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PROGRAMA DE PÓS-GRADUAÇÃO EM ECOLOGIA

INCORPORATING AGENT-BASED DECISION INTO SPATIAL PRIORITIZATION FOR FOREST RESTORATION

JULIA DE NIEMEYER CALDAS

Dissertação apresentada ao Programa de Pós-Graduação em Ecologia da Universidade Federal do Rio De Janeiro, como parte dos requisitos necessários à obtenção do grau de mestre em ciências biológicas (ecologia).

Orientadora: Dra. Mariana Moncassim Vale Co-orientador: Dr. Renato Crouzeilles

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Defendida em 16 de fevereiro de 2017

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RESUMO

Desmatamento e fragmentação de habitat são hoje problemas ambientais em escala global, com impacto negativo sobre a biodiversidade e serviços ecossistêmicos. A restauração florestal é, portanto, uma prioridade, porém é uma atividade extremamente cara e os financiamentos são limitados. Como o desmatamento está fortemente associado à conversão de florestas em agricultura/pasto, a tomada de decisão por proprietários rurais é uma questão central em restauração florestal. Neste trabalho, associamos fatores socioeconômicos e ecológicos em análises de priorização de áreas para restauração florestal visando cumprir a Lei da Proteção da Vegetação Nativa, incorporando a tomada de decisão de proprietários rurais. Nós apresentamos como estudo de caso uma paisagem de 10 mil hectares na zona de amortecimento da reserva Biológica do Tinguá, Rio de Janeiro, comparando cinco estratégias de restauração e cinco espécies com diferentes potenciais de dispersão. Nós simulamos a restauração florestal seguindo cada estratégia e efetuamos comparações ao longo do tempo-limite para cumprimento da lei (20 anos) em termos de custo-efetividade, i.e. aumento de disponibilidade de habitat por unidade de custo.

Houve o aumento de 2.6% de cobertura vegetal na paisagem através da restauração florestal. Estratégias incluindo priorização atingiram maiores benefícios para biodiversidade, quando comparadas à restauração aleatória. Buscando minimizar custo de transição e incorporando regeneração natural economizamos mais de R$ 2 milhões comparado a práticas que minimizam apenas custo de oportunidade, para um ganho similar em biodiversidade. Buscando maximizar biodiversidade e minimizar custo atingimos maiores benefícios para biodiversidade por um baixo custo adicional. Esperamos um maior ganho em disponibilidade de habitat pós-restauração em paisagens com menor porcentagem inicial de cobertura florestal.

A restauração florestal visando cumprir a lei ambiental deve acompanhar análises de priorização multicriteriosa como apresentamos aqui. A restauração *in-situ* deve levar em conta custo de oportunidade e custo de restauração (i.e., custo de transição), regeneração natural, e a dinâmica temporal de disponibilidade de habitat. Uma priorização espacial para restauração florestal incluindo o aumento de disponibilidade de habitat nos objetivos principais atinge melhores resultados para a biodiversidade por um baixo custo adicional.

Palavras-chave: Mata Atlântica Brasileira, Restauração florestal. GISMulti-escala, Tomada de decisão, Lei da Proteção da Vegetação Nativa, Regeneração natural.

ABSTRACT

Deforestation and habitat fragmentation are currently environmental problems at a global scale, with negative impacts on biodiversity and ecosystem services. Therefore, forest restoration is a priority, although extremely expensive and budget-limited. As deforestation is strongly linked to conversion of forest to agriculture/pasture, accounting for landowners' decision-making on land-use is a central issue in forest restoration. In this study, we combine socio-economic and ecological factors to prioritize areas for forest restoration to comply with the Native Vegetation Protection Law incorporating landowners' decision-making. We present as case study a 10.000 hectares landscape at the buffer zone of the Tinguá Biological Reserve, Rio de Janeiro, comparing five alternative prioritization strategies for forest restoration and five species with different dispersal abilities. We simulated forest restoration following each strategy and compared them across the time available for law compliance (20 years) in terms of cost-effectiveness, calculated as habitat availability improvement post-restoration per unit cost.

Forest restoration increased landscape's forest cover by 2.6%. Strategies including targets for restoration brought more benefits for biodiversity than random restoration. Aiming to minimize transition cost and incorporating natural regeneration could save more than R$ 2 million compared to practices minimizing opportunity cost only, for a similar improvement in habitat availability. Prioritizing for both biodiversity and minimizing cost resulted in better outcomes for biodiversity with low additional cost. We should expect higher habitat availability improvement in landscapes with lower initial forest cover percentage.

Forest restoration aiming at law compliance in Brazil should be coupled with prioritization analyses such as we presented here. *In-situ* restoration should account for both opportunity and restoration costs (i.e. transition cost), natural regeneration, and temporal dynamics of habitat availability. Finally, spatial prioritization for forest restoration including habitat availability improvement as one of the main targets could result in better outcomes for biodiversity long-term persistence for low additional cost.

Key-words: Brazilian Atlantic Forest, Forest restoration, GISMulti-scale, Decision making, Native Vegetation Protection Law, Natural regeneration

SUMMARY

INTRODUCTION

Human induced deforestation, fragmentation and degradation cause serious loss and changes in biodiversity and ecosystem services (Lewis et al. 2015). Between 2010 and 2015, worldwide forest loss reached an annual net rate of 0.08%, with 7.6 million ha converted mainly to agriculture, particularly in South America and Africa (FAO 2016). For that reason, forest restoration has become a global priority (Holl & Aide 2011), spurred by various initiatives around the world. The Bonn Challenge (http://www.bonnchallenge.org/) and the New York Declaration on Forests (Conway et al. 2015), for example, are international commitments targeting to restore 150 and 350 million ha of forests and disturbed ecosystems by 2020 and 2030, respectively. These targets are very ambitious, yet large-scale forest restoration is extremely expensive and budget-limited (Brancalion et al. 2012; Banks-Leite et al. 2014; Chazdon & Guariguata 2016). As deforestation is strongly linked to conversion of forest to agriculture/pasture (Gibbs, et al. 2010; Liu et al. 2016), one of the central issues is to account for individual landowners' decision on land-use (Matthews et al. 2007; Schouten et al. 2013). Nonetheless, although agent-based models have recently gained attention to support decision-making (Matthews et al. 2007), its use to solve restoration prioritization problems is still incipient.

Many reasons can encourage landowners to set aside productive lands for forest restoration, such as higher return-on-investments, for example through timber and non-timber exploitation and/or payment for ecosystem services (Brancalion et al. 2012; Latawiec et al. 2015), compliance with law (Tambosi et al. 2013; Latawiec et al. 2016), or even conservation awareness (Alves-Pinto 2016). In order to maximize return on investments, landowners may decide to set aside areas for restoration where opportunity cost, which means the cost of setting aside a piece of land for restoration instead of using it for other practices, is low (Budiharta et al. 2016; Mills et al. 2014, Brancalion et al. 2012). Forest restoration, however, also depends on other costs, such as those associated to restoration *in situ* (Chazdon et al. 2008; Holl & Aide 2011; Birch et al. 2010). Ecological restoration techniques are context-dependent and range from low-cost approaches, in assisted or spontaneous natural regeneration, to high-cost approaches in active restoration (e.g., tree plantations using nursery stock) (Helmer et al. 2008; Holl & Aide 2011), which can be the most expensive part of scaling up forest restoration (e.g. Crouzeilles et al. 2015). In areas with previous highly intense land use, low amount of surrounding forest cover, exposed soil and steeper slope the potential for natural regeneration is reduced, for seed bank, propagules arriving from zoochory or anemochory dispersal, and soil nutrients tend to become less available (Chazdon 2003; Lamb et al. 2005; Zuazo & Pleguezuelo 2009; Holl & Aide 2011). Thus, forest restoration should be spatially prioritized based on individual landowners' decision on land-use and the complex relationships between socio-economic and ecological factors, which are key elements to achieve more cost-effective forest restoration (Hyman & Leibowitz 2000; Chazdon 2014; Crouzeilles et al. 2015; Latawiec et al. 2015; Rappaport et al. 2015;).

Additionally, in order to be effective, decision-making on forest restoration also needs to account for biodiversity return to restored areas. This will depend on metapopulational dynamics in the long term, which is affected by population viability and species dispersal ability for population supplementation and re-colonization in habitat patches (Hanski & Ovaskainen 2000). Habitat availability is a simple graph-based concept that measures landscape's capacity to support a metapopulation (Crouzeilles et al. 2015). It considers both habitat quality/quantity and species' ability to disperse between habitat patches (i.e. functional connectivity) (Hodgson et al. 2009; Saura & Rubio 2010; Tambosi et al. 2013; Crouzeilles et al. 2014). Habitat availability is species-specific and increases as habitat amount increases and fragmentation decreases in a landscape (Saura & Rubio 2010; Crouzeilles et al. 2014).

In Brazil, the main environmental law that protects and regulates native vegetation in private lands (Native Vegetation Protection Law, n° 12.651) was amended in May 2012 (Metzger et al. 2010). It requires that all landowners declare the amount and position of native vegetation present in their land (rural environmental register; CAR) into the Federal Rural Environmental Registry System (SiCAR). Depending on properties' size, landowners must protect native vegetation in Areas of Permanent Preservation (APP, all marginal watercourse strips, for example) and Legal Reserve (LR, specific percentage of a property that depends on the region or biome where it is located, ranging for 20% in the Atlantic Forest to 80% in the Amazon). Rural properties are categorized by size in fiscal modules (Law nº 6.746/79). This area measurement unit, expressed in hectares, is fixed by county and calculated based on its predominant agriculture. The Native Vegetation Protection Law also requires landowners to achieve compliance within 20 years, restoring a minimum of 1/10 of native vegetation debt every 2 years (Art. 66, §2º, Law 12.651/12). CAR information uploaded in the SiCAR has the potential to become the central instrument to regulate the use of natural resources in private lands in Brazil, potentially increasing sustainable development by conciliating environmental conservation and rural development (Silva et al. under review).

