Title: A landscape approach for cost-effective large-scale forest restoration

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Statement of where we intend to archive our data: We provide access to all data of the underlying results presented in this manuscript at Zenodo.org (Dataset available at: http://doi.org/10.5281/zenodo.1256029). The archived data will allow each result in the published paper to be recreated and the analyses reported in the paper to be replicated in full to support the conclusions made.

Abstract:

1. Achieving global targets for forest restoration will require cost-effective strategies to return agricultural land to forest, while minimizing implementation costs and negative outcomes for agricultural production.
2. We present a landscape approach for optimizing the cost-effectiveness of large-scale forest restoration. Across three different landscapes within Brazil's Atlantic Forest biodiversity hotspot, we modelled landscape scenarios based on spatially-explicit data on the probability of natural regeneration, restoration costs, land opportunity costs, and forest restoration outcomes for increasing carbon stocking and landscape connectivity. We compare benefits of our cost-reduction approach to the legally mandated riparian restoration and randomly distributed approaches.
3. Compared with riparian prioritization and considering both implementation and opportunity costs, our cost-reduction scenario produced the greatest savings (20.9%) in mechanized agricultural landscapes.
4. When only considering implementation costs, our cost-reduction scenario led to the highest savings (38.4%) in the landscape with highest forest cover where natural regeneration potential is highest and enables cost-effective carbon stocking and connectivity.

Synthesis and applications. We present a guide for forest restoration planning that maximizes specific outcomes with minimal costs and reduction of agricultural production. Furthermore, we show how policies could encourage prioritization of low-cost restoration via natural regeneration, increasing cost-effectiveness. While our study focuses on Brazil’s Atlantic Forest, the approach can be parameterized for other regions.

Resumo:

1. Atingir metas globais para a restauração florestal exigirá estratégias economicamente viáveis para transformar terras agrícolas em floresta, minimizando custos de implementação e os resultados negativos para a produção agrícola.

2. Apresentamos uma abordagem de paisagem para otimizar a relação custo-eficácia da restauração florestal em larga escala. Em três diferentes paisagens, no Bioma da Mata Atlântica, modelamos cenários baseados em dados espacialmente explícitos sobre a probabilidade de regeneração natural, custos de restauração, custos de oportunidade da terra e resultados de restauração florestal com o objetivo de aumentar o estoque de carbono e a conectividade da paisagem. Por fim, comparamos os benefícios da nossa abordagem de redução de custos com a tradicional abordagem de restauração da paisagem em zonas ripárias (áreas de preservação permanente) e abordagens de espacialidade aleatoriamente distribuídas.

3. Comparado com a priorização ripária e considerando os custos de implementação e de oportunidade, nosso cenário de redução de custos produziu as maiores economias (20,9%) em paisagens agrícolas mecanizadas.

4. Ao considerar apenas os custos de implementação, nosso cenário de redução de custos levou à maior economia (38,4%) na paisagem com maior cobertura florestal, onde o potencial de regeneração natural é maior e permite uma melhor relação de custo-oportunidade no estoque de carbono e na conectividade da paisagem.

Síntese e aplicações. Apresentamos aqui um guia para o planejamento de restauração florestal que maximiza resultados específicos com redução de custos e mínima influência na produção agrícola. Além disso, mostramos como políticas públicas poderiam incentivar a priorização da restauração de baixo custo via regeneração natural, aumentando a relação custo-benefício. Enquanto nosso estudo se concentra na Mata Atlântica do Brasil, a abordagem pode ser parametrizada para outras regiões.

Keywords: carbon sequestration; forest restoration; landscape connectivity; landscape restoration; natural regeneration; low-cost restoration; cost-effective, agricultural production

Introduction

Consensus is growing among stakeholders that the mitigation of the most relevant global environmental problems of our time will require restoring forests across vast extents of agricultural and abandoned lands. A myriad of international organizations, multilateral agencies, countries and NGOs are promoting and committing to forest restoration initiatives globally to reach national and international targets, such as the Aichi Target 15, Bonn Challenge and the New York Declaration (Laestadius *et al.* 2011). Science-based principles (Suding *et al.* 2015), a policy-driven agenda (Chazdon *et al.* 2017), and emergent constraints (Menz, Dixon & Hobbs 2013) for large-scale forest restoration have already been proposed. However, few solutions have been proposed to address a major challenge for achieving global restoration commitments: making it financially viable for government and other project leaders (Brancalion & van Melis 2017).

Historically, substantial gains in forest cover in many parts of the world were mostly viewed in the context of forest transitions, which were driven in Latin America primarily by natural regeneration of forests following abandonment of agricultural land (Aide *et al.* 2013). However, the increased demand for land to feed a rapidly growing human population and to supply biofuels will disincentivize the abandonment of lands at large spatial scales in the coming decades (Tilman *et al.* 2011). Reaching restoration goals will require a pro-active strategy to replace marginal agricultural land with forest land uses, while minimizing restoration costs and negative outcomes for agricultural production (Latawiec *et al.* 2015). However, much restoration knowledge has been developed based on experiments conducted in small plots and in relatively few sites, revealing a spatial mismatch between the tested restoration approaches that are available (and affordable) to practitioners or landowners with those that are needed to implement large-scale restoration of forests (Holl 2017).

A landscape-approach for planning and implementing cost-effective restoration is needed to balance restoration costs and outcomes (i.e. cost-effectiveness analysis) (Birch *et al.* 2010;

Sayer *et al.* 2013). This approach relies on the investigation and modeling of biophysical and socio-economic costs and benefits of forest restoration in targeted landscapes, using scenarios, to reveal the impacts of implementing different restoration approaches and investment strategies (Metzger et al. 2017). Within a particular climatic region, restoration cost on private lands is mostly determined by costs of implementation and maintenance and land opportunity costs, which vary according to existing and prior land use, landscape features, and market contexts. Implementation and maintenance costs are directly associated with the levels of human interventions required to initiate the long-term process of forest restoration, with natural regeneration being the lowest-cost alternative for large-scale restoration (Holl & Aide 2011; Chazdon & Guariguata 2016).

