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Combining protection and restoration strategies enables cost-effective compensation with ecological equivalence in Brazil

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ABSTRACT

Ecological compensation and offsets have been used worldwide to repair the residual impacts caused by human activities. Achieving ecological equivalence in them has been challenging, and conflicts between development and environmental sectors commonly arise. We addressed this issue by testing an approach that is cost-effective and includes equivalence in compensation. We used the Brazilian Native Vegetation Protection Law's Legal Reserve (a native vegetation percentage of every rural property that must be conserved) compensation scheme as a study case. We created scenarios to test the law's three main compensation strategies (vegetation protection, restoration, and regularization of private lands inside public protected areas) separately and combined. We used a recently developed framework to assess ecological equivalence, including biodiversity, landscape, and ecosystem attributes measured and exchanged in a disaggregated manner. Cost-effectiveness was evaluated regarding deficit resolution (deficit in Legal Reserve needing compensation), economic costs, and native vegetation gained (additionality). The most effective strategy for deficit resolution was restoration (98.99 % of resolution), followed by protection (40.22 %) and regularization (0.15 %). Restoration was the most expensive strategy, but it also had the highest additionality. Combined scenarios resulted in balanced cost-effectiveness. The combination of protection followed by restoration was the best strategy, since its deficit resolution was high (99.47 %), with an intermediate cost and additionality. It is thus possible to make cost-effective compensation exchanges accounting for ecological equivalence adequately. We also used simple calculations in a new spatial optimization automated deficit and compensation prioritization path to generate spatially explicit results. Considering ecological equivalence guarantees additionality and more equitable spatial distribution of ecological benefits. These findings underscore the importance of incorporating equivalence in compensation, offering a promising avenue for bolstering efforts in compensation and offset schemes to address the ongoing climate and environmental global crisis by proposing a new approach to achieve this.

1. Introduction

Ecological compensation and biodiversity offsets have been used in many parts of the world to counterbalance 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; GIBOP, 2019; Gonçalves et al., 2015; Rosa et al., 2022). These mechanisms are important in achieving the recent international goal of becoming "Nature Positive" (Maron et al., 2023). Offsets require the exchanges (or trades) of losses and gains are made with ecological equivalence and at least no net loss of biodiversity (BBOP, 2012a; Bull et al., 2016). "Ecological equivalence" in the offsetting context is understood as the numerical and categorical attributes, summarized in the equivalence dimensions of biodiversity, landscape, and ecosystem services (Borges-Matos et al., 2023), that should be measured and compensated for according to the Business and

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Biodiversity Offsets Programme (BBOP, 2012a, 2012b). This Programme emphasized that offset sites must be highly comparable to the impacted sites (BBOP, 2012b). Therefore, a broader concept was needed, which included not only biodiversity and ecological attributes, but also landscape and socio-environmental attributes – i.e. ecosystem services, which are paramount to improve offsetting effectiveness (Habib et al., 2013; Jones et al., 2019; Mitchell et al., 2015; Sonter et al., 2020a). Ecological compensations are more general and less strict than offsets, as they do not require no-net-loss and may not require ecological equivalence (BBOP, 2012a). Yet, they often use attributes to assess and achieve distinct levels of ecological equivalence in their trades (Bennett et al., 2017; Mello et al., 2021a). Indeed, environmental outcomes of compensation and offset are improved when ecological equivalence is accounted for (BBOP, 2012a). On the other hand, equivalence is usually understood as a factor that significantly restricts the area available to compensate, since only equivalent areas would be eligible (Weissgerber et al., 2019). This could make compensation more expensive, as productive lands – with higher opportunity costs – may be requested for restoration (Mello et al., 2021a).

This discussion on offset and compensation implementation is present worldwide. This includes Brazil, with its Native Vegetation Protection Law, known as the New Forest Act (Law n° 12.651, dated May 25, 2012). This law establishes rules for land use and protection of native vegetation in private rural lands. It is an essential conservation tool in Brazil, given that 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. Permanent Protection Areas are ecologically vulnerable, such as areas of steep slopes and riparian forests, and they must be restored on-site in cases of degradation. Legal Reserves are a percentage of the property area (ranging from 20 % to 80 % depending on the Brazilian biome where the property is located) that should be covered by native vegetation. Legal Reserve deficits must be compensated, and the only ecological requirement provided in the Act is that it must be implemented in the same biome of the deficit.

In 2019, the Brazilian Federal Supreme Court reviewed the agreement document on the Forest Act (Declaratory Action of Constitutionality 42 – Judgment, February 28, 2018) and ruled that Legal Reserve deficits should be compensated in sites ecologically equivalent, in terms of "specific species and ecosystems". The decision recognized the significant heterogeneity existing within Brazilian biomes (e.g., Alho et al., 2019; Dambros et al., 2020; Silva and Casteleti, 2003). Therefore, if compensating in an entire biome was allowed, it could lead to unbalanced trades, with potentially more losses than gains (Metzger, 2010). The environmental and agricultural sectors criticized this demand for ecological equivalence, mainly because it did not define how to measure it 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, increasing the compensation costs to landowners (Mello et al., 2021a, 2021b). A new ruling in 2023 established that ecological equivalence should be included in all compensation forms described in the Act (Lopes et al., 2023). However, in October 2024, the Court reversed its decision, considering it legal to compensate within the same biome without any other ecological requirement (Lopes et al., 2024).