In this study, we combine socio-economic and ecological factors to prioritize areas for forest restoration to comply with the Native Vegetation Protection Law incorporating landowners' decision-making. We present a case study at the Baixada Fluminense in the state of Rio de Janeiro, located at the highly fragmented Atlantic Forest hotspot. We compared five alternative prioritization strategies: i) minimizing opportunity cost; ii) minimizing transition costs (i.e. restoration and opportunity costs); iii) maximizing habitat availability; iv) maximizing habitat availability while minimizing transition cost; and v) random restoration, contrasting five species with different dispersal abilities (10, 100, 500, 1000 and 3000m). We compared strategies across the time available for landowners to restore their lands according to the law (20 years), and in terms of cost-effectiveness, which was measured for each strategy and species based on habitat availability improvement per unit cost. By combining socio-economic and ecological factors, our findings can support local landowners in restoring their lands to comply with the Brazilian Native Vegetation Protection Law.

METHODS

The Brazilian Atlantic Forest is one of the most important biodiversity hotspots in the world (Myers et al. 2000), covering only 11.4–16% of its original distribution (Ribeiro et al. 2009). In this highly fragmented biome, there are few large forest remnants (< 100 ha), most of them under strictly protection areas, more than 80% are < 50 ha and mostly under private lands (Ribeiro et al. 2009). This is also the particular situation of the buffer zone surrounding the Tinguá Biological Reserve (REBIO Tinguá), the geographical region used in this study (Fig. 1). The REBIO Tinguá is a strictly protected area that covers 26,260 ha of Atlantic Forest and protects important watersheds that supply water for portions of the state of Rio de Janeiro (www.bvambientebf.uerj.br/arquivos/rebio_tingua.htm), and for that it is one of the seven Atlantic Forest Biosphere Reserves created by UNESCO (http://www.rbma.org.br/). It also holds several threatened, rare and endemic species. The 10 km buffer zone surrounding the REBIO Tinguá, an area defined by the Brazilian Environment Council Resolution (CONAMA 13/1990), aims to minimize negative human impacts on protected areas and ensure quality of life to local population (Brasil, 1990). Nonetheless, this buffer zone suffered a long history of disturbance due to intense urban expansion and land-use change to agriculture and pasture, resulting in a highly degraded and fragmented landscape (MMA 2006). Thus, the REBIO Tinguá is critical to increase biodiversity conservation and provision of ecosystem services, and must be considered as a source of species when solving restoration prioritization problems.

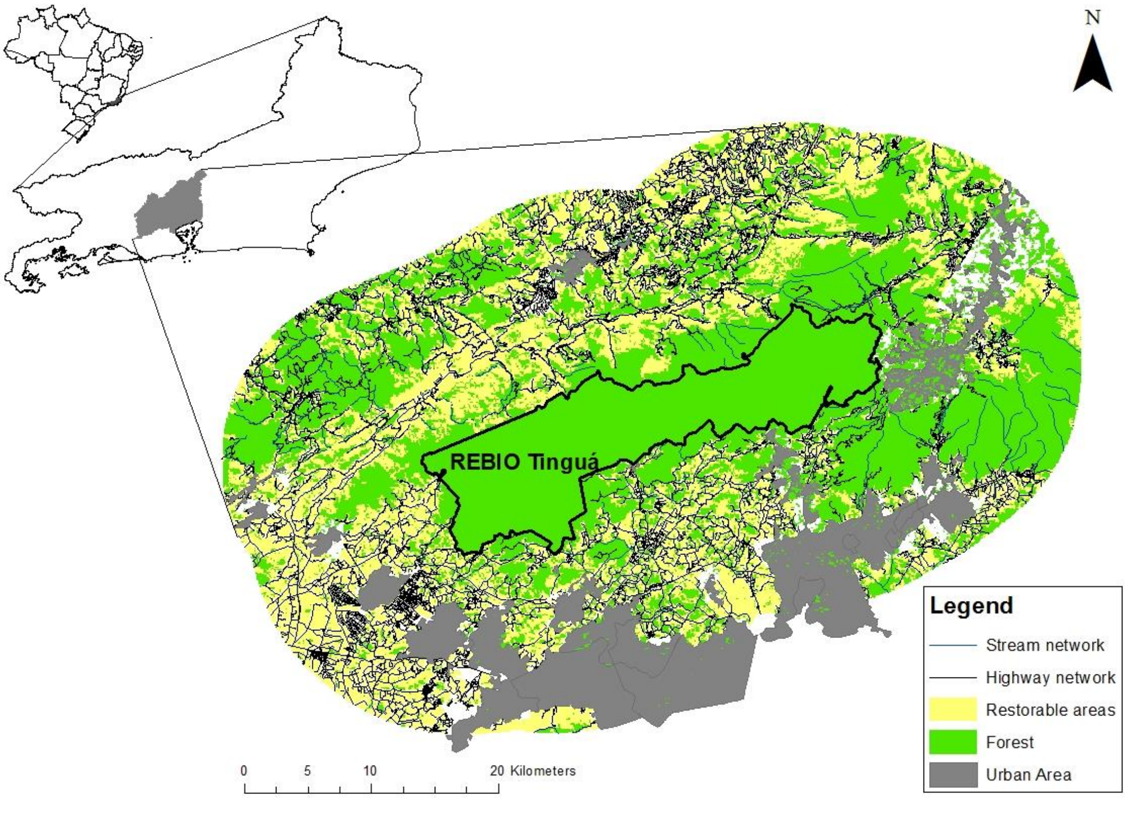

Figure 1: REBIO Tinguá (strong black line in the center) Buffer Zone. A 15km area surrounding the REBIO Tinguá, including the 10km wide buffer zone.

Our approach to prioritize areas for restoration in the buffer zone around REBIO Tinguá is based on seven main steps (Fig. 2): (1) map study area's biophysical and geopolitical attributes; (2) quantify habitat availability for hypothetical species with different dispersal abilities; (3) quantify environmental debts in Areas of Permanent Preservation and Legal Reserve within each property (see details below); (4) quantify costs for restoration: opportunity cost and transition cost (considering both opportunity and restoration costs) for each planning unit; (5) quantify contribution of each potentially restored planning unit to habitat availability; (6) prioritize planning units for restoration based on strategies' specific targets; and (7) simulate restoration of priority planning units for each strategy and then quantify total transition cost. We executed 10 simulations, restoring 1/10 of each property's debt at each run (see details below). After each simulation, there was a new distribution of forest remnants across the study area and environmental debts, as well as habitat availability, were re-analyzed (steps 2 and 3). Then, we calculated the cost-effectiveness for five different prioritization strategies (Box 1 below) for each species and at each run (totalizing 10 runs) by dividing post-restoration habitat availability per transition cost. After 10 runs, all properties had completely restored their environmental debts. Not every strategy followed all seven steps. We considered the following steps for each strategy: i) minimizing opportunity cost and ii) minimizing transition costs (steps 1-4, 6 and 7); iii) maximizing habitat availability and iv) maximizing habitat availability while minimizing transition cost (all seven steps); and v) random restoration (steps 1-4 and 7).

Box. 1: Prioritization strategies for forest restoration

i. Prioritization minimizing opportunity cost. In this strategy, we conducted restoration simulations of planning units with lower opportunity cost first, until all properties have achieved law compliance.

ii. Prioritization minimizing transition cost, i.e. both opportunity cost and restoration cost. In this strategy, we conducted restoration simulations of planning units with lower transition cost first, until all properties have achieved law compliance.

iii. Prioritization maximizing biodiversity long-term persistence, while minimizing transition cost. In this strategy, prioritization aimed at the most cost-efficient solution. We conducted restoration simulations of planning units with higher values of importance for *PC* improvement as well as lower values of transition cost first, until all properties have achieved law compliance.

iv. Prioritization maximizing biodiversity long-term persistence. In this strategy, we conducted restoration simulations of planning units with higher values of importance for *PC* improvement first, until all properties have achieved law compliance.

v. Random restoration. In this strategy, there was no prioritization of planning units. We conducted restoration simulations randomly among restorable planning units in Areas of Permanent Preservation and Legal Reserve within each property.