Since the likelihood of natural regeneration is not uniformly distributed within mosaic landscapes (Arroyo-Rodríguez *et al.* 2017), estimating restoration cost requires a spatially explicit approach to estimate the probability of natural regeneration based on land use and landscape features. The potential use of deforested lands for agriculture, and the cost of foregoing agricultural income for further forest regeneration are also heterogeneously distributed in landscapes. The same principles apply to expected restoration outcomes, such as carbon stocking and biodiversity conservation, which are heavily influenced by the spatial context of restoration interventions in landscapes. Therefore, developing spatially-explicit models that integrate forest restoration implementation and maintenance costs, land opportunity costs, and outcomes is a promising strategy for optimizing restoration investments and for achieving large-scale forest restoration targets.

The benefits of a landscape-approach to support large-scale forest restoration activities are particularly important in human-modified landscapes with high population densities, high land costs, and dominance of private land ownership, which all increase competition for land. Restoration interventions are particularly urgent in landscapes harboring threatened biodiversity and that supply key ecosystem services for large human populations (Melo *et al.* 2013). The

Atlantic Forest region of Brazil presents all these challenges and needs for restoration, as it: i) is home to nearly 60% of the Brazilian population (Calmon *et al.* 2011); ii) generates over 70% of Brazil's GDP; iii) supplies drinking water for nearly 75% of the country's population and generates 62% of the electricity used (Joly, Metzger & Tabarelli 2014); iv) has 89% of its territory under private ownership (Freitas, Guidotti & Sparovek 2017); v) has only 12% forest cover remaining (Ribeiro *et al.* 2009); vi) is a top five global hotspot for biodiversity conservation (Laurance 2009); and vii) urgently requires restoration to mitigate a high species extinction debt (Banks-Leite *et al.* 2014). Within the Atlantic Forest, the Piracicaba watershed can be considered a hotspot for forest restoration, as it supplies drinking water for almost 10 million people, of which almost 70% are in the city of São Paulo, and is part of the "interior" biogeographical zone – the second most threatened region within the Atlantic forest biome, with only 7% of forest cover remaining (Ribeiro *et al.* 2009).

We applied our approach to assessing restoration costs and outcomes in three landscape units with different features within the Piracicaba river basin. Within each landscape, we modeled the spatial probability of natural regeneration, land opportunity cost, and forest restoration outcomes for carbon stocking and increasing landscape connectivity for protecting biodiversity. We developed a model that can be adapted to other regions to support the implementation of global forest restoration commitments by countries, in support of initiatives such as the Bonn Challenge, the New York Declaration on Forests of the United Nations Climate Summit, the Aichi target 15 of the Convention on Biological Diversity, and the intended nationally determined contributions (INDCs) of the UNFCCC parties.

Materials and Methods

Study region

We selected the Piracicaba River basin (12,500 km^2) for this study (Fig. 1), because of its socioeconomic and conservation importance, as well as the high diversity of landscape features that are representative of Atlantic Forest landscapes and historical land-use changes. A total of

3.4 million inhabitants (272 inhabitants.km^{-2}) live within this basin and rely on it for supplying water for human consumption, irrigation, and industrial use. The Piracicaba River basin spans one of the most industrialized regions of Brazil, accounting for 33.9% of the national GDP. Most of the basin was deforested in the 20th century to establish coffee plantations, which were gradually substituted by sugarcane, pasture, orange groves, and silviculture. Forest cover increased slightly from 20.09% in 2000 to 21.75% in 2010, indicating an initial forest transition (Molin *et al.* 2017). Forest formations are composed of Atlantic Forest and Cerrado remnants, both considered biodiversity hotspots. To explore the cost reduction potential of targeting areas with higher regeneration potential for restoration, we selected three independent landscape units of 40,000 ha each within the basin that span the diversity of landscape features typically found in tropical regions (Fig. 1 and Tab. S1). The three landscapes represent a gradient of land use intensity and forest cover: Mechanized Agriculture Landscape with predominance of sugarcane plantations (50.6 %), low native forest cover (10.4 %), and relatively flat terrain (10.2 % mean slope); Pasture Landscape predominantly covered by pastures (46.0 %), in larger plots for beef production, followed by cropland, mainly corn and sugarcane (21.9 %) and native forests (19.9 %), with mean slope of 17.8 %; and Forest Landscape dominated by pastureland (48.1 %), in smaller plots and mainly for dairy, but with a higher forest cover (31.0 %), followed by crops (18.3 %), with an increased slope terrain (25.9 %).