Despite this recent change – and the frequent changes experienced in Brazilian legislation – ecological equivalence remains an important part of any compensation scheme that aims to improve a site's ecological condition. The Court's first decision generated a discussion about how to calculate equivalence in practice, preferably cost-effectively. This is a worldwide challenge, since there is yet no clear answer to how cost-effective inclusion of equivalence in compensation and offset can be made (Grimm, 2021; Sonter et al., 2020b). In the last 40 years, there has been an integration of main principles in offset policies globally (e.g. no net loss requirements), but also a diversification in the measures and actors involved (Droste et al., 2022). This increases the complexity of policies and may hinder the effectiveness of offsets (Droste et al., 2022). Moreover, only 14 countries have documented guidelines on how biodiversity should be assessed for offsetting, and most of these documents lack clarity on the calculation of metrics and/or fail to use the metrics most commonly recommended in offset literature (Marshall et al., 2023). This lack of consistency in biodiversity measurement undermines our ability to evaluate the effectiveness of offset and compensation (Marshall et al., 2023).

There are several methods for assessing ecological equivalence, and they are constantly being refined and developed. One reason is the challenge of measuring and achieving ecological equivalence between losses and gains (Borges-Matos et al., 2023; Gonçalves et al., 2015; Marshall et al., 2020), which leads to uncertainties about the real biodiversity gains of compensation and offset schemes (Apostolopoulou and Adams, 2017; Bull et al., 2013; Souza et al., 2023; zu Ermgassen et al., 2019). Also, transparency often lacks in such schemes and methods (Borges-Matos et al., 2023; Carmo and Kamino, 2023; Maron et al., 2016). In the US and European Union, no-net-loss policies rely greatly on a metric called Habitat Equivalency Analysis, which even counts on a specific software (Pioch et al., 2017), but it is focused only on the ecosystem services dimension of equivalence. In Australia, the Habitat Hectares metric (Parkes et al., 2003) was developed in the state of Victoria and is still in use today (Lorimer, 2024). It is one of the most widely recognized offset metrics (Borges-Matos et al., 2023 Sup. Mat.), but it has the limitation of data aggregation – combining the attribute values in one single final value. This usually results in unclear substitutions among the attributes (Hanford et al., 2017; Maseyk et al., 2016). The English metric originally called Biodiversity Offsetting Pilots (DEFRA, 2012), now called Statutory Biodiversity Metric (DEFRA, 2024), is becoming increasingly popular (Borges-Matos et al., 2023 Sup. Mat.). In spite of its successful use in England, it depends on a large number of ecological variables and data to be applied. This may hinder its implementation in many regions, particularly in the highly biodiverse countries of the Global South (Borges-Matos et al., 2023, 2025).

Here, we tackled all the above issues using the Brazilian Forest Act as a case study. We focused on the compensation strategies proposed in the new law (i.e., on-site or off-site restoration, and off-site compensation involving standing vegetation in private and public protected areas; see Section 2.1) and their economic costs, using a recently developed method to approach ecological equivalence called Condition Assessment Framework (Borges-Matos et al., 2025), which assumes equivalence as a central premise. We chose this method because it is the only one that simultaneously incorporates biodiversity, landscape and ecosystem services attributes in a disaggregated way, relying on a small number of attributes assessed through simple calculations, with spatially explicit results and flexibility in its application. We sought to understand (1) how effective each compensation strategy is when applied alone and (2) what strategy or combination of strategies is most effective in compensating Legal Reserve deficits. To answer these questions, we designed and tested compensation scenarios using the Atlantic Forest of São Paulo state as our study area. We used the automated prioritization path we developed here for spatial optimization. To our knowledge, this is the first approach that evaluates and maximizes compensation cost-effectiveness by combining economic costs with ecological equivalence based on biodiversity and socio-environmental attributes. The approach uses straightforward calculations to produce spatially explicit results, where attribute values are transparently disaggregated and can be flexibly substituted with others in different contexts.

2. Methods

2.1. Study area and its legal requirements

We developed compensation scenarios (see Section 2.2) for the Atlantic Forest in São Paulo, Brazil (Fig. 1). The mandatory Legal Reserve is 20 % of the property in this region.

