Environmental Science and Policy 120 (2021) 1–10

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

Achieving private conservation targets in Brazil through restoration and compensation schemes without impairing productive lands

Kaline de Mello [a,*], Arthur Nicolaus Fendrich [b], Gerd Sparovek [b], Jeremy S. Simmonds [c], Martine Maron [c], Paulo André Tavares [b], Alice Dantas Brites [b], Ricardo Ribeiro Rodrigues [d], Carlos Alfredo Joly [e], Jean Paul Metzger [a]

[a] University of São Paulo, Institute of Biosciences, Department of Ecology. Rua do Matão, 321, Trav. 14, São Paulo, SP, 05508-090, Brazil
[b] University of São Paulo, Luiz de Queiroz College of Agriculture, Soil Science Department, Av. Pádua Dias, 11, Piracicaba, SP, 13418-900, Brazil
[c] The University of Queensland, School of Earth and Environmental Sciences, St Lucia, Brisbane, QLD, 4072, Australia
[d] University of São Paulo, Luiz de Queiroz College of Agriculture, Department of Biological Sciences, Av. Pádua Dias, 11, Piracicaba, SP, 13418-260, Brazil
[e] University of Campinas, Biology Institute, Department of Plant Biology, Rua Monteiro Lobato, 255, Campinas, SP, 13083-862, Brazil

ARTICLE INFO

Keywords:
Environmental policy
Legal reserves
Forest protection
Brazilian Forest act
Ecological equivalence
Offsetting schemes

ABSTRACT

Environmental policies that require native vegetation conservation can be challenging to implement, especially in productive agricultural landscapes. In Brazil, the Brazilian Native Vegetation Protection Law mandates 'Legal Reserves', protected native vegetation that landowners must retain on their properties. If landowners do not have the required minimum amount of native vegetation on their properties (the Legal Reserve 'target'), they must either restore vegetation on the same property to meet the target, or compensate by protecting existing vegetation or restoring it on another property, ideally in ecologically equivalent areas. Here, we evaluate how different strategies (on-site/off-site protection and/or restoration), and different requirements for ecological equivalence when off-site strategies are used, affect the ability to achieve Legal Reserve targets, while minimising the need to restore native vegetation on productive farmland. We used a novel iterative tool to build scenarios that reflect different combinations of strategies to meet the minimum conservation target under different requirements for ecological equivalence, and compared their ability to achieve the target and their likely cost. The Atlantic Forest was the only biome where it was not possible to achieve the Legal Reserve target by protection of existing native vegetation, even when ecological equivalence rules were relaxed. As a consequence, vegetation restoration is required in this biome. Directing this required restoration to pasturelands that are less-suitable for agriculture allowed the target to be achieved in all states of Brazil, as long as only minimal ecological equivalence was required; however, for most states, the need to restore native vegetation on productive areas on farmlands could still be avoided while requiring medium to high ecological equivalence. These findings show the potential for moderate ecological equivalence to be achieved across most of Brazil in a cost-effective way and without impairing productive lands when seeking to meet the Legal Reserve targets.

1. Introduction

Effective environmental policy is essential to minimise the impacts of land-use and climate change on biodiversity, ecosystem services and human well-being (Bull and Strange, 2018; Sterner et al., 2019). However, implementing such policy can be challenging, as it is not an easy task to balance reduction in environmental losses while ensuring economic and social development. This policy needs thus to achieve desired environmental outcomes at low socio-economic costs, considering market and political forces (Sterner et al., 2019; Strassburg et al., 2019). Climate change, atmospheric pollution, land-use, and water policies have faced similar challenges worldwide in their implementation, which could be made even more difficult by the lack of an interdisciplinary approach, multi-level governance and involvement of the

* Corresponding author.
E-mail addresses: kaline.mello@usp.br (K. Mello), arthur.fendrich@usp.br (A.N. Fendrich), gerd@usp.br (G. Sparovek), j.simmonds1@uq.edu.au (J.S. Simmonds), m.maron@uq.edu.au (M. Maron), patavares@usp.br (P.A. Tavares), alicebrites@usp.br (A.D. Brites), rrresalq@usp.br (R.R. Rodrigues), cjoly@unicamp.br (C.A. Joly), jpm@ib.usp.br (J.P. Metzger).

https://doi.org/10.1016/j.envsci.2021.02.014
Received 17 July 2020; Received in revised form 27 January 2021; Accepted 21 February 2021
Available online 27 February 2021

private sector (Vandenbergh and Gilligan, 2017; Yao et al., 2017; Fang et al., 2019; Gallagher et al., 2019; Kanter et al., 2020; Salvia et al., 2021; Sehn and Blesl, 2021). Therefore, besides the policies enforcement, dialogue and negotiation among the sectors involved in the environmental policy implementation is critical, and solutions must be politically, economically, and socially feasible.

The implementation of environmental policies can be especially fraught in agricultural landscapes. Retaining and in some cases increasing natural vegetation cover is necessary in these landscapes to protect or recover species, ecosystems and their associated essential services such as maintaining quality of water supplies, crop pollination, and natural pest control (Boesing et al., 2017; Jenkins et al., 2010; Mello et al., 2018; Metzger et al., 2019; Saturni et al., 2016), but this reduces the area available for agriculture. Such conflicts present a challenge for the design of effective and plausible environmental policy.

In Brazil, the Native Vegetation Protection Law (2012) (formerly, the Forest Act (1965)) aims to achieve the protection of native vegetation in private rural lands for the benefit of biodiversity, natural resources and ecosystem service provision (Brasil, 2012). This law governs approximately 53 % of remaining native vegetation in Brazil that occurs in private lands (Brancalion et al., 2016). It requires the establishment of Permanent Preservation Areas (mainly riparian zones) and Legal Reserves. Legal Reserves are required to cover a fixed proportion of the rural property by area (the "target") and must maintain native vegetation cover (Sparovek et al., 2015). The target to be achieved by the Legal Reserve protection varies depending on the biome and region, ranging from 20 % to 80 %. If landowners do not have this amount of native vegetation, they can achieve compliance by restoring or regenerating the vegetation on their property, or by protecting or restoring it in another rural property.

Although Legal Reserves currently protect 29 % of the country's native vegetation (Metzger et al., 2019; Strassburg et al., 2019), there is still a deficit in the area that needs to be restored or compensated to meet the requirements of the law of more than 11 million ha (Freitas et al., 2017). Full implementation of the Native Vegetation Protection Law thus represents an opportunity to protect and restore many more areas of important native vegetation. However, seven years after the last revision of the Native Vegetation Protection Law, there is still a lot of uncertainty regarding the specific requirements of Legal Reserves (Tavares et al., 2019). A major area of contention relates to the requirement that Legal Reserve compensation sites should be 'ecologically equivalent' to the vegetation cleared/lost from the property for which the compensation deficit arises. This requirement was supported by a decision of the Supreme Federal Court in 2018, but 'ecological equivalence' remains undefined in the legislation, i.e., there is no definition of the degree of ecological equivalence and how to measure it.

The Native Vegetation Protection Law is not an offset policy, but rather, a target-based policy, which defines a fixed amount of native vegetation protection in the private lands. Thus, the definition of ecological equivalence requirement for Legal Reserve compensation is important, because stricter equivalency requirements, commonly adopted by offset policies ("like-for-like" trades) may restrict options of available areas for compensation (Habib et al., 2013). This might mean that compensation needs to be located on more expensive and productive agricultural land. A key gap in our knowledge is whether the Legal Reserve target can indeed be met without substantially compromising productive agricultural lands, and how specific policy settings might enable or impede this. There is an urgent need in Brazil for compelling evidence to guide policy implementation, showing that feasible solutions exist, thus reducing uncertainties at the national scale (Molin et al., 2018; Strassburg et al., 2019).

Here, we evaluate how different strategies for meeting the Legal Reserve target, and different requirements for ecological equivalence between the property with native vegetation deficit and the compensation site, affect the ability to achieve the Legal Reserves target while minimising the need to restore native vegetation on productive farmland. To do this, we compare what land would be required to meet the target under strategies including on-site and off-site restoration, and off-site vegetation protection, and with different requirements of ecological similarity of off-site vegetation protected or restored to meet the property's target. We used a novel iterative tool to produce scenarios that combine the different strategies and degrees of ecological equivalence in each of the 27 states in Brazil within the different biomes (Fig. 1).

2. Material and methods

2.1. Legal reserve target

The Legal Reserve target considered in this study is the total amount of protected native vegetation in private lands required by the law. The amount of protected native vegetation that each property is required to have varies among regions: 50–80% in forested areas of the Legal Amazon, 35 % in the Cerrado Biome in the Legal Amazon region, 30 % in the Cerrado Biome in the State of Piauí, and 20 % in all other non-Amazonian regions. If a property does not already have enough vegetation to meet the target, this represents a deficit that must be overcome by either restoring or protecting land on the same or other properties, such that the target is met.

