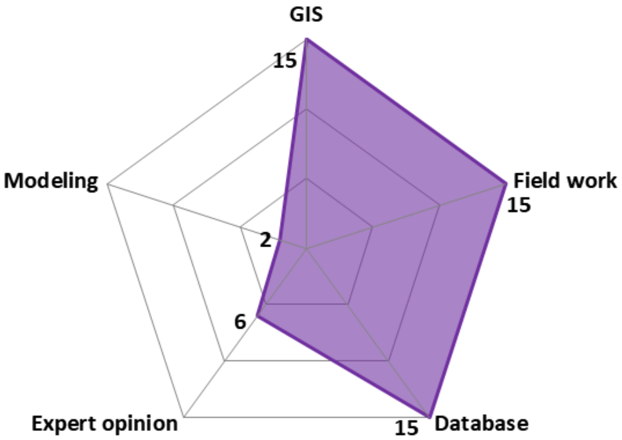

Figure 6: Types of method and data required to calculate the Condition Metrics (CMs) reviewed. The numbers at the vertices of the colored polygon represent the number of CMs by data type. We highlight that often a CM demands more than one method or data type. These data help in answering questions 1 and 3.

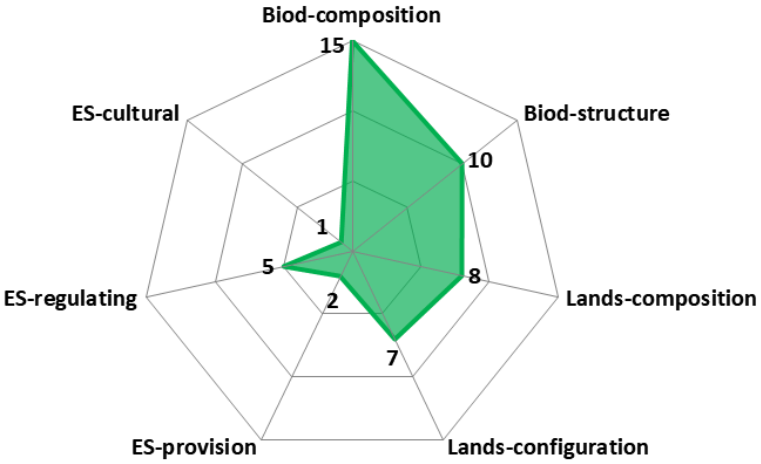

Figure 7: Equivalence dimensions' components included in the condition metrics (CMs) reviewed. The numbers at the vertices of the colored polygon represent the number of CMs per component type. Biod = biodiversity; Lands = landscape, ES = ecosystem services. We highlight that often a CM includes more than one component. These data help in answering questions 2 and 3.

4. Discussion

We found 17 condition metrics (CMs) in the peer-reviewed literature that are used to create currencies for comparing losses and gains in offsetting. In general, these CMs incorporated biodiversity attributes, but often lacked attributes from the landscape and ecosystem services components. Some of the CMs were not designed specifically for offsetting, so they might be fully appropriate for their primary goals. However, when applied to offset schemes, the lack of these dimensions may mean that ecological equivalence in trades is reduced, as the three dimensions are fundamental to ecological equivalence (BBOP, 2012b). Further, many CMs depend on a large number of ecological attributes, which are highly aggregated in almost all CMs formulas, meaning attributes can substitute for one another. Finally, most CMs reviewed were created in Global North countries, usually for particular environmental contexts (*e.g.* a type of vegetation or of aquatic ecosystem).

The predominance of the biodiversity dimension of equivalence in condition metrics was expected, since we explicitly searched for CMs used in "biodiversity" offset schemes. Indeed, this dimension has constantly been included in offsetting for many years (Bull et al., 2013; Carreras Gamarra et al., 2018; Gonçalves et al., 2015), an advance compared to the previous use of area alone as currency – the area of the offset should be at least the same size as the area impacted (King and Price, 2004). The "composition" component of biodiversity dimension was more frequently included, represented mostly by attributes related to species richness and key species assessments.

The “structure” component was mostly represented by attributes related to habitat pattern assessments. Despite biodiversity attributes being commonly included, these tended to be limited to species richness and habitat measures. Biodiversity is a general term that includes multitudes of characteristics, so measuring it more holistically is always a challenge (Walker et al., 2009). To address such challenge, the use of proxies that represent other biodiversity elements is frequent and may be preferable (Kiesecker et al., 2009), yet choosing such elements is not trivial and their relationships with the proxies are not always clear or strong (Kiesecker et al., 2009; Marshall et al., 2020a; Marshall et al., 2020b). Broader habitat-pattern metrics often do not reflect the ecological processes important to species persistence (Marshall et al., 2020a), which is the ultimate goal of conservation. The most common CMs broad currency group was vegetation structure and/or composition, which may not be sufficiently related to species persistence in offset sites (Marshall et al., 2020b). A series of species-specific metrics would be ideal, but they are also data-demanding (Marshall et al., 2020a). Thus, which biodiversity components and attributes to include in a condition metric is still an ongoing discussion.

The landscape dimension was incorporated in more than half of the CMs (10), an intermediate level of inclusion, and “composition” and “configuration” components were both similarly included. The lack of consideration of landscape context in offsetting has been a frequent criticism in the literature (Bruggeman et al., 2005; Gardner et al., 2013; Underwood, 2011; Reid et al., 2015). Its actual inclusion in practice seems heterogeneous: in some cases it has happened for longer time (*e.g.* Habitat Hectares in Australia - Parkes et al., 2003), and in others it is more recent (*e.g.* qualitative landscape inclusion in offsets in Brazil - Souza and Sánchez, 2018). This heterogeneity has many possible causes, such as the great difference in offsetting implementation among regions and countries, especially between Global South and North (Gonçalves et al., 2015; GIBOP, 2019). The delay in including landscape in CMs could be due to the existing science-practice gap in conservation biology (Bertuol-Garcia et al., 2018), which could have delayed the recognition among practitioners of the importance to make this inclusion. Also, the absence of landscape in the metrics may be due to their presence in the rules of offsetting – *e.g.* offset sites are required to have a similar landscape position as impact sites, rather than the landscape being included in the metric itself. In any case, our results indicate this concern is being addressed. This is positive, since the relationships among impact and offset sites and their surroundings matter (Bruggeman et al., 2005), and the species-specific landscape connectivity assessment can favor the species persistence in the landscape (Marshall et al., 2020a). Consolidating a landscape perspective in offsetting remains a challenge (Bergès et al., 2020). For example, inclusion of connectivity issues is limited (Kujala et al., 2015) and cumulative landscape-scale impacts are still ignored in offset schemes (Tarabon et al., 2019). The recent and important effort to address this theme (e.g. Bergès et al., 2020) contributes to the consolidation of this paramount dimension in condition metrics.

The ecosystem services dimension was seldom incorporated in CMs, in spite of recent calls for increased recognition of socio-environmental aspects in offset metrics (Jacob et al., 2016; Virah-Sawmy et al., 2014; Mandle et al., 2015). This could partially be due to the way offsetting policies were initially designed, more focused on biodiversity and usually with no clear concern to incorporate compensation for the socio-economic or socio-environmental consequences of losses in biodiversity and its services (Mandle et al., 2015; Sonter et al., 2020). Besides, ecosystem services can be hard to quantify, since supply and demand are often generated at different spatial scales, demands differ among stakeholders and assessing the actual delivery of service is difficult (Geijzendorffer and Roche, 2014). Recent works have addressed the gap between social and biodiversity factors in environmental impact assessment (Bull et al., 2018; Griffiths et al., 2019), which can aid in enhancing ES inclusion in condition metrics. ES are related to societal conservation-values, *e.g.* biodiversity and cultural services (Spash and Aslaksen, 2015; Fraser et al., 2016), and to the region's economic situation, *e.g.* crop yield enhanced by natural pest control and pollination (Ali et al., 2019; Borges et al., 2020). Considering these two factors in offsets can guide the choice of the most appropriate offset strategy (Habib et al., 2013), thus improving offset implementation and effectiveness (Habib et al., 2013; Sonter et al., 2020) across a wider spectrum of equivalence dimensions (BBOP, 2012b).

Many CMs combined a high number of ecological attributes. This may imply the inclusion of more dimensions of equivalence in the offset exchange. However, most ecological attributes included in the CMs reviewed belonged to a single dimension, *i.e.* biodiversity, and those attributes were often limited to species richness and similar habitat structural elements. Increasing the number of attributes in metrics may undesirably increase their complexity, as it usually makes metrics harder to understand by practitioners and general public (Bezombes et al., 2017) and leads to increased risk of attributes substitution (Maron et al., 2016; Hanford et al., 2017). This could hamper the use of CMs, especially in regions where there is no consolidated database or limited funding to collect field data, such as some countries of the Global South (Magnusson et al., 2005; Magnusson et al., 2013). To combine relative simplicity with inclusion of all important dimensions of equivalence in offset exchanges is therefore a challenge that remains (Gonçalves et al., 2015; Maseyk et al., 2016; Marshall et al., 2020a).

The numerous attributes used in CMs may explain why the metrics are strongly underpinned by field measurements (or well-established databases). If on the one hand fieldwork may be expensive and time-consuming, on the other it improves offsets planning and implementation (Souza and Sánchez, 2018), as knowing the present condition at impact and offset sites is required to conclude offsetting trades (BBOP, 2012a). GIS data is also often used in CMs, whereas modeling and expert opinion are rarely used. However, all three are complementary to fieldwork and could be explored more to enhance the inclusion of landscape and ecosystem services dimensions of equivalence in CMs. For example, GIS is already used in some CMs to calculate landscape metrics (CWMW, 2013; Morandeau & Vilaysack, 2012; Parkes et al., 2003); modeling could be used to spatialize and to infer information about those ecosystem services that are better-known, based on previous field studies (Mandle et al., 2016); expert opinion could be used to choose which ecosystem service to analyze in a certain region according to its regional importance, or which landscape features are more important to an endangered species (Burrows, 2014).

To develop more parsimonious condition metrics, understanding the relationships among their ecological attributes could help. Both trade-offs and synergies have been described for offset metrics (Bezombes et al., 2017; Gamarra et al., 2018; Sonter et al., 2020). It is then possible that attributes from dimensions of equivalence less represented in CMs are correlated with biodiversity-dimension attributes, which are more frequent in CMs. Testing the relationships between ecological attributes could reveal such redundancy (Dormann et al., 2013). If there is redundancy, the overall number of attributes to be measured could be reduced without losing relevant information.

The CMs reviewed are basically either aggregated or single-attribute measures. Despite criticism of aggregated metrics (Hanford et al., 2017; Maseyk et al., 2016; Gonçalves et al., 2015), they predominate. This is probably because aggregation results in a single value to describe complex environmental elements, which is simple and easily communicated (Gardner et al., 2013; Maseyk et al., 2016). Also, trades between sites become easier and quicker if only a single value is to be exchanged. Such characteristics come in handy to developers, as they are usually under time and cost constraints. Moreover, aggregation can be attractive as it increases flexibility in offsetting when no net loss for each separate ecological attribute is not a goal to be achieved. This is because aggregation may allow an increase in the condition metric value at a site to be achieved in different ways, since an increase in any one attribute could raise the metric final result.

However, these consequences must be made clear, because aggregation allows losses in one attribute to be compensated for gains in another, which decreases the ecological equivalence of trades (Gibbons and Lindenmayer, 2007; Gardner et al., 2013; Hanford et al., 2017). Besides, our results indicated aggregated metrics often include a high number of ecological attributes, which usually makes their measurements not only more complex, but more time-consuming and expensive to compute (Bezombes et al., 2018; Quétier and Lavorel, 2011). A disaggregated measurement framework allows greater visibility of what is being measured and what is being exchanged (Maseyk et al., 2016; Quétier and Lavorel, 2011), enhancing the transparency of the offset process. Maseyk et al. (2016) described a disaggregated model for a loss-gain metric that accounts for each biodiversity attribute individually. This type of measurement framework also diminishes the complexity of calculations, as a metric that combines several attributes through complex formulas is replaced by a series of simpler metrics (Maseyk et al., 2016).

Offset schemes are usually developed for a specific regional or local context (zu Ermgassen et al., 2019) and our results indicated condition metrics' development follows that pattern. There is evidence that using different offset metrics in a given offset scheme can result in divergent amounts of estimated gains to achieve no net loss (Bull et al., 2014b; Söderqvist et al., 2021). One of the likely reasons for this is that metrics can be specific to some habitats or regions and fail to capture important features of others (Bull et al., 2014b). Therefore, caution in transposing or adapting condition metrics among places is warranted (Bull et al. 2014). In some cases, developing new CMs that are tailored to the specific environment types the offset process targets will be necessary. This may be especially relevant to Global South countries. Our results showed that almost all the CMs reviewed were created in Global North countries. Overall, Global South countries retain high biodiversity (Myers et al., 2000) and yet their offsetting schemes are still in early stages compared to the Global North (Gonçalves et al., 2015; GIBOP, 2019) with no clear results yet (Reid et al., 2015; Bidaud et al., 2015). At the same time, they are the focus of substantial new development projects (Acosta, 2016) and may be more vulnerable to economic pressures, which may result in greater damage to the environment (Virah-Sawmy et al., 2014). Currently, many Global South countries lack standardized metrics and procedures for compensation and offset schemes (Reid et al., 2015; Souza and Sánchez, 2018). In Brazil, for example, the lack of methods to calculate losses and gains was among the main hindrances reported by offset practitioners (Souza and Sánchez, 2018). Thus, caution in adapting CMs and creating new ones is particularly important in countries of the Global South.

We recommend condition metrics should include the three dimensions of equivalence in a disaggregated framework. This framework could allow some level of aggregation of the attributes it includes, if this is needed to maintain the metrics simple (Maseyk et al., 2016), but the dimensions and components included should always be disaggregated. This would allow for the compensation of each component independently. Ecological attributes to be input in each CM could be chosen after proper testing of their synergies and trade-offs, aiming to capture as directly as possible the elements of ecological equivalence, given the data available. Using the methods of GIS, modeling and expert opinion more often could contribute to capture more of these ecological equivalence elements. Finally, when applying a CM in a place other than where it was originally created, adaptations in the metric – or even creating a new one – might be required especially in the Global South.

5. Conclusions

Even though offsetting has been increasing worldwide, the condition metrics described or mentioned in academic literature often don't include attributes that would bring more consistency to offset site selection, thus missing an opportunity to better contribute to achieving ecological equivalence within trades. Most of the 17 condition metrics reviewed measure primarily components and ecological attributes of the biodiversity dimension; the landscape dimension is incorporated in 10 metrics and the ecosystem services dimension in five. Most metrics include several ecological attributes aggregated in a single-value result and were created in Global North countries. We suggest condition metrics should be adapted when transposed to new environments or built according to the need, which may be more urgent in Global South countries. If data availability is low, testing for synergies and trade-offs among ecological attributes could check the possibility of using less attributes without losing information. This, alongside with incremented use of GIS, modeling and expert opinion methods, could facilitate including the three dimensions of equivalence, which should be presented in a disaggregated framework, permitting compensation of their components or attributes independently. This set of recommendations should substantially improve condition metrics contribution to achieve ecological equivalence and biodiversity no net loss in offsetting.

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Capítulo 2: Including biodiversity, landscape, and ecosystem services in a Disaggregated Condition Metric for ecological compensation schemes

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Abstract

Ecological compensation and biodiversity offsets have been largely applied worldwide using condition metrics to quantify losses and gains in the impact and compensation sites, respectively. However, these metrics present limitations that may prevent reaching real ecological equivalence in trades. For example, they often do not include the three dimensions of equivalence (biodiversity, landscape, and ecosystem services), present ecological attributes highly aggregated, and are context-specific – a problem when they are transposed elsewhere. Here, we launch the Disaggregated Condition Metric to fill these gaps. Using the Atlantic Forest of São Paulo state as a study system, we extracted values from biodiversity (6), landscape (4) and ecosystem services (2) attributes from equal-sized hexagons. We tested the attributes' variability, Spearman correlations and spatial complementarity to survey for their synergies and trade-offs and dismiss redundant attributes. The attributes included in the metric were subdivided into classes and compensation trades would only be allowed among hexagons of the same class for these attributes. We tested our metric by applying it in a hypothetical compensation scheme in the study area. We selected one attribute from each dimension: bird richness, landscape connectivity – Probability Connectivity index (400 m), and potential pollination service. The northwestern and southern regions of São Paulo's Atlantic Forest were tested separately; the former presented more candidate hexagons for compensation than the latter, but there were always options. A single attribute proved to be a poor surrogate to the others, but using two attributes showed similar results to the three-attributes test in some cases. To our knowledge, this is the first condition metric to include, at the same time, the three dimensions of equivalence in a disaggregated way, using simple calculations, with spatially explicit results and flexibility on the input attributes. The metric was designed for more general compensation schemes and is transposable to different regions and contexts, because of its flexible framework. The metric should contribute to enhancing the effectiveness of compensation schemes with ecological equivalence and future improvements should enlarge this contribution.

Key-words: Biodiversity Conservation; Biodiversity offset; Ecological Equivalence.

1. Introduction

In recent years, biodiversity offsets and ecological compensation have been increasingly adopted in environmental policies in many countries (Gonçalves et al., 2015; GIBOP, 2019), and their popularity among governments and other stakeholders appears unlikely to change (Maron et al., 2016). To quantify losses and gains in impacted and offset areas respectively, metrics to generate a currency – the biodiversity type that will be exchanged – are used (Bull et al., 2016; Gardner et al., 2013). Ecological compensations may not necessarily require ecological equivalence or its accurate measurement as demanded in biodiversity offsets, but use these kinds of metrics as well (Bennett et al., 2017). Since most of these metrics quantify the environmental condition or quality of sites and of what will be lost and gained, they are called Condition Metrics (CMs).