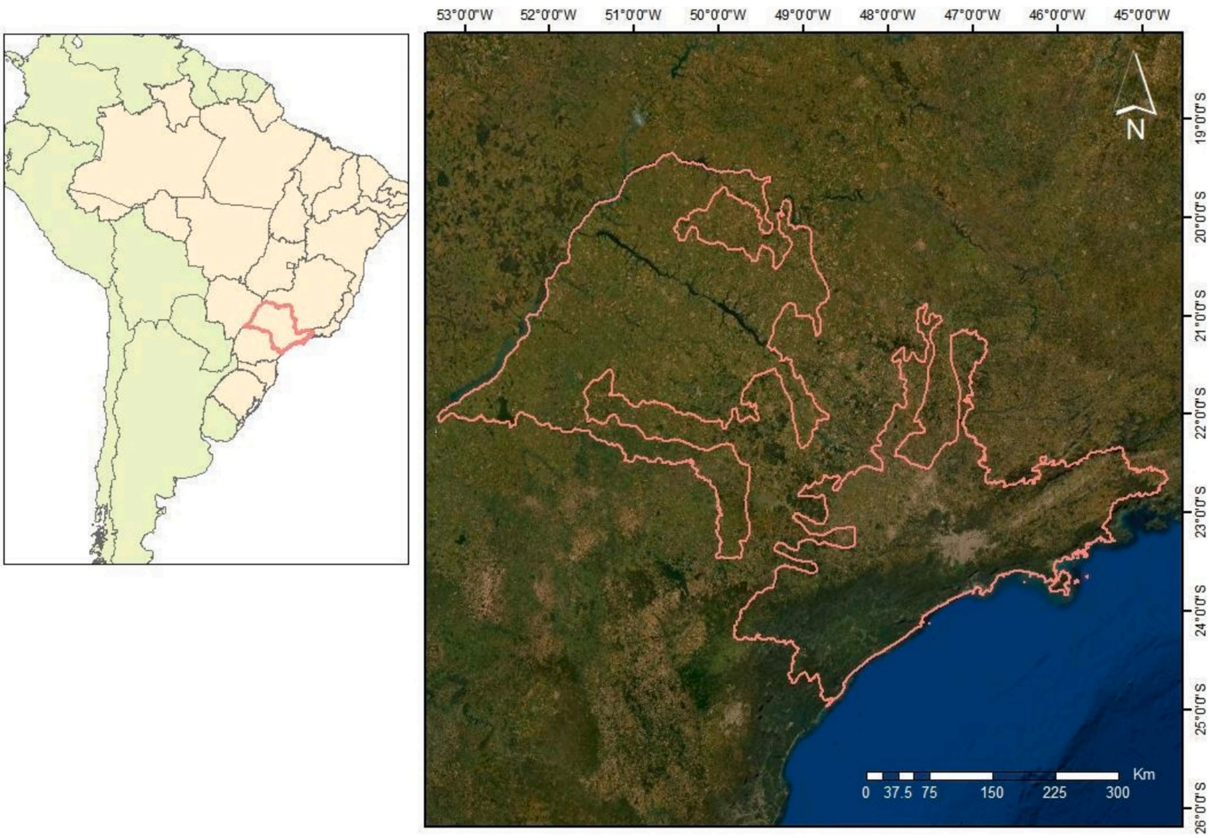

Fig. 1. The Atlantic Forest domain in São Paulo state – highlighted in pink in the larger map – our study area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article)

The Brazilian Native Vegetation Protection Law's compensation strategies for Legal Reserve deficits can be summarized as protection of standing vegetation, restoration of native vegetation (either in or outside the property with the deficit), and regularization of private properties inside public protected areas (Fig. 2). In the latter case, regularization occurs when the landowner with a deficit acquires a non-regularized property within a public protected area (i.e. an area not appropriated by the state when creating the reserve) and donates it to the state. The Legal Reserve surplus is the standing vegetation that exceeds the Legal Reserve of a property and it can be used to compensate for other landowners' deficits, through commercial transactions provided in the law. The New Forest Act allowed for the first time that Legal Reserves of small properties can also be used to compensate for deficits in larger properties. These Legal Reserves would function as standing vegetation areas. Thus, their owners can use them in compensation transactions; they cannot deforest their existing Legal Reserve, but they are no longer obligated to compensate for their deficit (if any).

2.2. Scenarios for Legal Reserve compensation

We designed six scenarios to answer our questions, all including ecological equivalence. First, we tested how each compensation strategy alone would perform in the Atlantic Forest of São Paulo. Then we tested combinations of these strategies, aiming to fully solve the Legal Reserve deficit and select the best combination. Four were called "simple scenarios" as they tested the strategies alone. Two were considered "composite scenarios" once they combined strategies to maximize deficit reduction or elimination (Table 1). Restoration was the last step in both composite scenarios because it was the strategy of higher cost per hectare (see Section 2.4). Since including small properties' Legal Reserves as a possibility for compensation is a novelty, we split the strategy of protecting standing 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 Law). 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, only protection including small properties' Legal Reserves was considered, as these scenarios aimed to eliminate the deficit.

We developed an automated spatial optimization tool using a prioritization path within the R environment (R Core Team, 2021) to define the hexagons that contained deficits and were ecologically equivalent to the hexagons with areas available for compensation, in accordance with the strategies outlined by the Law. The hexagon with a deficit itself was always considered a possibility for compensation. In all scenarios, compensation was made iteratively for each hexagon with deficit, and the compensation and deficit areas were updated at each turn. Hexagons that contained areas for compensation were ascending in order according to their compensation cost, so that spatial units of lower costs would be selected first for the compensation scheme. The hexagons containing deficit areas were descending in order; those with larger deficits were chosen first. The spatial optimization tool allowed compensation trades exclusively among ecologically equivalent hexagons. The iteration went on until trades among equivalent hexagons ran out.

The scenarios' cost-effectiveness performances were evaluated according to the area of deficit solved (hectares and percentage), economic compensation costs (in Brazilian *reais* (BRL) and United States dollars (USD)), and additionality (area in hectares of native vegetation gained relative to the current vegetation area). Further, we calculated the extent of the area available for protection, restoration, and regularization was used in the compensation scheme of each scenario (hectares and percentage). All analyses were performed in the R environment (R