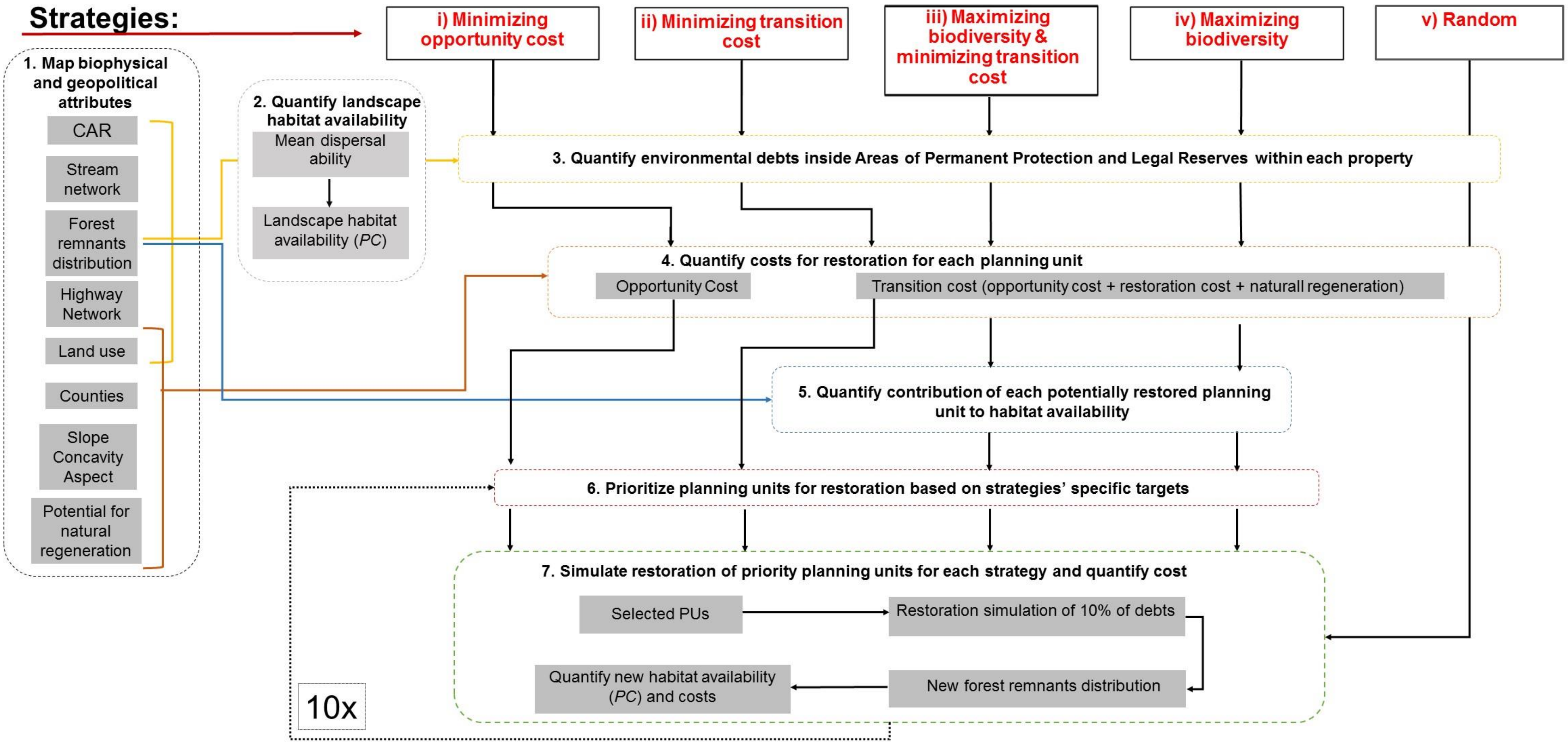

Figure 2: Seven main steps of the framework for prioritization of areas for forest restoration. PUs – Planning Units (1ha pixels)

Step 1. Map study area's biophysical and geopolitical attributes

We mapped the following study area biophysical and geopolitical attributes: i) forest cover; ii) land use and land cover; iii) highway network; iv) stream network; v) land slope; vi) slope orientation; vii) land curvature; viii) county membership; ix) planning units' potential for natural regeneration; and x) simulated rural environmental register (CAR). Forest cover data was built using ArcGIS Iso Cluster Unsupervised Classification tool over a September 2015 Landsat-8ETM satellite image (30 m resolution) of the study area available from the US Geographic Survey (http://glovis.usgs.gov/). We obtained land use and cover maps (i.e. agriculture, pasture, urban areas and forest cover) from the Brazilian Ministry of the Environment (MMA unpublished data) and updated it using our forest cover data. Highway network data was manually built using Google Earth's path tool over a 2015 DigitalGlobe Image (30 cm resolution). We obtained stream network data from the Brazilian Institute of Geography and Statistics (October 2013; 1:250.000 scale, IBGE). All data was updated and validated through visual interpretation using Google Earth and Landsat-8 ETM satellite image. We derived data on land slope, slope orientation, and land curvature based on a digital elevation model (Jarvis et al. 2008; Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 1:250.000, 90 m resolution) using ArcGIS 10.3.1 Spatial Analysts tools (ESRI 2015). We built land slope on Surface tool; slope orientation on Aspect tool and classified it as North (from -1° to 180°) and South (180° to maximum value); and land curvature on Curvature tool, classifying it as concave (<= -0.01), convex (>= 0.01) and plain (-0,01 – 0,01) (Schillaci et al. 2015; Giuseppe et al. 2016). Potential for natural regeneration was available from Crouzeilles et al. (in prep), which created a predictive model that considered biophysical and ecological variables to determine the potential for natural regeneration across the entire Atlantic Forest. We also used the counties membership map from the Brazilian Institute of Geography and Statistics (2013*;* 1:100 000 scale, BGE/DGC/CETE*)*. The CAR was available from TNC (unpublished data) and built based on data from both agricultural census (IBGE, 2015) and land management system (SIGEF, Portuguese acronym) (INCRA/MDA, 2014). Although this CAR is a simple simulation, it is sufficient to achieve our goal of incorporating landowner's decision on forest restoration, and not necessarily of modeling exact sites for restoration inside each property. Finally, we divided the study area into planning units of 100 x 100m (1 hectare), used as the minimum area for restoration.

We selected a 10.000 ha landscape (Fig. 3) inside the 10km buffer zone surrounding the REBIO Tinguá as case study. This choice was based on the Onda Verde's location, an NGO that is leading restoration initiatives in the area, without any explicit prioritization criteria, and so to which our study will be most useful. This area is covered by 135 rural properties, with a total of 633 hectares of environmental debt, of which 119 ha are inside Legal Reserve and 514 ha in riparian Areas of Permanent Preservation.

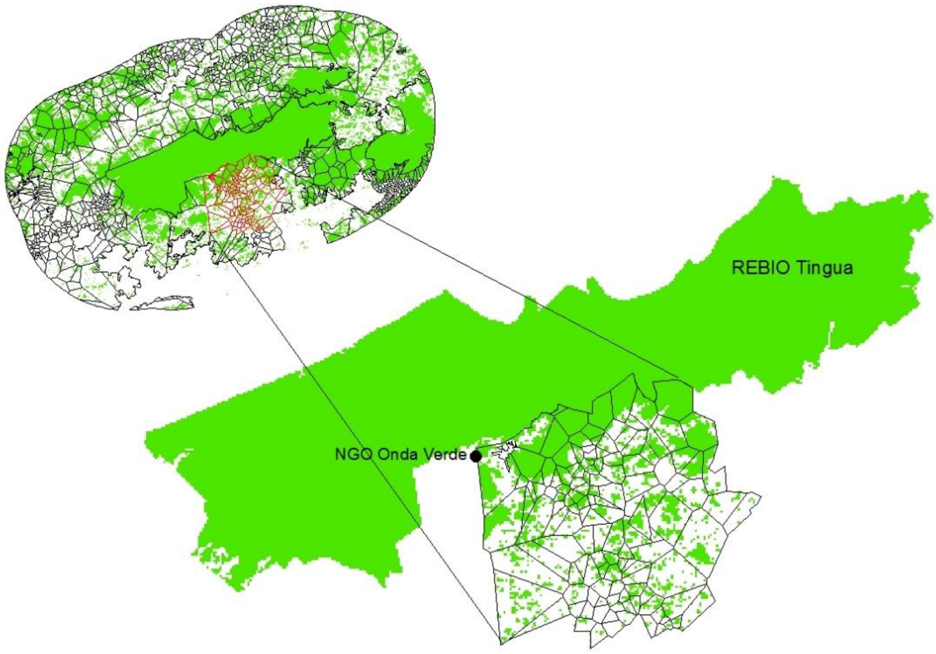

Figure 3: Landscape (10.000ha) used as case study. Black point represents the NGO Onda Verde's headquarter location.

Step 2. Quantify landscape habitat availability

We quantified landscape habitat availability using the Probability of Connectivity index (*PC*; Saura & Rubio, 2007). This index has been widely used to identify priority areas for conservation and restoration, as it measures landscape capacity to support a metapopulation by considering habitat amount and functional connectivity (e.g. Saura & Rubio 2010; Tambosi et al. 2013; Crouzeilles et al. 2014). We used this index because our aim is to quantify metapopulation dynamics in the long term and to increase population supplementation and re-colonization through forest restoration. *PC* was calculated was calculated using Conefor commends in R, as follows (Saura & Pascual-Hortal 2007):

$$\frac{PC = \sum_{i=1}^{n} \quad \sum_{j=1}^{n} \quad a_i a_j \ P_{ij}^{*}}{A_L^2}$$

where n is the number of patches, a_i and a_j are attributes of the patches i and j, and A_L^2 is total landscape area. The product probability (P_{ij}) of a path between two patches depends on species' dispersal ability and the presence of stepping-stones facilitating movement. P^*_{ij} is the path with the maximum product probability among all possible paths between patches i and j. When $i = j$ then P^*_{ij}= 1; which means that a patch itself is a space where connectivity exists. *PC* ranges from 0 (no habitat available) to 1 (maximum habitat availability) (Saura & Rubio 2007).

To calculate *PC*, we need three pieces of information: patch attribute, distance attribute and species dispersal ability. We used forest patch area as patch attribute, shortest Euclidean distance between two forest patches as distance attribute and a negative exponential function to measure species' dispersal viability based on different median dispersal distances. However, there is a lack of useful information on tropical species' life history, especially on movement and breeding ecology, data typically used in connectivity and dispersal distance models (Gardner et al. 2009; Witmee & Orme 2013; Fagan et al. 2016). For species that occur in Tinguá, for example, data on body size, diet and home range were frequently scarce. Thus, we simulated five hypothetical species that represent Atlantic Forest animals with low, medium and high median dispersal abilities (measured in meters): 10, 100, 500, 1000 and 3000m (Crouzeilles et al. 2010; 2014; Almeida-Gomes et al. 2016). Each value of dispersal distance represents a 50% probability of direct connection between two patches in a path. Habitat availability (*PC*) was calculated for present landscape using forest cover as it is today, and for future landscape using restored forest cover, a product of restoration simulations under each strategy.

