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How Legal-Oriented Restoration Programs Enhance Landscape Connectivity? Insights From the Brazilian Atlantic Forest

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Abstract

Environmental legislation has fostered ecological restoration programs worldwide, but few studies have reported the outcomes for landscape connectivity. Here, we investigated the contribution of forest restoration programs planned to comply with the Brazilian Forest Code for increasing forest cover and landscape connectivity in agricultural landscapes of southeastern Brazil. We gathered data for 85 landscapes and 2,408 rural properties, totalizing 748,601 ha of farmlands within the Atlantic Forest biome and its ecotone with Cerrado, two global hotspots for biodiversity conservation. Together, rural properties account for 50,783 ha of native vegetation deficit found on Areas of Permanent Protection (APPs). On the basis of this, we performed a landscape connectivity analysis by simulating scenarios in accordance with the requirements of the legislation for two sugarcane mills that are already under ongoing restoration efforts. We evaluated the relative changes promoted by restoring all deforested riparian buffers within APPs, as determined by the Forest Code. The simulation of restoration at the property-level resulted in the reconnection of isolated forest patches, reducing their number in the landscape and increasing their overall and core size. At the sugarcane mill level, the restoration of riparian forests increased the index of connectivity. Despite these benefits, final forest cover (remnant plus restored forests) would still be reduced (<20%—the minimum forest cover on the private land to comply with the environmental law) in most landscapes and insufficient to conserve species sensitive to forest fragmentation. The mandatory restoration of riparian buffers plays a relevant role for improving landscape connectivity in human-modified tropical landscapes, but this strategy shall be complemented by other approaches to increase forest cover and landscape connectivity to mitigate the enormous species extinction debt accumulated for tropical forests.

Keywords

ecological restoration, large-scale ecological restoration, forest restoration, forest landscape restoration, landscape ecology, fragmentation, ecological corridors, tropical forest restoration

Introduction

The increasing importance of environmental legislation for stimulating ecological restoration programs has been evidenced worldwide (Palmer & Ruhl, 2015). In a literature review, approximately 60% of the projects evaluated according to their restoration success were carried out for law compliance (Ruiz-Jaen & Aide, 2005). For instance, enforcement of the Brazilian Forest Code, replaced in 2012 by the Native Vegetation Protection Law (Brancalion, Garcia, et al., 2016; Soares-Filho

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et al., 2014), has influenced the expansion of restoration projects in Brazil (Calmon et al., 2011) and evidenced the key role of environmental legislation for scaling-up ecological restoration in tropical countries.

Given the global trends of deforestation and forest degradation in the tropics, large-scale (see local and regional examples in Calmon et al., 2011; Doyle & Drew, 2008; Sánchez-Azofeifa, Pfaff, Robalino, & Boomhower, 2007; Yin & Yin, 2009) and long-term restoration efforts are urgently needed (Holl, 2017). Bold international goals on ecological restoration have recently boosted this activity (Chazdon et al., 2017). For instance, the Bonn Challenge and the New York Declaration of Forests accumulate global commitments to restore 200 Mha by 2020 and 350 Mha by 2030, with most of the pledges coming from tropical regions (Holl, 2017).

Despite the growing international commitments to upscale forest restoration in tropical regions, government policies on restoration are few, vague (Chaves, Durigan, Brancalion, & Aronson, 2015) and emerge as a global priority (Meli et al., 2017). Clearly, there is a huge demand for robust ecological outcomes by reducing the gap between theory and practice to support legal instruments for regulating restoration projects (Chaves et al., 2015). In this context, the assessment of the benefits derived from the implementation of mandatory restoration projects plays a vital role for reinforcing the importance of developing specific legal instruments for this activity (Brancalion, Schweizer, et al., 2016).