We calculated the amount of native vegetation protection and restoration that would be needed to achieve the target, based on the estimated native vegetation deficit in properties for the whole country. The estimated native vegetation deficit in the properties was calculated based on the requirements of the Native Vegetation Protection Law, as specified in the Articles 12, 13, 15 and 67, but not considering Article 68 (see Supplementary Material). Because Legal Reserves cannot legally be compensated in a different Biome, and the Native Vegetation Protection Law will be essentially implemented at the state level, we intersected state and biome boundaries to identify macro-units for analysis (Fig. 1). The legislation does not consider the ecotones for Legal Reserves compensation, only the Biome boundaries. We accessed data on property boundaries and land use/land cover data within each macro-unit (Freitas et al., 2017). The land use map was created in 2016 with a spatial resolution of 50 m, while the property boundaries were defined from a composed dataset of land tenure, which integrates the available databases of georeferenced rural properties boundaries (including the Rural Environmental Registry, CAR), indigenous reserves, rural agrarian reform settlements, military land, urban areas and national, state and municipal protected areas (Freitas et al., 2017). The compilation of existing property boundaries databases covered about 80 % of the Brazilian territory. We excluded from our analyses the remaining 20 % ownership boundaries that were simulated by Freitas et al. (2017).

2.2. Strategies to achieve the legal reserve target

The Native Vegetation Protection Law allows the Legal Reserves requirement to be achieved in different ways. Landowners who have a native vegetation deficit can select one of the different options, or a combination of approaches. These options include restoration in the same property, or compensation using native vegetation in another property ("off-site compensation"). There are three options for off-site compensation: 1) protecting existing native vegetation on farms that have more native vegetation than what is legally required (native vegetation surplus); 2) protecting native vegetation in existing Legal Reserves in small farms (which are no longer obligated to maintain native vegetation in Legal Reserves after the revision of the law in 2012); or 3) restoring native vegetation off-site.

Thus, we considered four strategies to achieve the Legal Reserve target: 1) restoration in the same property (on-site); 2) off-site compensation in existing native vegetation surplus; 3) off-site compensation in existing (but no longer required) Legal Reserve in small farms; and 4) off-site compensation through native vegetation restoration in

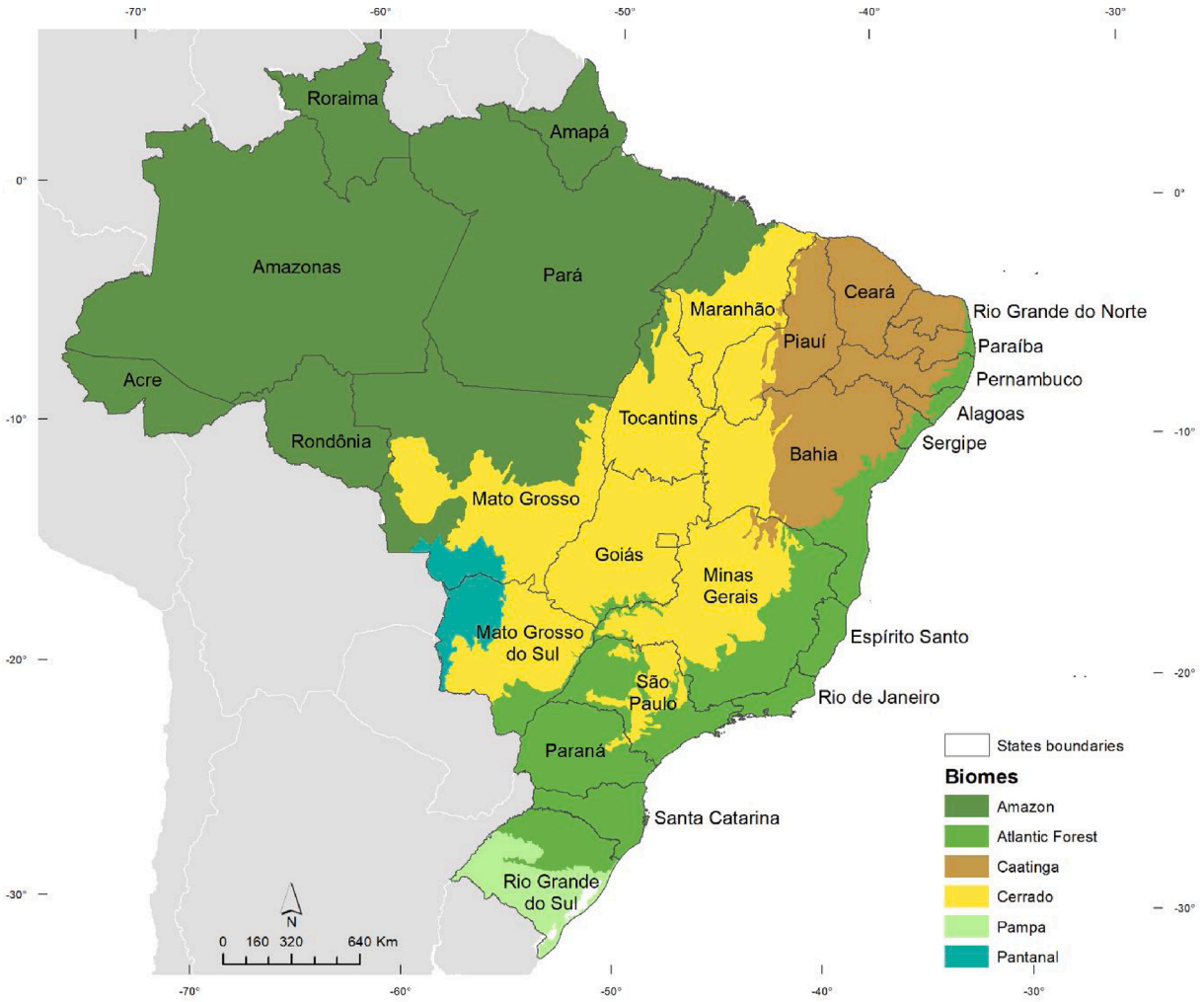

Fig. 1. Brazilian terrestrial biomes (6) and state boundaries (27). The scenarios for the Legal Reserve regularization consider a combination of state boundaries with biomes, resulting in 46 macro-units of analysis. Some states, as the "Amazonas", present only one biome and thus one macro-unit, however other states comprise up to 3 macro-units, as in the case of Bahia which has three biomes (Atlantic Forest, Cerrado and Caatinga).

other properties (Fig. 2).

The compensation in existing Legal Reserves in small farms only can be done by a new legal mechanism that was created in the revision in 2012, the Environmental Reserve Quota (CRA, Portuguese acronym). The CRA mechanism can also be used to acquire a credit of an off-site native vegetation surplus (including where this occurs on small farms, or not) or through off-site native vegetation restoration. Landowners can buy CRA certificates (native vegetation credits) in on-line platforms, which simplifies transactions and, besides, minimizes costs. This option also increases areas available for compensation because it includes compensation in existing Legal Reserves in small properties (Freitas et al., 2017). However, according to the opinion of most lawyers, CRA is the only mechanism that requires off-site compensation to be 'ecologically equivalent' to the vegetation that would have naturally occurred on the property for which the deficit is being compensated.

The other legal instruments for off-site compensation (acquisition of other property, arrangements for environmental easement, or donation of an area located inside of protected areas pending 'regularization' – private areas inside protected areas that were not yet indemnified by the government) only allow landowners to compensate the Legal Reserve deficit through native vegetation surplus protection or vegetation restoration. While according to most jurists (Farina et al., 2019) no strict rules around ecological equivalence are stipulated for these transactions, for this analysis, we consider that any off-site compensation – be it through the CRA mechanism or another legal instrument such as acquisition, donation or rent– needs to satisfy an ecological equivalence requirement. This assumption is more conservative and restrictive (limiting compensation to equivalent areas), but we believe this analysis is useful for testing the viability of compensation schemes, even under restrictive conditions. We examine different degrees of ecological equivalence and explore the implications for different approaches for compensating deficits and, thus, achieving Legal Reserve targets.