CMs present several limitations. First, the best known CMs in offset academic literature worldwide largely incorporate biodiversity attributes, but often lack attributes from landscape and ecosystem services (Borges-Matos et al., submitted), thus failing to incorporate the three ecological "dimensions of equivalence" (Borges-Matos et al., submitted) considered important to reach ecological equivalence (BBOP, 2012a). Second, many CMs depend on a large number of attributes, which are highly aggregated in almost all their formulas, meaning the attributes can substitute for one another, usually in an unclear way (Gibbons and Lindenmayer, 2007; Maseyk et al., 2016; Hanford et al., 2017). Furthermore, most CMs were created in Global North countries (Borges-Matos et al., submitted), frequently focused on their particular environmental contexts (zu Ermgassen et al., 2019). The problem is that one same metric is used in distinct places, even though it may work differently and inadequately (Söderqvist et al., 2021), mainly without cautious adaptions (Bull et al., 2014b).

These limitations may compromise reaching ecological equivalence in offset or compensation trades. Improved CMs should ideally include the three dimensions of equivalence in a disaggregated way (Borges-Matos et al., submitted), with flexibility for including different sets of attributes, according to data availability. Testing the attributes for synergies and trade-offs may indicate if some are carrying the same information and can, thus, be excluded from the metric. Creating or adapting the CM to the region where it will be applied may prevent unexpected outcomes, due to environmental differences between the region where the metric was created and the region of its application (Bull et al., 2014b). The latter demand is especially important to countries from the Global South, which suffer great pressure from new development projects (Acosta, 2016), are home to the largest biodiversity in the world (Myers et al., 2000) and yet are in early stages of offset and compensation implementation compared to the Global North (GIBOP, 2019), still counting on few CMs developed tailored to their needs (Reid et al., 2015; Souza and Sánchez, 2018).

This work aims to develop and test a condition metric that meets these demands in an ecological compensation context. We focused on a region of southeastern Brazil, in the Atlantic Forest biome, one of the world's hotspot of biodiversity (Mittermeier et al., 2011; Myers et al., 2000). Based on a consolidated data-set available for the Atlantic Forest of São Paulo state, we extracted a set of attributes from the three dimensions of equivalence, combined them in a new metric, the Disaggregated Condition Metric, and applied it to a hypothetical compensation scheme in the study area. This work is the first to our knowledge that, at the same time, fulfills the need to include the three dimensions of equivalence in a condition metric, uses disaggregated attributes and tests synergies and trade-offs among them, allowing for possible attribute exclusion. We expect our results can be implemented as a new tool for ecological compensation schemes, biodiversity offset planning and conservation management, especially in Global South countries.

2. Methods

The methodological procedure considered two main steps. First, we surveyed the variability, correlations, and heterogeneity of a set of ecological attributes to select the attributes to compound the Disaggregated Condition Metric. In a second step, we used this metric in a hypothetical forest compensation scheme in our study area.

2.1. Exploring the ecological attributes and testing their relationships

2.1.1 Extracting ecological attributes' values

As unit of analysis, we used a grid of hexagons with 10,000 hectares within the Atlantic Forest of the state of São Paulo (Figure 1). This unit size is sufficiently large to hold important ecological processes and sufficiently small to express environmental differences across the space, and has already been used in other ecological studies in the Brazilian Atlantic Forest (Banks-Leite et al., 2011; Martensen et al., 2012; Metzger, 2009; Pardini et al., 2010). We excluded from the analysis all the smaller hexagons at the map's borders, keeping only those equal to or larger than 5.000 ha, as this spatial unit size has also been used to describe ecological processes in the Atlantic Forest (Tambosi et al., 2014). The use of spatial units of approximately the same fixed size should diminish the bias when comparing the attributes among units – including when the attributes data are originally in different spatial resolutions.

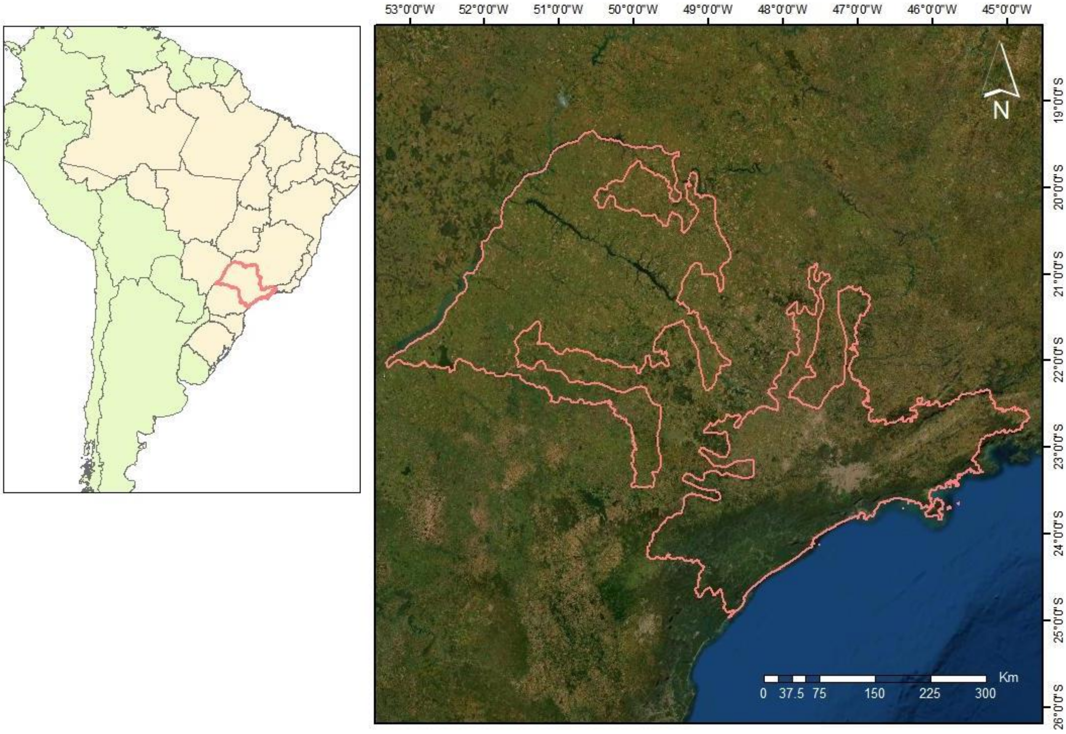

Figure 1: Our study area, the Atlantic Forest domain of São Paulo state highlighted in pink.

As attributes of biodiversity, we used the potential species richness and composition in each hexagon for Atlantic Forest endemic species from three taxonomic groups: birds, amphibians, and trees. These attributes were based on the potential distribution maps previously developed for these groups, based on presence-absence data at 1 km resolution (Strassburg et al., 2019 - Sup. Mat.). We worked with endemic species because of their sensitivity to habitat loss and their importance for conservation (Mittermeier et al., 2011; Myers et al., 2000; Posadas et al., 2001). We summed the maps of each taxonomic group to obtain their potential richness at 1 km resolution and calculated the average richness in each hexagon. To evaluate composition, we used the species potentially present in each hexagon to make an ordination using a Principal Coordinate Analysis (PCoA) with one dimension, based on Jaccard distance. The first PcoA axis assigned each hexagon a specific number – a score – that represented the potential species composition in it. As closer the hexagon scores, the more similar their species compositions were.

As landscape attributes, we used landscape composition and configuration measures. We overlapped a land-use map at 30 m resolution (FBDS - Fundação Brasileira de Biosiversidade Sustentável, 2019, https://geo.fbds.org.br/) with the hexagon grid and used each hexagon as a local landscape. Using the software Fragstats (McGarigal et al., 2012), we calculated the forest cover percentage in each local landscape as the composition component of this dimension of equivalence. The configuration component was a connectivity measure in each local landscape: the Probability of Connectivity index (PC) (Saura and Pascual-Hortal, 2007), calculated in Conefor software (Saura and Torné, 2009). PC was calculated for three distance thresholds: 50 m, 200 m and 400 m. These represented the distances beyond which the organism's capability of dispersion would fall below 50% (Saura and Pascual-Hortal, 2007). We assumed these three distances represented organisms with different dispersion capabilities, from less (50 m) to more mobile species (400 m), and they were considered as three different connectivity attributes.

As attributes of ecosystem services, we used proxies for two regulating services. As a proxy of climate regulating service, we used aboveground carbon (AGC) storage, based on the AGC map recently built by Englund et al. (2017) for the whole Brazil, at 50 m resolution and measured in tons of carbon per hectare. We calculated the average AGC for each hexagon. We also estimated a "potential pollination service", using a landscape metric as a proxy for this service: the distance from a non-forest pixel to the closest pixel of forest. We used Euclidean distance in meters within the limit of 600 m, as beyond this approximate distance the pollination service falls sharply below 50% for 16 different crops globally (Ricketts et al., 2008). As a conservative measure, we assumed no pollination service beyond 600 m distance, since it is known this threshold is lower in some cases. For example, in part of the study area, bee richness and abundance in coffee crops decrease by half when the distance between the crop and the closest forest patch surpasses 200 m (González-Chaves et al., 2020). We calculated the average distance for each hexagon, so that the shorter the distance, the greater the pollination service. To avoid a distorted perception of this attribute in relation to the others, we multiplied its values by -1.

2.1.2 Testing the ecological attributes' relationships

We evaluated the variability of each attribute within the whole study area by calculating their standard deviation (SD) based on their gross values. If ecological equivalence is not accounted for in the compensation trade, attributes with higher variability would be more likely to suffer greater losses. They would also lose more if the attributes were subdivided into fewer classes to be considered equivalent in trades.

Next, to understand how the attributes related to each other, we made simple pair-wise graphs and used a matrix of Spearman correlation including all attributes measured. We compared the correlations within and among dimensions of equivalence and calculated the average correlation of each attribute (*i.e.* its correlations with all other attributes) for the whole study area. For the average calculation, we considered three groupings: all attributes measured, attributes of the biodiversity dimension of equivalence and attributes of the landscape dimension. The ecosystem service dimension had only two attributes, so we did not calculate its average. The attributes with the highest averages should preferably be selected to compose the Disaggregated Condition Metric, since they would better summarize information from different attributes. We did not test for auto-correlation of attributes because we are interested not in explaining the attributes themselves, but in how they relate to each other in space and if they change together or not. Also, we have practically the entire sample universe in our measurements and strong auto-correlation is only a problem when general estimates are made from small samples.

Finally, to understand how ecological attributes were more or less complementary in space, we used the Mean Pair-Wise Distance (MPD) analysis. MPD calculates pair-wise differences of a given group of attributes in each hexagon, using Euclidean distance, and then it calculates the mean of these differences. If a hexagon has a high MPD, its attributes hold larger differences, *i.e.* the attributes are locally more heterogeneous. Lower MPDs reflect attributes that are more similar locally. Hence, higher MPDs indicate that the attributes included in the calculation carry more divergent information at the hexagon level. MPD was calculated using standardized values for all attributes (from 0 to 1) considering seven attribute groupings: biodiversity, landscape, ecosystem services, all attributes together, and three groupings with combinations of the attributes pre-selected to enter the condition metric according to our results (see section 3.1 below). To identify which grouping had more heterogeneous attributes, we calculated the average of all hexagons' MPD values for each grouping: the MPD average. Each grouping could be represented by a single number, which allowed more objective comparisons. The higher the MPD average, the more heterogeneous were the attributes of that grouping, thus more complementary, as complementarity is precisely related to the diversity among attributes.

Based on the ecological attributes' variability, correlations, complementarity and a step-by-step attribute selection framework, we selected the attributes to compound the Disaggregated Condition Metric. Next, we explain how it would function in practice in a hypothetical compensation scheme in our study area.

2.2. Testing the functioning of the Disaggregated Condition Metric

To test how the metric would work in a realistic situation of forest compensation, the ecological equivalence premise was a condition the compensation should necessarily comply with. We subdivided the attributes' values into a standardized number of classes to evaluate their ecological equivalence: hexagons of the same class were considered equivalent for a given attribute. Then, we overlaid these hexagons and extracted solely those equal in class for all attributes included. The impact in a hexagon from those that were extracted could be compensated in any hexagon of this grouping.

For this, we first applied the Sturges' Rule (Scott, 2009), a criteria used to define intervals or number of classes ($K = 1 + (3.3 \times \log N)$, in which N is the total number of samples). The class number is adequate when it is not so small that it groups the data excessively, nor too large, which would not allow summarizing the patterns in the sample. Using this rule for the 1,671 hexagons (N) lead to K=12, so we subdivided the values of the attributes selected in the previous steps into 12 classes (Figure S1).

Following, we randomly chose two hexagons in the study area where a hypothetical impact would have occurred, hereafter called the "impact-hexagons". These hexagons would have to compensate for their impacts either in the impact-hexagon itself or in other ecologically equivalent hexagons. We chose two impact-hexagons instead of one because this allowed exploring the metric in two regions of the study area with different environmental characteristics: the "northwestern region" and the "southern region" of São Paulo Atlantic Forest. The southern region is usually dominated by humid forests, but also presents transitional forests (between humid and semideciduous), and in the northwestern region seasonal semideciduous forests predominate.

Considering the limitations and different contexts in which compensation happens, using many ecological attributes simultaneously may be difficult. Therefore, and to further explore the Disaggregated Condition Metric, we tested what would happen when using different numbers and combinations of attributes. We tested the metric with only one attribute – the one with the highest mean correlation with all the attributes tested – and with pair-wise combinations of the selected attributes. The precise number and identity of attributes input were defined to the extent the results came out, as those more redundant were progressively excluded according to the tests on variability, correlation and complementarity. All statistical analyses were performed in R (R Core Team, 2021).

3. Results

3.1. The ecological attributes and their relationships

The species potential richness had similar patterns among the three taxonomic groups, but birds showed higher richness in the whole southern region of the state, compared to amphibians and trees, whose highest richness were concentrated in the south of the southern region (Figure 2). Potential species composition changed sharply from the northwestern to the southern region. Changes close to Cerrado ecotone (at the center of the state) and along three rivers in the northwestern region were noticeable, especially for amphibians (Figure 2).

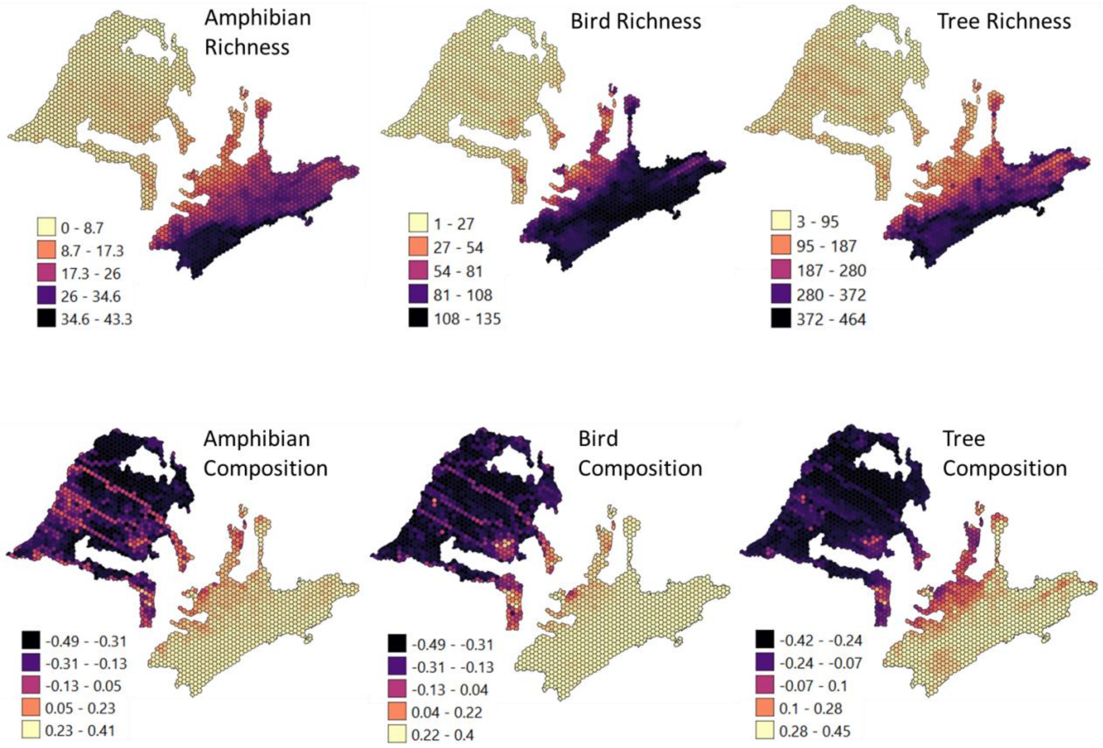

Figure 2: Gradients of biodiversity attributes in the Atlantic Forest of São Paulo state. The darker the color, the greater the mean potential richness per hexagon to each taxonomic group, for potential species richness maps. For potential species composition, more similar colors represent more similar species composition. Gross values are presented in standardized color classes: 100 classes split into equal intervals within each attribute; the legends were condensed into five classes to ease visualization.

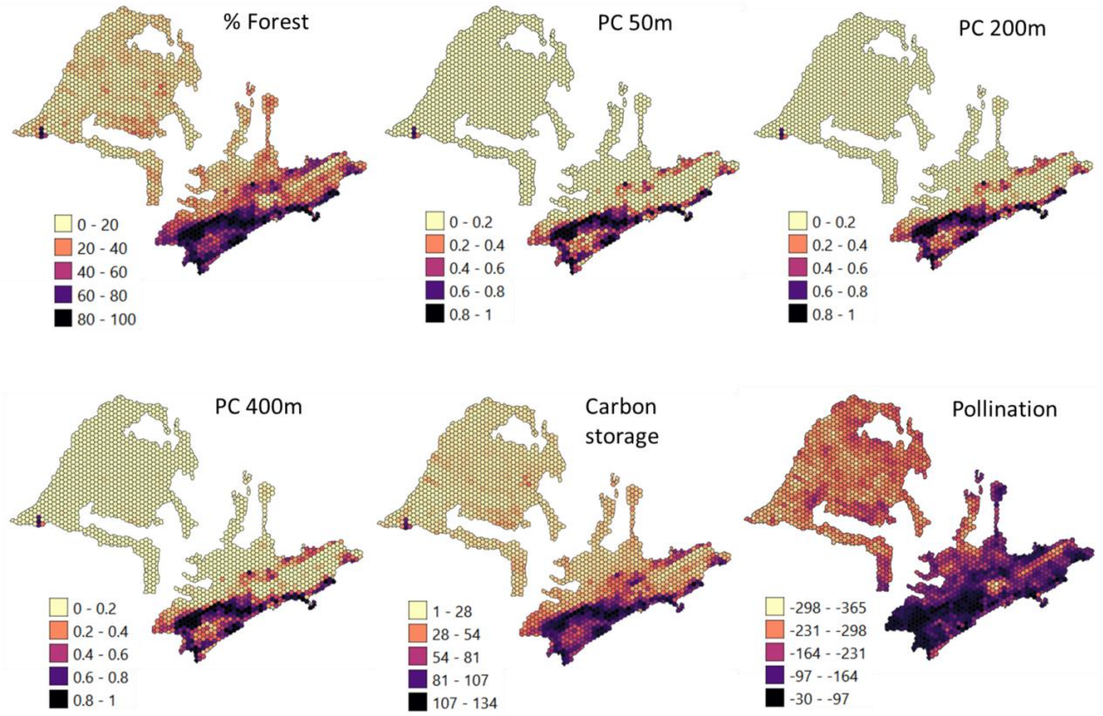

Figure 3: Gradients of landscape and ecosystem services attributes in the Atlantic Forest of São Paulo state. The darker the color, the greater the percentage of forest cover, the higher the Probability Connectivity index (“PC”) for each threshold distance, the greater the carbon storage and the greater the potential pollination service per hexagon. Gross values are presented in standardized color classes: 100 classes split into equal intervals within each attribute; the legends were condensed into five classes to ease visualization.