Step 3. Quantify environmental debts in Areas of Permanent Preservation and Legal Reserve within each property

According to the Native Vegetation Protection Law, properties measuring up to four fiscal modules are considered small properties and have different restoration obligations. For example, small properties are exempt from restoring offset native vegetation in Legal Reserve areas deforested before July 2008, while larger properties presenting forest cover under region or biome's percentage obligation (i.e. 20%) are enforced to reforest in Legal Reserve area, to which vegetated Areas of Permanent Preservation can be included. On the other hand, demands on vegetation cover width along riparian Areas of Permanent Preservation will depend on river and property's size and everyone must maintain forest cover in these areas (for more information see Zakia & Pinto 2013). We used CAR data to assess properties' area and forest cover, and then calculated environmental debt inside riparian Areas of Permanent Preservation and Legal Reserve within each local property. Legal Reserve was calculated as 20% of properties' area, APP included, and in small properties, we calculated debt only on riparian Areas of Permanent Preservation. Forest cover and debts inside riparian areas were calculated using buffers along rivers for each property following law demands (Table 1). Because of limitations on visual imagery interpretation, it was not possible to differentiate rivers by width; we then stipulated buffers' size (m) based solely on properties' fiscal modules.

Due to computational limitations, we conducted prioritization and restoration analysis over 1ha cell planning units. Therefore, we assumed that all riparian Areas of Permanent Preservation have 100m width, from which we could not exclude actual river width. Additionally, debt calculations were rounded to meet integer values in hectare. For these reasons, debt and restoration calculations may be underestimated.

Table 1: Methodology used to compute Legal Reserve and riparian Areas of Permanent Preservation (APP), based on Zakia & Pinto (2013).

Fiscal modules	Riparian APP (buffer)	Required Legal Reserve (forest cover)
≤ 1	5 m	Not Applicable
1 to 2	8 m	
2 to 4	15 m	
4 to 10	20 m	20% of the property
Above 10	30 m	

Step 4. Quantify costs of restoration: opportunity and transition costs for each planning unit

Large-scale prioritization studies generally adopt land acquisition cost (e.g. Banks-Leite et al. 2014; Crouzeilles et al. 2015). However, the adoption of this method is due to the difficulty of calculating local productivity for a large number of planning units. At smaller scales, calculating opportunity cost directly from local mean productivity is a more realistic and explanatory method. Following that, we built a map of local opportunity cost based on local mean productivity. We defined opportunity cost as the net revenue not realized due to the choice of restoring a piece of land. We assessed land opportunity cost in planning units designated to forest restoration considering the agricultural income that will be lost in these areas in the long-term, which was expressed as Net Present Value (NPV) for each rural activity. In order to estimate NPV, we gathered information on: i) counties' average production yield for each type of agricultural crop and livestock around the REBIO Tinguá (IBGE, 2014), ii) average cost of agricultural crops estimates (CONAB, s.d; EMBRAPA, s.d.), and iii) agricultural prices (IEA, s.d.; CEPEA, s.d.). Following that, we calculated NPV for all agricultural practices carried out on counties around Tinguá, and spatially allocated cost information considering a land use map – mean agricultural crop NPV in agricultural areas, and mean livestock NPV in pasture areas (Fig. 4:A). In financial analyzes, Net Present

Value is commonly used as an indicator to evaluate the net return on capital in the time-period established for a project. It consists on the cash flow of an activity with a discount rate or capital opportunity cost decrease. In this study, we considered a discount rate of 8% per year, which is the minimum interest rate practiced by the main rural credit lines in Brazil, such as the ABC credit. The time horizon was 20 years, the period determined by NVPL for landowners to complete forest restoration in their properties. NPV was calculated as follows:

$$\mathrm{NPV} = \frac{\sum(B - C)}{(1 + \mathrm{i})^{\mathrm{t}}} - I$$

where *B* is the financial gains and *C*, the costs in a pre-determined time period (*t*); *i* is the annual discount rate; and *I* is the initial investment for the activity analyzed.

The transition cost map (Fig. 4C) was developed based on three main information: probability for natural regeneration, opportunity cost and restoration cost, based on the Onda Verde NGO expertizes' restoration experience at the region. The Onda Verde NGO (www.ondaverde.org.br) is the main local institution developing restoration projects inside properties around the REBIO Tinguá. They provided information on economic costs for active restoration based on factors that influence their fieldwork. Following that, biophysical and socio-economic constraints affecting financial costs for active restoration were analyzed and mapped (Fig. 4B). We considered the following biophysical constraints: slope orientation (south/north), slope (0-15°, 15-35°, 35-45° and >45°), land curvature (concave, plan or convex) and land use (crops/pasture or others). At Tinguá, productivity comes mostly from crop plantations rather than livestock grazing (MMA 2006), so it was not essential to differentiate pasture from crop plantations. For each planning unit the combinations of these factors were analyzed and then associated with a financial amount in Reais (BRR$). Financial costs included socio-economic factors, such as seedling planting (human resources, activities and material), replanting, hoeing, management, fertilizing (implementation and management), firebreaks, pest controls and taxes, which vary according to biophysical attributes.

Moreover, assisted natural regeneration is very important to combine rural livelihoods with biodiversity and ecosystem services conservation (Chazdon 2008). In areas with less aggressive land use and nearby forest patches, dispersal agents ensure diverse seed rain and natural regeneration could allow forest restoration in faster and cheaper course (Chazdon 2003; Lamb et al. 2005). Thereby, we calculated transition cost as:

$$T.C. = O.C. + (1 - P.N.R.) \times R.C.$$

where *T.C.* is transition cost, *O.C.* is opportunity cost, *P.N.R.* is the probability for natural regeneration, and R.C. is restoration cost (Crouzeilles et al. in prep.).

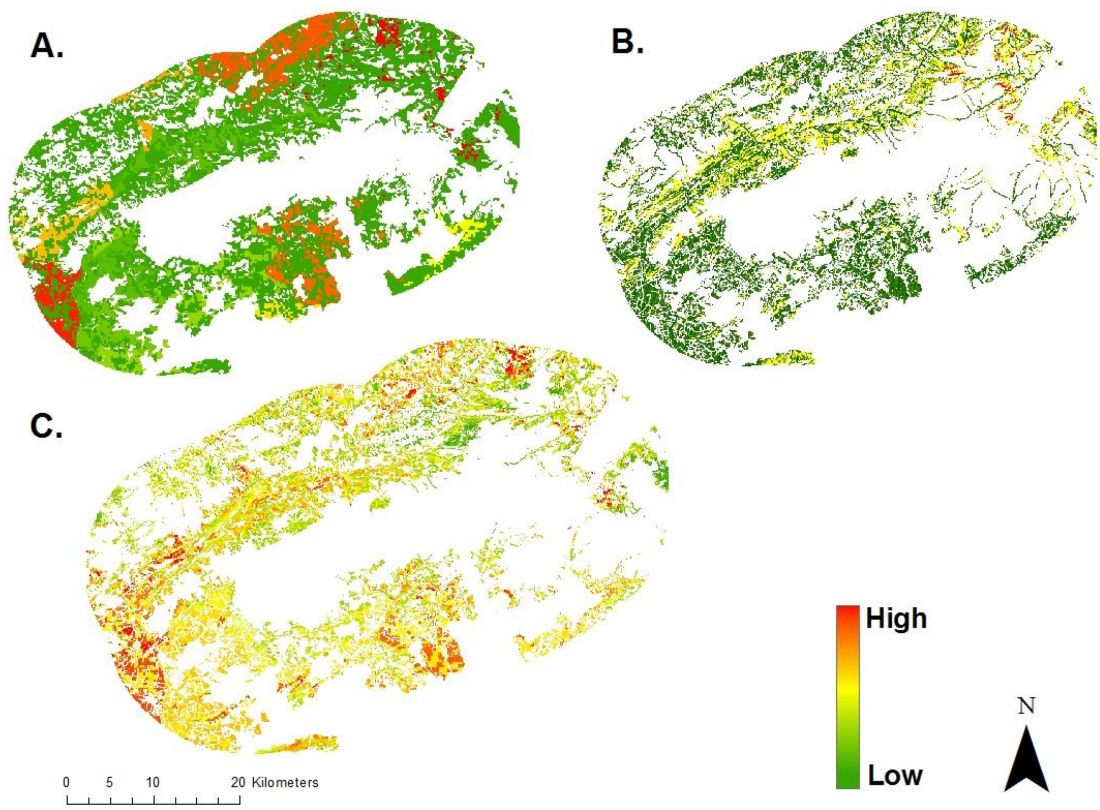

Figure 4: Costs in restorable planning units. **A.** Opportunity Cost map based on Net Present Values; **B.** Active restoration costs based on Onda Verde NGO's information; and **C.** Transition cost. Colors represent financial value in Brazilian Reais, from low values (green) to high values (red). White depicts non-restorable areas (urban areas, forest and highways).

Step 5. Quantify contribution of each potentially restored planning unit to habitat availability

We calculated potentially restored planning unit's contribution to habitat availability, i.e. the individual importance of a patch for improving the probability of connectivity (*PC*), through an individual habitat restoration experiment (Saura & Rubio 2010). This was calculated as follows:

$$\Delta PC(\%) = 100 \times \frac{PC\text{add} - PC}{PC}$$

where *PC* is the current value for habitat availability and PC_{add} is the value for habitat availability after the addition of that new habitat patch (i.e. restored planning unit) in the landscape. These restoration experiments allowed us to detect areas where restoration would most increase habitat availability for species, and results were used for prioritizing planning units and simulating restoration in strategies 3 and 4. In these strategies, we included an extra 5 km buffer area around our 10.000 ha landscape, in order to include the influence of surrounding forest cover on connectivity dynamics of marginal planning units.

Step 6. Prioritize planning units for restoration based on strategies' specific targets

We used planning units of 100x100 m (1 ha) as unit of analysis. We excluded planning units corresponding to urban areas and roads because these are not available for restoration. For the remaining planning units, we had information on: i) whether it was forest or potential area to be restored (i.e. agriculture/pasture); ii) whether it fell inside Areas of Permanent Preservation or Legal Reserve; iii) transition or opportunity cost value (depending on strategy); and iv) its importance for *PC* improvement (depending on strategy).