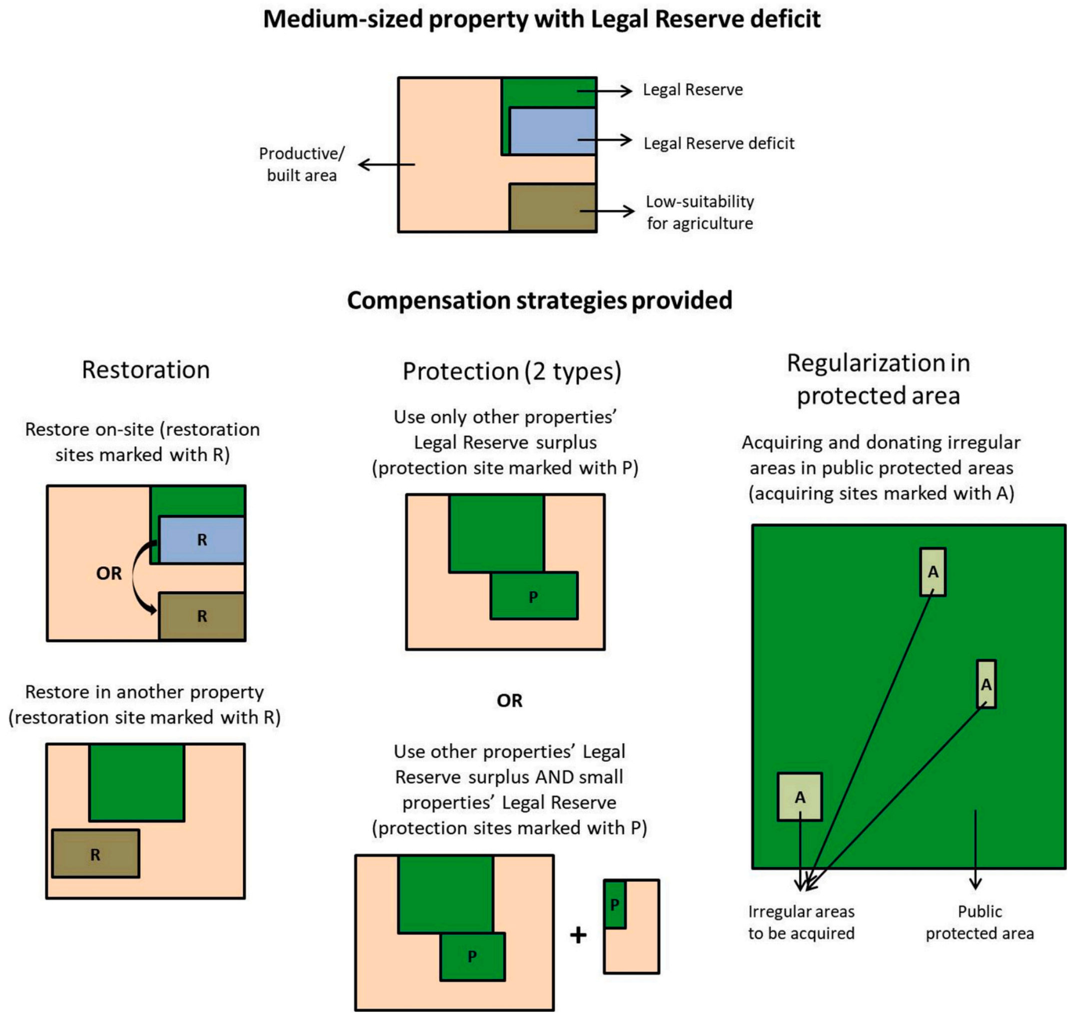

Fig. 2. Examples of possibilities to implement the different compensation strategies provided by the Forest Act and included in our analysis.

Core Team, 2021).

2.3. *Ecological equivalence, Legal Reserve deficit and compensation calculations*

We used the Condition Assessment Framework to calculate ecological equivalence applied to Legal Reserve compensation schemes, a method recently published (Borges-Matos et al., 2025). In this method, three ecological attributes were chosen among others to represent the three dimensions of equivalence: bird species 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 chosen from a pool of 12 attributes after running a multi-criteria analysis based on the attributes' redundancy (Spearman correlation), spatial complementarity (mean pair-wise distance analysis) and variability (standard deviation) (Borges-Matos et al., 2025). Therefore, these three chosen attributes hold lower correlation among them, more spatial complementarity, and higher variability, meaning they carry more different information about the study region than the other attributes. The attributes were averaged for each spatial unit: hexagons that vary in size from 5,000 to 10,000 hectares covering the entire Atlantic Forest in São Paulo, totaling 1,671 in number (see Table S1 for basic description of the attributes). This hexagon size range captures important ecological processes and, at the same time, reflects spatial environmental differences, making it widely used in Atlantic Forest studies (Banks-Leite et al., 2011; Metzger, 2009; Pardini et al., 2010; Tambosi et al., 2014). Each hexagon had an attribute value, and these values were grouped into 12 classes for each attribute (Fig. S1) to establish equivalence categories. The compensation trades were only allowed among hexagons of the same class for the three attributes at the same time (for more details, please see Borges-Matos et al., 2025).

To extract values of Legal Reserve surplus, Legal Reserves in small properties, and deficit area per hexagon, we used a database containing this spatial information in hectares for 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 (a total of 5,467 properties). When we intersected the properties with the hexagon grid, we could calculate the approximate area of each variable inside each hexagon (Fig. 3).

To approach the compensation strategy of restoring native vegetation, we calculated each hexagon's area potentially available for restoration. This calculation was based on previous data from São Paulo state, where polygons represented the areas in hectares considered adequate for restoration inside each property, avoiding competition with productive agricultural lands (Sparovek et al., 2020). These areas 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 intersected the low-suitability map with the hexagon grid, filtered the 5,467 properties of our study area, and summed the areas of patches that fell inside each hexagon (Fig. S2A).

Table 1
The six scenarios designed to test Legal Reserve (LR) compensation through the strategies provided by the Brazilian Native Vegetation Protection Law, including ecological equivalence.

Scenario type	Scenario name	Scenario rationale
Simple	Scenario 1 – LR surplus	Tests how well LR compensation based exclusively on protecting LR surplus can resolve the deficit
	Scenario 2 – Total surplus	Tests how well LR compensation based exclusively on protecting standing 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 restoring 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 resolved by using protection of standing 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 resolved by using regularization of private properties inside public protected areas, followed by protection of standing vegetation (LR surplus and LRs of small properties), followed by restoration of native vegetation

We estimated the area of private properties irregularly inside public protected areas based on their proportion relative to each protected area they are in (Forest Foundation – São Paulo government, personal communication). São Paulo government could not share the location and extension of the irregular areas because this is sensitive information. We used the map of São Paulo state protected areas (DataGEO, São Paulo government) and filtered the categories with higher levels of protection in the Atlantic Forest (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 the layer with the irregularities percentages with the hexagon grid, calculated the irregular private area corresponding to its percentage in each protected area for each hexagon, and summed these area values to obtain the approximate irregularity area per hexagon (Fig. S2B).