The maps representing connectivity (PC index) were very similar among them; the patterns of forest cover percentage and carbon storage were similar as well (Figure 3). The pollination map was the most different one, as its values were more homogeneously distributed across the study region (Figure 3). In all cases, the differences between the northwestern and southern regions of São Paulo state were clear: the latter in general presented higher values for all attributes and higher spatial heterogeneity, while the former presented the opposite pattern.

The variability (SD) of each attribute differed. Tree potential richness presented the highest SD (146.618 species), followed by potential pollination service (85.211 meters) and bird richness (53.411 species) (Table S1). This means they are the attributes more likely to suffer significant losses if equivalence is not taking in account in compensation schemes, so it is important to include at least one of them in the new metric. Connectivity attributes presented the lowest values of variability (around 0.25).

The matrix with the Spearman correlations within all attributes showed that correlations generally ranged from moderate to high (0.7 – 0.9) (Table S2). Attributes of a same dimension of equivalence in general presented higher correlations (0.8267 - 0.9979) than attributes from different dimensions (0.6534 - 0.9164) (Figure 4), which reinforces the importance of including the three dimensions in the new metric.

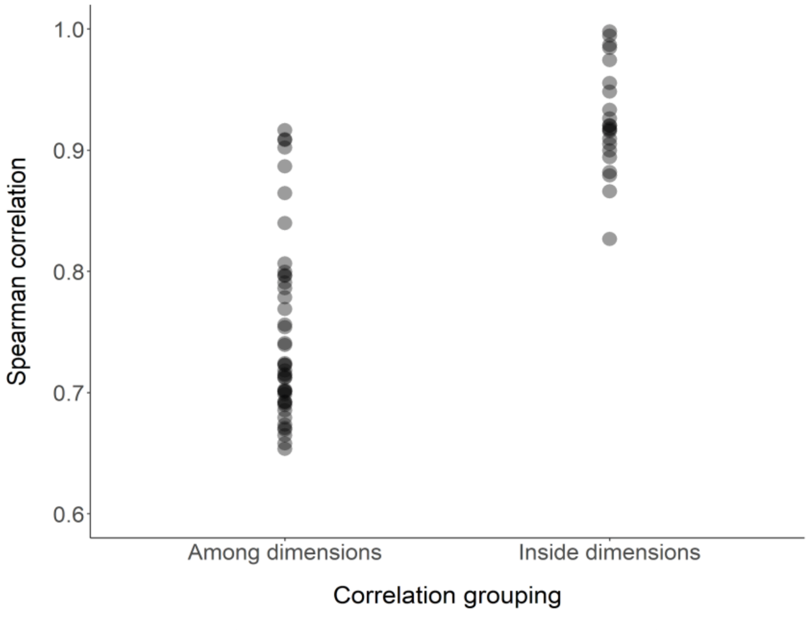

Figure 4: Spearman correlations between each pair of attributes among different dimensions of equivalence (“Among dimensions”) and belonging to the same dimension of equivalence (“Inside dimensions”).

All attributes of the biodiversity dimension were highly correlated (> 0.85; Table S2). Potential richness for amphibians and trees presented a linear relationship (Figure 5); bird richness had a positive relationship with the two groups, but with a logistic shape (Figure 5). Relationships for potential species composition showed exponential patterns (*e.g.* Figure 5), as well as for richness and composition (Figure 5). This showed species composition varies largely across low values of species richness, but not so much when richness sharply increases.

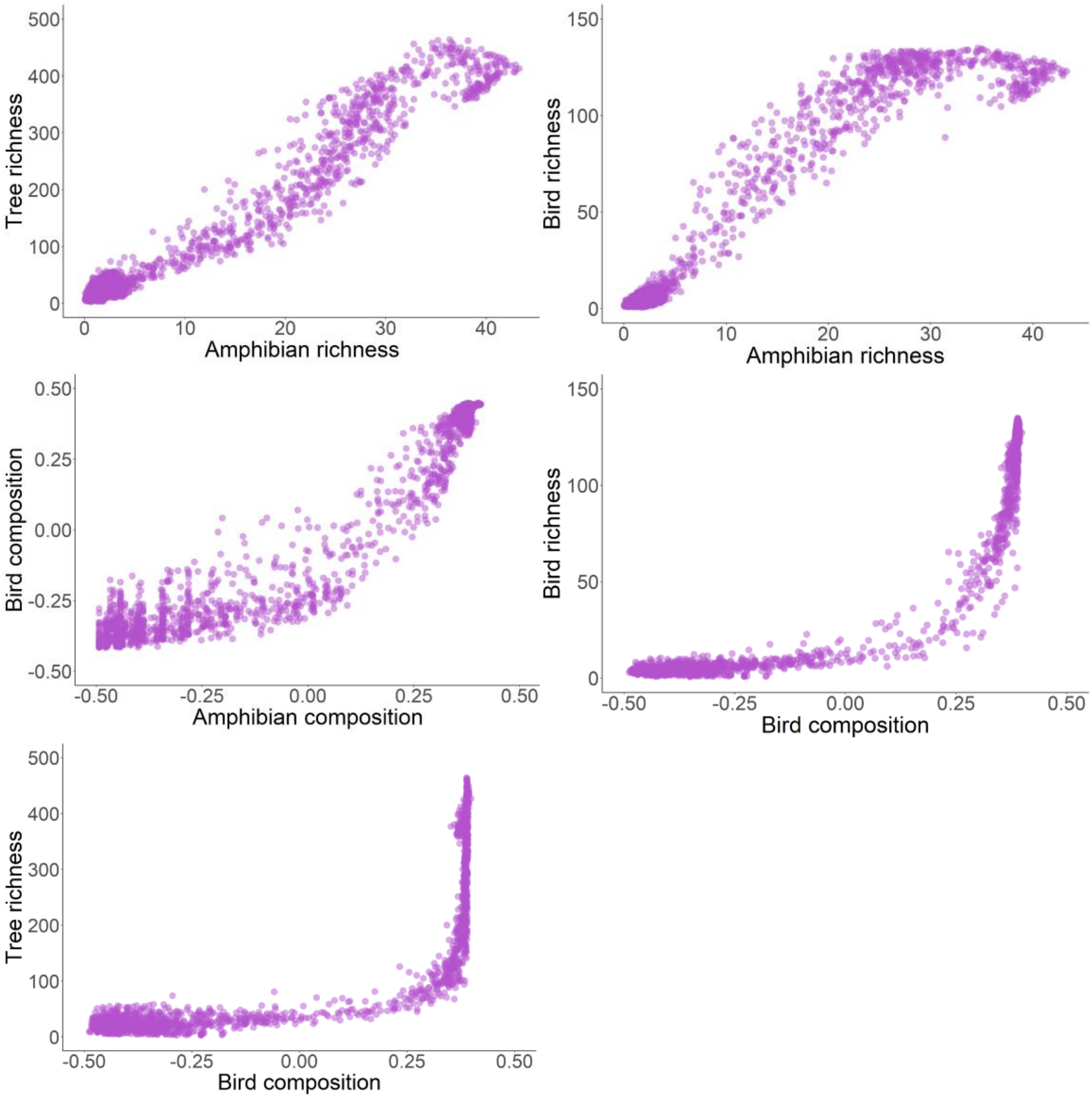

Figure 5: Biodiversity attributes' relationships: amphibian and tree potential richness, amphibian and bird potential richness, bird and tree potential richness, bird and tree potential composition, bird potential composition and tree potential richness.

For landscape dimension, attributes were even more highly correlated (> 0.95; Table S2). Forest cover percentage presented exponential relationships with the three PC indices (*e.g.* Figure 6), whose relationships were almost perfectly linear (*e.g.* Figure

6b). For ecosystem services (ES) dimension, carbon storage and potential pollination service presented a high correlation (0.8267; Table S2, Figure 6). All combinations with the pollination attribute had a sharp exponential shape (*e.g.* Figure 6). This showed this attribute varies greatly along a short interval of low values of the other attributes, but stabilizes across a long interval of increase of other attributes' values.

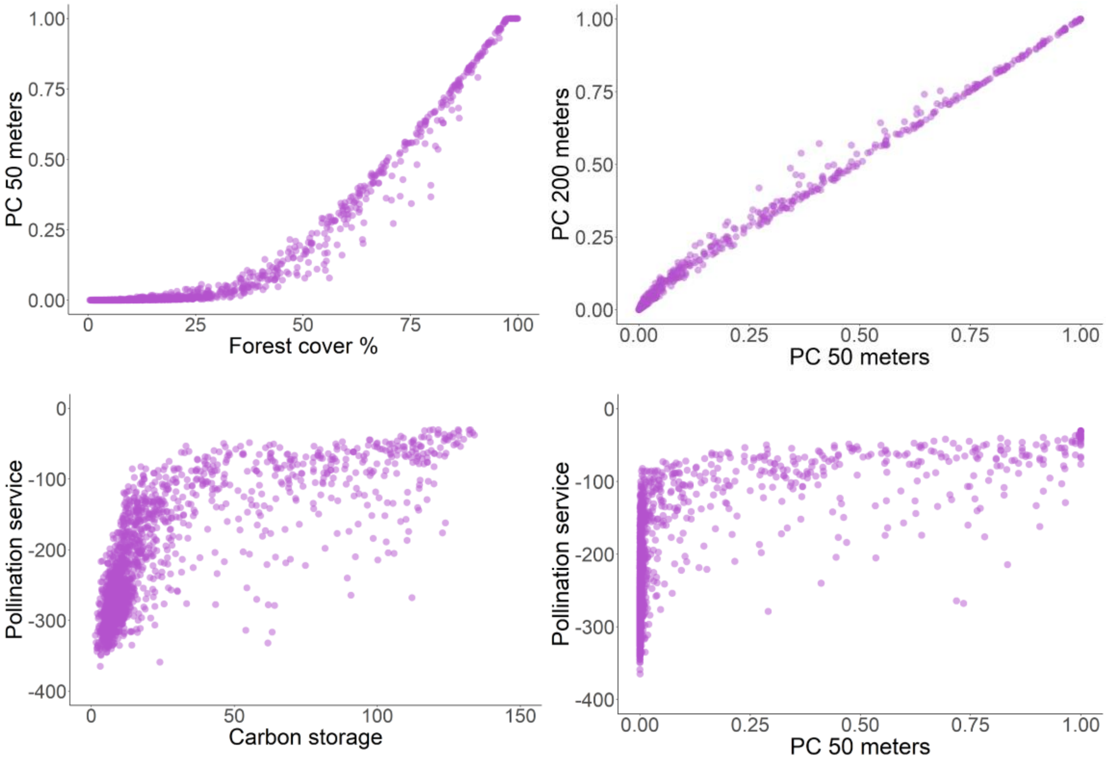

Figure 6: Landscape and ecosystem services attributes' relationships: forest cover percentage and PC index with 50 meters distance threshold, PC indices with 50 and 200 meters distance threshold, carbon storage and potential pollination service, PC index with 50 meters distance threshold and potential pollination service, an example of correlation between attributes from different dimensions of equivalence.

Considering the mean correlations in the three groupings tested (all attributes, biodiversity and landscape dimensions), and supposing an impossibility in measuring more than one attribute, carbon storage would be selected to represent ecological equivalence (Table 1 "All attributes"). Among biodiversity attributes, the most correlated to the remaining attributes was bird richness (Table 1 "Biodiversity"), and for landscape attributes it was PC index with 400 meters threshold (Table 1 "Landscape").

Table 1: Mean Spearman correlation of each ecological attribute in relation to the attributes included in three groupings, ordinated from highest to smallest correlation.

Groupings	Ecological Attributes	Mean correlation
All attributes	Carbon storage	0.8362
	% Forest cover	0.8234
	Connectivity PC 400 m	0.8139
	Bird composition	0.8109
	Bird richness	0.8108
	Tree composition	0.8093
	Connectivity PC 200 m	0.8043
	Amphibian composition	0.8042
	Tree richness	0.8011
	Amphibian richness	0.7956
	Pollination service	0.7912
	Connectivity PC 50 m	0.7827
Biodiversity	Bird richness	0.9191
	Tree composition	0.9165
	Amphibian composition	0.9135
	Bird composition	0.9054
	Tree richness	0.9049
	Amphibian richness	0.8943
Landscape	Connectivity PC 400 m	0.9897
	Connectivity PC 200 m	0.9890
	Connectivity PC 50 m	0.9788
	% Forest cover	0.9714

The mean pair-wise distance (MPD) showed that biodiversity attributes' spatial differences were concentrated at the center of the study area, precisely where the Cerrado ecotone is (Figure 7A). There were also notable differences along the rivers in the state northwest and at the central-north of the southern region. This was most likely a reflection of potential species composition attributes. The dimension with the smallest spatial difference was landscape: there were only some hexagons in the southern region with larger MPD values (Figure 7B). The ecosystem services dimension presented larger differences than the other dimensions, more equally distributed in the space, with larger differences in the northern portion of the southern region (Figure 7C). Indeed, ES average for MPD was the highest considering the three groups (Figure 7), which indicated ES attributes were the most complementary.

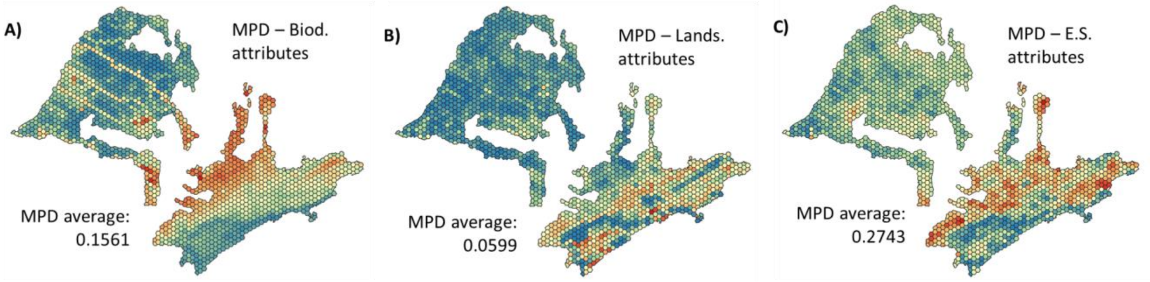

Figure 7: Mean pair-wise distance (MPD) maps for the Atlantic Forest in São Paulo state, representing the spatial differences across hexagons for the following groupings of attributes: A) biodiversity ("Biod."); B) landscape ("Lands."); and C) ecosystem services attributes ("E.S."). The cooler the color, the smaller the MPD; the hotter the color, the larger the MPD – or difference – among the attributes in a given hexagon. The MPD average for each attribute grouping is at the bottom left of each map. Values were represented in maps with no fixed number of color-classes, divided in standardized intervals of 0.01.

When all attributes measured were included in a MPD, differences were clearly concentrated in the northern portion of the southern region; in the northwestern region, differences were smaller, except for along the rivers and close to the Cerrado ecotone (Figure 8A). From the three combinations we tested for 3-attributes MPDs, the one that combined bird richness, PC 400 m and potential pollination service showed higher overall spatial difference and the highest MPD average (0.2724) (Figure 8B), indicating that pollination is more complementary than carbon storage to the attributes bird richness and connectivity PC 400 m (see the Supplementary Material and Figure S2 for more information on the other tests).

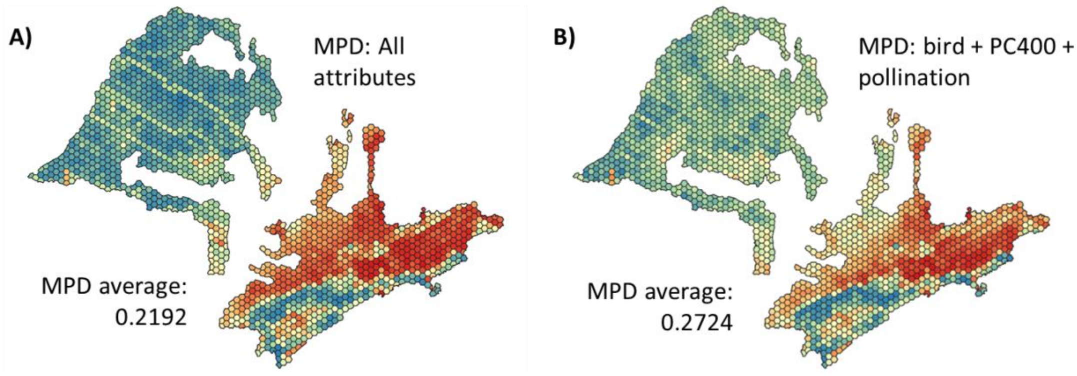

Figure 8: Mean pair-wise distance (MPD) maps for the Atlantic Forest in São Paulo state, representing the spatial differences across hexagons for the following groupings of attributes: A) all attributes measured and B) bird richness, connectivity (PC 400 m) and potential pollination service. The cooler the color, the smaller the MPD; the hotter the color, the larger the MPD – or difference – among the attributes in a given hexagon. The MPD average for each attribute grouping is at the bottom left of each map. Values were represented in maps with no fixed number of color-classes, divided in standardized intervals of 0.01.

