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Large-scale ecological restoration of high-diversity tropical forests in SE Brazil

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ABSTRACT

The complex interactions among endangered ecosystems, landowners' interests, and different models of land tenure and use, constitute an important series of challenges for those seeking to maintain and restore biodiversity and augment the flow of ecosystem services. Over the past 10 years, we have developed a data-based approach to address these challenges and to achieve medium and large-scale ecological restoration of riparian areas on private lands in the state of São Paulo, southeastern Brazil. Given varying motivations for ecological restoration, the location of riparian areas within landholdings, environmental zoning of different riparian areas, and best-practice restoration methods were developed for each situation. A total of 32 ongoing projects, covering 527,982 ha, were evaluated in large sugarcane farms and small mixed farms, and six different restoration techniques have been developed to help upscale the effort. Small mixed farms had higher portions of land requiring protection as riparian areas (13.3%), and lower forest cover of riparian areas (18.3%), than large sugarcane farms (10.0% and 36.9%, respectively for riparian areas and forest cover values). In both types of farms, forest fragments required some degree of restoration. Historical anthropogenic degradation has compromised forest ecosystem structure and functioning, despite their high-diversity of native tree and shrub species. Notably, land use patterns in riparian areas differed markedly. Large sugarcane farms had higher portions of riparian areas occupied by highly mechanized agriculture, abandoned fields, and anthropogenic wet fields created by siltation in water courses. In contrast, in small mixed crop farms, low or non-mechanized agriculture and pasturelands were predominant. Despite these differences, plantations of native tree species covering the entire area was by far the main restoration method needed both by large sugarcane farms (76.0%) and small mixed farms (92.4%), in view of the low resilience of target sites, reduced forest cover, and high fragmentation, all of which limit the potential for autogenic restoration. We propose that plantations should be carried out with a high-diversity of native species in order to create biologically viable restored forests, and to assist long-term biodiversity persistence at the landscape scale. Finally, we propose strategies to integrate the political, socio-economic and methodological aspects needed to upscale restoration efforts in tropical forest regions throughout Latin America and elsewhere.

1. Introduction

The rate and extent of deforestation and habitat fragmentation in tropical countries demand many actions to conserve – or at least minimize the losses of – tropical forest biodiversity and ecosystems services provided by those ecosystems (Becker et al., 2009; Jenkins, 2003; Gardner et al., 2009; Nepstad et al., 2009). Additionally, several tropical forest landscapes have already surpassed the recommended limits of percolation (*sensu* Stauffer, 1985) and the theoretical fragmentation threshold (Fahrig, 2003), and now have low potential to maintain native biodiversity over time if the isolated fragments are not re-connected so as to renew the possibility of biological exchanges among them (Metzger and Décamps, 1997). Hence, in addition to slowing forest degradation, and to supporting maintenance of native biodiversity in the remaining forest

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fragments of the tropics, it is important to highlight the key role of ecological restoration for biodiversity conservation (Chazdon, 2008). To face this challenge, it is urgent to expand ongoing tropical forest restoration projects from the current scale of hundreds to thousands of hectares, to an order or two greater magnitude (Rodrigues et al., 2009).[1]

Large-scale restoration is important in biomes where ecosystem functioning has been compromised and a vast portion of native biodiversity has become severely endangered (MA, 2005). This is particularly true in developing countries, where 26 of the 34 global biodiversity hotspots are located (Mittermeier et al., 2004). In these areas, truly large-scale restoration is now required, but since the goal is full-fledged restoration of degraded ecosystems, and not just functional rehabilitation or mere reforestation, attention to the vast wealth of native biodiversity must be incorporated into restoration efforts (Kanowski et al., 2003; Larjavaara, 2008). This is necessary to create self-perpetuating forests that truly support ecosystem functioning and adaptive evolution, as well as ongoing supply of ecosystem services to people (Chazdon, 2008; Loreau et al., 2001; Rey Benayas et al., 2009; Wright et al., 2009).

When up-scaling from local restoration efforts to the inclusion of biomes as a whole as the targets for restoration and reintegration, the way that we deal with biodiversity needs to be reviewed (Tabarelli et al., in press). An example of the new kind of approach required for restoration planning at large-scales is "The Atlantic Forest Restoration Pact", an ambitious program that aims to recover 15 million ha of the Brazilian Atlantic Forest by the year 2050 (http://www.pactomataatlantica.org.br/index.aspx?lang=en), and the Biota-FAPESP Program at São Paulo state (Joly et al., 2010). Defining the desired attributes of a restored ecosystem become particularly important (SER, 2004), as well as the use of a consciously selected ecological reference system (Aronson et al., 1995; Clewell and Aronson, 2007; Clewell, 2009), which in the case of tropical forests clearly must include high native biodiversity. These attributes and reference system can be used not only as a guide to monitor and evaluate restoration projects, but also for the purposes of comparison with other comparable restoration projects in the same region or elsewhere. In the case of human-modified tropical and subtropical landscapes, the reference system can be understood as establishing a group of scenarios for the desired trajectory of the ecosystems under management, rather than defining a strict and static ecosystem state to be copied or emulated (Rodrigues et al., 2009).