We first calculated total area to be restored (i.e. number of planning units) in each property to comply with the Native Vegetation Protection Law, and then we estimated the number of planning units to be restored at each run, i.e. 1/10 of total environmental debt every two years. We then analyzed properties following seven different contexts: i) properties that are smaller than 1 ha and cannot be analyzed; ii) properties that do not present environmental debt; iii) properties that are smaller than 4 fiscal modules, but do not have debt in Areas of Permanent Preservation; iv) properties that are smaller than 4 fiscal modules and have debt in Areas of Permanent Preservation; v) properties that are larger than 4 fiscal modulates and have debt in Areas of Permanent Preservation, but more than 20% of forest cover, i.e. do not need to restore Legal Reserve; vi) properties that are larger than 4 fiscal modulates and have debt only in Legal Reserve; and vii) properties that are larger than 4 fiscal modulates and have environmental debt inside both Areas of Permanent Preservation an Legal Reserve. Following each context above, we could select planning units available for restoration in Areas of Permanent Preservation and/or Legal Reserve inside each property. We then sorted them by increasing value of opportunity or transition cost (strategies 1 and 2, respectively) and decreasing value of importance for *PC* improvement (strategy 3). In strategy 4, we sorted planning units by both increasing value of transition cost and decreasing value of importance for *PC* improvement. In strategy 5, we only located planning units available for restoration inside each property, and conducted random simulations among them.

Step 7. Simulate restoration of priority planning units for each strategy and quantify opportunity and transition costs

Our goal was to restore native vegetation cover inside Areas of Permanent Preservation and Legal Reserve in all properties. After selecting priority planning units to be restored in each property, we simulated restoration first in planning units with lower opportunity or transition cost values, or higher values of importance for *PC* improvement (depending on strategies described below), until achieving complete restoration at the end of 10 simulation runs.

For each strategy, we ran 100 restoration simulations. First, we simulated restoration of priority planning units with lower values of costs or higher *PC* value, as described above, until restoring 10% of the environmental debt in all properties. This process was repeated ten times (i.e 10% of environmental debt restored every two years, see Kennedy et al. 2016) until all properties have completely restored all debt. After each run, we calculated total opportunity or transition cost and improved habitat availability (*PC*) for species with different dispersal abilities, and then re-analyzed forest cover and re-prioritized planning units according to each strategy. In some cases, there were several priority planning units with the same value of costs or importance for *PC* improvement, and prioritization was conducted randomly among them. Because of that, we decided to repeat all 10 restoration simulations 10 times for each strategy to make sure we selected the best set of planning units, i.e. most cost-effective.

Following complete restoration in each strategy, we calculated future habitat availability (PC_{future}) based on restored landscapes in order to assess which strategy provided the highest improvement of habitat availability relative to current situation. We calculated the mean values of PC and costs of all 10 restoration simulations for each strategy. For all strategies, cost-effectiveness was calculated as habitat availability improvement (PC_{future}) divided by total cost (opportunity cost or transition cost, depending on strategy). All analyses were carried out in R 3.3.0 (R Development Core Team, 2016) and ArcGIS 10.3.1 (ESRI, 2015).

RESULTS

Currently, the study landscape has ca. 40% forest cover. Forest restoration in Legal Reserve and riparian Areas of Permanent Preservation with forest debt increased forest cover by 2.6% and landscape configuration did not show noticeable differences among different strategies (Fig. 5).

As expected, consistently for species with different dispersal abilities, the restoration strategy which produced the greater habitat availability (as measured by PC), was either “maximizing habitat availability while minimizing transition cost” or that strategy together with “maximizing habitat availability only” (Table 2). For species with low to medium dispersal ability (≤ 500m), “random” restoration lead to the smallest increase in habitat availability. For species with high dispersal ability (≥ 1000m), however, "minimizing transition cost" lead to a smallest increase in habitat availability.

As expected, the least expensive restoration strategy was the one focused on "minimizing transition costs" (i.e. restoration and opportunity costs), costing about R$ 14 million; more than R$ 2 million cheaper than the second least expansive strategy (minimizing opportunity costs only) (Table 2). Also as expected, random restoration was the most expensive of all strategies, costing over R$ 17 million (Table 2). Prioritization strategies focused on "maximizing opportunity cost", "maximizing habitat availability" or "maximizing habitat while minimizing transition cost" still had a relatively high cost, around R$ 16,5 million.

Table 2: Present and future values of Probability of Connectivity index (PC) and mean transition cost (in Brazilian Reais) for restoration practices under each alternative strategy and species with different dispersal abilities (10, 100, 500, 1000, and 3000 m).

	Dispersal Ability					**Mean Transition Cost (R$)**
	10m	**100m**	**500m**	**1000m**	**3000m**	
Current	.40	.41	.44	.45	.46	-
Min. Opp. Cost	.425	.433	.457	.466	.474	16,081,789
Min. Trans. Cost	.425	.433	.457	.465	.473	14,018,892
Max. Hab.	.426	.434	.459	.468	.475	16,850,820
Max. Hab./Min. Trans. Cost	.426	.434	.461	.469	.475	16,313,586
Random	.423	.431	.456	.466	.474	17,036,766

Strategies including targeted restoration (i.e. prioritization for restoration in some way) brought more benefits than random restoration. Different strategies produced the same general tendency on gain in habitat availability throughout time and mean transition cost for all species (Fig. 6). Nonetheless, for species with low dispersal abilities (≤ 100m) differences in habitat availability improvement among strategies is clearer, especially at the beginning of restoration (Fig. 6A), but as species dispersal abilities increases these differences become less pronounced. Strategies focused on "maximizing habitat availability" and "maximizing habitat while minimizing transition cost" had a tendency to achieve higher values of habitat availability throughout time, whilst a random restoration strategy returned relatively small gains in habitat availability, except for species with high dispersal ability (≥ 1000m), to whom "minimizing transition cost" achieved the lowest values of habitat availability improvement (Fig. 6A).

Consistently for species with different dispersal abilities, the "random restoration" strategy achieved the lowest habitat availability values by cost (Fig. 6B). Also consistently through species, the lowest final transition cost was achieved by the "minimizing transition cost" strategy. That strategy produced relatively high habitat availability for species with low dispersal ability (≤ 100m), fluctuating along with "maximizing habitat availability" and "maximizing habitat while minimizing transition cost" strategies. For species with medium to high dispersal ability (≥ 100m), however, "minimizing transition cost" produced the lowest final transition cost, but also relatively low final habitat improvement. For those species, "maximizing habitat availability" and "maximizing habitat while minimizing transition cost" showed higher habitat improvement by cost, even though "minimizing opportunity cost" and "maximizing habitat availability" often compete.

As expected, the "minimizing transition cost" strategy shows the lowest values of transition cost, followed by "maximizing habitat availability", "maximizing habitat while minimizing transition cost" and "random" strategy (Fig. 6B). This ranking of strategies in terms of transition cost is very consistent, remaining the same among species (Fig. 6B). Contradicting what we expected, however, “minimizing transition cost” was the most cost-effective, i.e. adequate for species long-term persistence for the least possible cost, surpassing the even “maximizing habitat while minimizing transition cost” strategy for all species. Cost-effectiveness showed a tendency to decline with time for all species, showing higher values during the first years of the restoration practice (Fig. 7).

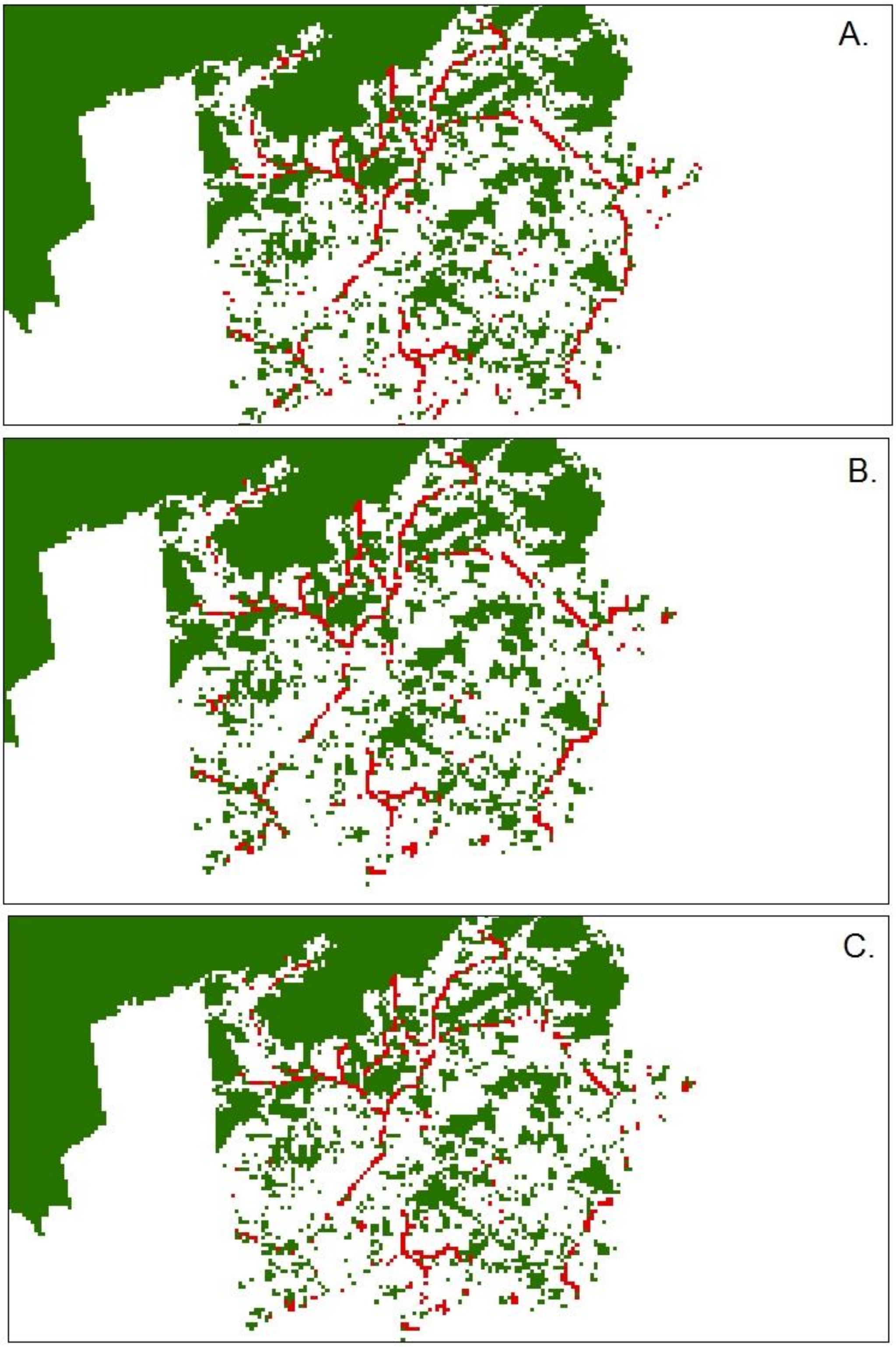

Figure 5: Landscape configuration after restoration practices following different prioritization strategies: **A.** Random restoration (for all species); **B.** Maximizing Habitat Availability (for species with dispersal ability of 3000m), and **C.** Minimizing transition cost (for all species). Areas in green represent current forest cover and areas in red, restored forest cover after 20 years