Geospatial database and modeling of forest regeneration probabilities

The main sources of information used in this study were a spatial database of the basin containing elementary information such as hydrology, topography, land use, and watersheds, as well as political-economic information such as municipal divisions, population distribution, and economic sources, all separated by municipalities (Tab. S2). We used a set of two raster land cover maps dated from 2000 and 2010 derived from Landsat 5 TM imagery with a pixel size of 30 m to classify each pixel according to seven classes: i) croplands, ii) native forest, iii) commercial tree plantations, iv) water bodies, v) pastures, vi) urban zones, and vii) perennial crops; minimum mapping units of 900 m^2 and a final scale of 1:50,000 were used (for more details on sources and maps see (Molin *et al.* 2017). We used the Dinamica EGO program for geospatial analysis, a model of discrete-type landscape dynamics based on cellular automata to assess weight of evidence of independent variables and probability of natural regeneration within the entire Piracicaba river basin, regions and selected landscape units within these regions. One of the main purposes and objectives of dynamic models is to simulate and investigate dynamic spatiotemporal changes to landscape structure and pattern, and their impacts of these changes on natural and ecological resources (Soares-Filho, Coutinho Cerqueira & Lopes Pennachin 2002). Weight of evidence consists of a Bayesian method, in which the effect of a spatial variable on a transition, or change, is independently calculated (Soares-Filho, Rodrigues & Costa 2009). The model was calibrated for the period 2000-2010 using the transition matrices and weight of evidence coefficients obtained by cross-tabulation of the 2000 and 2010 land cover maps (dependent variables) with regard to a selection of twelve independent variables (Table S2; for details on model procedures see Molin *et al.* (2017) and Annex 1 of Supporting Information). These were subdivided into *biophysical variables* (soil type, hydrographic network, forest type, rainfall, slope, and altitude), and *socioeconomic variables* (population density, rural population density, municipal Gross Domestic Product (GDP), road network, urban spots, and predominant land uses). Model procedures were processed for the three individual regions and the totality of the study area basin to compare the importance of variables associated with forest regeneration. These layers of information were used to investigate the transition from crop and pasture to native forests, resulting in spatially explicit values of forest regeneration probability for the totality of the study area and later clipped to individual landscape units (LUs). Regeneration probabilities were extrapolated for a period of 10 years (2010-2020), given that we used 2000-2010 land use transitions as a baseline for modeling. Regeneration probabilities do not express the intrinsic biophysical potential of non-forest areas to regenerate, since many areas with high resilience may have not regenerated in this period because of continued human disturbances. Rather, regeneration probabilities expressed the combined effect of biophysical potential and human agency, therefore providing a realistic approach for prioritizing areas with higher regeneration chances. Only areas covered by crops and pasture were considered and hereafter referred to as “restoration opportunity”.

Restoration implementation and land opportunity costs

For each pixel within the three landscapes, we modeled the forest regeneration probability from 0 to 100%. We then divided this probability into three categories and assigned restoration approaches to each category according to previous experiences of forest restoration in the region (Rodrigues *et al.* 2011; Brancalion *et al.* 2016): Pixels with 0-40% regeneration probability were assigned to ecological restoration plantations. Pixels with 41-70% regeneration probability were assigned to assisted natural regeneration (weeding and fertilization of spontaneously regenerating seedlings and tree planting in patches not covered by natural regeneration). Pixels with 71-100% regeneration probability were assigned to unassisted natural regeneration (land abandonment and fencing, in the case of pastures; no fencing in the case of agriculture). Restoration implementation cost includes planting (if necessary), maintenance of plantings or assisted natural regeneration for a period of three years [approximate cost obtained from a database on forest restoration costs in Brazil (Ministério do Meio Ambiente 2017), that incorporates planting density, number of species and technical assumptions of planting activities]. Fencing costs were added to restoration implementation costs when pixels targeted for restoration were occupied by pasturelands. Since fencing cost is determined by the total area and shape of the site to be fenced and we cannot pre-determine this information in a study like this, we allocated fences to 1/6 of a minimum mapping unit (30 x 30 m pixels). We considered a fencing cost of US\$3.38.m^{-1}, based on local market prices. Total restoration implementation costs varied from US\$500 ha^{-1} (unassisted regeneration in croplands) to US\$3,750 ha^{-1} (restoration plantations in pasturelands; Table S3).

Land opportunity cost was estimated using land rental cost as a proxy. We used official sources of land rental costs for the main agricultural activities in the region and considered a rental period of 10 years and annual interest rates of 10.5%, the regular value used in forestry projects in the region. Land rental costs for a period of 10 years ranged from US$ 1,233 (pasture in the Forest Landscape) to US$ 6,314.41 (crop production in the Mechanized Agriculture Landscape). Land rental costs for each landscape unit are a weighted average of regional crops production, mainly sugarcane and corn, and cattle production, of which we consider beef, dairy and mixed, originated from official governmental sources. Crops are based on production income per hectare while cattle are income for pasture rental per head adjusted per hectare (for more details see Table S4, S5 and S6). All costs were adjusted from a hectare scale to a pixel scale of 900 m^2 for mapping and tabulations. A complete workflow of this methodology is presented in Figure S2.

Forest restoration scenarios

We compared restoration implementation costs and total restoration costs (restoration implementation + land opportunity costs) among three restoration scenarios, determined according to the landscape factors considered for spatial prioritization: i) cost-reduction strategy – prioritization of pixels with the lowest total restoration costs (restoration implementation costs plus land opportunity costs) followed by highest probability of regeneration; ii) riparian restoration – prioritization of riparian buffers, starting from the smallest Euclidean distance from a water body and gradually increasing the width of restored riparian buffers, simulating restoration demands of the Forest Code in Brazil (Brancalion *et al.* 2016) and that of restoration programs worldwide focused on protecting water courses; iii) random restoration - selection of random pixels in the landscape, with no prioritization criteria (Table S7). We calculate mean per hectare costs, restoration implementation costs and total restoration costs for the first 15,000 ha of restoration opportunity within each landscape unit (also, 100% restoration in supplemental information).

Scenarios of cost-effectiveness of restoration for enhancing carbon sequestration and landscape connectivity

For each prioritization scenario, we assessed the cost-effectiveness of ecosystem service provisioning at the landscape scale, across the three landscape units. In this way, we could compare the cost savings of prioritizing low-cost restoration approaches (unassisted and assisted natural regeneration). With information on local restoration costs and probabilities of natural regeneration, this approach can be generally applied to improve the cost-effectiveness of investments in forest landscape restoration. As previously discussed, we considered a 10-year period for this analysis, and targeted a 15,000 ha increase in native forest cover for each landscape. We considered carbon stocking and biodiversity conservation (using landscape connectivity as a proxy) as targeted ecosystem services, due to their common global importance (Thompson *et al.* 2011). For carbon stocking, we considered an average stocking of 70 Mg of C ha^{-1} in the aboveground biomass of trees within a period of 10 years, based on local forest inventories (César *et al.* 2017). For biodiversity conservation, we used as proxy the landscape metric of overall Integral Connectivity Index (IIC), which considers both the proximity between forest patches and their individual area within a landscape unit (Pascual-Hortal & Saura 2006). A distance threshold of 2,000 m was used for this analysis, from patch edge to patch edge, with the exception of 500 m for the random strategies, reduced due to computational limits. To assess cost-effectiveness, we calculate restoration costs, land opportunity costs, and total costs to increase the carbon stock by 1 ton and increase the IIC by 1%.