To reach large-scale application with an approach that seeks to reestablish and maintain high biodiversity, without sacrificing effectiveness and attention to detail, ecological restoration has to be supported by well-founded investigation into the ecology of the various kinds of degraded forest ecosystems in the tropics, with particular emphasis on their potential for autogenic restoration, and their responses to active interventions designed to catalyze restoration. Furthermore, since ecological restoration often has to be implemented on private lands to achieve the above-mentioned goals, a socio-economic overview and justification is necessary to motivate landowners to participate voluntarily in the restoration programme (Lamb et al., 2005). This integrated approach is also required for any effort to restore natural capital, *i.e.* native ecosystems and biodiversity, in which the different systems of land use have to be considered when investigating the best methods of restoration to be applied in each situation (Aronson et al., 2007).

Within human-dominated tropical landscapes, conservation and restoration purposes have to be integrated within the broad context of all the main driving factors of ecosystem degradation, in which agriculture often has central importance in tropical countries (Igari et al., 2009; Knoke et al., 2009). Hence, restoration has to be guided by a pragmatic socio-economic and political systems overview, seeking direct linkages and synergy between restoration of native ecosystems, protection and maintenance of native biodiversity, sustainable use of resources, and augmented delivery of ecosystem goods and services to people (Aronson et al., 2007; Wright et al., 2009).

Considering that agriculture has a central importance in this context, by virtue of occupying the largest portion of land in the tropics, it is important to consider the heterogeneity of land use models and patterns, in order to propose effective strategies and incentives for ecological restoration. The recent advance of agribusiness in developing countries, led by agro-industry companies based on export-oriented monocultures, has divided land use into two main categories: small landholdings in mixed farms and large landholdings of monocultural crop production. To deal with these contrasting contexts, public policies and market tools concerning environmental protection may play a key role in reconciling conservationist and socio-economic development motivations for large-scale restoration of degraded areas.

In this paper, we present the Restoration Program we have developed for large-scale ecological restoration in southeastern Brazil over the past 10 years, which is based on the protection of the remaining forest fragments against anthropogenic impacts, on the proposal of site-specific restoration actions regarding different potentials of autogenic restoration, and on the establishment of high-diversity restored forests. By applying the proposed Restoration Program in large portions of land, we also aimed to compare the different ecological restoration strategies required on large landholdings devoted to monocultural production of sugarcane, and those appropriate for small landholdings in mixed farms. The comparison between these systems of land use may provide important insights about how to integrate the political, socio-economic and methodological aspects to permit up-scaling of restoration efforts in tropical forests throughout Brazil and elsewhere.

2. Site and project description

We illustrate our approach through discussion of 32 ongoing projects in São Paulo State, southeastern Brazil (Fig. 1). São Paulo is the most economically developed state in Brazil with 34% of Brazilian GNP, and important participation in the country's industrial, service, and agricultural sectors. The State's agriculture is mostly based on sugarcane, which occupies approximately 5.5 million ha, *i.e.* 32.2% of the agricultural land of the state, and produces on average 58% of the national harvest of sugarcane. In addition to this extensive, agro-industrial, export-oriented system of production, thousands of small (<50 ha) mixed farms also exist in the state. In fact they represent 77.7% of the number of farms, but only 19.9% of the total area in cultivation. These small farms produce most of the agricultural products consumed internally (São Paulo, 2008).

Needless to say, expansion of intensive agro-industry has brought several negative impacts for biodiversity conservation and ecosystem services: the state's natural forest cover was reduced from 82% to only 17.5% in the last 150 years (SIFESP, 2010). Additionally, if we remove the contribution of the forests on the steep slopes of the Atlantic mountain range, and consider only the agricultural landscapes of inland São Paulo state, natural forest cover represents no more than 9% of the area (SIFESP, 2010). This situation, plus high levels of species richness and endemism, led both of the biomes present in São Paulo state, namely Cerrado and Atlantic Forest, to be included in the IUCN list of global Biodiversity Hotspots (Mittermeier et al., 2004). The few remaining patches of natural vegetation have been also historically impacted,

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[1] LLS – large landholdings of sugarcane; SLMF – small landholdings in mixed farms; PPAs – permanent preservation areas.