2.4. Compensation costs estimation

To test the scenarios, we estimated two compensation costs: for restoring native vegetation and for protecting standing vegetation – including both strategies of standing vegetation protection and the regularization of private properties inside protected areas. To estimate the protection costs, we used the prices for land acquisition in a vegetated area as a proxy based on a national land-cost database (FNP, 2017). 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. As a proxy of 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 BRL 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 average price/hectare per municipality, weighted by the area covered by each category in the municipality. We assumed the category 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 compensation costs through the protection of standing vegetation (Fig. S3A) and the opportunity cost for restoration.

To complete the restoration cost estimation, we used a previously made calculation. It consisted of multiplying the cost to plant one hectare (Benini and Adeodato, 2017) by the local regeneration potential

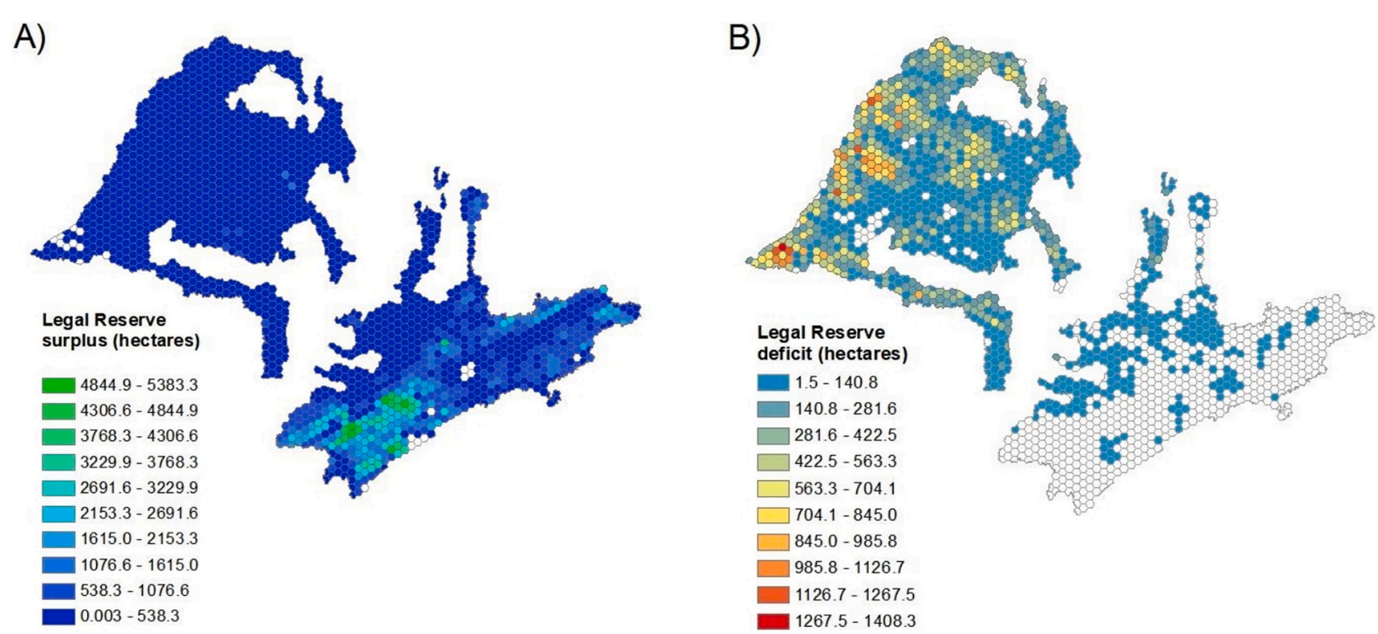

Fig. 3. Spatial distribution of (A) total Legal Reserve surplus, including the Legal Reserves of small properties, and (B) Legal Reserve deficit. The blank polygons represent either no surplus (A) or deficits lower than 1.5 hectares (B). Both maps were subdivided into the same number of categories, i.e. 10, to ease visualization, but their value intervals differ.

(Crouzeilles et al., 2020). The result was a 30 m resolution raster layer with prices in BRL per hectare (vegetation, water, and urbanization pixels were excluded). We extracted the mean restoration cost for each hexagon from this layer. We then summed these values with the opportunity costs per hexagon to achieve the total restoration cost (Fig. S3B). The values in BRL refer to the year 2017 (Benini and Adeodato, 2017) when the annual mean commercial exchange rate was BRL 3.1920 = 1.0 USD (IPEA data). We used this rate to calculate the final costs in USD. We acknowledge that these values are outdated, but, besides the fact that no other database was available at the time for our entire study area, our focus in this analysis is to capture the cost relationships among the different strategies and scenarios. These relationships are not likely to significantly fluctuate throughout time – as opposed to economy and politics.

3. Results

The compensation scenarios varied enormously in their ability to reduce Legal Reserve deficits (0.15–99.47 %), as well as in costs (approximately 104 thousand USD to 2 billion USD) and additionality (0–220 thousand hectares approximately) (Table 2, Fig. 4). The ability to reduce deficits was related to restoration and the inclusion of small properties' reserves as areas available for compensation, which nearly doubled the deficit resolution compared to the scenario including only the 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 effective of the four simple scenarios in this aspect and had the highest additionality of all six scenarios tested (Table 2).

On the other hand, the restoration strategy alone increased the total economic cost from USD 714 million (scenarios 1 and 2) to approximately USD 2.1 billion (scenario 3). The regularization scenario (scenario 4) was the cheapest, precisely because this strategy could only slightly reduce the deficit (Table 2, Fig. 3). The compensation economic costs in one single hexagon were also higher when the restoration strategy was included, and in all scenarios (except for 4) the costs were higher in the northwestern region of São Paulo (Fig. S4). Simple scenarios without restoration (scenarios 1, 2, and 4) did not result in any additionality. The area in hectares in each hexagon used to compensate varied in the four simple scenarios: larger areas would be needed in Scenario 3, but for fewer hexagons than in Scenarios 1 and 2 (Fig. S5). The hexagons with the largest areas needed for compensation were concentrated in the northwest region – except for scenario 4 (Fig. S5).