2.3. Ecological equivalence

We adopted a simplified method to estimate ecological equivalence (Appendix A, see also Mello et al. in press for more details) based on data available for all Brazilian territory. We used abiotic parameters to identify environmental similarities, and thus used "abiotic equivalence" as a proxy or as an operational variable to represent "ecological equivalence". Abiotic data, such as climate, soil, and terrain characteristics, are available worldwide and represent the main environmental conditions that affect the biota distribution (Pearson and Dawson, 2003; Hoorn et al., 2010; Laliberté et al., 2014; Antonelli et al., 2018). This data is widely available worldwide, and thus can be applied to infer ecological equivalence in different regions of the world, considering distinct types of compensation that exist today. Some ecological equivalence metrics worldwide have used or can use abiotic parameters to measure environmental equivalence (Fish and Wildlife Service, 1980; Miller Jr. and Gunsalus, 1999; Neale et al., 2011; Morandeau and

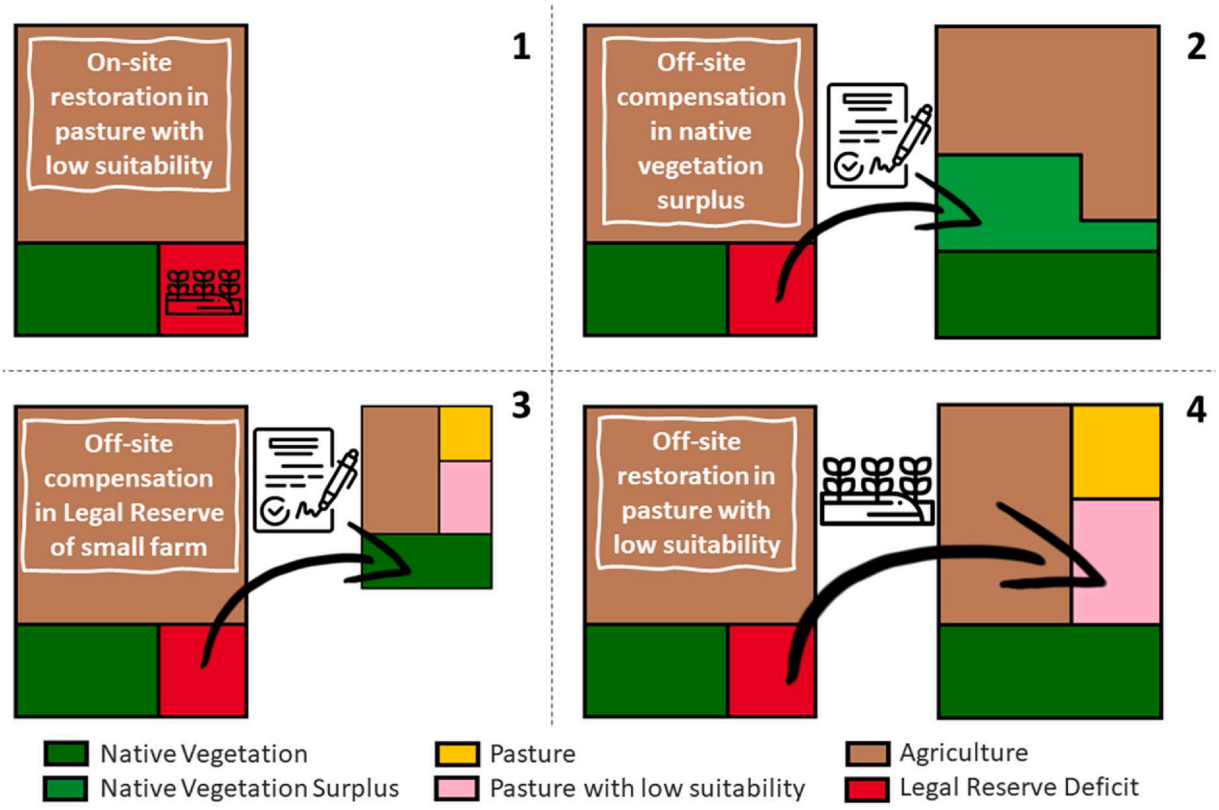

Fig. 2. Different strategies to achieve Legal Reserve target: 1) restoration in the same property ideally on lands with low agriculture suitability; 2) off-site compensation in existing native vegetation surplus; 3) off-site compensation in existing Legal Reserve in small farms; and 4) off-site compensation through native vegetation restoration in other properties.

Vilaysack, 2012). Biotic data is usually more difficult to obtain and it is more specific to each region than abiotic data. For this reason, we propose using abiotic similarity as a first step to set regional ecological equivalence, to divide the geographical space into more similar areas, where the impacted and compensation sites must necessarily be. Biotic data can be used to refine and stimulate higher ecological equivalence within the abiotic subdivisions, at the state level, as it was proposed for the state of São Paulo (Mello et al. in press for details). Currently, the Native Vegetation Protection Law only requires the same amount of area to be compensated, but does not require the same habitat conditions (e.g. successional stage or conservation status).

We selected fourteen variables including soil, terrain, temperature, and precipitation characteristics to calculate abiotic equivalence (Appendix A) considering catchment level 5 (ANA, 2013) as spatial units for each of the 46 macro-unit of analysis (resulting from the intersection of biome and state boundaries; Fig. 1). The abiotic variables were selected based on previous studies that showed their influence on biodiversity or ecosystem spatial distribution (Ribeiro et al., 2011; Valdujo et al., 2013; Antonelli et al., 2018) and in consultation with experts. The mean value of each variable was extracted per catchment and standardized, and abiotic similarities between pairs of watersheds belonging to the same macro-unit of analysis were calculated based on Euclidian distance considering the same weight for all the variables.

A hierarchical clustering procedure with a spatial constraint was then applied to create clusters (groups) of similar catchments and with spatial proximity, depending on the level of abiotic similarity required (Chavent et al., 2018). For this, two dissimilarity matrices were created: one for the distance between abiotic variables (Euclidian distance) of watersheds and one for the geographical distance between watersheds. For geographical distance, we used a discrete definition: first-order neighbours are watersheds that share a common boundary; second-order neighbours are those watersheds neighbours of a first-order neighbour; and so forth. The geographic distance was included to avoid grouping watersheds that are not necessarily neighboring, that could be dispersed in the territory, which is undesirable from the management perspective, also for an water protection perspective in terms of keeping and improving ecosystem services locally. We attach greater importance to the abiotic equivalence matrix; thus, the spatial constraint was defined to have one-fourth of the weight of abiotic criteria in the clustering procedure.

Considering that Legal Reserves cannot legally be compensated in a different Biome, and that most states will limit the implementation of the Native Vegetation Protection Law at the state level, compensation will occur across the whole macro-unit of analysis if we do not consider abiotic equivalence. If we consider equivalence, then compensation will be limited to the most similar watersheds, which varies with the degree of similarity to be considered (Fig. 3). We consider 20 levels of abiotic equivalence, varying from none (compensation can be done anywhere in the whole macro-unit of analysis) to very high (the macro-unit of analysis is subdivided into 20 groups of watersheds with more similar abiotic characteristics, and compensation can only be done within the same subdivision). In short, when there is a demand for greater equivalence, the extent of areas that meet this demand is smaller. Thus, the greater the degree of equivalence required, the greater the number of subdivisions created - it is a direct cause-effect relationship.

2.4. Native vegetation surplus

We considered as native vegetation surplus an amount of native vegetation higher than the minimum that is legally required. To find the available areas for off-site compensation by protecting existing native vegetation on farms with native vegetation surplus, we used the same model that was applied to estimate the Legal Reserve deficit (Freitas et al., 2017). Thus, native vegetation in private properties that was not

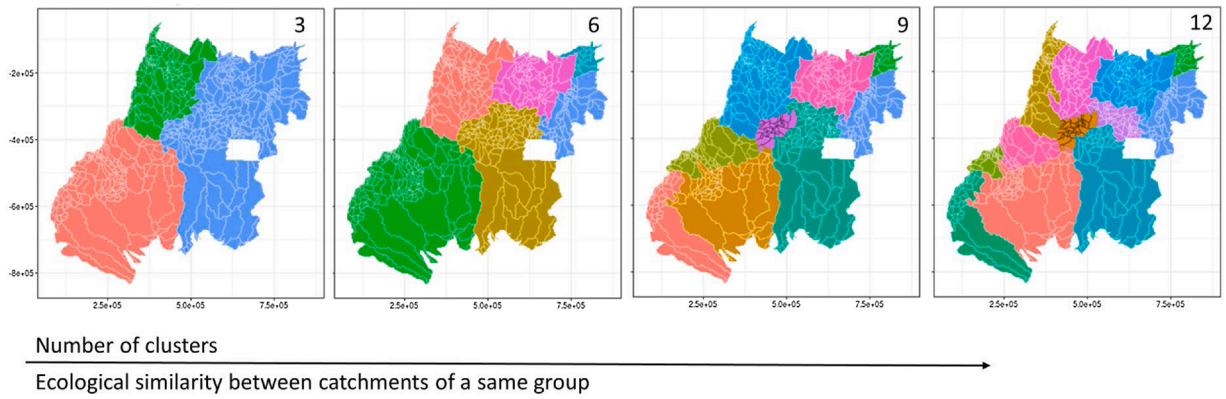

Fig. 3. Representation of the abiotic equivalence gradient within the Cerrado Biome in the State of Goiás from a lower similarity (one unit – biome boundary in the state) to a higher similarity (9 groups or clusters of catchments). The greater the number of subdivisions, the greater the similarity between catchments from a same group.

computed in the amount of native vegetation protected by the law (Item 2.1) was classified as native vegetation surplus.