Legal compliance is the main driver of forest restoration on private lands in Brazil (Brancalion, Schweizer, et al., 2016; Rodrigues et al., 2011). In general, farmers are obliged to keep or restore native vegetation along springs and streams, and also a proportion of natural vegetation called "Legal Reserve." The legal reserve is the area of rural property that, covered by natural vegetation, can be exploited with sustainable forest management, within the limits established by law for the biome in which the property is located. Such legal enforcement, especially along springs and streams, has been stimulating large-scale restoration programs in Brazil (Melo, Pinto, et al., 2013). Those initiatives may play a relevant role for biodiversity conservation in human highly modified landscapes, such as the Brazilian Atlantic Forest (Melo, Arroyo-Rodriguez, Fahrig, Martinez-Ramos, & Tabarelli, 2013), where the majority of forest fragments (~90%) are located within private lands (Ribeiro, Metzger, Martensen, Ponzoni, & Hirota, 2009).

One of the most important benefits expected from large-scale restoration efforts is the increase of landscape connectivity, since restored ecological corridors may increase biological flows in unfavorable matrices (Becker, Fonseca, Haddad, Batista, & Prado, 2007; Rappaport, Tambosi, & Metzger, 2015) and mitigate the enormous species extinction debt accumulated for tropical forests (Banks-Leite et al., 2014; Newmark, Jenkins, Pimm, Mcneally, & Halley, 2017). In this context, the evaluation of the potential outcomes of ecological restoration programs designed for legal compliance in private lands may provide a science-based background for improving existing legal instruments and creating new public policies to leverage large-scale restoration on private lands (Joly et al., 2010).

Previous investigations have assessed the local ecological outcomes of restoration projects established to comply with environmental legislation in Brazil (Brancalion, Garcia, et al., 2016; Rodrigues et al., 2011), but little is known regarding the potential of these projects to improve landscape connectivity. Simulations evaluating the impacts of the aforementioned law on the demand for restoration interventions in Brazil has been widely explored in the literature (e.g., Soares-Filho et al., 2014; Strassburg et al., 2017), but there is a lack of information on impacts on at the level of restoration programs, within landscapes were land use decisions are made and impact biodiversity connectivity and ecosystem services. Here, we investigated the contribution of forest restoration programs focused on riparian buffers and planned to comply with the Brazilian Forest Code applicable until 2012 for increasing forest cover and landscape connectivity in agricultural landscapes of southeastern Brazil.

Material and Methods

Study Area

To represent the overall agricultural landscapes of southeastern Brazil, we gathered data for 85 landscapes and 2,407 rural properties, totalizing 748,601 ha of farmland. Information included the amount of remaining forests within and outside Areas of Permanent Preservation (APPs; Table 1). APPs are land portions that must be set aside exclusively for environmental protection, and they are mostly represented by riparian corridors along springs, streams, and rivers. They have different widths depending on the size of the watercourse (Taniwaki et al., 2018) and have a circular shape buffering 50 m around springs (Brancalion, Garcia, et al., 2016). The data were collected by the Forest Ecology and Restoration Laboratory (University of São Paulo) under restoration programs developed for small and large landholdings to comply with environmental laws and apply for green certificates (see details in Rodrigues et al., 2011). The properties are located within the states of São Paulo, Minas Gerais, Rio de Janeiro, Paraná, and Mato Grosso do Sul. These landscapes include mostly private lands producing sugarcane, followed by mixed crops, cattle ranching, orange, and coffee (Table 1). This data set provided

Table 1. Characteristics of the Agricultural Landscapes Where Mandatory Restoration Projects Were Implemented in Southeastern Brazil.

Main land use	No. of landscapes	Total farm area (ha)	No. of farms	Mean area per farm (ha)
Coffee	3	567.18	3	189.06 ± 235.17
Sugarcane	40	607,721.87	2,326	629.09 ± 941.13
Orange	4	2,376.62	7	393.09 ± 270.67
Mixed land uses	21	72,591.25	11	1,199.96 ± 1,827.86
Pastureland	17	65,344.26	60	878.37 ± 1,047.79
Total	85	748,601.18	2,407	724.395 ± 1,075.64

information to evaluate the amount of native forests within and outside APPs in typical agricultural landscapes from southeastern Brazil.