Composite scenarios 5 (scenarios 2 + 3) and 6 (scenarios 4 + 2 + 3) returned virtually the same result (Table 2). The percentage of deficit solved was the same and very high (Fig. 4; Table 2), with only 16 hexagons left with some deficit (less than 1 % of the Atlantic Forest area in São Paulo). These hexagons are at the *Cerrado* - Atlantic Forest ecotone (Fig. S6), meaning ecological equivalence may be more complex to achieve in those ecotone regions. The 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 approximately 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 (restoration) in terms of deficit reduction, which was the only simple scenario that significantly reduced the deficit in São Paulo state's Atlantic Forest. However, scenarios 5 and 6 were cheaper (around USD 865 million – 40 % less) and less additional (88,543.84 hectares less) than scenario 3. Since the cost difference was much larger than the difference in additionality, scenarios 5 and 6 should be preferred over scenario 3. Scenarios 5 and 6 had similar results, but 5 presented fewer steps – more straightforward implementation – and lower cost. Therefore, scenario 5 would be the best choice as a general scheme to compensate Legal Reserves with ecological equivalence.

4. Discussion

Our results demonstrate that implementing ecological compensation with ecological equivalence as a core principle is not only cost-effective but also can be fully compliant with existing legal requirements. In our study case, we found that the Legal Reserve compensation strategies presented by the Native Vegetation Protection Law had different effectiveness regarding deficit resolution, economic costs, and additionality. Regularization of private properties in protected areas performed poorly, protection of standing vegetation had an intermediate performance, and restoration of native vegetation had the best performance, as seen in the four simple scenarios tested. Restoration presented the highest cost among all scenarios, so combining strategies improved the cost-effectiveness of the compensation scheme, which was seen in the two composite scenarios. The best option was Scenario 5, which combined protection of standing vegetation with restoration. We highlight the approach that led to these results: a simple yet innovative spatial optimization based on an automated prioritization process developed by the authors, alongside a new spatially explicit method for assessing ecological equivalence, the Condition Assessment Framework. This method accounted for not only biodiversity attributes, but also landscape and ecosystem services. The attributes were calculated in a disaggregated way and could be switched by others according to the region's needs. This combination of characteristics makes our approach unique and different from other similar assessment methods (e.g., da Fontoura et al., 2024; Marshall et al., 2022; Mello et al., 2021a).

We found that including equivalence necessarily intensified the need for restoration, confirming previous findings for the region (Mello et al., 2021b). From an environmental perspective, this is positive and aligns with international agreements and goals in force (e.g. Paris and Bonn Agreements, Nature Positive goals, Global Biodiversity Framework). Without ecological equivalence, in our study area it would be allowed to simply exchange Legal Reserve deficits for surplus in the whole Atlantic Forest biome, a measure with no additionality (Mello et al., 2021b; Tavares et al., 2021). Increasing vegetation cover is crucial in this biome, recognized as a world biodiversity *hotspot* (Mittermeier et al., 2011; Myers et al., 2000) and which continues to lose old-growth forests (Rosa et al., 2021). Furthermore, protection alone cannot reach full legal compliance for this biome, hence restoration is needed (Mello et al., 2021b). Integrating ecological equivalence would lead to more additionality than privileging Legal Reserve compensation in priority areas (Strassburg et al., 2019), which are predominantly located in the coastal region of our study area, where large protected areas already exist

Table 2
Comparative results of the six scenarios created to test Legal Reserve compensation with different strategies. "ha" stands for hectares.

Scenario name	Deficit resolution (ha)	Deficit resolution (%)	Compensation area used (%)	Economic costs (USD)	Additionality (ha)
Scenario 1 – LR surplus	38,578.81	17.32	7.23	7,740,614.01	0
Scenario 2 – Total surplus	89,609.49	40.22	12.07	14,302,814.64	0
Scenario 3 – Restoration	220,536.32	98.99	12.23	2,156,238,638.49	220,536.33
Scenario 4 – Regularization	336.69	0.15	0.07	104,080.39	0
Scenario 5 – scen. 2 + 3	221,601.98	99.47	19.39	1,291,167,026.02	131,992.49
Scenario 6 – scen. 4 + 2 + 3	221,601.98	99.47	19.42	1,291,196,882.94	131,992.49