For a compensation process seeking ecological equivalence in the study area, the Disaggregated Condition Metric we propose here should be based on three ecological attributes: bird richness, connectivity with PC 400 m and potential pollination service.

3.2. The Disaggregated Condition Metric in practice

The “impact-hexagons” are shown in detail in Figure S3 and are highlighted in Figures 9 and 10. To find ecological equivalence, we used the three selected attributes together (bird richness, connectivity with PC 400 m and potential pollination service), their pair-wise combinations and carbon storage for the 1-attribute test – because of its higher mean correlation (see Table 1). The hexagons ecologically equivalent to the impact-hexagons for each attribute were depictured in new maps (Figures S4 and S5, northwestern and southern regions, respectively). The overlaid-hexagons extracted from these maps are shown in Figures 9 and 10 for the northwestern and southern regions, respectively.

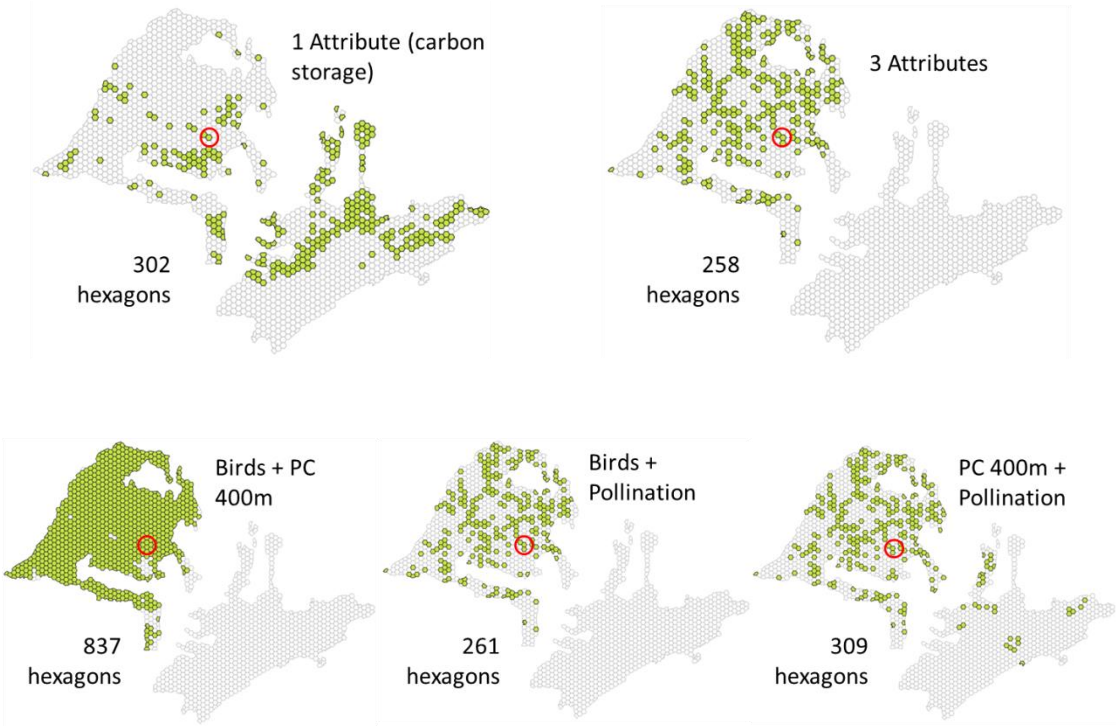

Figure 9: Hexagons candidate for compensation in the northwestern region of São Paulo state Atlantic Forest. The number of candidate hexagons, including the impact-hexagon itself (highlighted by a red circle), is on the bottom left of each map. Besides 1-attribute map, we tested the preferable three attributes selected (bird richness, PC index – 400 m and potential pollination service), as well as three pair-wise combinations of them (bird richness + PC 400 m; bird richness + pollination, pollination + PC 400 m).

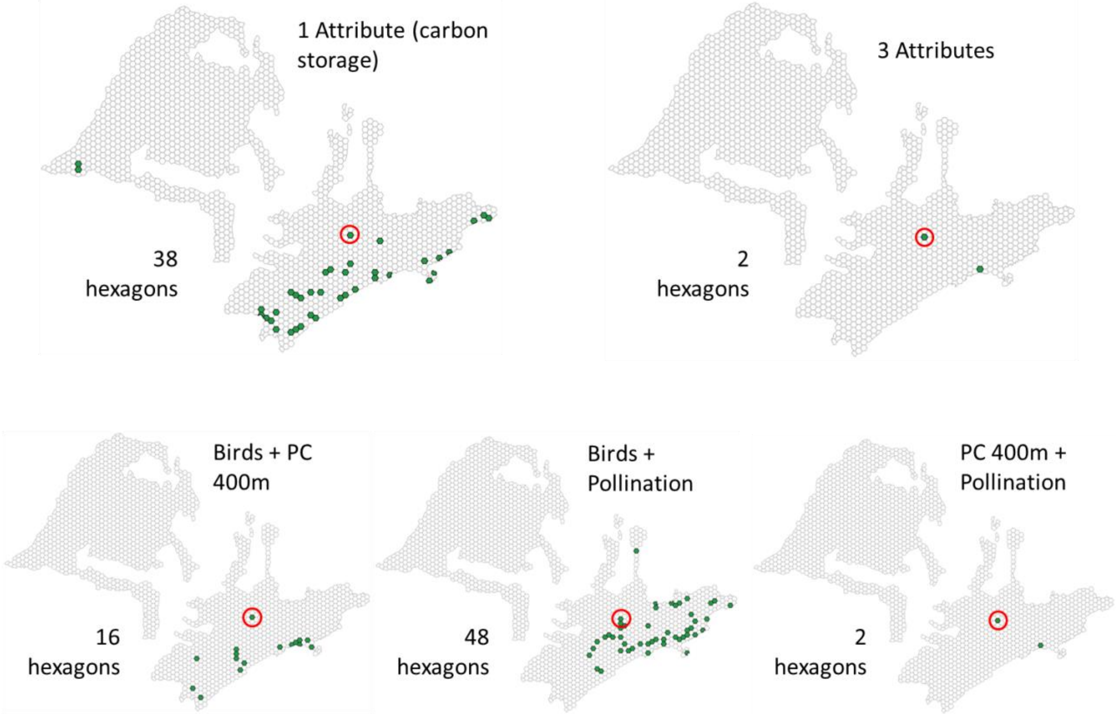

Figure 10: Hexagons candidate for compensation in the southern region of São Paulo state Atlantic Forest. The number of candidate hexagons, including the impact-hexagon itself (highlighted by a red circle), is on the bottom left of each map. Besides 1-attribute map, we tested the preferable three attributes selected (bird richness, PC index – 400 m and potential pollination service), as well as three pair-wise combinations of them (bird richness + PC 400 m; bird richness + pollination, pollination + PC 400 m).

For all tests performed, there were more candidate hexagons for compensation in São Paulo's Atlantic Forest northwestern than the southern region. In the northwest, the potential pollination service seemed to be the most limiting attribute to select candidate hexagons, as all maps in which it was included looked alike and presented similar number of hexagons. On the other hand, in the southern region the connectivity attribute PC 400 m seemed to limit hexagons selection, because the maps which included this attribute presented fewer candidate hexagons. The 1-attribute carbon storage maps for both northwestern and southern regions were quite different from the 3-attribute map of each region, especially for confounding hexagons from these two highly distinct regions, so it does not seem a good surrogate for the three ecological attributes. However, some of the 2-attribute combinations showed results close to the 3-attribute results. This was true for the maps that comprised potential pollination for the northwestern and connectivity for the southern region, probably a reflection of how these attributes limited hexagon selection in their regions.

4. Discussion

Here, we showed it is possible to combine the three dimensions of equivalence represented by a few attributes in a disaggregated way to usage in ecological compensation schemes. Including the three dimensions is important to reach more ecological equivalence in trades (BBOP, 2012a) and our results reinforced it, since together the three attributes encompassed more of the environmental heterogeneity of São Paulo's Atlantic Forest. In fact, ecological equivalence would diminish if only one attribute was used alone, as it would enable trades among regions with clear environmental differences, such as the northwestern and the southern regions of the study area. Although the attribute selection framework and the metric implementation have many steps, the calculations are simple and both the intermediate and final results are spatially explicit, which may facilitate the metric comprehension by a broad public interested in compensation.

Despite the improvement in ecological equivalence when including the three dimensions in the metric, there were combinations of two attributes that allowed a fair representation of the regional environmental heterogeneity. More specifically, it happened for bird richness and pollination in the northwestern region, and for pollination and connectivity in the southern region. This indicates a possibility of adjustment in the metric, going from requiring three attributes to two in cases of logistic restriction or insufficient data. Particularly, pollination and connectivity were important to the northwestern and southern regions, respectively. They were probably the most heterogeneous attributes in their regions, so they deserve attention and should probably be included in compensation schemes at the study area. However, this may not be true for other sites. In these cases, we recommend running through the selection framework we proposed, previously testing the attributes relationships, to check if results achieved are similar or divergent from those of our study area. A condition metric developed for a specific habitat or region may not capture the important ecological characteristics of others (Bull et al., 2014b). Besides, the dynamic and the relationships among attributes change across distinct biomes, due to differences in their diversity (Zappi et al., 2015), and inside a same biome, due to its intrinsic heterogeneity (Alho, 2019; Dambros et al., 2020; Silva and Casteleti, 2003) and different land use history (Fernandes Neto et al., 2019; Giles et al., 2021; Ribeiro et al., 2009).

The condition metrics most commonly present in offset and compensation academic literature rarely include the three dimensions of equivalence at a time; most include biodiversity attributes solely and lack especially the ecosystem services dimension (Borges-Matos et al., submitted). This was resolved by the Disaggregated Condition Metric. Further, very few metrics disaggregate their attributes, instead they usually include attributes altogether in the same formula (Borges-Matos et al., submitted). The problem is this allows for unaware and undesirable attribute substitutions in compensation trades (Gibbons and Lindenmayer, 2007; Maseyk et al., 2016; Hanford et al., 2017). Recently, the disaggregation metrics have been recommended (Maseyk et al., 2016; Bezombes et al., 2018), and there have been effort in building metrics this way (Bezombes et al., 2018; Maseyk et al., 2016; Stone et al., 2019). Our metric is thus in consonance with this current demand and confirms its importance.

The framework we created for the metric attributes' selection is flexible, as one can include any attribute as input. This enables practitioners to choose the attributes more relevant and/or that are available to their specific region, which sharply diminishes the problems of transposing metric's among socio-environmentally distinct places (Bartkowski et al., 2015; Bull et al., 2014b; Söderqvist et al., 2021). In addition, our metric is spatially explicit, generating clear maps at each step of framework and metric implementation. Few condition metrics provide such maps (Drobnik et al., 2020; Mandle et al., 2015), even though they facilitate comprehension by different publics interested in compensation and offset, as they make the process visual. Therefore, our metric not only is flexible about the attributes to be input, - since others are too (*e.g.* Maseyk et al., 2016; Bezombes et al., 2018) - as it also includes the three dimensions of equivalence, in a disaggregated way, using simple calculations and presenting spatially explicit steps and results. It is the first metric to our knowledge to combine all these factors at the same time.

Despite the fact the metric itself presented only three attributes, coming to this result was only possible because the selection framework included tests with many attributes first. The dilemma of simple (one or few attributes) and little informative metrics versus complex (many attributes) and more informative metrics have proven difficult to resolve (Bezombes et al., 2018; Gonçalves et al., 2015). For greater completeness, simple metrics could be combined, but it would still lack standardization and implementation information. On the other hand, complex metrics can be difficult to understand as well as to implement (Hanford et al., 2017; Quétier and Lavorel, 2011). Here, we tried to find a compromise: we built a metric with few attributes, based on previously tested synergies and trade-offs among many attributes. This allowed us to use fewer attributes losing as less information as possible. Varied ecological data is crucial in compensation trades, because they bring wide knowledge of sites' characteristics and of what is actually lost and gained (Marshall et al., 2020b, 2020a). Thus, accounting for several ecological attributes in developing a condition metric seems to be something practitioners will have to deal with when the goal is to achieve ecological equivalence.

The Disaggregated Condition Metric was designed focused on general compensation schemes that include ecological equivalence, such as the volunteer offsets for private lands in South Africa (Von Hase et al., 2010), or the compensations of private reserves in rural properties in Brazil (Mello et al., 2021a, 2021b). However, it could also attend to more exigent compensation schemes, such as biodiversity offsets. Our metric's framework and spatial data representation allow it to be used in offsets interested in trading a single specific ecological attribute, for example. Nonetheless, in this case, the data used would have to be precisely from the impact and offset sites or collected in the field, because offsets demand accurate quantification of ecological attributes lost and gained (BBOP, 2012b; Gardner et al., 2013; Maron et al., 2016).

The selection framework developed here can be easily adapted to other similar regions, considering some basic precautions or adaptations to the local conditions. We highlight that the number of hexagons available for compensation should not be a reference through which compensation trades should be evaluated, since ecological equivalence is the main driver to select compensation sites. If the number of candidate hexagons to compensate an impact-hexagon is too low in a given region, compensating in hexagons of one or two classes above the impact-hexagon original classes is an acceptable adaptation of the metric, making it more feasible in operational and economic terms (Mello et al., 2021a, 2021b). Also, in many cases, extensive databases do not exist or are not readily available due to many factors, *e.g.* economic limitations, especially in Global South countries (Magnusson et al., 2013). In these situations, we recommend using as many attributes as possible, but always accounting for the three dimensions of equivalence.

Finally, testing our selection framework and metric implementation in other parts of the Atlantic Forest, in other biomes, and including more attributes, especially from the ecosystem services dimension of equivalence, could improve the understanding of the metric behavior in different contexts. This would improve the metric itself. We expect the Disaggregated Condition Metric contributes to developing more effective compensation schemes that ensure broader ecological equivalence in trades.

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Capítulo 3: Compensating Legal Reserve deficits with ecological equivalence

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Abstract

Ecological compensation and offsets have been used worldwide as conservation mechanisms to repair the residual impacts caused by human activities. They are often criticized about the difficulties in measuring and achieving ecological equivalence in the trades. Also, conflicts between development and environmental sectors commonly arise, as in the case of the implementation of the New Forest Act in Brazil. The Act mandates a percentage of every rural private property must be conserved with native vegetation, the Legal Reserve, or must be compensated if there is a deficit. The Brazilian Federal Supreme Court decided Legal Reserve compensation should be made with ecological equivalence, but did established specific rules or methods to apply it. Here, we attended this demand by testing the Act's different compensation strategies seeking the most cost-efficient option, using the Disaggregated Condition Metric to approach ecological equivalence. We created scenarios to test separately and combined the Act's three main compensation strategies: protection of stand vegetation, restoration, and regularization of private lands inside public protected areas. We subdivided our study area – the Atlantic Forest of São Paulo state – into equal-sized hexagons in which we estimated the Legal Reserve deficit and surplus, the areas possibly available for restoration, the lands irregularly inside protected areas and the costs to compensate by restoration and by protection of stand vegetation. Cost-efficiency was evaluated in terms of deficit resolution, economic costs, and additional native vegetation (additionality). Scenarios including the strategies separately had a maximum of 40.22% of deficit resolution for protection, 0.15% for regularization, and 98.99% for restoration. Regularization was inefficient and should not be preferred over the other strategies; restoration was the most expensive strategy, but had the highest additionality. The two combined scenarios resulted in good cost-efficiency. The protection of stand vegetation followed by restoration was the best option since its deficit resolution was 99.47% with an intermediate cost and additionality. Our results showed it is possible to compensate

Legal Reserves accounting for ecological equivalence in cost-efficient trades. Despite some disadvantages, including ecological equivalence guarantees additionality and more equal spatial distribution of ecological benefits. Currently, restoration goals are at the center of many environmental agreements. Therefore, choices about ecological compensation demonstrate the path governments are willing to take in fighting the global climate and environmental crisis we are going through.

Keywords: Brazilian Forest Act; environmental public policy; vegetation restoration; conservation; biodiversity offset.

1. Introduction

Ecological compensation and biodiversity offsets have been used in many parts of the world to counterbalance the rapid habitat loss and fragmentation due to development projects and agricultural enterprises, as an attempt to contribute to species and ecosystem services conservation (Bull and Strange, 2018; Gardner et al., 2013; Gonçalves et al., 2015). However, the actual biodiversity gains of compensation and offsets are often questioned (Evangelia Apostolopoulou and Adams, 2017; Bull et al., 2013; zu Ermgassen et al., 2019), mostly because of the difficulty in measuring and achieving ecological equivalence between losses and gains traded (Gonçalves et al., 2015; Marshall et al., 2020b), as well as the lack of transparency in these schemes (Maron et al., 2016a). Besides the methodological difficulties, there is also the constant conflict between the environmental and agricultural and development sectors' goals. Including ecological equivalence in trades improves the environmental outcome of the compensation or offset (BBOP, 2012a), but this measure is usually seen as a great restriction of the area available to compensate (Weissgerber et al., 2019), which makes compensation more expensive and demands protecting lands of higher opportunity costs (Mello et al., 2021a).

These conflicts have been present in the implementation of the compensation rules within the Brazilian Native Vegetation Protection Law, known as the New Forest Act (Law 12.651 - Brasil, 2012). This law establishes rules for land use and protection of native vegetation in private lands. It is a paramount conservation tool in Brazil, because more than 50% of the country's remaining native vegetation is inside these private lands (Sparovek et al., 2015). The Act demands the maintenance of Permanent Protection Areas (APPs, Portuguese acronym) and Legal Reserves in each property. APPs are areas ecologically vulnerable, such as steep slopes and riparian forests, and, in case of degradation, they must be restored in-site. Legal Reserves are a percentage of the property area (ranging from 20 to 80% according to the biome) that should be covered with native vegetation; their deficits can be compensated by different strategies, either in or off-site. Originally, the only ecological requirement in Legal Reserve compensation was that trades should be made inside the same biome of the deficit.