Impacts on Forest Cover Promoted by Mandatory Restoration Within Agricultural Landscapes

We first evaluated the forest cover and the spatial distribution of forest patches within farms included in the restoration landscapes described in the previous section. We classified LANDSAT 5 images, with a 30 m resolution, into "natural vegetation" and "matrix." This land cover classification was based on supervised classification through the Maximum Likelihood algorithm, processed in remote sensing Software Erdas 9.1 (ERDAS, 2006) and assuming 90% threshold acceptance. After we got the supervised classification maps, we compared the native vegetation cover with field maps previously created for each property. When field map differed from the supervised classification map, we used the first as the corrected one, given its higher reliability. This procedure was adopted to correct errors because of the lower resolution of the LANDSAT images. All the subsequent analysis were made with this corrected native vegetation map. Then, we established in the maps of the farms the boundaries of APP dual corridors along streams and around water springs, according to the former Brazilian Forest Code norms applicable until 2012, and assessed the area covered and not covered by native forests within APPs. The area not covered by native forests was assumed as the area where restoration is mandatory by law.

Study Case: Simulation of the Impacts of Mandatory Restoration on Landscape Connectivity

We selected as case studies two representative sugarcane mills from São Paulo State, southeastern Brazil: São João Sugarcane Mill (SJSM), located in Araras (22°21′25″S; 47°23′03″O), and Batatais Sugarcane Mill (BSM), located in Batatais, (20°53′28″S; 47°35′06″O). The SJSM have restored 626.30 ha in APPs since 1999 and BSM, 860 ha since 2006. The both mills have declared nothing about the Legal Reserve restoration. We classified land use in the farms of these sugarcane mills according to the same approach described earlier. We considered three scales of analysis to better understand the effects of them on the landscape metrics before and after the simulated restoration of native forests in riparian buffers protected as Areas of Permanent Protection: (a) farm level, (b) farm + 1 km boundaries' buffer, and (c) all the properties from the same sugarcane mill, with a 3-km buffer around them. We considered the scenarios (A) before restoration implementation (i.e., forest cover was exclusively composed of remnant forests) and (B) after restoration (i.e., considering that all nonforested APP area would be restored, and total forest cover as remnant + restored forests; Figure 1). It is important to highlight that we have considered only the APPs requirements that, in fact, are the areas target to be restored by the sugarcane mills to comply with the legislation in those programs.

For each scenario, we calculated the forest cover (ha), the number of fragments, and their mean area as descriptive landscape metrics for all properties (Scales 1 and 2). These metrics were calculated considering "core" fragments, defined by the vegetation patch remaining after the exclusion of a 50-m edge strip. For the third scale, we calculated the Integral Index of Connectivity, which is a graph-based index ranging from 0 to 1 that considers the size of the fragments and the distance and connections among them (Pascual-Hortal & Saura, 2006). We compared mean values of response variables between Scenarios A (before restoration) and B (after restoration), through a repeated measures analysis of variance using the R software (R Core Team, 2017).

Results

Landscapes within agricultural areas had very low native vegetation cover (below 20%), except landscapes where coffee or pasturelands were the main land use (Table 2). Approximately 40% of the 57,554 ha of forests remaining on farms were found within APPs, whereas 50,783 ha of native vegetation deficit was found on APPs (Table 2). Consequently, the restoration of forests within APPs up to the limits determined by law would increase forest cover in private lands in about 53.13% (Table 2).