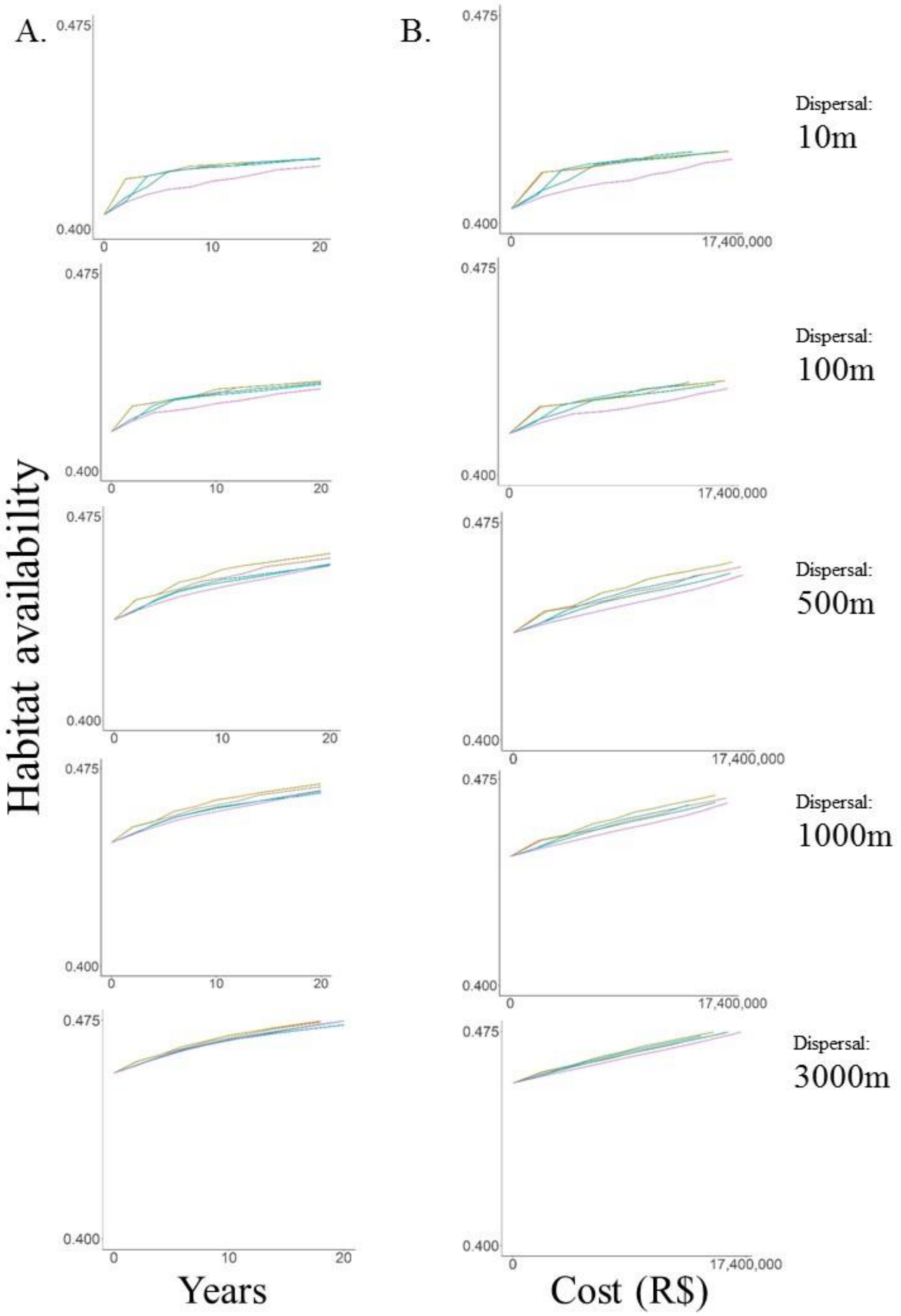

Figure 6: Habitat availability improvement **A.** throughout time (in years) and **B.** by transition cost (R$), for species with different dispersal abilities (10, 100, 500, 1000 and 3000m) after forest restoration simulations following alternative prioritization strategies: Minimizing opportunity cost (—); Minimizing transition cost (—); Maximizing habitat availability (—); Maximizing habitat availability while minimizing cost (—); Random restoration (—).

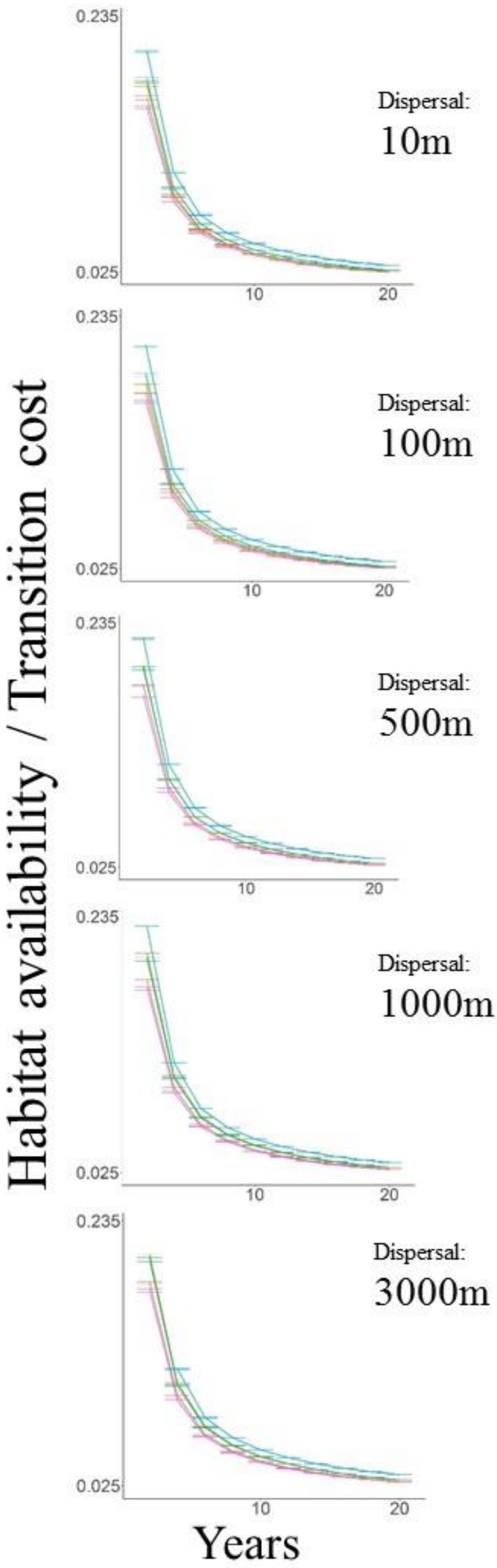

Figure 7: Improvement in habitat availability by cost (i.e. cost-effectiveness) for species with different dispersal abilities (10, 100, 500, 1000 and 3000m) after forest restoration simulations following alternative prioritization strategies: Minimizing opportunity cost (—); Minimizing transition cost (—); Maximizing habitat availability (—); Maximizing habitat availability while minimizing cost (—); Random restoration (—).

DISCUSSION

Forest restoration should be spatially prioritized based on individual landowners' decision on land-use and the complex relationships between socio-economic and ecological factors. In order to maximize improvements for biodiversity conservation, restoration initiatives must be efficient and cost-effective altogether (Ikin et al. 2016). Time may also affect restoration prioritization as changes in landscape show time-lag effects on biodiversity recovery (Brooks et al. 1999; Rappaport et al. 2015; Ikin et al. 2016). Science-based cost-effective approaches considering both opportunity cost and restoration cost, as well as biodiversity outcomes may help scaling-up restoration projects but are scarce (Melo et al. 2013). Nonetheless, large-scale restoration tends to ignore ecological attributes and political, social and economic issues at the local scale and few incorporate temporal dynamics.

We present a multi-scale prioritization approach for restoration at local property-level, under a landscape-scale planning, using as case study a 10.000 hectares landscape at the buffer zone surrounding the REBIO Tinguá. This area offers great opportunities for restoration actions aimed at law compliance, and recovering areas of forest debt by law may be one of the greatest contribution to biodiversity conservation in Brazil (PLANAVEG 2014). We incorporate an agent-based approach, where human decision-making on the environment is key for forest restoration, which is extremely important for Brazil's rapid deforestation and restoration practices in agricultural landscapes. We analyzed the increase in habitat availability through restoration practices in riparian Permanent Preservation and Legal Reserve areas (i.e. for law compliance) and compared the outcomes of forest restoration simulations in term of cost-effectiveness for five hypothetical species with different dispersal abilities, under alternative restoration prioritization strategies. By doing so, we tried to increase local biodiversity, considering the REBIO Tinguá as an important source of species.