2.5. Low-productivity pasturelands

Data on agricultural suitability of the land was obtained from Sparovek et al. (2015), which consider variables of soil quality (soil depth, soil drainage, clay content, and soil fertility), slope and climate (water capacity available, water and temperature index, which evaluate the water deficit in the field) to define suitability. Combining those data with land use information, we identified pasture in areas of low agricultural suitability (hereafter "low productive pasturelands") within each rural property. Those pasturelands provide low economic return to the landowners, and thus represent areas likely to have the lowest economic impact (or even, a positive economic impact) if converted to forest through restoration (Strassburg et al., 2014).

2.6. Scenario comparison

To evaluate how different strategies and different ecological requirements affect the ability to achieve the Legal Reserves target we considered five implementation scenarios that combine four strategies to achieve the Legal Reserve target (Table 1, Fig. 4) for all 46 macro-units of analysis in Brazil. The prevalent strategy is off-site compensation in existing native vegetation. Because this strategy is usually considered the one with the lowest cost and does not require converting agricultural areas by landowners, we considered this strategy for all scenarios. In Brazil, there is a concern from farmers to lose arable land for forest conversion, so compensation in existing vegetation is expected to be prioritized by landowners (Freitas et al., 2017). The second strategy is on-site restoration, which depends on the landowners' interest in converting part of their property (which will vary with the opportunity cost of their land). Third, the compensation in Legal Reserves of small properties is a strategy allowed only by CRA, which mandatorily requires ecological equivalence, which will also depend on the interest of the landowner. Finally, off-site compensation with restoration implies higher costs, related both to restoration and land costs, and thus is the less attractive option. For this reason, we only adopted this strategy for the last scenario. For each scenario we tested the 20 different levels of abiotic equivalence, resulting in 100 combinations.

Table 1
Scenarios of compliance with the Native Vegetation Protection Law with different strategies to achieve the Legal Reserve target in Brazil.

Scenarios	Strategies			
	1. Restoration in the same property	2. Off-site compensation in existing native vegetation surplus	3. Off-site compensation in Legal Reserves of small farms	4. Compensation through restoring native vegetation in other properties
Scenario A		✓		
Scenario B		✓	✓	
Scenario C	✓	✓		
Scenario D	✓	✓	✓	
Scenario E	✓	✓	✓	✓

To evaluate and compare the capacity of each scenario to achieve the conservation target, we calculated a "target achieving indicator", which is the percentage of the Biome or the Brazilian territory that achieved the target. For this, we sum the macro-units' area that achieved the target, where the land supply (which is the amount of native vegetation surplus, plus Legal Reserve on small farms, plus pasturelands with low suitability where restoration and/or compensation can occur without impairing productive lands) was equal or higher than the land demand (i.e., the amount of Legal Reserve deficit which needs to be compensated). Let us denote by i the index of each territory (i.e., each biome or the Brazilian territory) with area A_i divided into y_i macro-units with areas (A_{i1}, A_{i2}, …. A_{ij}) that achieved the target and others macro-units that did not. Then the "target achieving indicator" is the percentage:

$$p_i = \frac{\sum_{j=1}^{y_i} A_{ij}}{A_i} \quad (1)$$

The ideal situation for Legal Reserve compensation scheme is to have values close to the maximum (100 %, when all macro-units of a focal unit of analysis achieved the target). Reducing abiotic equivalence requirements, should, in theory, increase supply. Because the first strategy (restoration in the same property) does not include off-site compensation, when this strategy is combined with other ones, the amount of restored area through this strategy is deduced from the total deficit, and the remaining deficit will be used for off-site compensation (Fig. 4).

To calculate the target achieving indicator for the different scenarios, we built a iterative tool that enables combining the different strategies to achieve the Legal Reserves target across the different states and Biomes in Brazil considering the different degree of abiotic equivalence (Fig. 5). This tool is based on a previous framework developed for the State of São Paulo (Mello et al. in press). Using a control panel, decision makers can choose restoration/compensation strategy options and the level of equivalence, which will generate as output a map representing

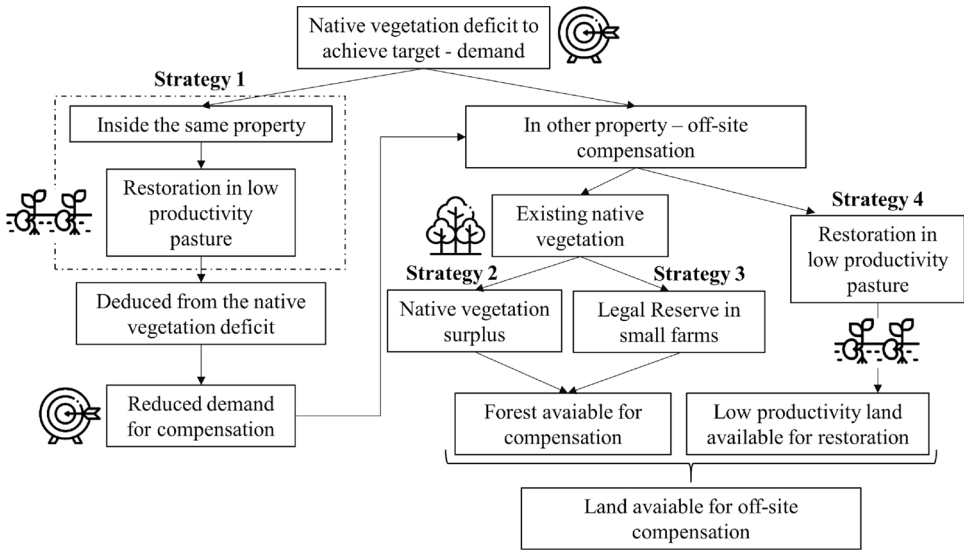

Fig. 4. The combination of the main strategies considered to achieve Legal Reserve target (demand), which should affect the supply of land for compensation: (1) on-site restoration in the same property, (2), off-site compensation in existing native vegetation using native vegetation surplus, (3) off-site compensation in Legal Reserves in small farms (compensation through CRA or other legal instruments), and/or (4) off-site compensation through restoring pasture.

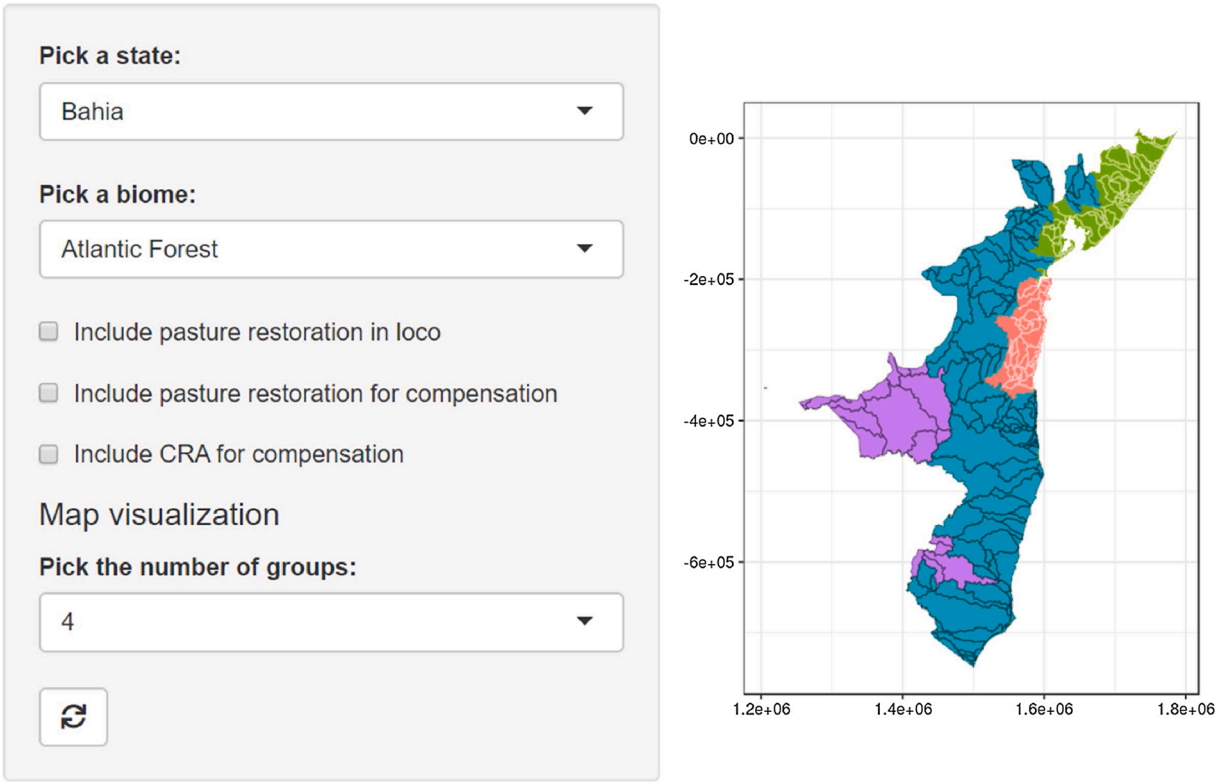

Fig. 5. Iterative tool to build scenarios of Legal Reserve restoration and compensation in Brazil. Here we present an example from the Atlantic Forest biome in the State of Bahia. In the control panel, it is possible to choose the strategies to achieve the target. The map window shows the abiotic groups (different colours) according to the number selected by the user, and black watershed boundaries represent the regions with land demand higher than land supply.

watershed where land demand is or not higher than land supply– representing thus the ability to achieve the target. This tool is available at https://compensacao.shinyapps.io/offset_br/ and can be accessed from any computer or device with internet. The source code for the tool is also available as a Supplementary Material. The tool also allows users to download the output map (Fig. 5) for offline use.