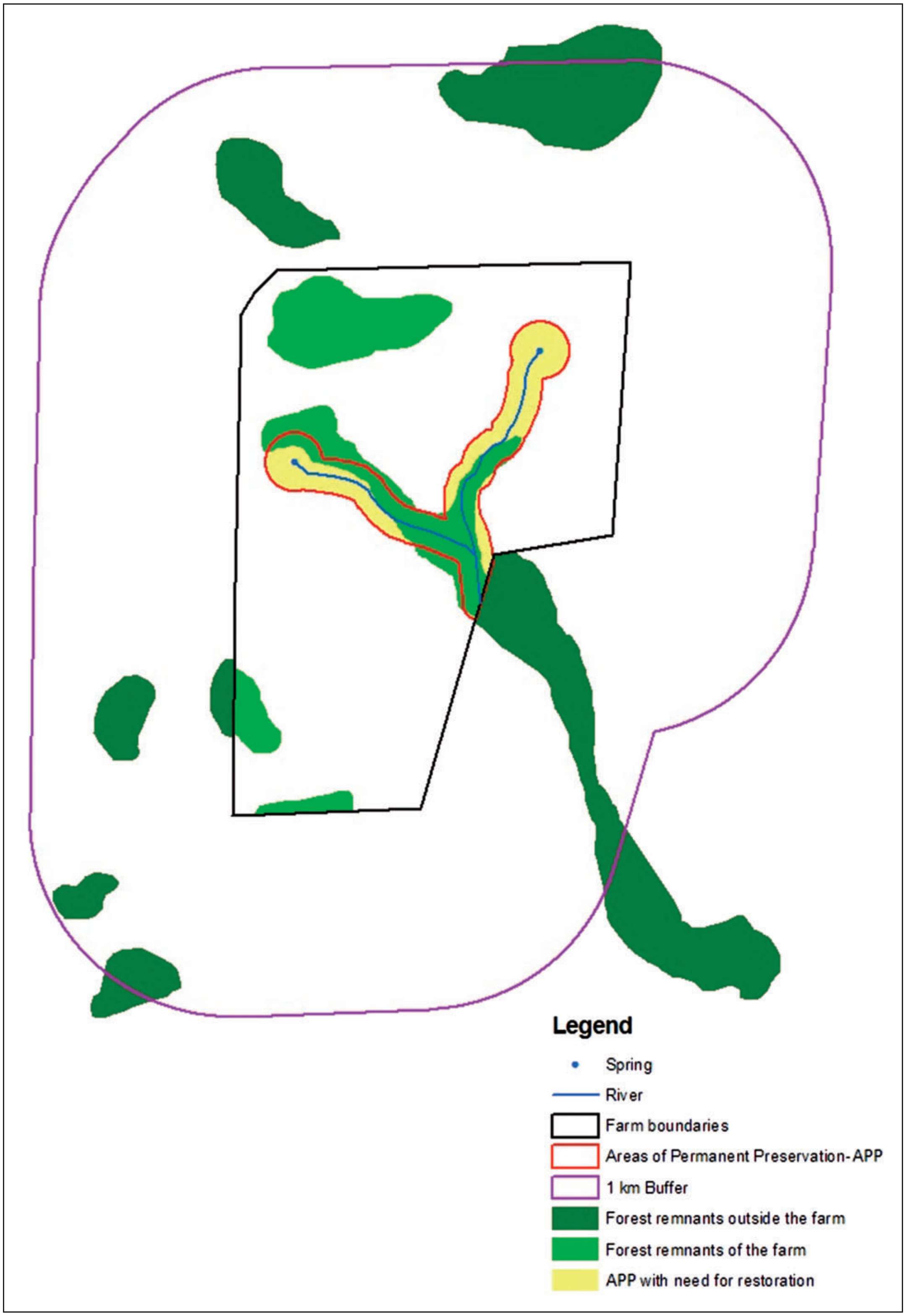

Figure 1. Schematic representation of a farm with its Areas of Permanent Preservation (APPs), covered by native forests or with need for restoration, forest remnants outside APPs, and forest remnants within a 1-km buffer around the farm boundaries.

Table 2. Current and Potential Forest Cover (ha), If Restoration Fully Supplies the Legal Deficit of Native Vegetation in Riparian Buffers Protected as Areas of Permanent Protection (APPs), in Agricultural Landscapes in Southeastern Brazil.