"Minimizing opportunity cost" and "minimize transition cost" strategies include targets that landowners for example, will most probably account for before *in-situ* restoration. "Maximizing habitat availability" and "maximizing "maximizing habitat while minimizing transition cost" (i.e. cost-effectiveness) include targets that aim at biodiversity long-term persistence, and are less likely of being landowners' primary concern. Nonetheless, NGOs and other restoration practitioners may be interested in these targets as well, if biodiversity conservation is their goal and can help in this process trough landowner's awareness to biodiversity conservation. Random restoration reflects the reality of most current restoration practices, where landscape or even local-scale prioritization is uncommon and the *in-situ* restoration is an opportunistic and much localized activity (Melo et al. 2013).

Our results corroborate previous studies showing that considering some sort of target for prioritizing areas before *in-situ* restoration achieves more cost-effective results for species with different dispersal abilities, whilst random restoration is less efficient for biodiversity conservation and costs more than when some sort of target is taken into account **(**Wilson et al. 2009; Crouzeilles et al. 2015; Latawiec et al. 2015; Fagan et al. 2016). By including targets, we could save a minimum of ca. R$ 186,000 (when maximizing biodiversity) and a maximum of R$ 3,018,000 (when minimizing transition cost). Moreover, restoration practices aimed at minimizing transition cost (i.e. both opportunity and restoration costs) and incorporating natural regeneration could save more than R$ 2 million compared to practices minimizing opportunity cost only, for a similar improvement in habitat availability.

We can see that even though final cost for restoration practices focusing on minimizing transition cost is very low compared to other strategies, outcomes for biodiversity via improvement on habitat availability are also low. Prioritizing for both biodiversity and minimizing cost resulted in better outcomes for biodiversity with low additional cost. Crouzeilles et al. (2015) have shown that incorporating habitat availability into systematic planning for restoration resulted in the most cost-effective strategy for two Atlantic Forest mammal species with widely different dispersal abilities. This should be expected in our results, even though “minimizing transition cost” seems to be the most cost-effective. Because this landscape initially presents 40% of forest cover, relative gain in habitat availability was lower than expected even when using the “maximizing habitat availability” strategy. We should expect higher habitat availability improvement in landscapes with low forest cover percentage (< 30%), as well as for the whole Atlantic Forest, which has less than 15% of forest cover (Ribeiro et al. 2009). The fact that restoration practices in this study focused on law compliance may also interfere on cost-effectiveness. That is because as time passes, some properties achieve compliance before 20 years, which means that the amount of forest restored at the end is lower than at the beginning of restoration practices, therefore habitat availability improvement is lower, while cumulative restoration cost continues to rise.

Restoration in areas of forest debt by law also limited landscape configuration (Fig. 5), which may be the reason why final habitat availability improvement was not optimal and did not vary strongly among prioritization strategies, especially for species with lower dispersal abilities. These species showed lower values of habitat availability than species that move to longer distances, but had a similar improvement of 2-2.5% after restoration. This is a small but expected variation in this study, where restoration is limited to a small area, and probability of connectivity metrics include habitat area

(Fagan et al. 2016). Less mobile species are more sensitive to habitat loss and fragmentation than species with higher mobility, thus connectivity for those is usually lower (Prugh et al. 2008; Gardner et al. 2009; Fagan et al. 2016). Furthermore, for species with very low dispersal abilities (10m), final habitat availability improvement was similar between different strategies of targeted restoration, and differences became clearer for species with higher mobility. Crouzeilles et al. (2015) showed that for less mobile species maximum values of habitat availability might not be achieved for a given amount of forest, reflecting reduced probability of connectivity because of limited dispersal ability. These authors argue that less mobile species are the most affected by landscape configuration. Since final landscape configuration did not vary strongly among strategies in this study, increases in habitat availability were limited and differences in final connectivity improvement between strategies were less evident for species more strongly affected by this attribute. For species with lower dispersal ability it is evident the importance of including habitat availability as a target for prioritization, especially during the first years, where there is a huge increase in connectivity for a lower cost. For these species, it may be possible to achieve good results sooner than for other species. Hence, it is extremely important to account for landscape connectivity in strategic planning in order to achieve representativeness and benefits in the long-term for biodiversity through large-scale restoration (Banks-Leite et al. 2014). Temporal dynamics also affect restoration prioritization via habitat availability, as changes in landscape affect forest cover and show time-lag effects on biodiversity recovery, highlighting the importance of considering not only current landscape configuration but also its configuration after restoration when performing prioritization analysis (Rappaport et al. 2015).

Landscape configuration after restoration practices aiming at law compliance within properties located at the buffer zone surrounding the REBIO Tinguá resulted in corridors and stepping-stones, rather than large habitat patches (Fig. 5). The importance of restored patches for species depends not only on its size, but also on their relationship with other patches in the landscape (i.e. connectivity; Benayas et al. 2009; Crouzeilles et al. 2015). In this study, size of riparian corridors did not vary within the landscape, which may be unrealistic since Areas of Permanent Preservation's widths depend on rivers' size as well as property area (Zakia & Pinto 2013). Following that, improvement on habitat availability may be under or overestimated, depending on the property,but we believe that this will not affect results significantly. Studies have shown that parameters related to landscape connectivity, such as distance among patches, and presence and density of stepping stones and corridors, influence metapopulational dynamics and thus, species long-term persistence and restoration effectiveness (Boscolo et al. 2008; Martensen et al. 2008). While larger patch area increases population viability, spatial configuration influences population supplementation and recolonization of potential habitat patches (Bélisle 2005). The theory of metapopulation suggests that several isolated populations might function as one larger and more resilient population when individuals are able to disperse from one patch to another, which is particularly important in landscapes suffering from fragmentation by human activity (Levins 1969; Doerr et al. 2010). Rodrigues et al. (2009) emphasize the importance of corridors and stepping-stones for recolonization dynamics and restoration effectiveness. Moreover, Fagan et al (2016) demonstrate that restoration of small, riparian forest patches in Costa Rica might have been a key component for maintaining landscape connectivity for bird species highly sensitive to forest fragmentation. Our results imply that forest gains and habitat connectivity improvement resulting from restoration practices aiming at law compliance were low, but not negligible. Furthermore, studies emphasize the importance of reconnecting habitat patches to reduce their number and isolation, hence reducing fragmentation, but argue that improvement of habitat availability varies according to landscapes' initial percentage of forest cover (Crouzeilles et al. 2015), and cost-effectiveness of different prioritization strategies could also be affected by this variation. However, according to Tambosi et al. (2014), landscapes with intermediate forest cover and level of connectivity (like ours) should be a priority for restoration practices, presenting high probability of restoration success.

Habitat loss and fragmentation are considered the greatest threads to biodiversity persistence at the present, especially at the Atlantic Forest, where deforestation is closely associated to conversion from forest to agriculture (Liu et al. 2016). Landscapes dominated by agriculture/pasture are of even greater concern, for remaining forest patches may suffer from a long period of "faunal relaxation" (Brooks et al. 1999). Loss of connection between populations of a species hampers interchange of individuals and genetic flow, and consequently enhances local extinctions probability (Cushman et al. 2006; Fagan et al 2016). For example, forest clearing around protected areas increases isolation between protected forests and fragmentation affecting their ability to protect species. This is the case of the buffer zone surrounding the REBIO Tinguá (MMA 2006), where maintaining functionally connected populations is very important for biodiversity persistence and interchange of individuals between the REBIO and other forest areas, such as as several Environmental Protection Areas in the region (APAs, Portuguese acronym) and the Parque Nacional da Serra dos Orgãos (PARNASO, Portuguese acronym), another very important forested protected area in Rio de Janeiro. Forest in protected areas can act as source of seeds and seed-dispersers that enhance recolonization, reforestation and restoration success of surrounding disturbed sites

(Chazdon 2003) undergoing active restoration or natural regeneration. In Puerto Rico, natural regeneration following ceasing of drivers of disturbance and abandonment of pasture and plantations achieved secondary forests similar to reference mature forests in term of biomass, density and species richness (Chazdon 2008). Natural regeneration is a cheaper alternative to active restoration; therefore, it may prevail over active restoration techniques in large-scale restoration (Latawiec et al. 2016). Natural regeneration likelihood depends on distance from site to nearby forest patches, soil characteristics, intensity of previous land use and degradation, climate and time since deforestation started (Lamb et al. 2005; Crouzeilles & Curran, 2016; Poorter et al. 2016). Studies have shown that this strategy is the most cost-effective for large-scale restoration (Chazdon 2014: Chazdon & Guariguata 2016), and one of the main challenges for large-scale restoration projects is to cover their high costs.

Scaling up restoration is essential to enable biodiversity long-term persistence and ecosystem services, but large-scale restoration practices are hampered by many social, financial and political challenges (Rodrigues et al. 2011). Most of the Atlantic Forest has been illegally occupied (Tambosi et al. 2013), particularly in riparian zones that must be preserved according to the Native Vegetation Protection Law as Areas of Permanent Preservation. The estimated average cost per hectare for active restoration at the Atlantic Forest is U$ 5.000 and this is highly above most landowners' financial ability. In order to gain scale, landowners' must become interested in restoration initiatives; thereby, restoration must be seen as a viable economic activity instead of a cost burden (Brancalion et al. 2012; Mello et al. 2013; Strassburg et al. 2014). Hence, the urgency of incorporating the loss in farming opportunities associated to restoration practices in analysis of cost-effective prioritization within agricultural landscapes (Ikin 2016). Restoration initiatives emphasizing social and economic benefits of restoration, and incorporating landowners' decision, is also crucial to enhance participation in restoration practices (Schouten et al. 2013). Ikin et al. (2016) highlight that investments in restorations should be guided not only by knowledge on biodiversity and financial cost, but also landowners' interests and willingness to engage in restoration practices. We consider landowners' decision indirectly by targeting sites for restoration where either opportunity or transition cost are low.