We used the iterative tool to obtain the results for each of the 46 macro-units of analysis. These results were used to calculate the target achieving indicator for each Brazilian Biome and for the entire Brazilian territory. Because we have a large number of combinations of implementation scenarios and equivalence levels (100), we categorize the results by levels of abiotic equivalence: none (no subdivision; the whole macro-unit of analysis is considered for compensation), low (2 subdivisions), medium (5 subdivisions) and high (10 subdivisions). The proposed breaks were selected to serve to demonstrate results across the broader range of possible breaks (1–20). This is a common practice in

studies using models such as multicriteria evaluation, where the levels of priority are classified commonly into a manageable number of classes, commonly 3–5 (Vettorazzi and Valente, 2016). We used a graph generated by the interactive tool to choose the breaks based on the variation of the abiotic similarity (Appendix A).

3. Results

When abiotic equivalence is not considered (compensation done in the whole macro-unit), the Legal Reserve target is achieved for more than 95 % of the biomes in all scenarios, with the exception of the Atlantic Forest (Fig. 6). When we consider only off-site compensation within existing native vegetation surplus (scenario A), only 66.86 % of the target was achieved for this biome. In Scenario B, which considered off-site compensation with native vegetation surplus and in existing Legal Reserves of small farms, the ability to achieve the target in the Atlantic Forest increased to 85.42 %. When on-site vegetation restoration on pastureland of low productivity is used (Scenario C), it increased to 98.78 %, achieving 99.06 % when both strategies were applied (Scenario D) (Fig. 6). The macrounits that did not achieve the target were the state of Goiás in Atlantic Forest, São Paulo in Cerrado and Tocantins in Amazon (Supplementary Material), but they represent only 1 %, 4 % and 0.6 % of the biome extent, respectively. The total target (100 %) is achieved for the whole country when we applied all the strategies to meet the target without compromising productive lands (Scenario E). The differences among the scenarios were most prominent for Atlantic Forest, Cerrado and Amazon Forest biomes, as we can observe for the next degrees of abiotic equivalence.

When we consider a low abiotic equivalence requirement, except for the Cerrado in the State of São Paulo, the ability to achieve the target only decreased in the Atlantic Forest comparing to none ecological requirement (Fig. 6; Table S1). It varied from 51.90 % (only native

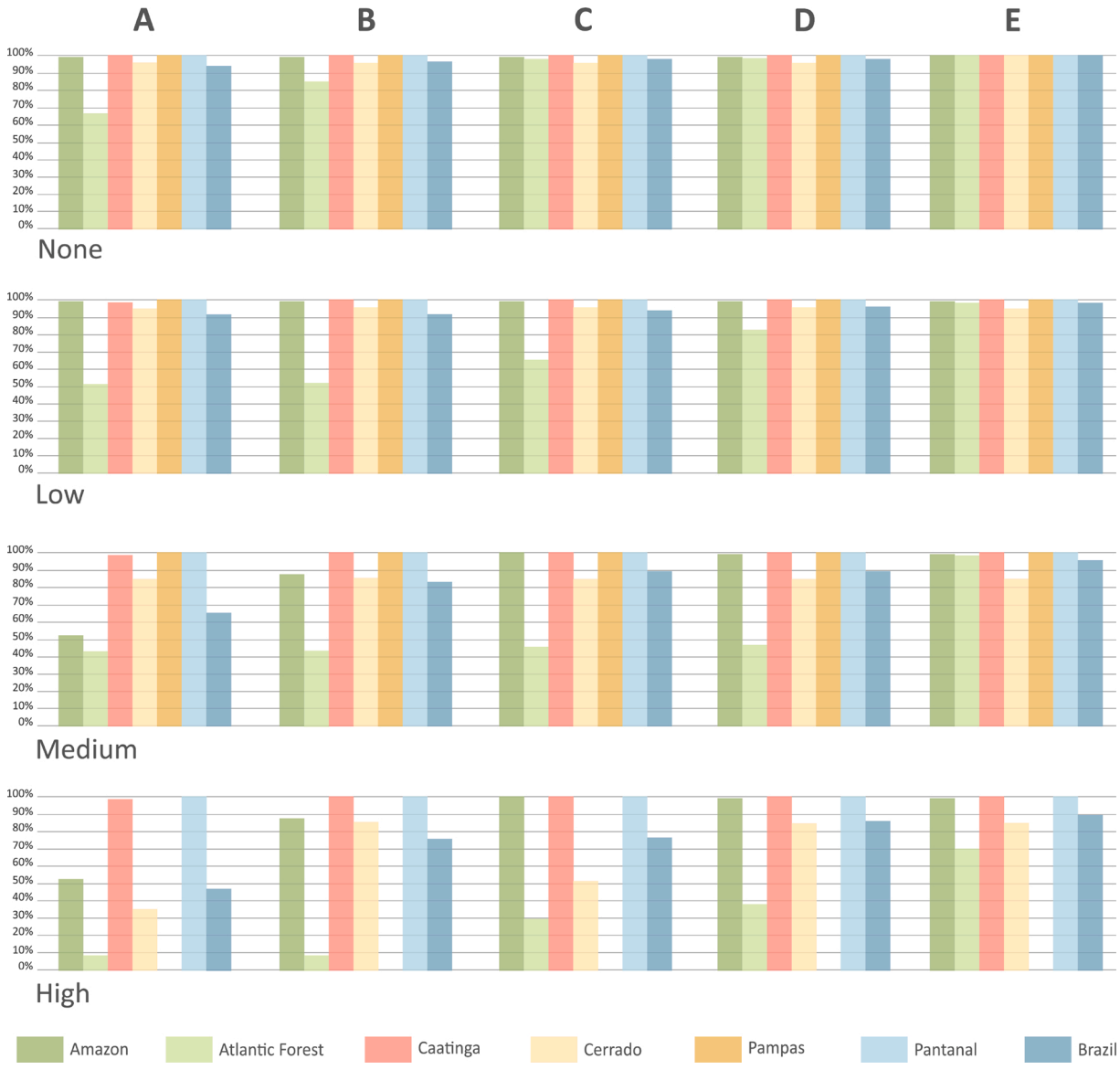

Fig. 6. The *target achieving indicator* for Legal Reserve compensation schemes. The results are shown for each biome and for the entire Brazilian territory in each scenario for different degrees of abiotic equivalence: none (no subdivision; the whole macro-unit of analysis is considered for compensation), low (2 subdivisions), medium (5 subdivisions) and high (10 subdivisions). Scenario A = off-site compensation in existing native vegetation surplus; Scenario B = off-site compensation in existing native vegetation surplus and/or in Legal Reserves of small farms (CRA); Scenario C = off-site compensation in existing native vegetation surplus and restoration in the same property; Scenario D = off-site compensation in existing native vegetation surplus and/or in Legal Reserves of small farms (CRA) and restoration in the same property; Scenario E = off-site compensation in existing native vegetation surplus and/or in Legal Reserves of small farms (CRA), restoration in the same property and restoration in other properties.

vegetation surplus – Scenario A) to 99.06 % (all the strategies – Scenario E) (Fig. 6). Combining CRA compensation and on-site vegetation restoration allowed to reach 84 % of the target for this biome.

The same pattern is observed when we considered a medium abiotic equivalence requirement for the Atlantic Forest, which the ability to achieve the target decreased compared to the previous abiotic equivalence requirement, varying from 43.27% to 98.78 %. Amazon presented a lower ability to achieve the target when only compensation in existing native vegetation (scenarios A and B) is applied. In addition to the State of São Paulo, which did not reach the target for the previous requirement in the Cerrado Biome, for a medium equivalence requirement, the macro-unit of Mato Grosso do Sul also did not reach the necessary amount of available land, which decreased the ability to achieve the target to 85.34 % in the Cerrado biome.