Main land use	APPs (ha)	Forest within APPs (ha)	Agricultural lands within APPs (ha)	Forests outside APPs (ha)	Current total forest cover (ha)	Total forest cover after restoration (ha)
Coffee	106	26	80	91	117	197
Sugarcane	55,926	17,640	38,286	26,206	43,846	82,132
Orange	254	128	126	48	176	302
Mixed land uses	10,881	2,507	8,374	4,439	6,946	15,320
Pastureland	6,385	2,468	3,917	4,001	6,469	10,386
Total	73,552	22,769	50,783	34,785	57,554	108,337

We have also observed clear benefits of mandatory restoration within APPs for landscape connectivity when sugarcane mills were used as case studies, in the two first scales of analysis (Table 3). Overall, at the farm-level, the restoration of riparian forests within APPs would significantly increase total and "core" forest cover (for SJSM: 7 ha to 12.5 ha; $F = 38.6$, $p < .001$, and 1.8 ha to 3.7 ha; $F = 17.8$, $p < .001$, respectively; for BSM: 19.7 ha to 25.5 ha; $F = 112.9$, $p < .001$, and 5.3 ha to 6.7 ha; $F = 17.5$, $p < .001$, respectively); the mean area of total and "core" fragments cover, and the number of "core" fragments would increase, whereas the total number of fragments would be reduced (Table 3). The inclusion of a 1-km buffer around each property (second scenario) did not dilute the importance of ecological restoration to increase landscape connectivity. Surprisingly, it increased the effect of ecological restoration to increase the mean area of fragments and core fragments (Table 3). Regarding the evaluation of the "landscape" created by each sugarcane mill (third scenario), the Integral Index of Connectivity was highly increased by the simulation of the restoration of APPs. The mean area of fragments and the core fragments are important parameters for allowing percolation considering Integral Index of Connectivity. In the SJSM, this index increased from 0.000132 to 0.000312 (increase of 236%), while in the BSM from 0.001636 to 0.002378 (increase of 145%), and this is specifically translated as an increase of the total and "core" forest cover, the mean area of total and "core" fragments cover, and the number of "core" fragments at the landscape level.

Discussion

The very low native vegetation cover of the landholdings included in the evaluated landscapes revealed that agricultural regions actually provide unsuitable conditions for biodiversity persistence overtime, as already discussed in the literature (Banks-Leite et al., 2014; Gardner et al., 2009; Tabarelli, Aguiar, Ribeiro, Metzger, & Peres, 2010). The lack of spatial continuity with forest remnants and the reduced width of APPs indicate that riparian corridors restored to comply with the law may have played a suboptimal role in biological fluxes of more sensitive species. Consequently, restoration efforts would be essential to complement and increase the role of riparian buffers as ecological corridors, by increasing forest cover and corridor width and by improving their shape (Brancalion, Melo, Tabarelli, & Rodrigues, 2013). As a direct consequence of the increase of the size of each forest patch, the number, size, and cover of "core" forest increased, thereby improving the quality of the habitat for forest-dependent species. In addition, ecological corridors also should be established outside APP limits to improve landscape connectivity as a complementary action to legal compliance (Tambosi, Silva, & Rodrigues, 2012).

Given that the percolation threshold is likely to occur at around 60% (Stauffer, 1985), this seems to be a practical target for conservation and restoration plans in order to maintain populations in fragmented landscapes. Our results showed, however, that, despite the importance of riparian corridors, the very low forest cover of the studied areas (usually lower than 10%) is much lower than the theoretical limits of percolation (Stauffer, 1985) and fragmentation threshold (Banks-Leite et al., 2014; Fahrig, 2003). For instance, although restoration of APPs increased by 145% and 236% the index of connectivity in the two sugarcane mills, the values resulted from the analysis were very low in both scenarios (before and after ecological restoration; Lechner, Bown, & Raymond, 2015). This result indicates that, although restoration actions improved the amount of forest cover, connectivity would still be weak in such landscapes.