To become a viable land use, restoration practices must be accompanied by return-on-investments higher than previous land use, such as exploitation of timber and non-timber forest products from native species and payments for ecosystem services (Brancalion et al. 2012; Latawiec et al. 2015). Payment for Ecosystem Services is still incipient in Brazil and should be treaded carefully, as it might turn restoration activities towards certain outcomes, neglecting others such as biodiversity persistence (Bullock et al. 2011).

Achieving the ambitious targets set for the Atlantic Forest by national and international commitments would increase forest cover from less than 12% to approximately 30% of its original extent (Melo et al. 2013). Most land addressed for restoration in Brazil consists of areas that must be reforested according to the Native Vegetation Protection Law and, despite the law, landowners are still concerned about the potential burden that the NVPL will bear to agricultural productivity. Restoration analysis prioritizing areas of lower transition cost, as well as considering natural regeneration, may help increase restoration acceptance among landowners and the total amount restored forest in the country. Kennedy et al. (2016) contradict the generalized concept that the NVPL will bear a burden to producers, demonstrating that it can generate substantial benefits for biodiversity conservation, not to mention ecosystem services such as water quality improvement and carbon storage, for a relatively small cost. Many benefits arising from forest restoration might be seen as strictly environmental, as nutrient cycling, water quality, climate regulation and polinization, but all have great impact in the economy and quality of life for local population (MEA 2005; PLANAVEG 2014). Studies have shown that restoration can become a more economically attractive practice than traditional activities (Rodrigues et al. 2009), and others estimates that by 2050 forest restoration could generate up to 6 million jobs in sustainable exploitation of forest products in the Atlantic Forest, alleviating poverty (Brancalion et al. 2012; Melo et al. 2013).

CONCLUSIONS AND PRACTICAL APPLICATIONS

The establishment of protected areas surrounded by buffer zones is key to avoid loss of large habitat areas and to preserve biodiversity. Buffer zones are generally agricultural landscapes, covered mainly by private rural properties; therefore, restoration in these areas will probably aim at law compliance (Alexandre et al. 2010). The impact of the Native Vegetation Protection Law on biodiversity depends on several attributes, such size, connectivity, and number and suitability of habitat patches (Kennedy et al. 2016). Scaling up restoration is crucial to achieve conservation goals, biodiversity long-term persistence and to improve ecosystem services. It is then critical to offer assistance and information on social economic benefits that derive from restoration activities, in order to increase landowners' participation. Thus, before deciding where and how to restore we need detailed information on both landscape and local ecological and socioeconomic contexts.

We suggest that before starting *in-situ,* practitioners should account for both opportunity and restoration costs (i.e. transition cost), as well as temporal dynamics of habitat availability for local species. Moreover, locating areas for natural regeneration reduces cost significantly, which may help increase restoration acceptance and the amount of restored forest, helping scaling up restoration practices while achieving biodiversity conservation. Adopting this multi-scale prioritization for forest restoration leads to better conservational and socio economic outcomes than local random restoration activities that currently occur. Following that, this study offers information for the Onda Verde NGO, as well as other practitioners that may be interested, on where and how to perform forest restoration at the buffer zone surrounding the REBIO Tinguá. Our results indicate that whenever money is available, practitioners performing forest restoration inside rural properties should follow the "maximizing habitat availability while minimizing opportunity cost" strategy, and if financial investments are too scarce, following the "minimizing transition cost" strategy should be sufficient. We offer maps of priority areas throughout the time available for landowners to achieve law compliance, which may serve as guides to follow any of the strategies present here. We also offer information on how restoration may become a viable economic activity, so practitioners could inform landowners and enhance acceptance.

Our results suggest that forest restoration aimed at law compliance in Brazil should be coupled with targeted reforestation identified through analyses such as those presented here to actually achieve functional connectivity improvement for species with widely different dispersal abilities. Spatial prioritization for forest restoration should be based on individual landowners' decision on land-use and the complex relationships between socio-economic and ecological factors in order to achieve efficiency and cost-effectiveness. In landscapes of intermediate forest cover percentage, minimizing transition cost and including natural regeneration might be enough to achieve cost-effectiveness; nonetheless, by adding habitat availability as one of the main targets in restoration initiatives we could obtain better outcomes for biodiversity for low additional cost. Habitat availability improvement was relatively low in this landscape, but in areas with low forest cover percentage (<30%) we could expect better outcomes, especially from strategies aiming at maximizing habitat availability. Future research should consider differences between prioritization strategies in landscapes with different initial forest cover percentage in order to better assess cost-effectiveness comparisons. Moreover, results suggest that landscape configuration after restoration practices aiming at law compliance may be limited for species more vulnerable to habitat loss and fragmentation, thus including habitat availability is of extreme importance to allow biodiversity conservation.

Our study offers a framework for decision-making on which restoration strategy to apply at agricultural landscapes in Brazil, which can be replicated for other biomes and regions, although it must be coupled with good research on specific socioeconomic attributes.

APPENDICES

Appendix A.1: Biophysical and socio-economic constraints affecting financial costs for active restoration, based on the Onda Verde NGO expertizes' restoration experience. Values were used to build transition cost map.

Base value for restoration of 1 hectare	**R$ 33000**											
Ideal base factor	**1**											
Slope orientation Curvature Slope	**South** Plain 0 a 15°	**South** Plain 15 a 30°	**South** Plain 30 a 45º	**South** Plain > 45º	**South** Concave 0 a 15°	**South** Concave 15 a 30º	**South** Concave 30 a 45º	**South** Concave > 45	**South** Convex 0 a 15°	**South** Convex 15 a 30º	**South** Convex 30 a 45º	**South** Convex > 45
Mowing for clearence	1	1.5	2	2.5	1	1.5	2	2.5	1	1.5	2	2.5
Pre-planting management	1	1.5	2	2.5	1	1.5	2	2.5	1	1.5	2	2.5
Pre-planting fertilization and soil correction	1	1.5	2	2.5	1	1.5	2	2.5	1	1.5	2	2.5
Seedling planting	1	1.5	2	2.5	1	1.5	2	2.5	1	1.5	2	2.5
Plant fertilization	1	1.5	2	2.5	1	1.5	2	2.5	1	1.5	2	2.5
Ant control	1	1.5	2	2.5	1	1.5	2	2.5	1	1.5	2	2.5
Firebreaks installation	1	1.5	2	2.5	1	1.5	2	2.5	1	1.5	2	2.5
Soil mnagement	1	1.5	2	2.5	1	1.5	2	2.5	1	1.5	2	2.5
Plant management	1	1.5	2	2.5	1	1.5	2	2.5	1	1.5	2	2.5
Replacement of dead seedlings	1	1.5	2	2.5	1	1.5	2	2.5	1.5	2	2.5	3
Fertilization of cover	1	1.5	2	2.5	1	1.5	2	2.5	1	1.5	2	2.5
Fencing	1	1.5	2	2.5	1	1.5	2	2.5	1	1.5	2	2.5
Displacement (R$ Km/l)	1	1.5	2	2.5	1	1.5	2	2.5	1	1.5	2	2.5
Cost (R$)	33,000.00	49,500.00	66,000.00	82,500.00	33,000.00	49,500.00	66,000.00	82,500.00	34,269.23	50,769.23	67,269.23	83,769.23

Appendix A.2: Biophysical and socio-economic constraints affecting financial costs for active restoration, based on the Onda Verde NGO expertizes' restoration experience. Values were used to build transition cost map.

Base value for restoration of 1 hectare	**R$ 33,000**											
Ideal base factor	**1**											
Slope orientation	**North**	**North**	**North**	**North**	**North**	**North**	**North**	**North**	**North**	**North**	**North**	**North**
Curvature	Plain	Plain	Plain	Plain	Concave	Concave	Concave	Concave	Convex	Convex	Convex	Convex
Slope	0 a 15°	15 a 30°	30 a 45º	> 45º	0 a 15°	15 a 30º	30 to 45 º	> 45	0 a 15°	15 a 30º	30 a 45º	> 45
Mowing for clearence	1	1.5	2	2.5	1	1.5	2	3	1	1.5	2.5	3.5
Pre-planting management	1	1.5	2	2.5	1	1.5	2	3	1	1.5	2.5	3.5
Pre-planting fertilization and soil correction	1	1.5	2	2.5	1	1.5	2	3	1	1.5	2.5	3.5
Seedling planting	1	1.5	2	2.5	1	1.5	2	3	1	1.5	2.5	3.5
Plant fertilization	1	1.5	2	2.5	1	1.5	2	3	1	1.5	2.5	3.5
Ant control	1	1.5	2	2.5	1	1.5	2	3	1	1.5	2.5	3.5
Firebreaks installation	1	1.5	2	2.5	1	1.5	2	3	1	1.5	2.5	3.5
Soil mnagement	1	1.5	2	2.5	1	1.5	2	3	1	1.5	2.5	3.5
Plant management	1	1.5	2	2.5	1	1.5	2	3	1	1.5	2.5	3.5
Replacement of dead seedlings	1.5	2	2.5	3	1.5	2	3	4	2	2.5	3.5	4.5
Fertilization of cover	1	1.5	2	2.5	1	1.5	2	3	1	1.5	2.5	3.5
Fencing	1	1.5	2	2.5	1	1.5	2	3	1	1.5	2.5	3.5
Displacement (R$ Km/l)	1	1.5	2	2.5	1	1.5	2	2.5	1	1.5	2	2.5
Cost (R$)	34,269.23	50,769.23	67,269.23	83,769.23	34,269.23	50,769.23	68,538.46	100,269.23	35,538.46	52,038.46	83,769.23	115,500.00

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