Legal Reserve deficits are likely to be compensated mostly through a market of quota trading, known in Brazil as Environmental Reserve Quotes (CRA, Portuguese acronym; Soares-Filho et al., 2016). In this market, landowners with Legal Reserve surplus – more vegetation in the property than the minimum required by law to compound the Legal Reserve – compensate the deficit of other landowners. Nonetheless, CRA is not enough to reach full law compliance for all Brazilian biomes, such as the Atlantic Forest, so restoration is also needed (Mello et al., 2021b). On the other hand, the Legal Reserve surplus may easily exceed the deficit in some cases (Tavares et al., 2019). This means there would be no additionality – gains in native vegetation relative to the current vegetation area – from Legal Reserve compensation, with little or no increase in the recovery of biodiversity and ecosystem services (Tavares et al., 2019).

However, in 2019 the Brazilian Supreme Federal Court judged their agreement document from 2018 on the Forest Act (Brasil, 2018) and decided that Legal Reserve deficits should be compensated in sites ecologically equivalent, in terms of "specific species and ecosystems" (Brasil, 2018). The decision recognized the wide heterogeneity existing within Brazilian biomes (*e.g.* Alho et al., 2019; Dambros et al., 2020; Silva and Casteleti, 2003) and that this heterogeneity could lead to unbalanced trades if compensating in an entire biome is allowed, with more environmental losses than gains in some situations (Metzger, 2010). Yet, this demand for ecological equivalence was criticized by environmental and agricultural sectors, mostly because it lacked a definition of how to measure ecological equivalence and what levels of equivalence would be required (Mello et al., 2021a, 2021b). There was also a fear that it could reduce the areas available for compensation, which could increase the compensation costs to landowners (Mello et al., 2021a, 2021b). Despite the criticism and the lack of specifications about ecological equivalence, the Court did make clear that Legal Reserve compensation schemes should include ecological attributes that represent the biotic diversity and the ecological processes of sites, aiming for the rehabilitation of these processes and the conservation of biodiversity (Brasil, 2018).

Therefore, the demand for ecological equivalence in Legal Reserve compensation is set, but the questions about how to do it in practice, preferably cost-efficiently, remain open. Here, we tackled these questions focusing on the compensation strategies proposed in the new Forest Act (*i.e.*, in-site or off-site restoration, off-site compensation in stand vegetation, and compensation in public protected areas) and their economic costs, using a recently developed condition metric to approach ecological equivalence (Borges-Matos et al., *in prep*). We assumed the inclusion of ecological equivalence as the main premise and sought to understand (1) how efficient each compensation strategy is when applied alone and (2) what strategy or combination of strategies is most efficient in compensating Legal Reserve deficit. To answer these questions, we designed and tested a set of compensation scenarios using the Atlantic Forest of São Paulo state as our study system.

2. Methods

2.1. Scenarios for Legal Reserve compensation

The Brazilian Forest Act established some strategies with which landowners could compensate their Legal Reserve deficits to comply with the Law. These strategies can be resumed in three: protection of stand vegetation, restoration of native vegetation (either in or outside the property with the deficit), and regularization of private properties that remain inside protected areas. This regularization takes place when the landowner with a deficit buys a non-regularized property within a public protected area (*i.e.* an area that was not expropriated by the state when creating the public reserve) and donates it to the state. The Legal Reserve surplus is the stand vegetation that exceeds the Legal Reserve of a property and it can be used in the CRA market. The New Forest Code also allows the inclusion of the Legal Reserves of small properties as a possibility to compensate deficits. The owners of small properties cannot deforest their existing Legal Reserve, but they are no longer obligated to compensate their deficit (if there is any), and they can use their Legal Reserve in the CRA market.

We tested how each compensation strategy alone would perform in the Atlantic Forest of São Paulo state (Figure 1), always considering ecological equivalence (see below). Then we tested combinations of these strategies, aiming at fully solving the Legal Reserve deficit and at selecting the best combination. We designed six scenarios to test our questions. Four were called “simple scenarios”, as they tested the strategies alone, and two were considered as “composite scenarios”, once they combined strategies to maximize deficit reduction or elimination (Table 1). The restoration was the last step in both composite scenarios because it was the strategy of higher cost/hectare (see section 2.3). Since including small properties' Legal Reserves as a possibility for compensation is a new rule, we split the strategy of protecting stand-vegetation into two scenarios: one that considered only the Legal Reserve surplus (as established by the previous Forest Act) and another that considered the sum of this surplus with the Legal Reserves of small properties (New Forest Act). Testing both possibilities showed if there were substantial differences between them in terms of deficit resolution and the consequent need for restoration. For the composite scenarios, we only used the stand-vegetation protection including small-properties' Legal Reserves, because this is the rule of the current Forest Act and the goal of these scenarios was to fully eliminate the deficit.

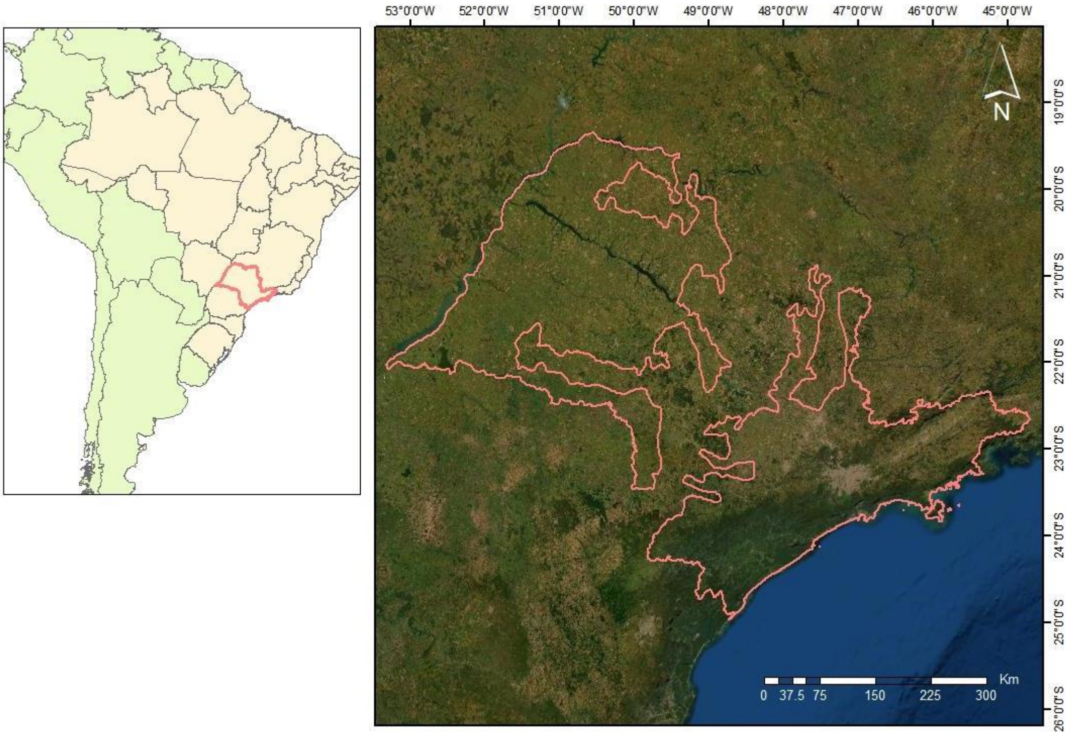

Figure 1: Our study area, the Atlantic Forest domain of São Paulo state highlighted in pink.

Table 1: The six scenarios designed to test Legal Reserve (LR) compensation through the strategies provided by the Brazilian New Forest Act, including ecological equivalence.

Scenario type	Scenario name	Scenario rationale
Simple	Scenario 1 – LR surplus	Tests how well LR compensation based exclusively on protection of LR surplus can resolve the deficit.
	Scenario 2 – Total surplus	Tests how well LR compensation based exclusively on protection of stand vegetation (constituted of LR surplus and LRs of small properties) can resolve the deficit
	Scenario 3 – Restoration	Tests how well LR compensation based exclusively on restoration of native vegetation can resolve the deficit
	Scenario 4 – Regularization	Tests how well LR compensation based exclusively on regularization of private properties inside public protected areas can resolve the deficit
Composite	Scenario 5 – scenario 2 followed by scenario 3	Tests if LR deficit can be fully resolved by using protection of stand vegetation (LR surplus and LRs of small properties), followed by restoration of native vegetation
	Scenario 6 – scenario 4 followed by scenario 2, and then followed by scenario 3	Tests if LR deficit can be fully resolved by using regularization of private properties inside Conservation Units, followed by protection of stand vegetation (LR surplus and LRs of small properties), followed by restoration of native vegetation

The performances of the scenarios were evaluated according to the area of deficit solved (hectares and percentage), compensation economic costs (in *reais* and in dollars), and additionality (area in hectares of native vegetation gained relative to the current vegetation area). Furthermore, we calculated how much of the area available for protection, restoration, and regularization was used in the compensation scheme of each scenario (hectares and percentage).

In all scenarios, compensation was made iteratively for each spatial unit (see section 2.2) and the compensation and deficit areas were updated at each turn. Units that contained areas for compensation were ascending ordered according to their compensation cost, so that spatial units of lower costs would be first selected to the compensation scheme. The units containing deficit areas were descending ordered;

those with larger deficit areas were selected first. The scenarios allowed compensation trades exclusively among units ecologically equivalent (see section 2.2). The iteration went on until trades among equivalent units ran out.

2.2. Legal Reserve deficit and compensation data

To meet the requirement of compensating Legal Reserve deficits with ecological equivalence, we used the Disaggregated Condition Metric (Borges-Matos et al., *in prep*) in our scenarios. In this metric, three ecological attributes represent the dimensions of equivalence: bird richness (*biodiversity* dimension), the Probability of Connectivity index with the distance threshold of 400 meters (*landscape* dimension; Saura and Pascual-Hortal, 2007), and the potential pollination service (*ecosystem service* dimension). The attributes were individually averaged for each spatial unit: hexagons that vary in size from 5,000 to 10,000 hectares covering all the Atlantic Forest of São Paulo state. Each attribute was subdivided into 12 classes (Figure S1) and trades were only allowed among hexagons of the same class for the three attributes (Borges-Matos et al., *in prep*). We created a prioritization path in R environment (R Core Team, 2021) to define the hexagons that contained deficit and were ecologically equivalent to each hexagon that presented area available for compensation through some of the strategies provided by the New Forest Act. The hexagon with deficit itself was always considered as a possibility for compensation.

The mandatory Legal Reserve in the Atlantic Forest biome is 20% of the property. To extract values of Legal Reserve surplus, Legal Reserves in small properties, and deficit area per hexagon, we used a database containing this information on each property of São Paulo state (Tavares et al., 2021). To aggregate this property-level data in the hexagons, we filtered the data for the Atlantic Forest and assumed the surplus, the small properties' Legal Reserves, and the deficit were equally distributed in each property. When we intersected the properties with the hexagon grid, we could calculate the approximate area of each variable inside each hexagon (Figure 2).

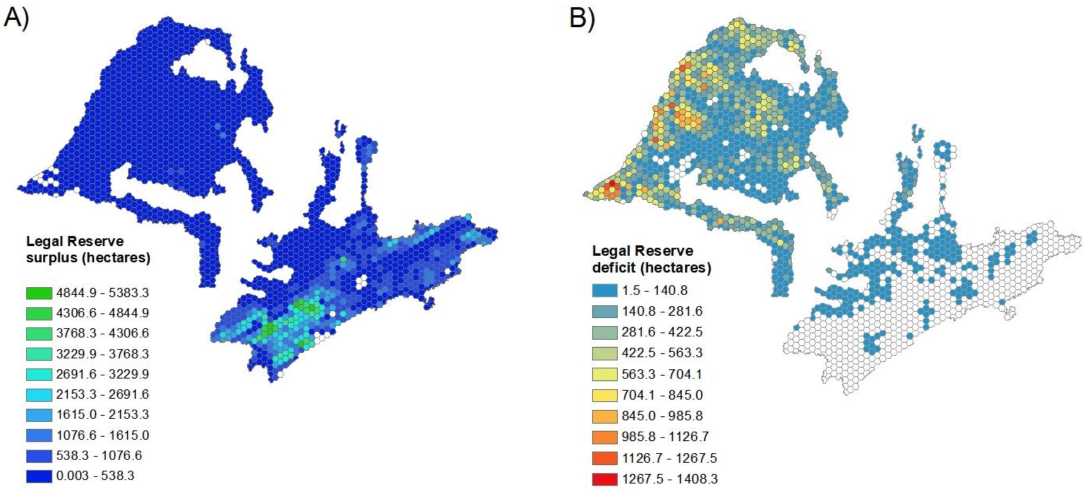

Figure 2: Spatial distribution of (A) total **Legal Reserve surplus**, including the Legal Reserves of small properties, and (B) **Legal Reserve deficit**.

To approach the compensation strategy of restoring native vegetation, we calculated the area available for restoration in each hexagon. This calculation was based on previous data of São Paulo state, where the polygons represented the area available for restoration inside each property (Sparovek et al., 2020). We intersected this map with the hexagon grid and summed the areas of patches that fell inside each hexagon (Figure S2A). The areas considered available for restoration are pastures of low suitability for agriculture (degraded pastures), previously measured and classified in a single category of "low suitability" (Sparovek et al., 2015).

We estimated the area of private properties irregularly inside public protected areas of the Atlantic Forest of São Paulo based on their proportion relative to the total area of each protected area (Forest Foundation – São Paulo government, personal communication). We used the map of São Paulo state protected areas (DataGeo – São Paulo government; https://datageo.ambiente.sp.gov.br/) and filtered the categories with higher level of protection (equivalent to IUCN categories Ia, Ib, II, and III; Dudley, 2013) that presented some percentage of irregularity in their areas. We assumed this percentage was equally distributed in each protected area. Similar to the surplus and deficit calculations, we intersected this layer with the irregularities percentages with the hexagon grid, calculated the irregular private area corresponding to its percentage in each protected area, and summed these area values to obtain the approximate area of irregularity per hexagon (Figure S2B).

2.3. Compensation costs estimation

To test the scenarios, we estimated two types of compensation costs: costs for restoration of native vegetation and costs for protecting stand vegetation – including both strategies of stand-vegetation protection and the regularization of private properties inside protected areas. To estimate the protection costs, we used the prices for land acquisition in vegetated areas as a proxy, based on a national land-cost database (FNP, 2017; https://ihsmarkit.com/products/agribusiness-brazil.html). Restoration costs were estimated based on the price to fully restore one hectare, considering the regeneration potential of the site, summed with its opportunity cost. To estimate the opportunity cost, we used land acquisition prices of pasture and agriculture areas (FNP, 2017).

The FNP (2017) prices for land acquisition were originally estimated per municipality and in Brazilian currency (*reais* per hectare). We calculated the proportion of the municipalities in our study area occupied by each of the three FNP land-cover categories (vegetation, pasture, and agriculture areas), then we calculated their mean weighted average price/hectare per municipality. We assumed the categories percentages were equally distributed within each municipality, then we intersected the municipalities' polygons with the hexagon grid and calculated the weighted average prices per polygon inside each hexagon. We summed the price values in each hexagon to estimate the costs of compensation through the protection of stand vegetation (Figure S3A) and of the opportunity cost.

To complete the restoration cost estimation, we used a "partial" restoration cost previously calculated. This partial cost consisted in the multiplication of the cost to plant one complete hectare (Benini and Adeodato, 2017) by the local regeneration potential (Crouzeilles et al., 2020). The result was a 30 m resolution raster layer with prices in r*eais* (R$) per hectare; vegetation, water and urbanization pixels were excluded (Forest Code Thematic Project). The values in *reais* refer to the year 2017 (Benini and Adeodato, 2017), when the annual mean commercial exchange rate was R$ 3.1920 = 1.0 American dollar (USD) (Brazilian Institute of Applied Economic Research, IPEA - http://www.ipeadata.gov.br/ExibeSerie.aspx?serid=31924). From the partial cost layer, we extracted the mean restoration cost for each hexagon. We then summed these values with the opportunity costs per hexagon to achieve the total restoration cost (Figure S3B). All analyses were performed in R environment (R Core Team, 2021).

3. Results

The compensation scenarios varied enormously in their ability to reduce Legal Reserve deficits (0.15-99.47%), as well as in costs (104 thousand dollars to 2 billion dollars approximately) and additionality (0-220 thousand ha approximately) (Table 2, Figure 3). The ability to reduce deficits was related to the use of restoration and the inclusion of small properties' reserves as areas available for compensation, which nearly doubled the deficit resolution when compared to the scenario including only Legal Reserve surplus (scenario 1 vs 2). It was possible to solve almost all deficits when considering solely the restoration strategy (scenario 3), which was the most efficient of the four simple scenarios in this aspect and had the highest additionality from all six scenarios tested (Table 2).

On the other hand, the use of restoration strategy increased tremendously the total economic cost, from USD 7-14 million (scenarios 1 and 2) to USD 2.1 billion approximately (scenario 3). The regularization scenario (scenario 4) was the cheapest one, but precisely because this strategy could reduce little deficit (Table 2, Figure 3). Scenarios 1, 2, and 4 did not present any additionality. Figures S4 and S5 in the Supplementary Material depict the economic values that would be inverted in each hexagon where compensation would occur, as well as the area used to compensate by protection, restoration, and regularization in all six scenarios.