In such high degraded scenarios, the restoration of riparian forest may be not enough for biodiversity persistence if the dominant matrix presents low percolation. More than just increasing landscape connectivity, these landscapes need increases in forest cover. The low percolation for the studied landscapes means that the survival of strictly forest species is limited due to the reduced potential organism flow. This indicates that conservation efforts should focus on forest maintenance or restoration to reach the limit of forest cover and connectivity—required to maintain ecological processes.

Table 3. Comparison of Landscape Metrics Before and After the Simulated Restoration of Native Forests in Riparian Buffers Protected as Areas of Permanent Protection (APPs), Up to the Full Mitigation of the Legal Deficit of Native Vegetation, in Two Sugarcane Mills From Southeastern Brazil.

	Before restoration (Mean ± *SD*)	After restoration (Mean ± *SD*)	Difference (Mean ± *SD*)	*F*	*p*	Before restoration (Mean ± *SD*)	After restoration (Mean ± *SD*)	Difference (Mean ± *SD*)	*F*	*p*
São João sugarcane mill (279 farms)	Farms					Farms + buffer 1 km				
Total forest cover of the farm (ha)	7 ± 18.1	12.5 ± 26.9	5 ± 15	38.6	< .001	37.9 ± 60	43.3 ± 4.9	5.4 ± 14.6	38.3	<.001
Number of forest fragments per farm	1.4 ± 1.9	1.1 ± 1.2	(−)0.3 ± 1.3	9.7	.002	5.1 ± 4.3	4.9 ± 3.7	(−)0.2 ± 1.3	9.2	.001
Mean area of forest fragments of each farm (ha)	2.4 ± 4.4	6.9 ± 13.9	4.6 ± 11.5	44.1	<.001	3.8 ± 4.1	4.4 ± 4.6	0.6 ± 3.2	9.2	.002
Total "core" forest cover of each farm (ha)	1.8 ± 8.9	3.7 ± 12.3	1.8 ± 7.4	17.8	<.001	15.1 ± 38.1	16.8 ± 39.2	1.7 ± 7.2	16.8	<.001
Number of "core" forest fragments of each farm	0.8 ± 1.8	1.5 ± 2.7	0.7 ± 1.7	47.4	<.001	3.1 ± 3.1	3.2 ± 3.1	0.1 ± 0.8	6.3	.013
Mean area of "core" forest fragments of each farm (ha)	0.5 ± 2.1	0.9 ± 2.4	0.4 ± 2	10.4	.001	3.6 ± 7.3	3.9 ± 7.3	0.3 ± 2.3	4.7	.032
Batatais sugarcane mill (277 farms)	Farms					Farms + buffer 1 km				
Total forest cover of the farm (ha)	19.7 ± 34	25.5 ± 39.8	5.8 ± 9.1	112.9	<.001	208.5 ± 186.8	213.2 ± 189.6	4.7 ± 7.2	120.0	<.001
Number of forest fragments per farm	3.9 ± 3.5	2.5 ± 2.2	(−)1.4 ± 2	128.5	<.001	17.9 ± 9.8	16.6 ± 8.5	(−)1.3 ± 2.1	103.6	<.001
Mean area of forest fragments of each farm (ha)	10.2 ± 16.8	10.2 ± 16.8	0.0 ± 0.1	3.0	.084	7.8 ± 7.7	8.4 ± 8.2	0.6 ± 1.2	67.3	<.001
Total "core" forest cover of each farm (ha)	5.3 ± 15.9	6.7 ± 17.9	1.3 ± 5.3	17.5	<.001	82.6 ± 98.8	83.7 ± 99.8	1.2 ± 4.2	20.9	<.001
Number of "core" forest fragments of each farm	1.8 ± 2.8	2.7 ± 3.5	0.9 ± 1.7	83.1	<.001	10.5 ± 5.4	10.1 ± 4.8	(−)0.4 ± 1.1	40.8	<.001
Mean area of "core" forest fragments of each farm (ha)	1.8 ± 5.3	1.8 ± 5.3	0 ± 0	1.2	.27	8.4 ± 11.8	8.8 ± 12.2	0.4 ± 1.2	33.4	<.001

Note. Repeated measures ANOVA with *F* values below 0.05 were considered statistically significant. ANOVA = analysis of variance.