Results

Weights of evidence of forest regeneration drivers

Among the twelve variables used to model the spatial probability of natural regeneration (Table S2), the six socioeconomic variables showed negligible weights of evidence. Slope, distance to watercourses, and distance to forest remnants were the main biophysical drivers of forest regeneration in the basin (Fig. 2). For both crop and pasture land uses across the entire basin, natural regeneration was favored in areas with slopes above 10%, within 200 m of a water body, and within 100 m from a forest remnant. This trend was consistent across the three regions, except the forest unit, which did not show an effect of slope (Fig. 2). Slope effects were mediated by prior land use in both mechanized agricultural and pasture regions; however, there was no effect of slope for pastureland uses in the mechanized agriculture region and reduced effects on pasture land use in the pasture region (Fig. 2).

Spatially explicit assessment of forest regeneration potential and restoration costs

Forest regeneration probabilities and costs were heterogeneously distributed within all landscape units, with some areas showing much higher regeneration potential and therefore reduced restoration implementation costs (Fig. 1). Variation in land use, topography, and presence of forest remnants led to marked differences among landscape units in the extent of land with a high predicted probability of natural regeneration (>70%) over 10 yr (mechanized agriculture LU: 7.3%; pasture LU: 15.7%; forest LU: 44.9%; Fig. 1).

Cumulative restoration costs within landscape units

Mean per hectare costs of restoration implementation increased with the cumulative restored area, increasing abruptly after the restoration of all areas with high regeneration potential. (Fig. 3A; see Fig. S1 for values up to 100% of the total restoration opportunity). A higher proportion of the total restoration opportunity could be restored at lower per hectare costs in the forest LU (9.1%), followed by the pasture LU (7.9%), and the mechanized agriculture LU (4.2%) (Fig. 3A). The cost reduction strategy of restoration, based on prioritization of lower-cost implementation through natural regeneration and prioritization of land uses with lower opportunity cost, resulted in enormous savings for both implementation costs and total costs in all three LU (Fig. 3B,C and Fig. S1B,C). Compared to prioritization based on riparian zones, the cost-reduction strategy reduced total restoration implementation costs by 19.6 % (US$ 7 million) in the mechanized agriculture LU, 31.3 % (US$10.5 million) in the pasture LU, and 34.8 % (US$ 10.1 million) in the forest LU for achieving the first 15,000 ha of the total restoration opportunity area. When land opportunity costs were included, the cost-reduction strategy was also the most effective, but the magnitude of the cost savings was lower in the pasture and forest landscape units while in mechanized agriculture, savings were 20.9 % lower (US$ 20.5 million), in comparison to prioritization based on riparian zones (Fig. 3C; Fig. S1C).

When considering opportunity costs, the cost reduction approach produced greater savings in landscapes with higher trade-offs between production and conservation, as in mechanized agricultural landscapes, and during the first 40% of restoration opportunity, compared with the full restoration of non-forested areas (Fig. S1). When only considering restoration implementation costs, the cost reduction scenario produced greater savings in landscapes with higher remnant forest cover, such as forest and pasture landscapes, up to the first 50% of restoration opportunity (Fig. S1).

Cost-effectiveness of restoration for carbon sequestration and enhanced landscape connectivity

The cost-reduction scenario was consistently highly effective for minimizing the total cost of aboveground carbon storage (Fig. 4A) in all three landscape units, averaging US$74 per additional ton of carbon stored in restored forests within mechanized agriculture, US$58 in pasture and US$41 in forest landscapes. The cost-reduction scenario also enhanced cost-effectiveness of increasing landscape connectivity for biodiversity, considering both implementation costs and total restoration costs, except for the mechanized agriculture landscape, where costs where similar to riparian prioritization (Fig. 4B). For all carbon sequestration and landscape connectivity increase in all landscapes, and both for restoration implementation and total costs, the scenario based on random distribution of restoration areas in the landscape led to the lowest cost-effectiveness in any given scenario. Cost-effectiveness of increasing landscape connectivity was highest in the forest LU, followed by pasture LU, and was lowest in the mechanized agriculture LU (Fig. 4).

Discussion

Drivers of forest regeneration

Slope, distance to watercourses and distance to forest remnants were decisive factors determining where forest regrowth occurred from 2000–2010, corroborating other studies in the Atlantic Forest region (Teixeira *et al.* 2009; de Rezende *et al.* 2015; Molin *et al.* 2017). With the exception of the Forest landscape unit, where industrial crop production is found, natural regeneration was favored in previous croplands when slopes were above 10%. Slope had a greater importance for natural regeneration in the Mechanized Agriculture landscape, which is consistent with machinery operations for industrial sugarcane production, the dominant crop of the region, which requires slopes below 12% (Rudorff *et al.* 2010). Steep areas were hand harvested in the past, but machines have replaced manual labor extensively over the last 15 years, favoring forest expansion on steeper areas that were no longer used for crops. However, slope had no or little importance in explaining natural regeneration in former pasturelands, where restrictions to mechanization are not a major management issue. Most of the pastures in Brazil are extensive and occupied by quite a low stocking rate (< 1 cow ha^{-1}) (Strassburg *et al.* 2014), which favors the expansion of planted pastures or the maintenance of existent ones in steep areas. For similar reasons, slope did not favor natural regeneration in the Forest landscape. Thus, slope is not a biophysical driver of regeneration potential *per se*, but a surrogate for land-use intensification and land abandonment, a human decision with critical importance for natural regeneration potential.