For a high abiotic equivalence requirement, considering only off-site compensation in existing native vegetation (scenarios A and B), 14 of the 15 macro-units in the Atlantic Forest have less forest available for compensation than is needed to meet the target (Table S1), which allowed only 8.52 % of the biome to achieve the target. When on-site restoration is combined with off-site compensation in existing native vegetation, this percentage increased to 37.97 % (Scenario D, Fig. 6). The ability can increase to 69.65 % when off-site restoration is considered. The ability to achieve the target is also lower for the Cerrado Biome when we consider only native vegetation surplus and on-site restoration (scenarios A and C), but when compensation in Legal Reserves of small properties is used (strategy 3) or when it is combined with restoration, the value is the same as for medium equivalence requirement (scenarios B, D and E). The target was not achieved in the Pampas in all scenarios of high abiotic equivalence. For Caatinga, Pantanal and Amazon, the ability to achieve the target did not change compared to the previous ecological equivalence requirement.

4. Discussion

We presented the ability to reach the Legal Reserve target for native vegetation cover in Brazil under different on-property and off-property strategies of restoration and compensation, and considering different requirements for ecological equivalence when compensating off-site. We found that, broadly, the Atlantic Forest is the only Biome where it is not possible to achieve (or almost achieve) the Legal Reserve target only through off-site compensation in existing native vegetation, regardless of the degree of ecological equivalence. For this biome, it will be necessary vegetation restoration actions to be undertaken in addition to offsite compensation to achieve the target in at least some states.

Under all scenarios, the Atlantic Forest biome had the lowest ability to achieve the target, followed by the Cerrado, especially when high ecological equivalence requirements were simulated. These biomes are the most threatened and over-exploited regions in Brazil, with Atlantic Forest having suffered the most habitat loss (MapBiomas, 2019). Both biomes are global biodiversity hotspots (Mittermeier et al., 2011) and most native vegetation is on private land, which demonstrates the importance of Legal Reserves for biodiversity conservation and ecosystem services provision (Joly et al., 2014). In the case of Atlantic Forest, there is a national zero-deforestation policy for the biome launched in 2006 – The Atlantic Forest Law, which protects all the current forest cover. However, exceptions are made in cases of "public interest" under Brazilian Law (Metzger et al., 2019), and recent proposals could reduce even more the protection of the Atlantic Forest law (RMA and CN-RBMA, 2020). Therefore, Legal Reserve implementation in this biome is especially important. The restoration of part of the Legal Reserve deficit can help the Atlantic Forest to go beyond biodiversity hotspot status and become a hopespot (Rezende et al., 2018).

4.1. How different strategies affect the ability to achieve the target?

Using off-site compensation within areas of existing native vegetation surplus (scenario A) was inadequate to achieve the target in some parts of Brazil, but especially for the Atlantic Forest biome. Off-site compensation that includes both native vegetation surplus and compensation in Legal Reserves of small farms (scenario B) increased the land availability for compensation. This raised the ability to achieve the target in all biomes, but it is still not enough supply to meet the target in Atlantic Forest. CRA is an important pathway to facilitate legal compliance and achieving the Legal Reserve target, but it may have little or no additional effects on the protection of native vegetation, because most of the compensation is likely to take place where native vegetation is already protected by prevailing legislation (Freitas et al., 2017), i.e., the Legal Reserves in small farms, all the Atlantic Forest and Cerrado in the State of São Paulo (São Paulo, 2009). Thus, restoration (both on-site and off-site) is still the most appropriate action to achieve the target ensuring additional protection.

We showed that implementing vegetation restoration in pasturelands with low suitability (scenarios C to E) make it possible to achieve the target for all the Brazilian territory requiring at least low ecological equivalence degree, and for most of the States, it is possible to require medium to high ecological equivalence without the need to restore native vegetation on productive farmland. In our models, we proposed vegetation restoration only in pasturelands with low agriculture suitability, which in general have never been developed because they have steep terrain or other unfavourable characteristics, and because of that they are easier to restore with low cost than productive areas, as they usually have some level of natural regeneration (Crouzeilles et al., 2020). Recent studies have shown an increase in secondary forest regeneration in areas with low agricultural potential (Molin et al., 2017; Rezende et al., 2018).

The on-site native restoration represents an important strategy to achieve the Legal Reserve target, where 89 % (scenario C) of the Brazilian territory can meet the target with at least a medium ecological equivalence requirement. The on-site restoration decreases the Legal Reserve deficit to be compensated in other properties, and can be a cost-effective alternative – the highest ecological equivalence with relatively low cost (Molin et al., 2018). The Native Vegetation Protection Law allows the use of exotic species of high economic interest for the restoration of Legal Reserves, if combined with native species, and also livestock in natural grassland regions, which can represent a great economic opportunity for landowners in low agricultural potential regions (Metzger et al., 2019). However, in areas with high potential for agriculture, as in the State of São Paulo and Paraná (Freitas et al., 2017), only on-site restoration of the Legal Reserve deficit is not enough to achieve the target. Moreover, it can be not adopted by most of landowners due to the costs for implementing and monitoring restoration, especially in areas where the landscape does not favour the natural regeneration (Strassburg et al., 2019).

Thus, we showed the importance to use different strategies to achieve the Legal Reserve target, combining both the off-site compensation in existing native vegetation protection and on-site and off-site restoration (scenarios D and E). The scenario D, which does not consider off-site restoration, presents 86 % of the territory able to achieve the target adopting high levels of ecological equivalence, which represents a good strategy to achieve the target in most of the states. In this scenario, there are still problems to achieve the target at low ecological equivalence especially for Goiás in Atlantic Forest, São Paulo in Cerrado and Tocantins in Amazon Forest. These exceptions were also observed by Freitas et al. (2017) because of the high Legal Reserve deficit and low land supply for compensation in these regions.

Different strategies to reach the Legal Reserve target can be adopted by the States, and the best solution may not depend on only one strategy. We showed that the different mechanisms of Legal Reserve compensation that the legislation offers can be a good opportunity for landowner to comply with the law. We showed that each biome in Brazil has a different scenario, and, for example, on-site restoration will be essential for Atlantic Forest, but not essential in the Amazon Forest to comply

with the law. The same occurs at the state level. States with different realities will need different strategies to reach the target. The examples discussed before, in Goiás, São Paulo and Tocantins, show regions where native vegetation restoration will be essential to meet the target, whereas for other states as Amazonas and Pernambuco (Appendix B), there is enough native vegetation surplus available for trade.

4.2. How the ecological equivalence requirement affects the ability to achieve the target?

The increase in ecological equivalence requirement for Legal Reserve compensation did not change considerably the ability to achieve the target in general, with the exception of the Atlantic Forest. For this biome, however, it is possible to achieve 99 % of the target considering a medium ecological equivalence and adopting all the strategies, which can be an interesting approach to meet the target for this biome.

Increasing the equivalence requirement only affects the ability to meet the target in the Amazon when only off-site compensation through native vegetation is considered. When we consider restoration in pasture with low productivity, the ability to meet the target did not decrease even requiring a high ecological equivalence. In fact, in the Amazon region the availability of this type of land is high, because many areas are abandoned after some years of pasture use due to the low potential for agricultural and cattle ranch (Fearnside, 1996; Lennox et al., 2018). This natural regeneration on abandoned pasture represented 38 % of the increase in secondary forest in Amazonia between 2004 and 2014 (INPE and Empraba, 2016).

In the Cerrado biome, the ability is affected only when strategy 3 is not adopted (only allowed by CRA mechanism), showing that CRA can require stricter ecological equivalence than the biome boundary. Pampas did not reach the target when high ecological equivalence was required, however, there is only one macro-unit in this biome, and the medium equivalence considered in this study should be enough for Legal Reserve compensation in this biome.

4.3. Is it possible to achieve the target avoiding the conversion of productive lands?

Overall, we showed that it is possible to achieve the target in most of the country without converting productive lands, even when requiring a higher degree of ecological equivalence than the Biome boundary. The exceptions, as the Cerrado in the State of São Paulo, do not hinder the implementation of ecological requirement for Legal Reserve compensation, and to achieve the target at the national scale. In these particular cases where the land supply is low, and on-site restoration is not enough to supply the deficit, we can adopt off-site restoration in low-productivity lands (scenario D), which allows 100 % of the territory to achieve the target at a low degree of ecological equivalence, and 96 % at medium ecological equivalence degree. Thus, areas with low land supply could adopt a degree of ecological equivalence that allows achievement of the target through a combination of protection of existing native vegetation and restoration in low productive pasturelands.

It is important to highlight that our Legal Reserve deficit data do not include the application of the Article 68 of the Native Vegetation Protection Law, created with the revision of the law in 2012, which exempts landholders from Legal Reserve obligations if native vegetation was converted without offending the legislation in place at the time of the conversion. The application of this legal mechanism can decrease in 58 % the environmental deficit from properties deforested illegally before 2008 (Soares-filho et al., 2014). In the state of São Paulo, for example, this mechanism can reduce the Legal Reserve deficit by 50 % (Tavares et al., 2019), which would make it possible to achieve the Legal Reserve target in the Cerrado biome in this state, even considering higher levels of ecological equivalence.