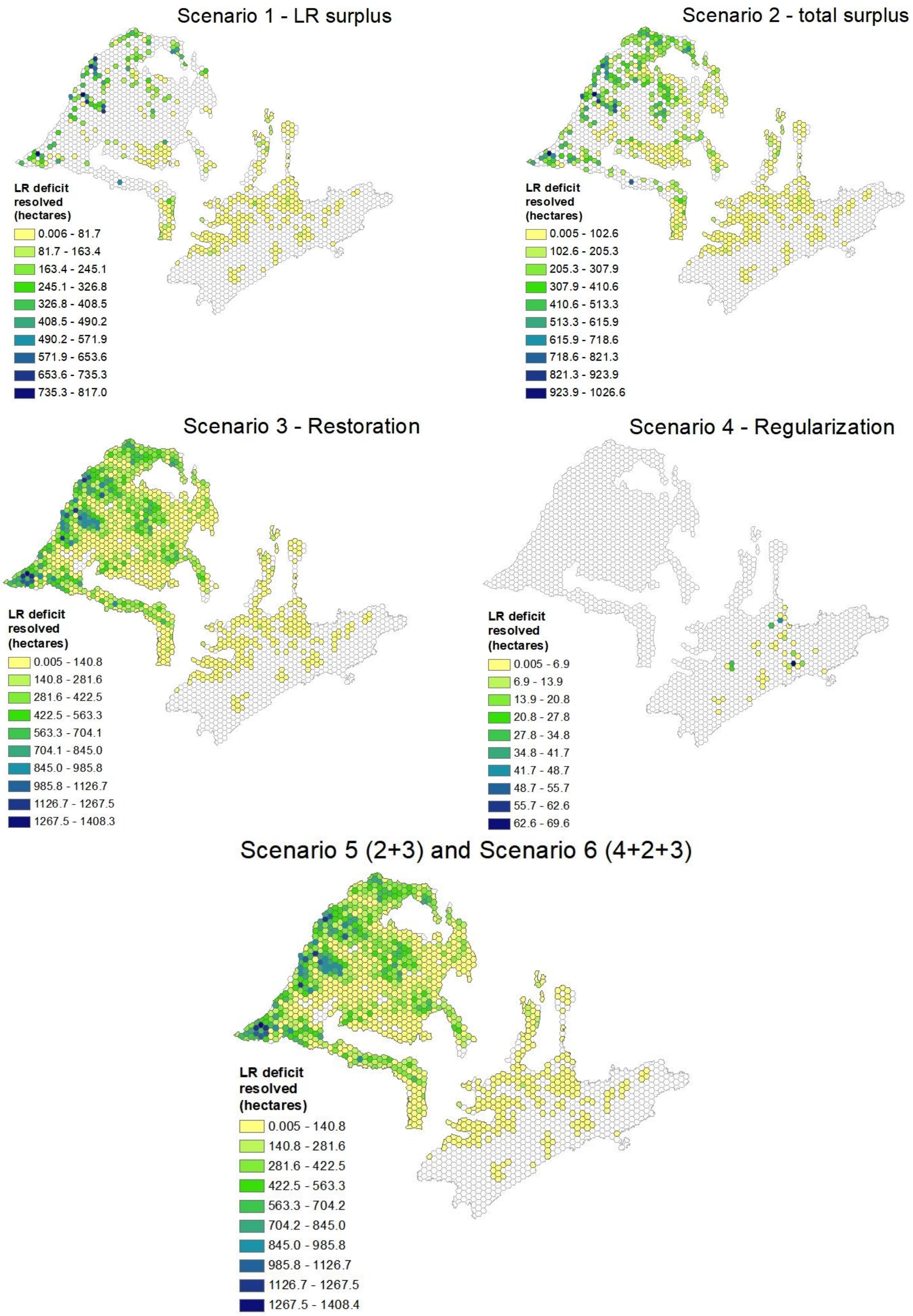

Figure 3: Spatial distribution of Legal Reserve (LR) deficit solved in each hexagon by the compensation strategies applied in each of the six scenarios tested. We highlight there was no difference between scenarios 5 and 6.

Table 2: Comparative results of the six scenarios created to test Legal Reserve (LR) compensation with different strategies.

Scenario name	**Deficit resolution (ha)**	**Deficit resolution (%)**	**Compensation area used (%)**	**Economic costs (U$)**	**Additionality (ha)**
Scenario 1 – LR surplus	38,578.81	17.32	7.23	7,740,614	0
Scenario 2 – Total surplus	89,609.49	40.22	12.07	14,302,815	0
Scenario 3 – Restoration	220,536.32	98.99	12.23	2,156,238,638	220,536.33
Scenario 4 – Regularization	336.69	0.15	0.067	104,080	0
Scenario 5 – scen. 2+ 3	221,601.98	99.47	19.39	1,291,167,026	131,992.49
Scenario 6 – scen. 4+ 2+ 3	221,601.98	99.47	19.417	1,291,196,883	131,992.49

Composite scenarios 5 (scenarios 2 + 3) and 6 (scenarios 4 + 2 + 3) returned virtually the same result (Table 2). In both, the percentage of deficit solved was the same and very high (Figure 3; Table 2), with only 16 hexagons left with some deficit. These hexagons are at the Cerrado - Atlantic Forest ecotone (Figure S6) and their amount of remaining deficit varied from 0.94 to 218.47 hectares. Additionality and percentages of compensation area used were the same in both scenarios (Table 2). However, scenario 6 was about USD 29.8 thousand more expensive than scenario 5.

The outcomes of the two composite scenarios were only comparable to the outcome of simple scenario 3 in terms of efficiency (deficit reduction, economic costs, and additionality). Therefore, scenario 3 was the only simple scenario capable of greatly reducing the deficit in São Paulo state's Atlantic Forest. Scenarios 5 and 6 were cheaper (around USD 865 million less), but also less additional (88,543.84 ha less) than scenario 3. Since the differences in costs were much larger than the difference in additionality, scenarios 5 and 6 should be preferred over scenario 3. Considering scenarios 5 and 6 had very similar results, but 5 presented fewer steps – simpler implementation – and lower costs, scenario 5 seems to be the best choice as a general scheme to compensate Legal Reserves with ecological equivalence.

4. Discussion

Our results showed the Legal Reserve compensation strategies presented by the New Forest Act had different efficiencies when applied isolated, in terms of Legal Reserve deficit resolution, compensation economic costs, and additionality. Regularization of private properties in protected areas performed poorly, protection of stand vegetation had an intermediate performance, and restoration of native vegetation performed well. The latter, however, presented the highest cost among all scenarios, so combining strategies improved the cost-efficiency of the compensation scheme. The best option was Scenario 5, which combined protection of stand vegetation (Legal Reserve surplus and Legal Reserves in small properties) and restoration. All scenarios comprised ecological equivalence as a prime premise. Therefore, we showed that it is indeed possible to achieve full compliance with the Law including ecological equivalence. Besides, compliance is possible even when the compensation scheme is limited to one federal state (*i.e.* São Paulo). The argument that it would lack area to compensate when accounting for equivalent areas inside one state (Mello et al., 2021b) proved to be invalid in our study area when using the Disaggregated Condition Metric. It is likely invalid in other regions of Brazil as well, once São Paulo is the state with the largest Legal Reserve deficits in the country (Freitas et al., 2017).

The two most important compensation strategies were protection of existing native vegetation and restoration. While restoration brought additionality and was more efficient in resolving the Legal Reserve deficit than the protection of existing vegetation – which alone could resolve only around 40% of the total deficit – it was also more expensive. We did not account here for the transaction costs, *e.g.* technical assistance and input production, which could enhance the restoration costs. On the other hand, landowners may restore their native vegetation by simple natural regeneration, which involves practically no cost, and can be successfully stimulated in regions with higher regeneration potential (Crouzeilles et al., 2020). Even if fences are employed in the regeneration process, costs should be much lower than for active restoration (Benini and Adeodato, 2017). It is likely that several landowners choose to restore by natural regeneration, at most using fences, precisely because of its practicality and lower prices (Gastauer et al., 2021).

Even though the total costs for restoration reached millions of dollars state-wide, they would be divided among the 5,467 properties of São Paulo State's Atlantic Forest. The 1,600 properties that are considered larger in size would be the only ones to pay higher values, as they would be proportional to their sizes. Moreover, while most of the cost would be spent during the implementation stage of the restoration process (Benini and Adeodato, 2017), the remaining costs would be diluted across at least 20 years – an average restoration time (Crouzeilles et al., 2016). Restoration costs are lower than the subsidies granted annually by the Brazilian federal government to farmers as agricultural benefits from 2003 to 2019 (R$ 8.8 billion on average; do Amaral and Bacha, 2022). Thus, restoration total costs may be higher than our estimations, due to the inclusion of transaction costs, but may also be lower, due to the employment of exclusive natural regeneration by landowners. In any case, restoration costs should be put in perspective, in terms of the number of landowners that will afford them and the distribution of the expense across time.

Compensating the Legal Reserve deficit in irregular private properties inside public protected areas was the least efficient strategy of all and made no difference in efficiency when included in composite scenarios. The availability of land to compensate with this strategy was low, probably because the protected areas with irregularities in São Paulo Atlantic Forest are all near the coast. This region is highly heterogeneous environmentally, both in abiotic and biotic features, and has less deficit than the northwest region of São Paulo. This makes it harder to find hexagons with deficit that are ecologically equivalent to the hexagons in these coastal protected areas. This strategy had no additionality and no gains in terms of land protection, because all these private properties are inside established protected areas. Compensation through regularization is a bureaucratic transaction, with basically no environmental gains. These negative and inefficient outcomes go in the opposite direction of the latest tendencies of the São Paulo state government concerning Legal Reserve compensation, since the regularization strategy has been preferred or indicated over the others (São Paulo, 2020). Nonetheless, compensation by protecting stand vegetation was a better option in terms of deficit resolution, restoration was even better, and the combination of both strategies was the best option in terms of cost-efficient deficit resolution and of additionality.

Our scenarios assumed ecological equivalence as a non-negotiable premise, since the Brazilian Supreme Court decided it is mandatory, and we suggested ways of measuring and applying it in the New Forest Act. Our findings indicated that including ecological equivalence had the implications of restricting the areas for compensation and increasing compensation prices, as the inclusion necessarily intensified the need for restoration. Indeed, Mello et al. (2021b) found that when ecological equivalence (based on abiotic variables) levels increased, the demand for restoration to compensate all Legal Reserve deficits in the Brazilian Atlantic Forest also increased. Yet, their method resolved only around 70% of the deficit for the biome when the highest level of equivalence was considered (Mello et al., 2021b). The method we proposed here resolved more than 99% of the São Paulo state deficit, using ecological equivalence based on biodiversity, landscape, and ecosystem services, which is a promising result for the biome as a whole. Increasing the demand for restoration due to ecological equivalence had the advantage of bringing additionality to the Legal Reserve compensation scheme. When considering merely the biome as the ecological requirement for compensation, simply exchanging deficits by surplus would be allowed, a measure that brings no additionality to the Atlantic Forest (Mello et al., 2021b; Tavares et al., 2021). Also, including ecological equivalence tended to restrict compensation within the state where the deficit is, which is good because it guarantees the environmental benefits generated by the compensation will not be "exported" to other places that do not suffer the consequences of the deficits.

It has been suggested that restoration to compensate Legal Reserve deficit in the Atlantic Forest should be realized in areas of conservation priority, while mandatory APPs' restoration would fulfill the need for conservation and ecosystem services of non-priority landscapes (Strassburg et al., 2019). However, besides the fact this would disregard the recent Supreme Court decision, these priority areas in São Paulo state, for example, are mainly at the coast region (Strassburg et al., 2019), where there is little deficit and, at the same time, large areas already protected in ecological reserves. Our results indicated it is possible to compensate Legal Reserves by restoring many hectares in the northwest region of the state in a cost-efficiently way. This would avoid the maintenance of the existing spatial inequality in the distribution of ecosystem services (*e.g.* Hohlenwerger et al., 2022 for pest control; Borges-Matos et al. *in prep* for potential pollination service) and would aid in the Atlantic Forest biome recovery (Rezende et al., 2018).

In the big picture, the choice about how to solve the conflicts related to ecological compensation is a reflection of what path we take to face the world's environmental crisis we are going through. What governments prioritize in their environmental policies will indicate whether they are truly committed with changing our socioeconomic system to actually stop this massive destruction of nature, which has had several negative consequences to our lives currently, or whether they are simply the continuity of the system that has brought us to this crisis. Restoration of native vegetation is one of the measures widely suggested in most of the actual environmental agreements, such as the Aichi Biodiversity Targets and Bonn Agreement (Chazdon et al., 2021). We found that compensating Legal Reserves by using restoration can bring an additionality of at most around 221 thousand ha, in case of applying scenario 3 (restoration only), or of at least around 132 thousand ha, in case of applying scenarios 5 or 6. The government of São Paulo state announced in 2021's COP26 the goal to restore 1.5 million hectares of its Atlantic Forest until 2050 ("Programa Refloresta SP"; São Paulo, 2022). The restoration of 221 thousand ha corresponds to 14.7% of this total goal. Summing this number with the mandatory APP restoration (~656 Mha) in São Paulo Atlantic Forest (Tavares et al., 2019) still does not achieve the state's restoration goal – but would already represent 60% of the goal. Furthermore, considering the constantly growing carbon-credit market, landowners could earn money from restoring vegetation in their properties. This would diminish their expense with restoration, maybe even generating profits in the future (Bradbury et al., 2021). Therefore, compensating Legal Reserve deficit using restoration is not only desirable from an environmental perspective, as it is necessary to comply with local and national restoration commitments (Crouzeilles et al., 2019). Restoration can also generate profits via increased agricultural productivity or the provision of ecosystem services (Hua et al., 2022), and there are funds to finance it (via the carbon market, for example).

The approach presented here points towards a clear and feasible way to compensate Legal Reserves accounting for ecological equivalence and should stimulate native vegetation conservation and restoration practices. This should provide multiple benefits in terms of biodiversity conservation and climate mitigation and adaptation, in addition to benefiting local landowners through a range of local services provided by native vegetation. Our approach is intended to be a tool in the process of building an alternative path to face – and solve – this current world climate and environmental urgency.

Acknowledgments

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We provided all the R scripts for the scenarios we tested and the prioritization path in the following address: https://github.com/franciscodalbertas/doutorado_Clarice/blob/main/trading_LR.R.

Discussão Geral e Conclusões

Diante da urgente necessidade de frear os impactos de atividades humanas sobre a biodiversidade, causadores de uma série de problemas em nível global como as mudanças climáticas, torna-se igualmente urgente desenvolver e aperfeiçoar medidas para evitar e reverter os impactos, e compensar os impactos residuais (considerados inevitáveis). Mecanismos relacionados à “hierarquia da mitigação”, dos quais os esquemas de compensação e *offset* fazem parte, são fundamentais para se cumprir esse objetivo. Neste trabalho, buscamos compreender melhor o funcionamento de compensações e *offsets*, desde a perspectiva de medição e implementação de equivalência ecológica nas trocas. Investigamos onde se encontravam as falhas e fortalezas desse processo para então criarmos ferramentas que pudessem contribuir para sua melhora.

Inicialmente, agrupamos as métricas de condição ambiental encontradas em nossa busca na literatura acadêmica e fizemos detalhada análise delas. Assim, avançamos no conhecimento sistematizado dessas métricas, especialmente porque o estudo desse recorte de métricas não havia sido realizado anteriormente. Identificamos padrões nas características das métricas, tanto positivos quanto negativos, e levantamos as principais demandas em relação a elas na literatura de compensação e *offset*, a fim de compreender seus avanços e as lacunas até então. Os resultados permitiram avaliar as métricas revisadas e apontaram a direção para a qual adaptações em métricas atuais ou novas métricas deveriam evoluir. Os *offsets* são tipos de compensação mais exigentes, como mencionado na introdução geral desta tese, por isso a adaptação dos resultados da análise de métricas usadas em *offset* para esquemas de compensação mais gerais é coerente, desde que tenham objetivo de alcançar equivalência ecológica nas trocas.

A partir desses resultados, pudemos desenvolver a nossa própria métrica de condição ambiental, chamada Métrica de Condição Ambiental Desagregada. Mostramos que é possível cobrir todas as lacunas encontradas na revisão bibliográfica em uma métrica que envolve cálculos simples, além de ser espacialmente explícita. Os testes de relação entre os atributos ecológicos utilizados mostram que é possível abrir mão de atributos mais redundantes sem perder informação relevante. Isto desfaz os argumentos de que uma métrica mais completa seria necessariamente mais complexa. Nossa métrica tem como premissa a garantia da equivalência ecológica nas trocas de compensação, portanto outro argumento desfeito foi o de que áreas para compensação são drasticamente reduzidas ao se incluir a equivalência ecológica. No teste da métrica a partir de um impacto hipotético e dados reais da Mata Atlântica do estado de São Paulo, vimos que, em muitos casos, a redução não é relevante, e apenas em alguns casos é mais acentuada. No entanto, em todos os casos houve opção de área para compensação. Este foi o primeiro teste da Métrica de Condição Ambiental Desagregada, que poderá ser aperfeiçoada, mas até aqui se mostrou uma métrica de condição ambiental completa e ao mesmo tempo factível. A ideia é que ela possa ser uma ferramenta nos esquemas de compensação implementados por órgãos ambientais, prontamente em nossa área de estudo e talvez futuramente em outras áreas.

Finalmente, para mostrar como a métrica que desenvolvemos pode funcionar na prática, fizemos um teste utilizando-a em uma situação real: a compensação de Reserva Legal na Mata Atlântica do estado de São Paulo. Criamos cenários baseados nas estratégias de compensação propostas pelo Novo Código Florestal para buscar as combinações de melhor custo-benefício incluindo equivalência ecológica nas trocas. Vimos que é possível praticamente solucionar o déficit dessa região de São Paulo usando uma combinação de proteção de vegetação em excedentes de Reserva Legal com restauração de áreas degradadas, a um custo mais baixo que, por exemplo, compensar somente por restauração, e ainda obtendo vegetação nativa adicional (“adicionalidade”). Sendo assim, mostramos que incluir equivalência ecológica em esquemas de compensação como o de Reserva Legal é possível, tanto em termos financeiros quanto de área para se compensar. Mostramos inclusive que essa inclusão foi possível mantendo as compensações dentro do mesmo estado, uma questão por vezes polêmica no contexto do Novo Código Florestal brasileiro, que ficou pendente de ser resolvida pelos Programas de Regularização Ambiental (PRA) de cada estado.

Segundo informações detalhadas que organizamos em nossa revisão bibliográfica, construímos a Métrica de Condição Ambiental Desagregada para alcançar equivalência ecológica nas trocas por compensação. A métrica é relativamente simples e ao mesmo tempo informativa e completa. Ela também pode ser aplicada em situações práticas, como indicaram os resultados dos testes de impacto hipotético e de esquema de compensação de Reserva Legal em nossa área de estudo, este com condições e dados reais.