Distance to watercourses and distance to forest remnants showed a more consistent pattern of influence on natural regeneration in all studied landscapes. Proximity of forest remnants has been identified as a major driver of regeneration potential of tropical forests across the world (Lamb, Erskine & Parrotta 2005; de Barros *et al.* 2012; Chazdon 2014; Sloan, Goosem & Laurance 2016), since it is directly associated with the dispersal of seeds to, and faunal recolonization of, abandoned areas. Although proximity to remnants can be considered a universal driver of forest regeneration potential, little is known about the spatial influence of remnants. In this study, the positive impact of remnants on regeneration declined rapidly with distance, thus indicating that restoration projects implemented more than 200 m from existing forests may have lower chances of success due to dispersal limitation. Proximity to watercourses may have a dual effect on regeneration. The first relates to the chances of land abandonment, since conservation and restoration of riparian buffers in Brazil is mandatory

(Brancalion *et al.* 2016), while also showing restriction to mechanization related to soil flooding and abrupt changes in terrain. The second effect relates to the biotic potential of these riparian areas to support regeneration, as a consequence of reduced water limitation to plant growth in a region with seasonal climate, higher fauna movement, and presence of remnant trees and forests supplying seeds for regeneration. Natural regeneration potential is a function of multiple and complex associations between drivers of land abandonment (e.g. slope) and biophysical potential (e.g. distance to remnants and watercourses) (Farinaci & Batistella 2012).

Reducing restoration costs to upscale programs

Restoration costs are determined by both socio-economic and biophysical factors that are spatially dependent and exhibit both local and regional variation, as embodied in the three landscape units of our study. In the highly mechanized landscape unit, the cost-reduction approach yields the least overall savings in achieving a 15,000 ha restoration target, because of lower potential for low-cost restoration. Nevertheless, when land opportunity costs are considered, this same landscape reveals the greatest overall savings, as a consequence of the high aptitude of lands for profitable agriculture. In this type of landscape, the prioritization of marginal lands for restoration lowers costs in two ways: marginal lands for mechanized agriculture tend to have higher regeneration potential because they usually have more forest remnants and soil was not intensively used; and opportunity costs for restoration are lower in lands that are marginal for agriculture. These factors create a synergy between restoration and production, as restoration on marginal agricultural land does not displace crop production. Given the very low productivity of pasture in this region and across Brazil (Strassburg *et al.* 2014), the intensification of cattle ranching is a promising strategy to spare lands for tropical forest restoration (Phalan *et al.* 2011; Latawiec *et al.* 2014), and our landscape approach illustrates how to take advantage of this important opportunity.

For the Piracicaba basin, prioritizing investments in restoration using natural regeneration clearly provides the greatest opportunity to upscale forest restoration within a fixed budget compared to existing approaches. This advantage is maximized when efforts are focused on areas with greater levels of forest cover, where areas with very high regeneration potential are identified and selected. Even so, when adopting a cost-reduction approach, restoring forests within the Piracicaba basin is expensive, reaching US$28,644,705, US$22,913,573 and US$18,879,750 for the first 15,000 ha in the mechanized agriculture, pasture, and forest landscape units, respectively. Although legislation has played a role in fostering forest restoration in the region, especially in riparian buffers (Rodrigues *et al.* 2009), it is evident that this approach is not economically viable to upscale restoration at the level required to reverse historical degradation. Reducing forest restoration costs is thus imperative, as well as avoiding future degradation and deforestation.

Although previous studies showed that prioritizing natural regeneration is the best strategy to reduce costs (Brancalion *et al.* 2016; Chazdon & Guariguata 2016), they have not offered ways to operationalize this strategy at large spatial scales. Our landscape approach is unique in this regard, and has great potential to support forest and landscape restoration programs globally. Cost reduction is a first and critical step to make restoration financially viable, but it is not sufficient. Funding forest restoration is expected to be a perpetual challenge, so it is also essential to make the best use of existing funds and prioritize areas with higher returns on investments. Researchers have proposed different approaches to prioritize forest restoration (Tambosi *et al.* 2014; Carwardine *et al.* 2015; Vettorazzi & Valente 2016), but few have included restoration costs to guide decisions (Torrubia *et al.* 2014). The integration of our landscape approach to reduce restoration costs with the assessment of the spatial distribution of expected restoration outcomes can further aid restoration programs to make better use of available funds.

Towards a cost-effective forest restoration

The cost reduction scenario presented here was highly effective compared to riparian or random scenarios to sequester carbon in aboveground forest biomass, even when land opportunity costs are included. Strategies to enhance the cost-effectiveness of carbon sequestration through forest restoration are especially welcome in times of falling prices (European Union Emission Trading Schemes: from €29,20.CO_2ton^{-1} in July 2008 to €3.91.CO_2ton^{-1} in September 2016; (Ellerman, Marcantonini & Zaklan 2016). Although market prices for sequestered CO_2 are well known, the cost of sequestering CO_2 via forest restoration is poorly known. Our results showed that the market price of sequestered CO_2 is much lower than that of the cost of CO_2 sequestration through forest restoration, even when using a cost-effective approach. This finding illustrates a clear failure of the carbon market to incentivize forest restoration. Nonetheless, governments, private companies, and environmental NGOs are implementing forest restoration projects across the world with the main aim of climate mitigation, so our landscape approach can still be useful in this context.

In terms of the cost-effectiveness of restoration for enhancing landscape connectivity, similar results were obtained in the riparian and cost-reduction scenarios. Although establishing riparian corridors across the landscape is the easiest way to increase connectivity (Mitchell, Bennett & Gonzalez 2013), the higher restoration cost of this strategy may yield a similar cost-effectiveness outcome of a cost-reduction scenario, in which connectivity increase is not optimal but restoration prices are lower. In addition, the cost reduction scenario shows substantial savings when comparing only restoration implementation costs for the same connectivity increment. However, considering that forest restoration cost is a major barrier for implementation, our approach can be used to guide programs that prioritize landscape connectivity for biodiversity conservation.