Even with the reduction of the Legal Reserves requirement after 2012, part of the agribusiness sector still criticizes the Legal Reserves requirement claiming that it impedes the agricultural expansion and, consequently, the economic development (Metzger et al., 2019). A recent bill (n. 2362/19) has been presented to the Brazilian Congress to extinguish Legal Reserves, representing a great risk for the environmental protection in Brazil, where 27 % of the nation`s remaining native vegetation would be made available for clearing (Guidotti et al., 2017). We showed here that it is possible to achieve the target without converting productive lands. Protection via Legal Reserves is important for native vegetation in Brazil, most of which is on private land (Brancalion et al., 2016). Further, native vegetation protection under Legal Reserves in Brazil could help decrease the current forest loss in the Amazon and Cerrado, which has increased in recent months (INPE, 2020).

5. Conclusion

We show that it is possible to achieve the Legal Reserve target without converting productive lands. To achieve the target, it is important to combine different strategies that include protecting existing native vegetation through off-site compensation, and restoring it (on-site and off-site) in pasturelands with low agricultural suitability. Native vegetation restoration on-site can be an important cost-effective strategy that reduces land demand for compensation, which in turn increases the ability to achieve the target, while requiring the highest ecological equivalence. By combining strategies, it is possible to achieve the target even requiring a higher degree of ecological equivalence for Legal Reserve compensation than the Biome boundary without compromising productive lands. The example of the Brazilian Native Vegetation Protection Law shows that it is possible to balance environmental and agricultural production during implementation of environmental policy.

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.

Funding

This work was supported by the São Paulo Research Foundation (FAPESP) [grant numbers 2013/07375-0; 2013/50718-5; 2016/17680-2; 2017/24028-2; 2018/25147-8]; Brazilian National Council for Scientific and Technological Development (CNPq); and World Wide Fund for Nature Brazil – WWF.

CRediT authorship contribution statement

Kaline de Mello: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **Arthur Nicolaus Fendrich:** Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - review & editing. **Gerd Sparovek:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing - review & editing. **Jeremy S. Simmonds:** Conceptualization, Methodology, Writing - review & editing. **Martine Maron:** Conceptualization, Methodology, Resources, Software, Supervision, Writing - review & editing. **Paulo André Tavares:** Data curation, Methodology, Writing - review & editing. **Alice Dantas Brites:** Conceptualization, Writing - review & editing. **Ricardo Ribeiro Rodrigues:** Conceptualization, Funding acquisition, Methodology, Writing - review & editing. **Carlos Alfredo Joly:** Conceptualization, Funding acquisition, Methodology, Writing - review & editing. **Jean Paul Metzger:** Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Supervision, Writing - review & editing.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2021.02.014.

References

Antonelli, A., Kissling, W.D., Flantua, S.G.A., Bermúdez, M.A., Mulch, A., Muellner-Riehl, A.N., Kreft, H., Linder, H.P., Badgley, C., Fjeldsa, J., Fritz, S.A., Rahbek, C., Herman, F., Hooghiemstra, H., Hoorn, C., 2018. Geological and climatic influences on mountain biodiversity. Nat. Geosci. 11, 718–725.

Boesing, A.L., Nichols, E., Metzger, J.P., 2017. Effects of landscape structure on avian-mediated insect pest control services: a review. Landsc. Ecol. 32, 931–944. https://doi.org/10.1007/s10980-017-0503-1.

Brancalion, P.H.S., Garcia, L.C., Loyola, R., Rodrigues, R.R., Pillar, V.D., Lewinsohn, T. M., 2016. A critical analysis of the Native Vegetation Protection Law of Brazil (2012): updates and ongoing initiatives. Nat. e Conserv. 14, 1–15. https://doi.org/10.1016/j.ncon.2016.03.003.

Bull, J.W., Strange, N., 2018. The global extent of biodiversity offset implementation under no net loss policies. Nat. Sustain. 1, 790–798. https://doi.org/10.1038/s41893-018-0176-z.

Chavent, M., Kuentz-Simonet, V., Labenne, A., Saracco, J., 2018. ClustGeo: an R package for ierarchical clustering with spatial constraints. Comput. Stat. 33, 1799–1822.

Crouzeilles, R., Beyer, H.L., Monteiro, L.M., Feltran-Barbieri, R., Pessôa, A.C.M., Barros, F.S.M., Lindenmayer, D.B., Lino, E.D.S.M., Grelle, C.E.V., Chazdon, R.L., Matsumoto, M., Rosa, M., Latawiec, A.E., Strassburg, B.B.N., 2020. Achieving cost-effective landscape-scale forest restoration through targeted natural regeneration. Conserv. Lett. 1–9. https://doi.org/10.1111/conl.12709.

Fang, D., Chen, B., Hubacek, K., Ni, R., Chen, L., Feng, K., Lin, J., 2019. Clean air for some: unintended spillovereffecs of regional air pollution policies. Sci. Adv. 24 (4), eaav4707 https://doi.org/10.1126/sciadv.aav4707.

Farina, E., Zechin, M.R., Rodrigues, A.P., Belon, J.G.O., Sousa, E.L., Kutas, G., Phillips, L., Camargo, R., Szwarc, A., Zilmar, J.S., 2019. Cenários de desafios no setor Sucroenergético (Challenges scenarios in the Sugarcane sector). AgroANALYSIS 38 (5), 30–36. ISSN 0100-4298. Available in: <http://bibliotecadigital.fgv.br/ojs/index.php/agroanalysis/article/view/78303/74989>. Acessed on: 09 Jun. 2020.

Fearnside, P.M., 1996. Amazonian deforestation and global warming: carbon stocks in vegetation replacing Brazil's Amazon forest. For. Ecol. Manage. 80, 21–34.

Fish and Wildlife Service, 1980. Habitat Evaluation Procedures Handbook. Avaiable in. Division of Ecological Services, U.S. Fish and Wildilife Service, Department of the Interior, Washington D.C. https://www.fws.gov/policy/esmindex.html.

Freitas, F.L.Mde, Sparovek, G., Mörtberg, U., Silveira, S., Klug, I., Berndes, G., 2017. Offsetting legal deficits of native vegetation among Brazilian landholders: effects on nature protection and socioeconomic development. Land Use Policy 68, 189–199. https://doi.org/10.1016/j.landusepol.2017.07.014.

Gallagher, K.S., Zhang, F., Orvis, R., Rissman, J., Liu, Q., 2019. Assessing the Policy gaps for achieving China's climate targets the Paris Agreement. Nat. Commun. 10, 1256. https://doi.org/10.1038/s41467-019-09159-0.

Guidotti, V., Freitas, F.L.M., Sparovek, G., Pinto, L.F.G., Hamamura, C., Carvalho, T., Cerignoni, F., 2017. Números Detalhados Do Novo Código Florestal E Suas Implicações Para Os Pras Principais Resultados E Considerações 1–9. https://doi.org/10.13140/RG.2.2.23229.87526.

Habib, T.J., Farr, D.R., Schneider, R.R., Boutin, S., 2013. Economic and ecological outcomes of flexible biodiversity offset systems. Conserv. Biol. 27, 1313–1323. https://doi.org/10.1111/cobi.12098.

Hoorn, C., Wesselingh, F.P., ter Steege, H., Bermudez, M.A., Mora, A., Sevink, J., Sanmartín, I., Sanchez-Meseguer, A., Anderson, C.L., Figueiredo, J.P., Jaramillo, C., Riff, D., Negri, F.R., Hooghiemstra, H., Lundberg, J., Stadler, T., Sarkinen, T., Antonelli, A., 2010. Amazonia through time: andean uplift, climate change, landscape evolution, and biodiversity. Science 330, 927–931.

INPE – Instituto Nacional de Pesquisas Espaciais (National Institute of Space Research), Embrapa – Empresa Brasileira de Pesquisa Agropecuária (Brazilian Agricultural Research Corporation, 2016. TerraClass Project. Avaiable in. http://www.inpe.br/cra/projetos_pesquisas/dados_terraclass.php.

Jenkins, W.A., Murray, B.C., Kramer, R.A., Faulkner, S.P., 2010. Valuing ecosystem services from wetlands restoration in the Mississippi Alluvial Valley. Ecol. Econ. 69, 1051–1061. https://doi.org/10.1016/j.ecolecon.2009.11.022.

Joly, C.A., Metzger, J.P., Tabarelli, M., 2014. Experiences from the Brazilian Atlantic Forest: ecological findings and conservation initiatives. New Phytol. 204 (3), 459–473. https://doi.org/10.1111/nph.12989.

Kanter, D.R., Chodos, O., Nordland, M.R., Winiwarter, W., 2020. Gaps and opportunities in nitrogen pollution policies around the world. Nat. Sustain. 3, 956–963. https://doi.org/10.1038/s41893-020-0577-7.

Laliberté, E., Zemunik, G., Turner, B.L., 2014. Environmental filtering explains variation in plant diversity along resource gradients. Science 345 (6204), 1602–1605.