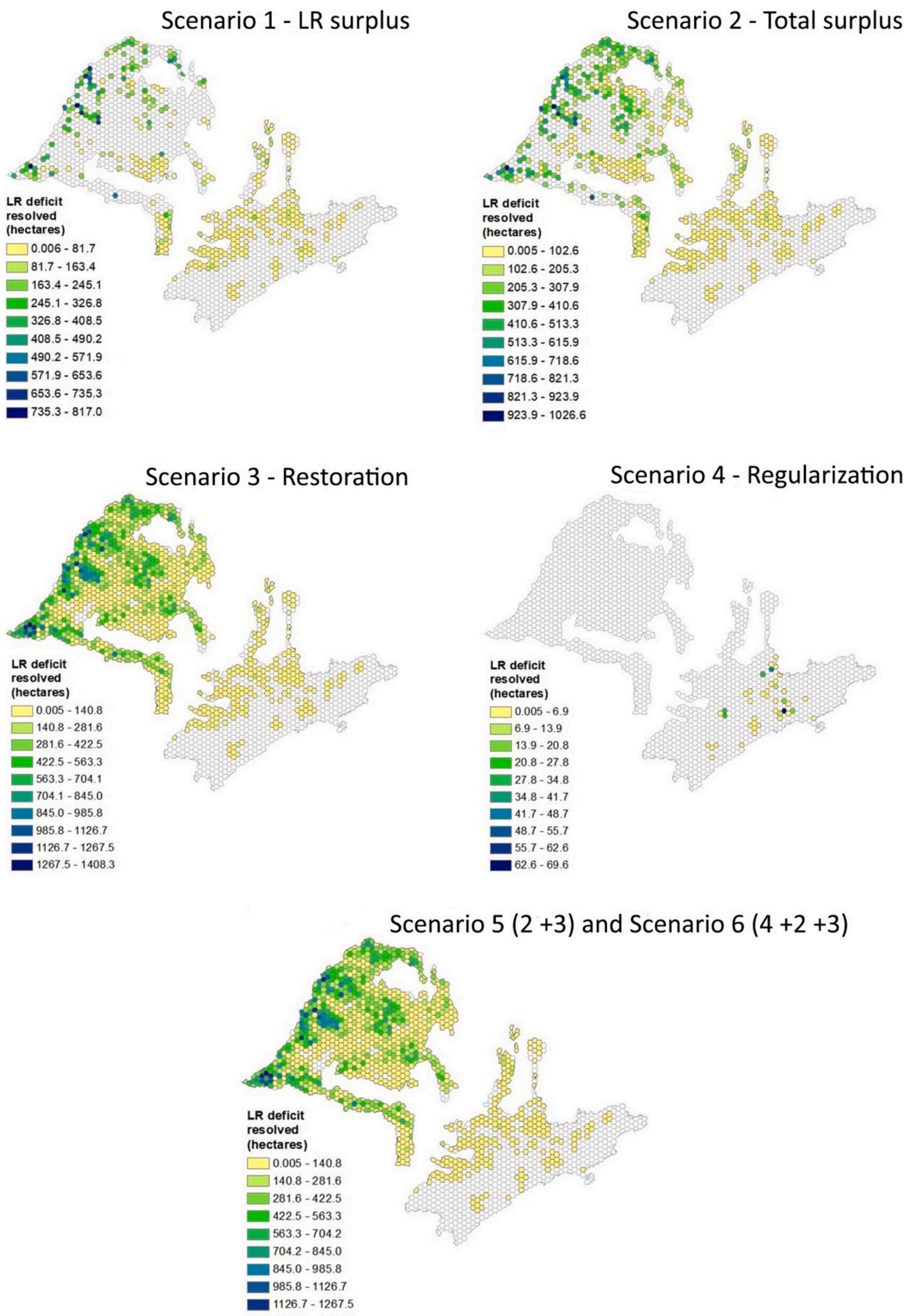

Fig. 4. Spatial distribution of Legal Reserve (LR) deficit solved in each hexagon by the compensation strategies applied in the six scenarios tested. We highlight that there was no difference between scenarios 5 and 6.

(Strassburg et al., 2019). Also, protecting and restoring vegetation in the northwest interior of São Paulo – the primary region of deficit – would reduce the existing spatial inequality in the distribution of ecosystem services (e.g., Borges-Matos et al., 2025 for potential pollination service; Hohlenwerger et al., 2022 for pest control).

The strategy of compensating Legal Reserve deficits in irregular private properties inside public protected areas was the least effective and made no difference in effectiveness when included in composite scenarios. The availability of land to compensate with this strategy was low, as most protected areas in São Paulo Atlantic Forest are in a region of low deficit and high environmental heterogeneity. This strategy had no additionality and no gains in terms of land protection, because all these private properties are inside established protected areas. Thus, compensation through regularization turns into a simply bureaucratic transaction, with no environmental gains. These adverse and ineffective outcomes contradict the latest tendencies of Brazilian state governments: 19 states have made regulations favoring this compensation strategy (Lopes et al., 2024), while São Paulo state has facilitated it with the implementation of its "Programa Agro Legal" (Decree N° 65.182, 16 of September 2020). Institutional pressures towards such type of bureaucratic-only solutions are common worldwide. In addition, in São Paulo state, the Legal Reserve surplus may easily surpass the deficit (Tavares et al., 2019), which means that applying protection without ecological equivalence would result in little or no increase in the recovery of biodiversity and ecosystem services (Tavares et al., 2019). Our results indicated the extent to which these measures may fall short of achieving real ecological benefits, the so-called no net loss or Nature Positive goals, potentially leading to greenwashing (Maron et al., 2023; zu Ermgassen et al., 2022, 2019).

Here we showed better options in terms of deficit resolution and cost-effectiveness: compensating by protecting standing vegetation, restoration, or the combination of both strategies – which is ideal. Our method was about 29 % more effective in eliminating São Paulo Legal Reserve deficits than previous methods tested with the same goal in the Atlantic Forest biome, based only on abiotic variables (Mello et al., 2021b). This is a promising result, as São Paulo has the country's largest deficits (Freitas et al., 2017). We showed compliance with the Law was possible even when the compensation scheme was limited to one federal state (i.e., São Paulo), a matter of discussion in Brazil. The argument that compensating Legal Reserves using equivalency within Brazilian states would lack available land (Mello et al., 2021b) proved invalid when using the Condition Assessment Framework. In other countries, the same type of argument (Grimm, 2021; Sonter et al., 2020b) could perhapsbe refuted if our approach was implemented. However, we do recognize that including ecological equivalence restricted the number of candidate areas for compensation (Weissgerber et al., 2019), especially in regions of high ecological heterogeneity. Also, we understand that increasing the need for restoration makes compensation more expensive, as seen here and in other works (Mello et al., 2021b). Clearly, the less ecologically and financially demanding, the easier it becomes to compensate from a practical perspective, as any area of the biome could be used – in the case of the Atlantic Forest – and minimal restoration would be required. However, this approach may result in significant environmental losses. By incorporating ecological equivalence, our approach aimed to maximize socio-environmental gains in the most cost-effective way possible (Reid et al., 2015).