Our model provides a novel approach for estimating the total cost of forest restoration at large landscape scales, and provides clear evidence that prioritizing low-cost restoration is an essential approach for upscaling restoration from the site level to the landscape level, with improved cost-effectiveness. We found that even in landscapes with low levels of forest cover, prioritizing low-cost restoration through natural regeneration could increase cost-effectiveness.

This finding applies most importantly to agricultural landscapes where most land is privately owned, since restoration must navigate trade-offs between production and conservation. In addition, policies would need to be changed or enhanced to encourage this prioritization, as they now favor prioritization of riparian areas. Selecting and prioritizing riparian areas with high potential for natural regeneration could be an important policy step.

Authors' Contributions

P.G.M., R.C., S.F.B.F and P.H.S.B. conceived the ideas and designed methodology. P.G.M. collected and compiled the data and performed the analysis; P.G.M, R.C. and P.H.S.B led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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Data accessibility

Data available via the Zenodo digital repository http://doi.org/10.5281/zenodo.1256029 (Molin, Chazdon, Ferraz & Brancalion, 2018).

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Figures

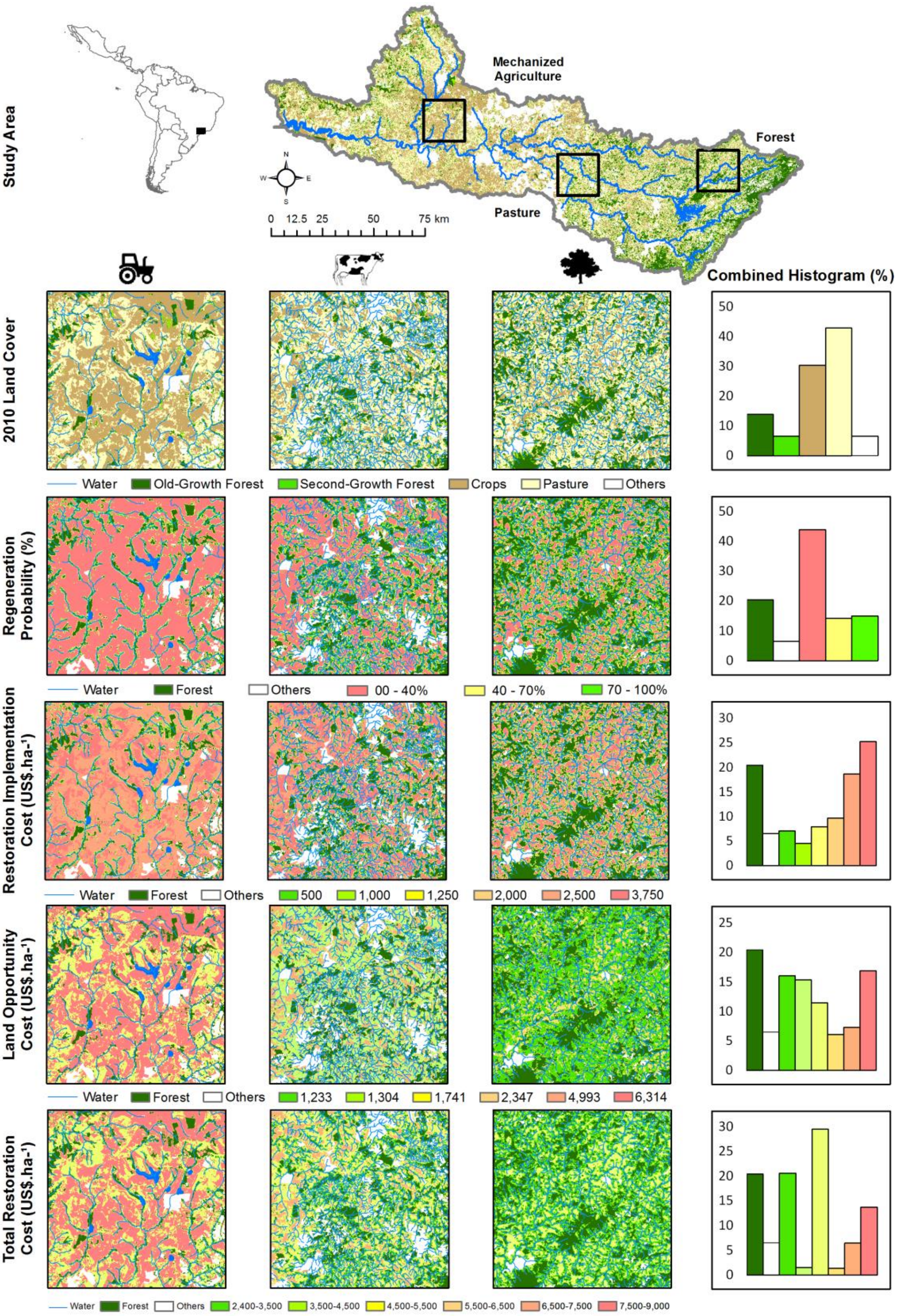
Study Area
Mechanized Agriculture
Forest
Pasture
N
W
E
S
0
12.5
25
50
75 km
Combined Histogram (%)
2010 Land Cover
Water
Old-Growth Forest
Second-Growth Forest
Crops
Pasture
Others
Regeneration Probability (%)
Water
Forest
Others
00 - 40%
40 - 70%
70 - 100%
Restoration Implementation Cost (US$.ha-1)
Water
Forest
Others
500
1,000
1,250
2,000
2,500
3,750
Land Opportunity Cost (US$.ha-1)
Water
Forest
Others
1,233
1,304
1,741
2,347
4,993
6,314
Total Restoration Cost (US$.ha-1)
Water
Forest
Others
2,400-3,500
3,500-4,500
4,500-5,500
5,500-6,500
6,500-7,500
7,500-9,000
50
40
30
20
10
0
30
25
20
15
10
5
0

Figure 1: **Land cover, regeneration probability and restoration costs in three landscape units of the Piracicaba river basin.** Maps of 2010 land cover, regeneration probability, restoration implementation cost, land opportunity cost, and total restoration cost (sum of restoration implementation cost with land opportunity cost), for each studied 40,000 ha landscape unit. For each mapped class, histograms are shown for the three landscape units combined. Tractor symbol indicates Mechanized Agriculture landscape; Cow symbol indicates Pasture landscape; and tree symbol indicates Forest landscape.