As mentioned by Fahrig (2017), the potential role of matrix quality in mediating positive or negative responses of biodiversity to habitat fragmentation suggests that a more holistic view of the landscape may be needed. In the context of agricultural landscapes, Duelli (1997) recognized significant positive effects of landscape spatial heterogeneity in contrast to habitat patch size and isolation effects. Combining these two approaches, in the context of ongoing global habitat loss and fragmentation, our results emphasize, in a practical way, the need to conserve natural remnants within the private properties combined to restoration, but these two practices could be more effective if accompanied of spatial heterogeneity (i.e., matrix diversification) planned beyond the properties' boundaries.

It is also important to highlight that (a) high-diversity models of forest restoration may be essential to support the establishment of biologically viable restored forests in such low favorable scenario for biodiversity persistence (Aronson et al., 2011), and (b) each landscape has its peculiarities and a specific model of large-scale restoration should be applied to each situation. Increasing forest cover beyond the APP limits would be possible through compliance with another instrument of the Native Vegetation Protection Law: the Legal Reserves. In all regions of Brazil, except in the Amazon (80%), Legal Reserves are constituted by 20% of forest cover per property (for properties above a predefined area for each municipality), including the forests protected in APPs. Our results reinforce that forest patches acting as Legal Reserves could play a different, but complementary, role than that provided by APPs (Brancalion, Garcia, et al., 2016). Therefore, ecological restoration is necessary in both situations for transforming such human-modified landscapes into biodiversity-friendly landscapes (Melo, Arroyo-Rodriguez, et al., 2013).

Contrary to these observations, the New Forest Code (Native Vegetation Protection Law) allows private landowners to join remnants in APP with those outside APP for achieving a minimum forest cover of 20% on the private land, in addition to removing any need of restoration of Legal Reserves in small landholdings. In addition, farmers are now allowed to compensate for the lack of Legal Reserve forests within their farms in other farms of the biome with surplus of forest cover, instead of being obliged to restore the deficit of native forests in their own farms. Off-farm compensation of Legal Reserves are expected to consolidate a high native forest cover in marginal regions for agriculture, where the surplus of native forests is concentrated, and consolidate a very low native forest cover in regions of highly profitable agriculture (Soares-Filho et al., 2016). Since compensation is allowed in the whole biome, and each Brazilian biome is composed of many different and particular biogeographical zones, it is evident that biodiversity conservation may receive a more limited support of restoration in regions of intense agriculture. Such setbacks in environmental legislation evidence the importance of assessing the benefits and limitations of current legal instruments for supporting any changes in their content.

Our study highlights that programs developed for small and large landholdings to comply with environmental laws are contributing not only to reach green certification but also for landscape improvement. Our findings emphasize that restoration of riparian buffers included in APPs may play a relevant role for improving landscape connectivity in regions dominated by intensive agriculture, and an increase in forest cover outside the limits of such areas is not only desirable but also essential for improving the chances of biodiversity persistence in the mid- and long-term.

Implications for Conservation

Restoration projects implemented to comply with environmental laws may play a relevant role for establishing riparian forest corridors and increase landscape connectivity within agricultural regions. Compared to other studies, the index of connectivity we found was really low but the changes promoted by restoration efforts are important to the landscape. In addition to restoring riparian buffers, it is necessary to increase (a) forest cover beyond the minimum percolation thresholds to mitigate species extinctions debt and (b) the heterogeneity in human-modified tropical landscapes.

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