Lennox, G.D., Gardner, T.A., Thomson, J.R., Ferreira, J., Berenguer, E., Lees, A.C., Nally, R.M., Aragão, L.E.O.C., Ferraz, S.F.B., Louzada, J., Moura, N.G., Oliveria, V.H. F., Pardini, R., Solar, R.R.C., Mello, F.Z.V., Vieira, I.C.G., Barlow, J., 2018. Second rate or a second chance? Assessing biomass and biodiversity recovery in regenerating Amazonian forests. Glob. Chang. Biol. 24, 5680–5694.

MapBiomas, 2019. Brazilian Annual Land Use and Land Cover Mapping Project. Accessed in 23/09/2019. http://mapbiomas.org.

Mello, K.D., Valente, R.A., Randhir, T.O., dos Santos, A.C.A., Vettorazzi, C.A., 2018. Effects of land use and land cover on water quality of low-order streams in Southeastern Brazil: watershed versus riparian zone. Catena 167. https://doi.org/10.1016/j.catena.2018.04.027.

Metzger, J.P., Bustamante, M.M.C., Ferreira, J., Fernandes, G.W., Librán-Embid, F., Pillar, V.D., Prist, P.R., Rodrigues, R.R., Vieira, I.C.G., Overbeck, G.E., 2019. Why Brazil needs its legal reserves. Perspect. Ecol. Conserv. https://doi.org/10.1016/j.pecon.2019.07.002.

Miller Jr., R.E., Gunsalus, B.E., 1999. Wetland Rapid Assessment Procedure (WRAP). Technical Publication REG-001. Natural resource management division, Regulation department, South Florida Water Management District.

Mittermeier, R.A., Turner, W.R., Larsen, F.W., Brooks, T.M., Gascon, C., 2011. Global biodiversity conservation: the critical role of hotspots. In: Zachos, F.E., Habel, J.C. (Eds.), Biodiversity Hotspots: Distribution and Protection of Conservation Priority Areas. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 3–22. https://doi.org/10.1007/978-3-642-20992-5_1.

Molin, P.G., Gergel, S.E., Soares-Filho, B.S., Ferraz, S.F.B., 2017. Spatial determinants of Atlantic Forest loss and recovery in Brazil. Landsc. Ecol. 32, 857–870. https://doi.org/10.1007/s10980-017-0490-2.

Molin, P.G., Chazdon, R., Frosini de Barros Ferraz, S., Brancalion, P.H.S., 2018. A landscape approach for cost-effective large-scale forest restoration. J. Appl. Ecol. 55, 2767–2778. https://doi.org/10.1111/1365-2664.13263.

Morandeau, D., Vilaysack, D., 2012. Compensating for damage to biodiversity: an international benchmarking study. La Défense Cedex : COMMISSARIAT GÉNÉRAL AU DÉVELOPPEMENT DURABLE.

Neale, M.W., Storey, R.G., Rowe, D.K., Collier, K.J., Hatton, C., Joy, M.K., Parkyn, S.M., Maxted, J.R., Moore, S., Phillips, N., N, Quinn, J.M., 2011. Stream Ecological Valuation (SEV): A User's Guide. Auckland Council. ISBN 978-1-927169-17-19.

Rezende, C.L., Scarano, F.R., Assad, E.D., Joly, C.A., Metzger, J.P., Strassburg, B.B.N., Tabarelli, M., Fonseca, G.A., Mittermeier, R.A., 2018. From hotspot to hopespot: an opportunity for the Brazilian Atlantic Forest. Perspect. Ecol. Conserv. 16, 208–214. https://doi.org/10.1016/j.pecon.2018.10.002.

Ribeiro, M.C., Martensen, A., Metzger, J.P., Tabarelli, M., Scarano, F.R., Fortin, M., 2011. The Brazilian Atlantic Forest: a shrinking biodiversity hotspot. In: Zachos, F., Habel, J. (Eds.), Biodiversity Hotspots. Springer, Berlin.

Salvia, M., Reckien, D., Pietrapertosa, F., Eckersley, P., Spyridaki, N., Krook-Riekkola, A., Olazabal, M., Hurtado, S.D.G., Simoes, S.G., Geneletti, D., Viguié, V., Fokaides, P.A., Ioannou, B.I., Flamos, A., Csete, M.S., Buzasi, A., Orru, H., Boer, C., Foley, A., Riznar, K., Matosovic, M., Balzan, M., Smigaj, M., Bastakova, V., Streberova, E., Sel, N.B., Coste, L., Tardieu, L., Altenburg, C., Lorencová, E.K., Orru, K., Wejs, A., Feliu, E., Church, J.M., Grafakos, S., Vasilie, S., Paspaldzhiev, I., Heidrich, O., 2021. Will climate mitigation ambitions lead to carbon neutrality? An analysis of the local-level plans of 327 cities in the EU. Renewable Sustainable Energy Rev. 135, 110253 https://doi.org/10.1016/j.rser.2020.110253.

São Paulo, E., 2009. Lei Nº 13.550, DE 02 DE JUNHO DE 2009.

Saturni, F.T., Jaffé, R., Metzger, J.P., 2016. Landscape structure influences bee community and coffee pollination at different spatial scales. Agric. Ecosyst. Environ. 235, 1–12. https://doi.org/10.1016/j.agee.2016.10.008.

Sehn, V., Blesl, M., 2021. Implications of national climate targets on the energy-water Nexus in Germany: a case study. J. Sustain. Dev. Energy Water Environ. Syst. 9 (1), 1080344 https://doi.org/10.13044/j.sdewes.d8.0344.

Soares-filho, B., Rajão, R., Macedo, M., Carneiro, A., Costa, W., Coe, M., Rodrigues, H., Alencar, A., 2014. Cracking Brazil' s forest code supplemental. Science 344 (80), 363–364. https://doi.org/10.1126/science.124663.

Sparovek, G., Barretto, A.G.D.O.P., Matsumoto, M., Berndes, G., 2015. Effects of governance on availability of land for agriculture and conservation in Brazil. Environ. Sci. Technol. 49, 10285–10293. https://doi.org/10.1021/acs.est.5b01300.

Sterner, T., Barbier, E.B., Bateman, I., van den Bijgaart, I., Crépin, A.S., Edenhofer, O., Fischer, C., Habla, W., Hassler, J., Johansson-Stenman, O., Lange, A., Polasky, S., Rockström, J., Smith, H.G., Steffen, W., Wagner, G., Wilen, J.E., Alpízar, F., Azar, C., Carless, D., Chávez, C., Coria, J., Engström, G., Jagers, S.C., Köhlin, G., Löfgren, Å., Pleijel, H., Robinson, A., 2019. Policy design for the anthropocene. Nat. Sustain. 2, 14–21. https://doi.org/10.1038/s41893-018-0194-x.

Strassburg, B.B.N., Latawiec, A.E., Barioni, L.G., Nobre, C.A., da Silva, V.P., Valentim, J. F., Vianna, M., Assad, E.D., 2014. When enough should be enough: improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. Glob. Environ. Chang. 28, 84–97. https://doi.org/10.1016/j.gloenvcha.2014.06.001.

Strassburg, B.B.N., Beyer, H.L., Crouzeilles, R., Iribarrem, A., Barros, F., de Siqueira, M. F., Sánchez-Tapia, A., Balmford, A., Sansevero, J.B.B., Brancalion, P.H.S., Broadbent, E.N., Chazdon, R.L., Filho, A.O., Gardner, T.A., Gordon, A., Latawiec, A., Loyola, R., Metzger, J.P., Mills, M., Possingham, H.P., Rodrigues, R.R., Scaramuzza, C.A.de M., Scarano, F.R., Tambosi, L., Uriarte, M., 2019. Strategic approaches to restoring ecosystems can triple conservation gains and halve costs. Nat. Ecol. Evol. 3, 62–70. https://doi.org/10.1038/s41559-018-0743-8.

Tavares, P.A., Brites, A.D., Sparovek, G., Guidotti, V., Cerignoni, F., Aguiar, D., Metzger, J.P., Rodrigues, R.R., Pinto, L.F.G., Mello, Kde, Molin, P.G., 2019. Unfolding additional massive cutback effects of the native vegetation protection law on legal reserves, Brazil. Biota Neotrop. 19 https://doi.org/10.1590/1676-0611-bn-2018-0658.

Valdujo, P.H., Carnaval, A.C.O.Q., Graham, C.H., 2013. Environmental correlates of anuran beta diversity in the Brazilian Cerrado. Ecography 36 (6), 708–717.

Vandenbergh, M.P., Gilligan, J.M., 2017. Beyond Politics: the Private Governance Response to Climate Change. Cambridge University Press. https://doi.org/10.1017/9781316848555.

Yao, L., Zhao, M., Xu, T., 2017. China's water-saving irrigation management system: policy, implementation and challenge. Sustainability 9 (12), 2339. https://doi.org/10.3390/su9122339.