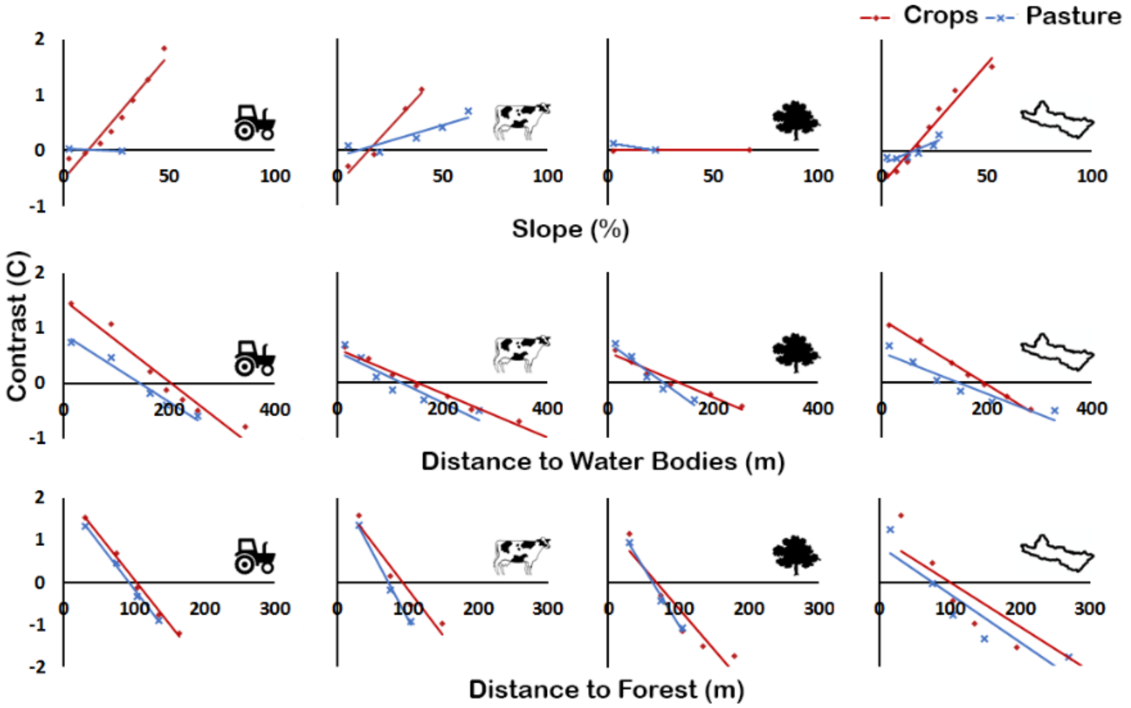

Figure 2. **Drivers of spontaneous forest regeneration from 2000 to 2010 in three landscape units of the Piracicaba river basin.** Weights of evidence contrasts for predictive models of biophysical drivers of natural regeneration of forests in areas covered by crops and pastures (blue and red lines, respectively) in three landscape units within the Piracicaba basin and within the entire basin. Positive values of contrast indicate that the factor promotes regeneration; negative values indicate an inhibitory effect on regeneration. Tractor symbol indicates Mechanized Agriculture landscape; Cow symbol indicates Pasture landscape; Tree symbol indicates Forest landscape; and basin symbols indicates Piracicaba river basin.