In the big picture, how conflicts related to ecological compensation are tackled reflects what path we take to face the current world's environmental crisis. Government priorities in environmental policies reveal their commitment to addressing the destruction of nature and its consequences. Restoration of native vegetation is a key strategy in most environmental agreements, such as the Bonn Agreement (Chazdon et al., 2021). Compensating Legal Reserves in São Paulo state by using restoration can bring an additionality from 132 to 221 thousand hectares of forest (scenarios 5 or 6, and scenario 3). The state's goal announced in 2021's COP26 is to restore 1.5 million hectares of its Atlantic Forest by 2050 ("Programa Reflloresta SP"; Decree N° 66.550, 7 of March 2022). Restoring 221 thousand hectares corresponds to 14.7 % of this total goal. Summing this with the mandatory APP restoration (~656 thousand hectares) (Tavares et al., 2019) would account for 60 % of the goal. Restoration, besides environmental gains, can also provide financial benefits to landowners through mechanisms like carbon credits and biodiversity credits markets (d'Albertas et al., 2024; Peng et al., 2024). Therefore, we recommend compensation policies integrate ecological equivalence and consider using a combination of both restoration and protection to improve their socio-environmental outcomes cost-effectively. The high costs of restoration can be balanced depending on the method employed (Crouzeilles et al., 2020; Gastauer et al., 2021) and the economic incentives governments may provide, such as payment for ecosystem services or tax reductions for large agricultural producers (d'Albertas et al., 2024; Ruggiero et al., 2022; Salzman et al., 2018). Governments should make efforts to clearly define in their policies the methods to calculate ecological equivalence, find compensation sites, and implement restoration, as has been done in the Biodiversity Net Gain policy in England (DEFRA, 2024) and the BioBanking policy in Australia (DECCW, 2010). Policies such as the new Forest Act, the voluntary biodiversity offsets in South Africa (Brownlie et al., 2017), and the compensation system in Peru (Reid et al., 2015) would benefit from these measures. Approaches like ours can help in developing science-based solutions, reducing the science-practice gap (Bertuol-Garcia et al., 2018).

Lastly, our approach presents some limitations. Regarding the Condition Assessment Framework, it uses a fairly large number of attributes in its initial stages, which may not be available, and it did not include cultural ecosystem services or attributes directly related to human aspects (Borges-Matos et al., 2025). The method also lacks an automated system to perform all its analyses, which would broaden its usage by practitioners (Borges-Matos et al., 2025). These issues are challenges to be tackled in future studies. As for the approach developed here, we assumed a level of imprecision when making all calculations for each hexagon. We believe this should not be a problem, since the method aims to be a spatially explicit guidance for compensation schemes and does not need to be sharply precise in numbers – the general patterns won't change if the irregular area of a protected area in one hexagon is a little smaller or larger, for example. Moreover, we used a proxy for economic costs that may lead to underestimations (e.g., by not accounting for transaction costs). Exact cost values may need to be updated and perhaps calculated with another method. We also did not account for financial benefits generated by restoration (such as carbon credits), which goes beyond the scope of the present analysis. These factors can be included, corrected, and updated in further tests of this approach. Nonetheless, we understand our goal was reached when calculating the economic costs: understanding the relationships and proportionality among the compensation strategies tested here.

5. Conclusion

The approach we presented here points towards a straightforward, feasible and cost-effective way to compensate for losses of native vegetation, by combining strategies of restoration and protection of standing vegetation while accounting for ecological equivalence. Importantly, we employed a method to assess ecological equivalence that fully addresses its concept in the offset context: encompassing biodiversity, landscape, and ecosystem services attributes, all flexibly selected based on regional characteristics, measured and traded separately (i.e., disaggregated), and with spatially explicit results. Our approach relied on an automated prioritization path we developed for spatial optimization of compensation efforts. This combination of features highlights the uniqueness and significance of our results: cost-effectiveness was reached through a rigorous assessment of ecological equivalence with a simple approach – increasing its feasibility for real-world application. The approach can be applied far beyond our study area or the Brazilian Native Vegetation Protection Law. It is designed as a tool to support comprehensive public policies on environment and conservation. We hope these results enhance the understanding that integrating ecological equivalence in trades brings socio-ecological benefits that would not be achieved otherwise. Examples of such benefits are biodiversity conservation, climate change mitigation and adaptation, and direct advantages for local landowners and communities, since a range of local services provided by native vegetation would return with vegetation recovery. This could encourage compensation and offset practitioners to combine measures of native vegetation protection and restoration more often.

Author statement

The approach presented in this study offers a straightforward, feasible, and cost-effective method to compensate for losses of native vegetation by integrating restoration and protection strategies while considering ecological equivalence. Our method provides a comprehensive framework for assessing ecological equivalence, addressing biodiversity, landscape, and ecosystem service attributes, all of which are flexibly selected based on regional characteristics, measured and traded separately, and yielding spatially explicit results. A key feature of our approach is the automated prioritization path we developed for spatial optimization of compensation efforts, ensuring both efficiency and effectiveness. By rigorously assessing ecological equivalence in a simple yet effective manner, our approach enhances the feasibility of real-world application, providing a valuable tool for informing public policies related to environment and conservation. This methodology is not limited to the Brazilian context but can be applied globally, contributing to biodiversity conservation, climate change mitigation and adaptation, and benefiting local landowners and communities. Ultimately, our approach encourages a more frequent combination of native vegetation protection and restoration, fostering socio-ecological benefits that would otherwise remain unachieved.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2025.107922.

Data availability

Data will be made available on request.

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