A métrica e o procedimento de trocas considerando equivalência ecológica propostos aqui podem ser aplicados para outros sistemas ou regiões, como, por exemplo, para todo o bioma Mata Atlântica e para outros biomas brasileiros, considerando cenários similares ou complementares aos que usamos no estado de São Paulo. Dessa forma, teríamos em mãos sugestões de boas práticas factíveis baseadas em ciência para esquemas de compensação em geral e, mais especificamente, para a implementação do Novo Código Florestal no tocante a compensação de Reserva Legal. Esperamos que nosso estudo abra portas para a implementação de métricas que incluam equivalência, como a Métrica de Condição Ambiental Desagregada, e para outras ferramentas de *offsetting* em diferentes regiões e contextos de compensação ambiental.

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Apêndice A: Material Suplementar – Capítulo 1

Table S1: Information about the papers included in the review.

Authors reference	Year of publication	Journal / Book	Condition metrics described or mentioned	Type of paper (according to the data analyzed)	Geographic/climatic zone of the data or examples given
Bull et al	2013	Oryx	HH	Theoretical	Global (but most examples are of Global North countries)
Spake et al	2015	Conservation Biology	LRR	Review (meta-analysis)	Boreal, Temperate and Mediterranean
Gamarra et al	2018	Journal of Environmental Management	HEP, HH, BOP, MAM, CSI	Review	Global
Bezombes et al	2017	Environmental Management	HEP, HH, BOP, CRAM, SHEP	Theoretical / Review	Temperate
Poll et al	2016	Landscape Ecology Engeneering	CBV	Empirical	Temperate
Gordon et al	2011	Environmental Modelling and Software	HH	Empirical	Temperate
Gardner et al	2013	Conservation Biology	HH	Review	Global
Bull et al	2014	Biological Conservation	HH	Empirical	Temperate / Subtropical
Brown et al	2014	New Zealand Journal of Ecology	SEV	Empirical	Temperate
Sangermano et al	2015	Applied Geography	HH	Empirical	Tropical
Bull et al	2014	Conservation Biology	HH, BOP	Empirical	Temperate
Jacob et al	2016	Ecosystem Services	HH	Theoretical / Review	Global
Maron et al	2015	Biological Conservation	HH	Empirical	Temperate
Mandle et al	2016	Environmental Modeling and Software	LCI	Empirical	Global
McLaughlin & Cohen	2013	Ecological Applications	FWCI	Empirical	Sub-tropical
Moreno-Mateos et al	2015	Biological Conservation	HH, BOP	Theoretical	Global
Bidaud et al	2015	Ecosystem Services	HH, QH	Empirical	Tropical
Virah-Sawmy et al	2014	Journal of Environmental Management	CSI	Empirical	Temperate / Tropical
Brownlie & Treweek	2016	Book: Handbook on Biodiversity and Ecosystem Services in Impact	HEP, HH	Theoretical	Global

		Assessment			
Koh et al	2019	Journal of Environmental Management	QH	Empirical	Global (but most examples are of Global North countries)
Ives & Bekessy	2015	Frontiers in Ecology and the Environment	HH	Theoretical	Global
Stone et al	2019	Ocean and Costal Management	BOP, DMRH	Empirical	Temperate
Grimm	2020	Journal for Nature Conservation	ECF	Empirical	Temperate
Bergès et al	2020	Journal of Environmental Management	ECF	Empirical	Global
Cuckston	2019	Accounting, Auditing & Accountability Journal	VIS	Theoretical	Global
Ferreira & Ferreira	2018	Review of Social Economy	BOP	Theoretical / Empirical	Temperate
Sullivan & Hannis	2015	Ecosystem Services	BOP	Empirical	Temperate
Sullivan & Hannis	2017	Accounting, Auditing & Accountability Journal	BOP	Empirical	Temperate
Carver & Sullivan	2017	Conservation Biology	BOP	Empirical	Temperate
Reid & Nsoh	2013	Environmental Law and Management	BOP	Theoretical	Temperate
Drobnik et al	2020	Journal of Environmental Management	SQUID	Empirical	Temperate

Apêndice B: Material Suplementar – Capítulo 2

Table S1: Standard deviation for each measured attribute; the units are the same as the respective attribute.

Attributes	Standard deviation
Tree richness	146.6182
Pollination service	85.2110
Bird richness	53.4112
Carbon storage	32.4230
% Forest cover	26.7848
Amphibian richness	13.3141
Bird composition	0.3637
Amphibian composition	0.3462
Tree composition	0.3434
Connectivity PC 400 m	0.2512
Connectivity PC 200 m	0.2500
Connectivity PC 50 m	0.2463

Table S2: Spearman correlations for each pair of ecological attribute measured.

	Amphibian richness	**Bird richness**	**Tree richness**	**Amphibian composition**	**Bird composition**	**Tree composition**	**% Forest cover**	**Connectivity PC 50 m**	**Connectivity PC 200 m**	**Connectivity PC 400 m**	**Carbon storage**	**Pollination service**
Amphibian richness	1											
Bird richness	0.9167	1										
Tree richness	0.8997	0.9332	1									
Amphibian composition	0.8941	0.9095	0.9201	1								
Bird composition	0.8791	0.9156	0.8660	0.9177	1							
Tree composition	0.8819	0.9206	0.9052	0.9262	0.9484	1						
% Forest cover	0.7142	0.7182	0.7119	0.7124	0.7392	0.7229	1					
Connectivity PC 50 m	0.6534	0.6581	0.6694	0.6708	0.6734	0.6647	0.9553	1				
Connectivity PC 200 m	0.6793	0.6853	0.6912	0.6921	0.7009	0.6897	0.9744	0.9945	1			
Connectivity PC 400 m	0.6923	0.6987	0.7006	0.7015	0.7151	0.7023	0.9843	0.9867	0.9979	1		
Carbon storage	0.7997	0.8065	0.7907	0.7785	0.7962	0.7861	0.9164	0.8866	0.9021	0.9090	1	
Pollination service	0.7408	0.7561	0.7242	0.7229	0.7689	0.7539	0.9083	0.7968	0.8399	0.8646	0.8267	1

Figure S1 shows the maps using the gross values of the four ecological attributes chosen to test the functioning of the Disaggregated Condition Metric. The attributes' values were divided in 12 color-classes, following Sturges' Rule (Scott, 2009).

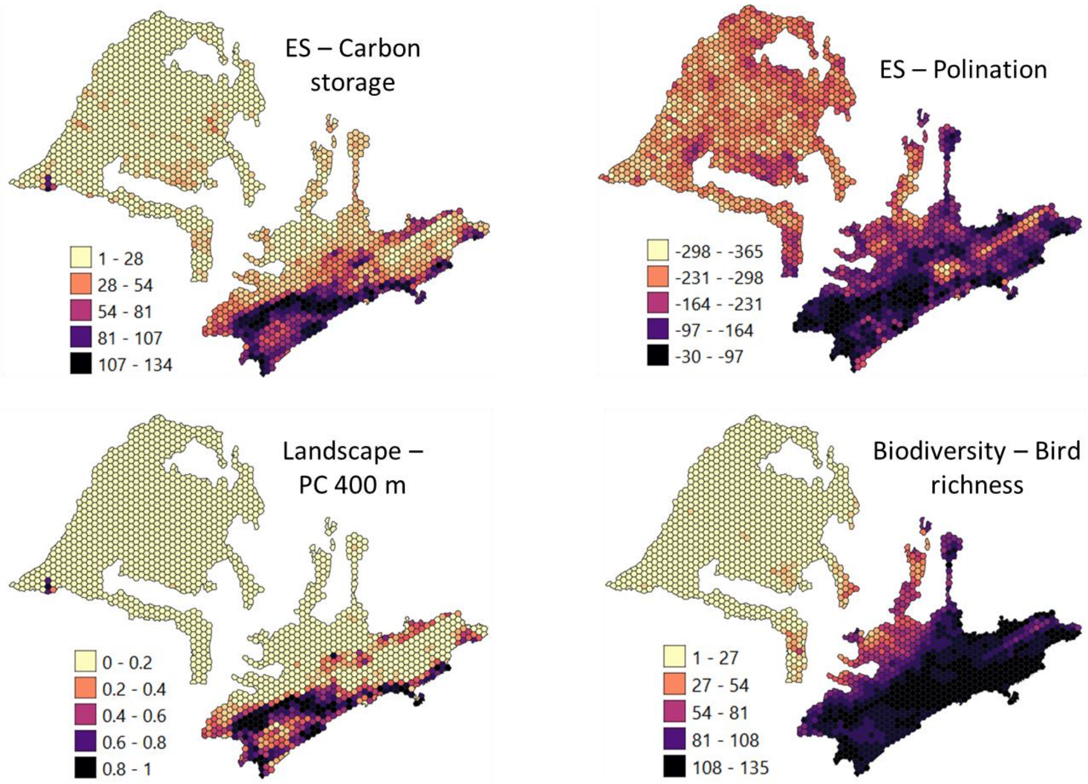

Figure S1: Gradients of the four ecological attributes selected to test the Disaggregated Condition Metric in the Atlantic Forest of São Paulo state, with gross-values subdivided in 12 color-classes. The darker the color, the greater the attribute value. ES = Ecosystem Services, PC 400 m = Probability Connectivity index with 400 meters distance threshold.

We made three exploratory tests with 3-attributes Mean Pair-Wise distance (MPD) in the selection process of attributes to be included in the Disaggregated Condition Metric. The first test included the three attributes with the highest mean correlation in each grouping (Table 1; carbon storage, bird richness and PC 400 m). Its MPD patterns were similar to all-attributes MPD, but sharper (Figure S2A). The second test was the chosen 3-attributes MPD in the main text, which was equal to the first, but substituting carbon storage by potential pollination service, since the latter presented an overall lower correlation with attributes in general and a higher variability (SD) compared to carbon storage. The third test included bird richness, pollination instead of carbon storage as well, and landscape attribute forest cover percentage instead of Probability of Connectivity (PC) 400 m. We switched the landscape attributes because the correlation between forest cover percentage and carbon storage was high (0.9164) and forest cover percentage is a more intuitive and easier to calculate measure than PC index. The result was similar to the second MPD test, but differences were smaller at the coast region (Figure S2B), and the MPD average was also smaller (0.2158). Therefore, forest cover percentage was less complementary than the connectivity index to the biodiversity and ecosystem services attributes selected.

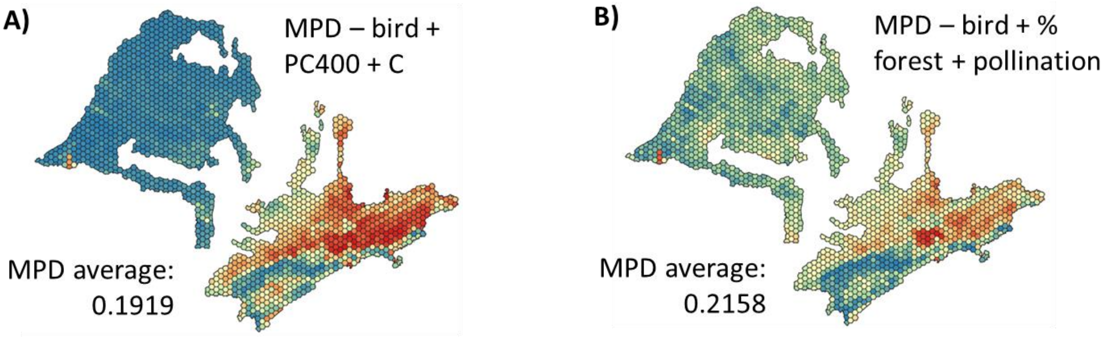

Figure S2: Mean pair-wise distance (MPD) maps for the Atlantic Forest in São Paulo state, representing the spatial differences among hexagons for the following groups of attributes: A) the 3 attributes with highest mean correlation within each grouping (bird richness + connectivity PC 400 m + carbon storage); B) bird richness and pollination, with % forest cover replacing connectivity. The cooler the color, the smaller the MPD; the hotter the color, the larger the MPD – or difference – among the attributes in a given hexagon. The MPD average for each attribute group is at the bottom left of each map. Values were represented in maps with no fixed number of color-classes, divided in standardized intervals of 0.01.

The “impact-hexagons” randomly chosen from each of the two different regions of São Paulo’s Atlantic Forest (northwestern and southern regions) are shown in detail in Figure S3.

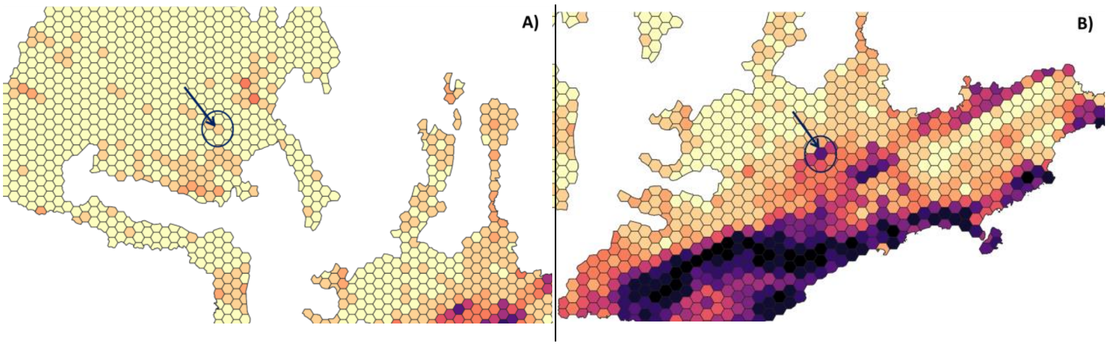

Figure S3: The hexagons randomly chosen to test the Disaggregated Condition Metric where a hypothetical impact would have occurred at (A) the northwestern and (B) the southern regions of São Paulo state Atlantic Forest. The carbon storage map was used as model for this figure.

The hexagons ecologically equivalent to the impact-hexagons for each of the four ecological attributes chosen to test the functioning of the Disaggregated Condition Metric were depictured in Figure S4 and S5 for northwestern and southern regions of the Atlantic Forest in São Paulo, respectively.

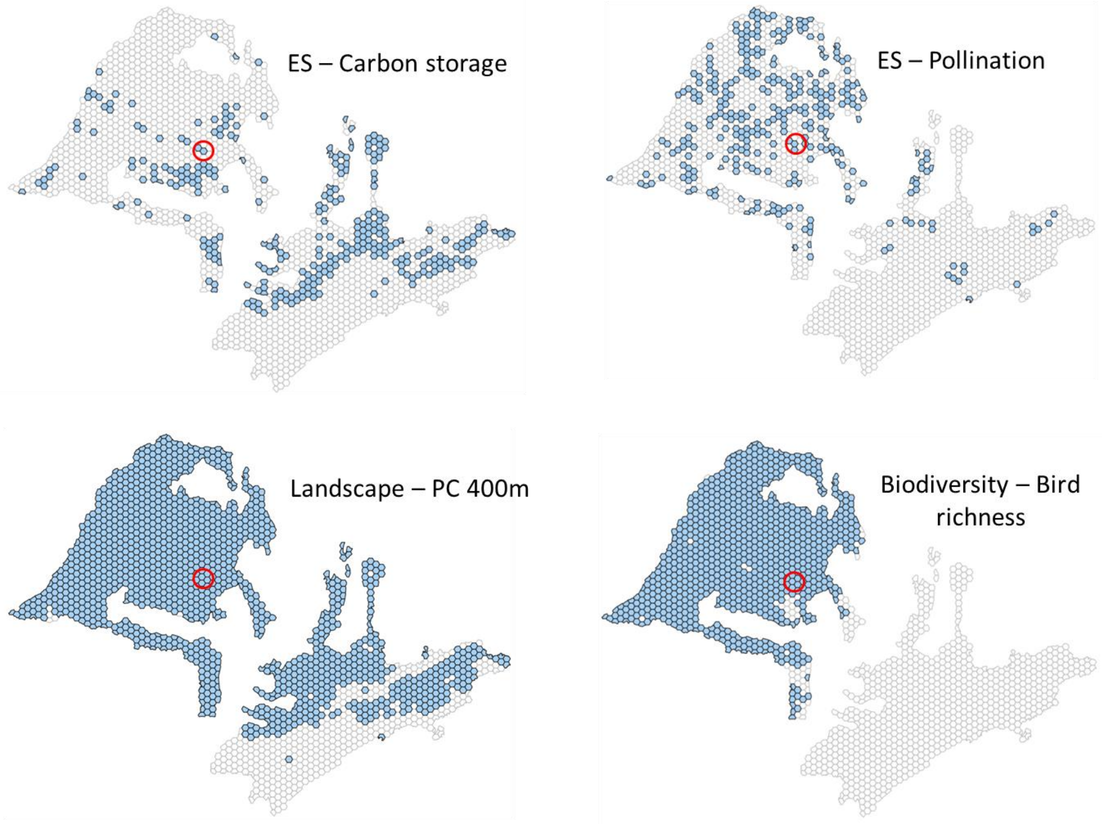

Figure S4: Hexagons of the same class for each of the four ecological attributes chosen for this test. These classes are correspondent to those of the impact-hexagon (highlighted by a red circle) in the northwestern region of São Paulo state Atlantic Forest. ES = Ecosystem Services, PC 400 m = Probability Connectivity index with 400 meters distance threshold. The correspondent classes to each attribute were: bird richness - class 1, PC index 400 m - class 1, carbon storage - class 2, potential pollination service - class 4.