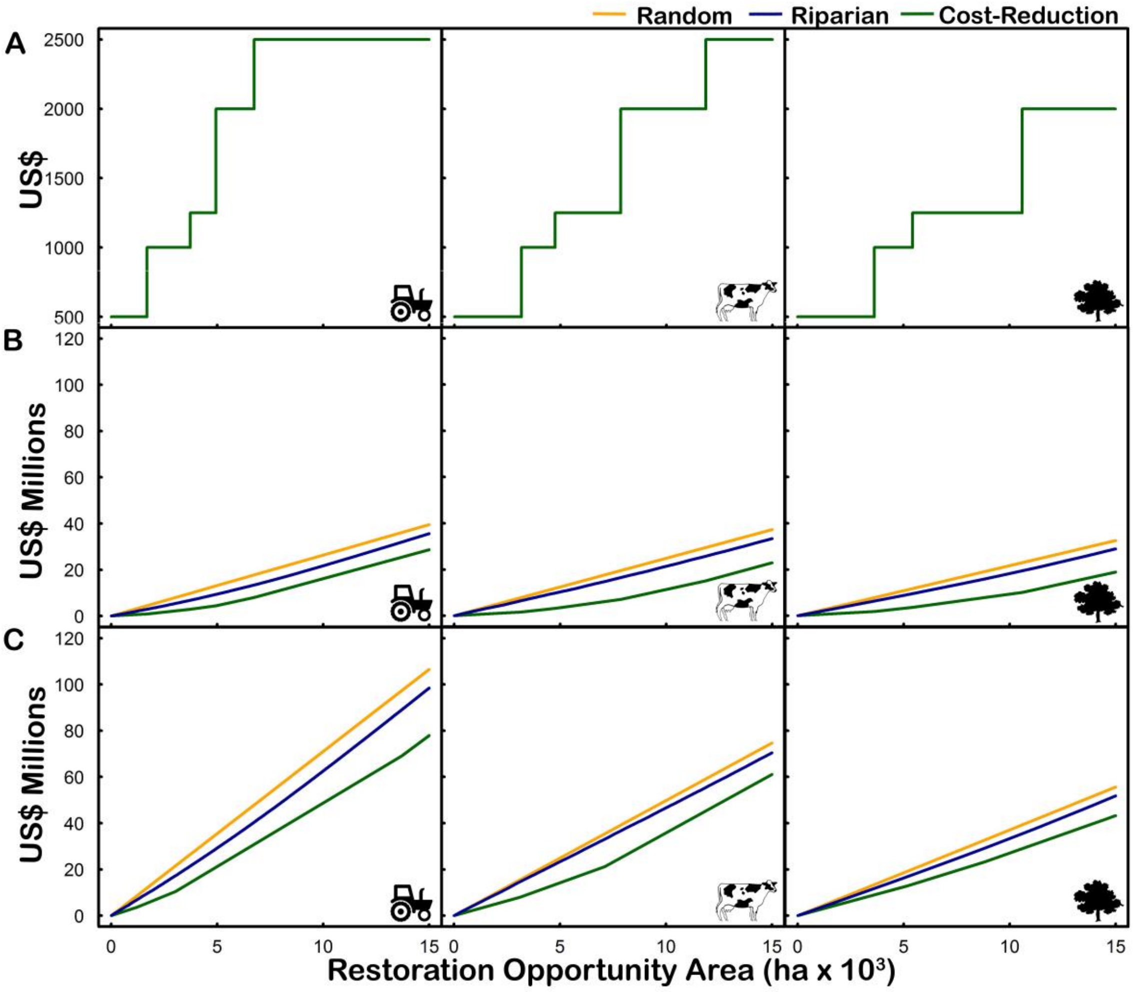

Figure 3: **Mean per hectare and cumulative restoration costs of prioritization scenarios in three landscape units of the Piracicaba river basin.** Mean per hectare costs of restoration implementation (A), cumulative restoration implementation costs (B) and cumulative total restoration costs (with added land opportunity costs) (C) for each restoration strategies for the first 15,000 ha of the total restoration opportunity in three landscape units with different features and dominant land uses. Tractor symbol indicates Mechanized Agriculture landscape; Cow symbol indicates Pasture landscape; and tree symbol indicates Forest landscape.

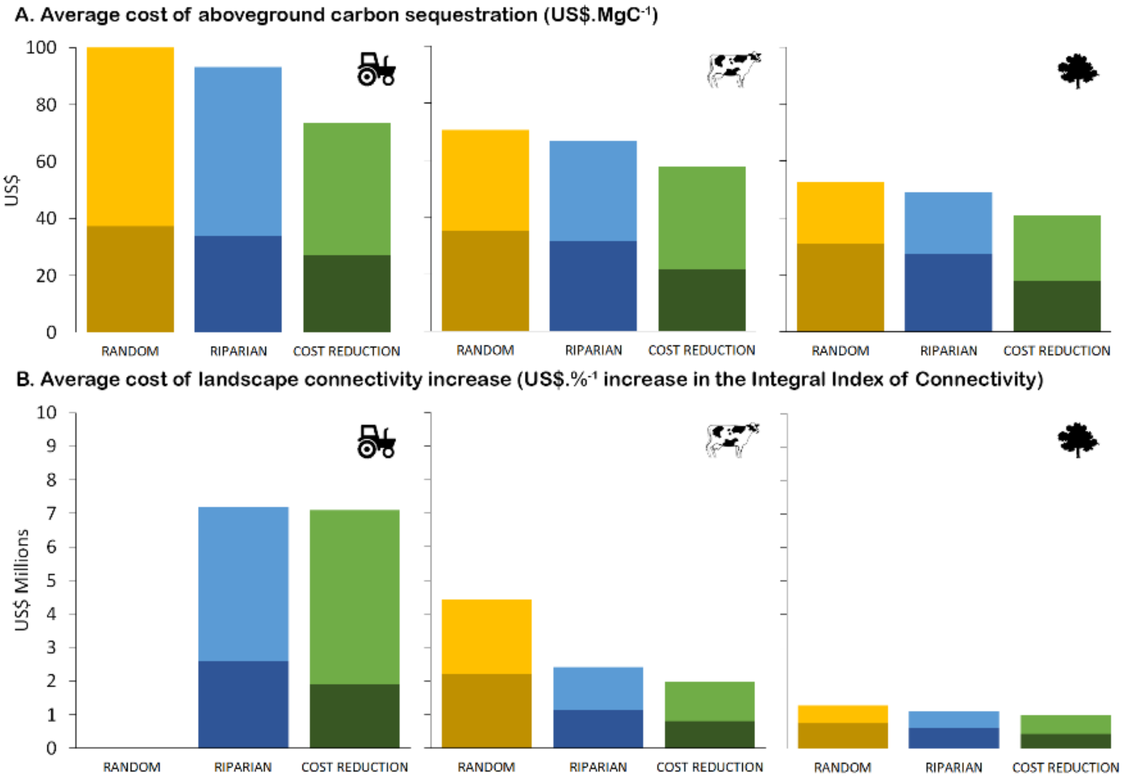

Figure 4. **Restoration cost effectiveness for sequestering carbon and increasing landscape connectivity of prioritization scenarios in three landscape units of the Piracicaba river basin.** Estimated cost effectiveness (US$) of restoring increments of aboveground carbon (A) and landscape connectivity (B) using three different restoration strategies within the three selected landscapes. For each strategy, darker bars represent restoration implementation cost and the lighter bars represent the land opportunity cost. Tractor symbol indicates Mechanized Agriculture landscape; Cow symbol indicates Pasture landscape; and tree symbol indicates Forest landscape. * Random information for mechanized agriculture in (B) is not available due to insufficient computational power for calculating small random forest patches scattered in the landscape.