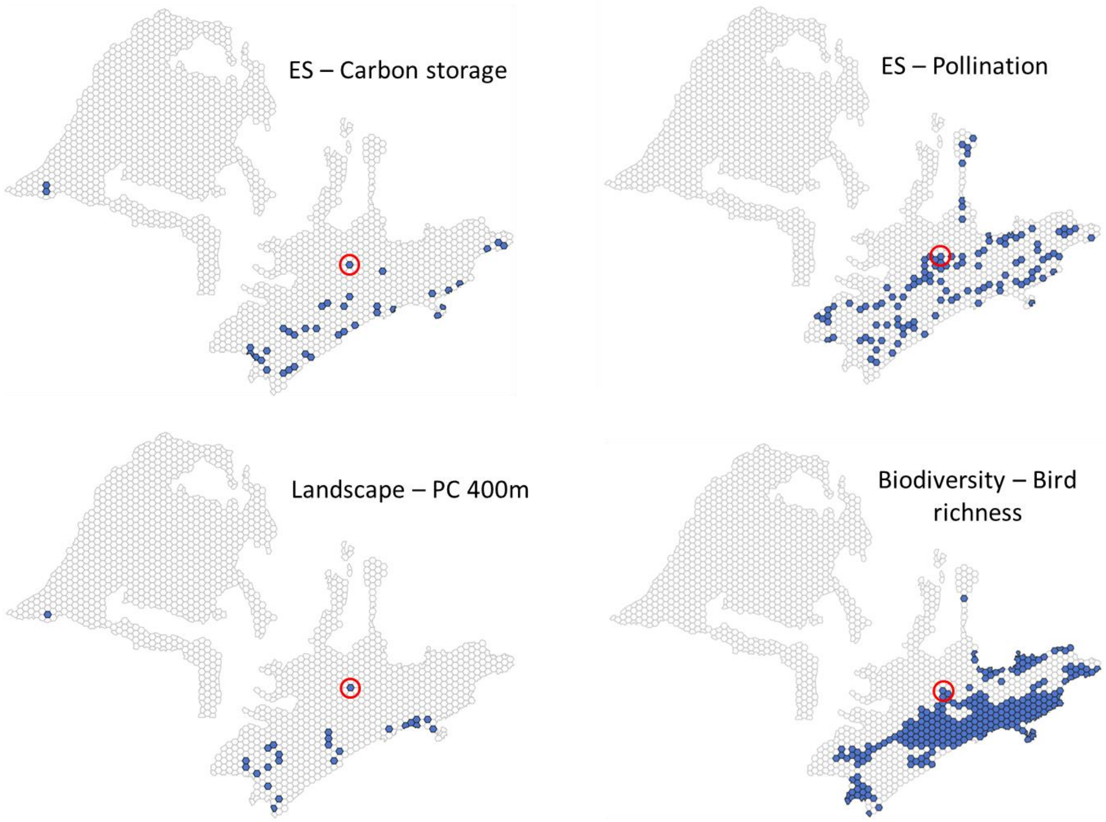

Figure S5: Hexagons of the same class for each of the four ecological attributes chosen for this test. These classes are correspondent to those of the impact-hexagon (highlighted by a red circle) in the southern region of São Paulo state Atlantic Forest. ES = Ecosystem Services, PC 400 m = Probability Connectivity index with 400 meters distance threshold. The correspondent classes to each attribute were: bird richness - class 12, PC index 400 m - class 11, carbon storage - class 9, potential pollination service - class 10.

Apêndice C: Material Supplementar – Capítulo 3

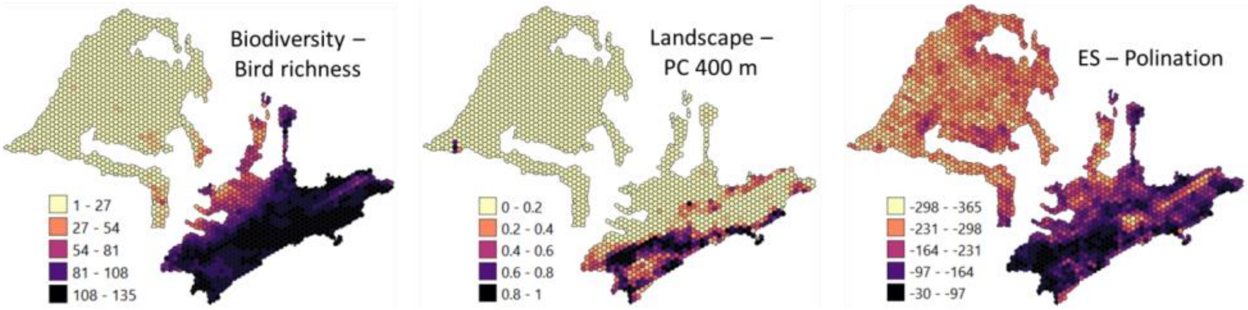

Figure S1: Spatial distribution of the three ecological attributes of the Disaggregated Condition Metric in São Paulo state's Atlantic Forest, with their gross-value per hexagon grouped in 12 classes. The darker the color, the higher the attribute's value. ES = Ecosystem Services, PC 400 m = Probability Connectivity index with 400 meters distance threshold. Richness was measured in number of species, pollination in meters, and the PC index has no unit of measure. For more information, see Borges-Matos et al. (*in prep*).

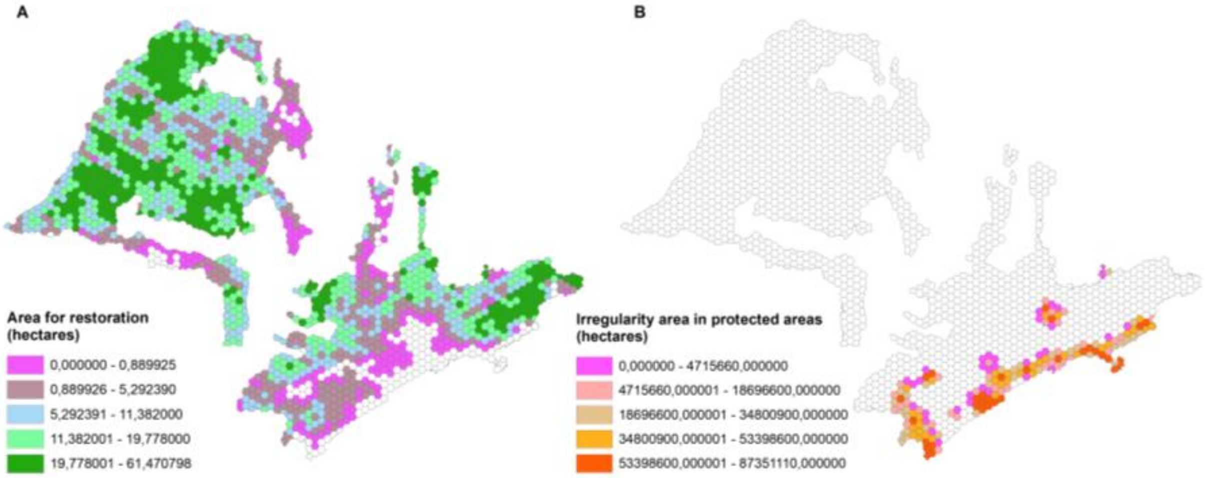

Figure S2: Spatial distribution of (A) the area available for restoration (pasture of low agricultural suitability) and (B) the area of private properties irregularly inside protected areas (approximate values) per hexagon.

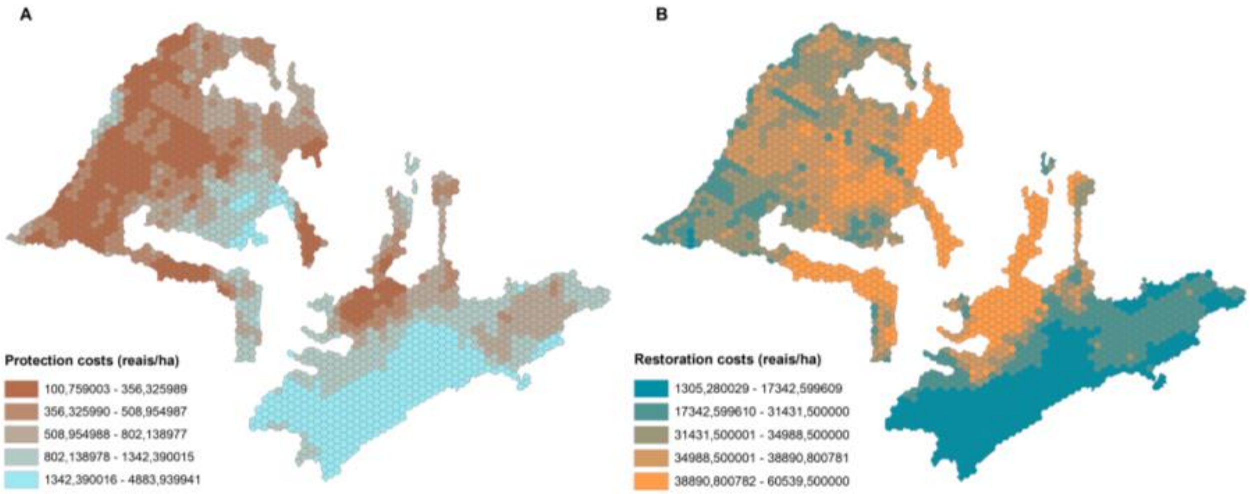

Figure S3: Spatial distribution of the economic costs (R$ per hectare) per hexagon to compensate (A) through protection of stand vegetation and (B) through restoration of native vegetation.

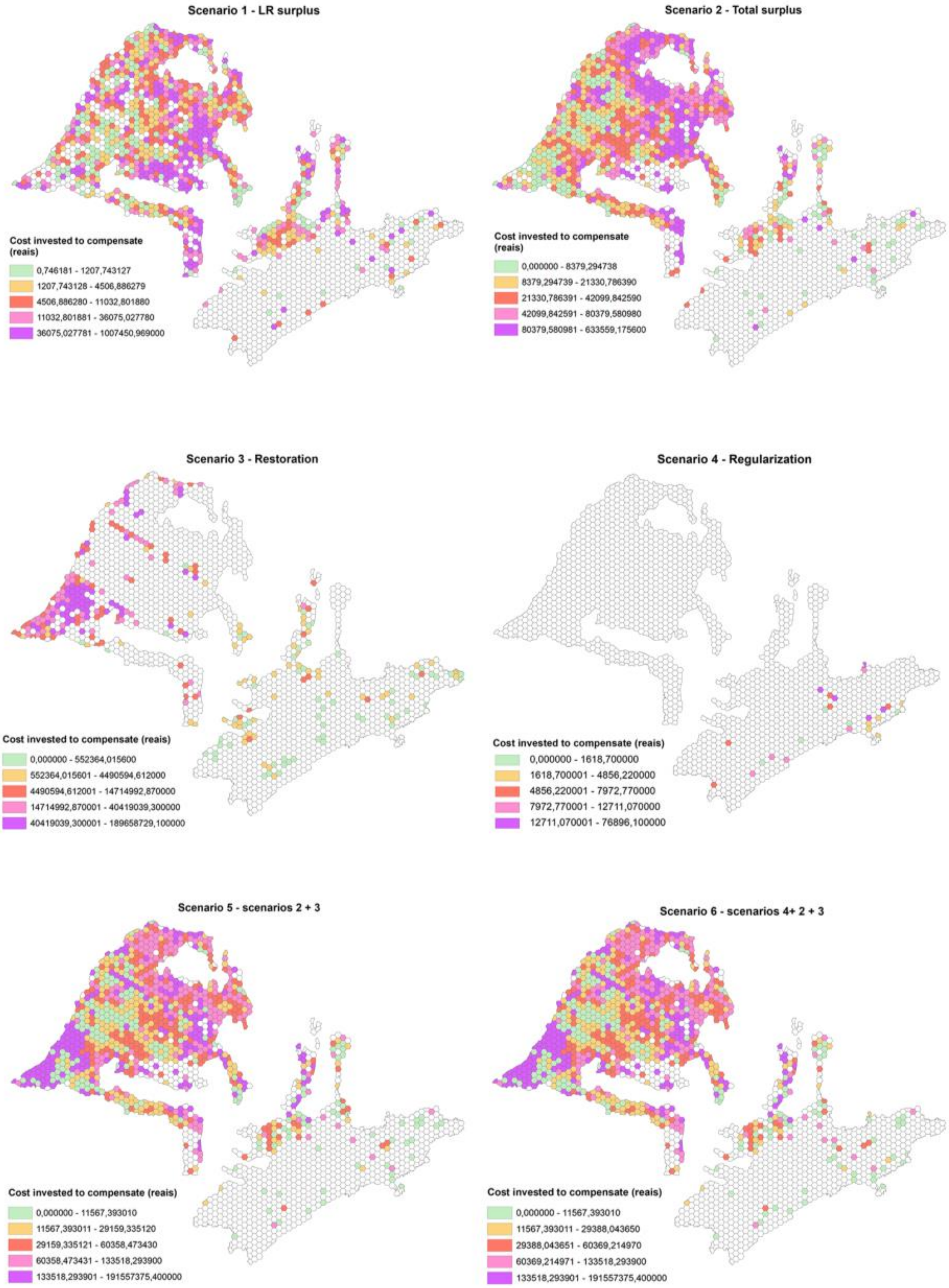

Figure S4: Spatial distribution of the costs (*reais*) that would be invested to compensate in each hexagon in the six scenarios tested for Legal Reserve compensation.

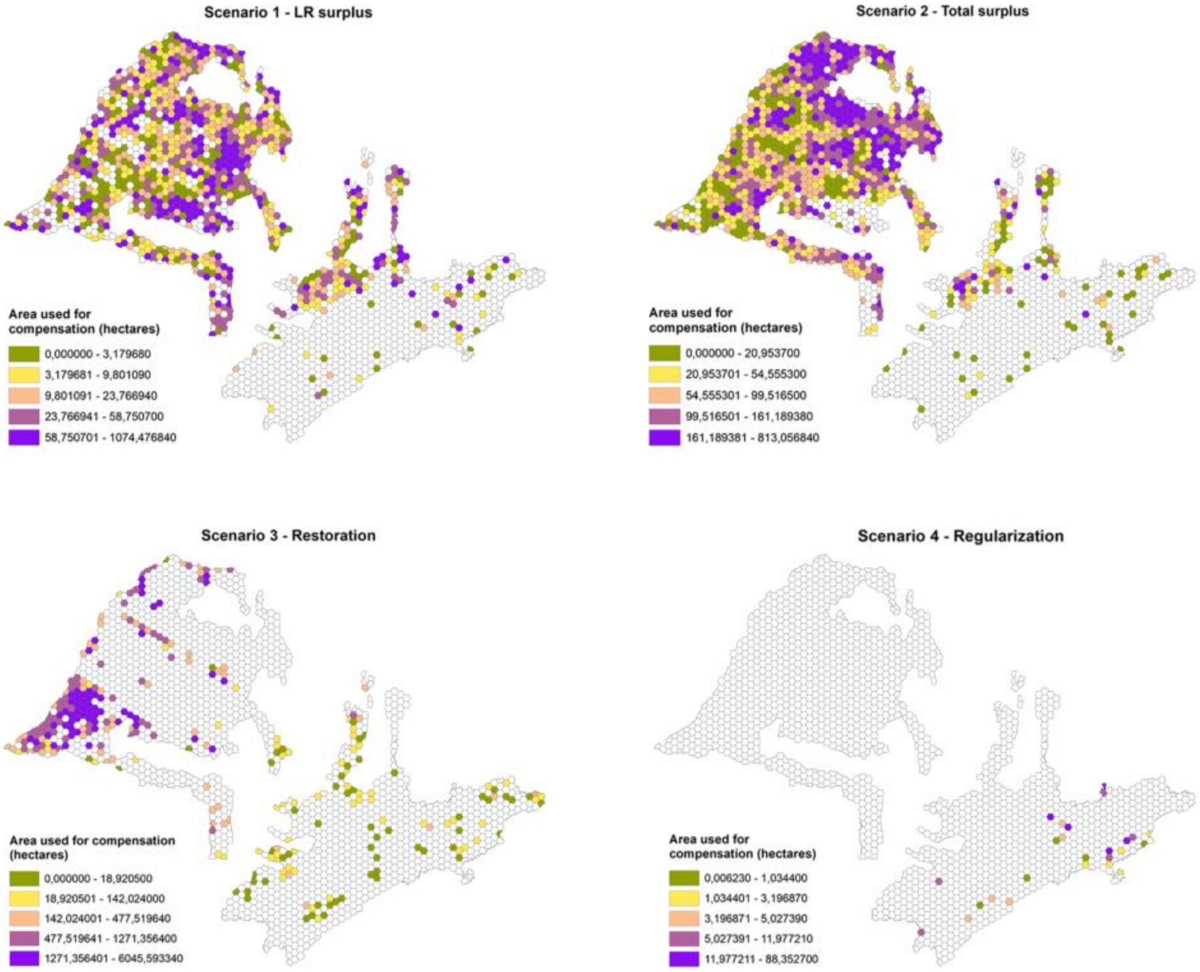

Figure S5: Spatial distribution of the area used in each hexagon to compensate in the four simple scenarios tested for Legal Reserve compensation.

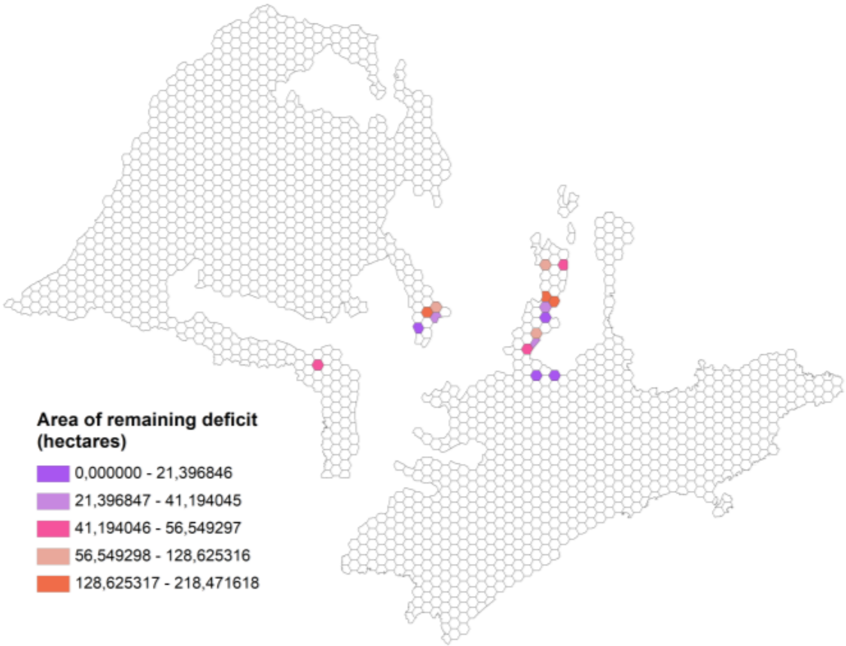

Figure S6: The 16 hexagons that remained with Legal Reserve deficit in scenarios 5 and 6.