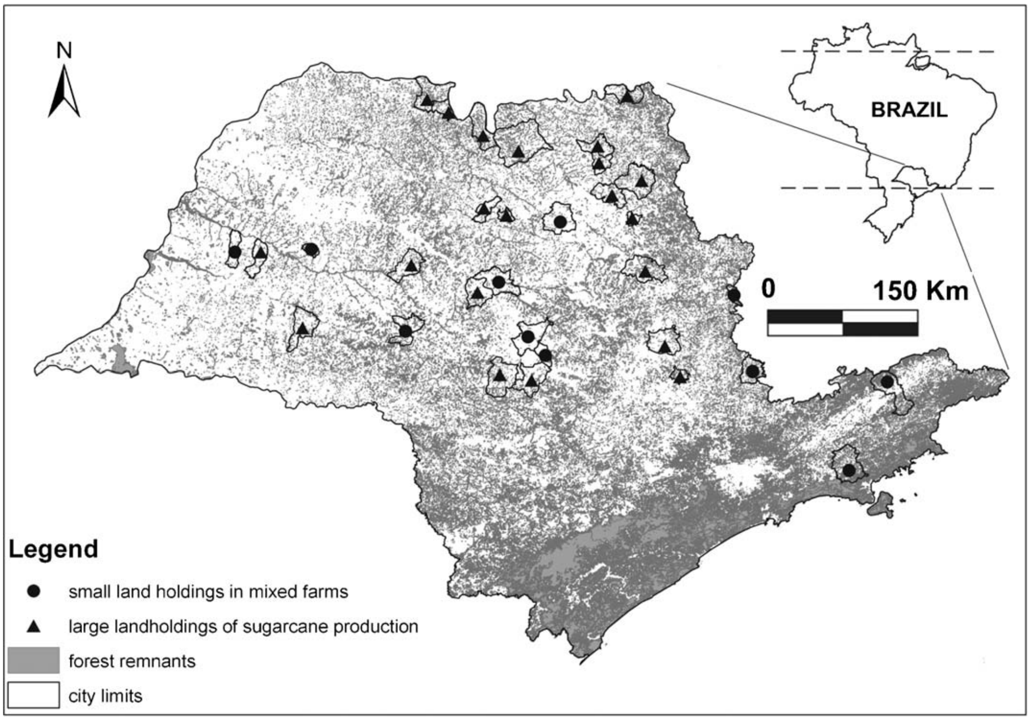

Fig. 1. Location of the projects of ecological restoration under study both on large landholdings devoted to sugarcane production, and on small landholdings in mixed farms, in the state of São Paulo, southeastern Brazil. The map with the remaining forest vegetation in the state was modified from Kronka et al. (2005).

and degraded, in these biomes through fragmentation, overexploitation, logging, fire, cattle foraging, and biological invasions (Durigan et al., 2007; Klink and Machado, 2005; Ribeiro et al., 2009; Tabarelli et al., in press). The complex interactions among endangered biomes, landowners' interests, varying models of agriculture and land tenure, and varying strategies of ecological restoration in human-modified tropical and subtropical landscapes constitute an important challenge for large-scale restoration and maintenance of biodiversity and delivery of ecosystem services.

The data presented here, and the accompanying discussion, are intended to indicate the feasibility of large forest restoration projects focused on reestablishing high-diversity tropical forests using native species only. The projects reported on are all part of the outreach program "Environmental Planning Program of Farms", carried out from 2000 to 2010 by the Laboratório de Ecologia e Restauração Florestal (LERF), Universidade de São Paulo (www.lerf.esalq.usp.br). This program is engaged in planning restoration on private and public lands, and teaching people to run these projects, with the help of graduate and undergraduate students, primarily from agronomy, forestry, biology, and ecology, under the coordination of a senior manager and two professors from the laboratory. However, our lab does not execute them directly; rather this task lies with the landowners themselves.

In order to highlight the possible differences in restoration strategies according to land tenure and land use of rural areas, these projects were grouped in two categories – "large landholdings in sugarcane" (hereafter LLS, or sugarcane farms), and "small landholdings in mixed farms" (hereafter SLMF, or small mixed farms). Considering sugarcane fields, our sample represented 8.8% of the total area occupied by this crop in the state of São Paulo. The average size of the sugarcane farms was 518 ± 453 ha.

3. Decision-making framework

Our approach to large-scale restoration is based on assisting ecological succession which, in general terms, has three basic prerequisites for success in degraded or transformed lands such as those with which we are concerned. These are: (1) the existence of sites with favorable abiotic and biotic conditions for native plant establishment and growth, (2) the spontaneous arrival of new species over time, coupled with the presence of soilborne seed banks of native tree species *in situ*, and (3) the presence of species with differing and complementary ecological behaviors (Pickett and Cadenasso, 1995) . The absence of one or more of these basic conditions represents a barrier to natural succession, which consequently must be overcome through varying restoration methods. In order to investigate these conditions and apply the knowledge generated for development of a large-scale approach, it is necessary to develop an 'Environmental Zoning' strategy through adoption of a two-step diagnostic protocol and choice of restoration procedures. The 'Diagnostics' protocol is used to identify the different barriers to forest succession and, consequently, the requirements for, and suitability of, distinct restoration actions required in the varying types of target areas.

In general, the diagnostic method applied to the described projects was designed to answer the following questions:

- Does the local micro-site provide favorable conditions for native plant establishment and growth? If not, what kinds of actions are needed to overcome the barriers, such as soil or substrate degradation, presence of exotic aggressive grasses, and/or intense herbivory and seed predation?
- What is the potential of autogenic restoration of the target site? In other words, is there a satisfactory soil seed bank, and corresponding cohort of sprouts, seedlings and saplings of native tree and shrub species?
- What kind of life forms (*e.g.*, herbs, shrubs, trees) and successional groups (pioneer or non-pioneer) are present among naturally regenerating plants, and in what relative abundance levels (high, medium, or low)?
- Are there forest fragments of appropriate forest type close enough to the restoration area to contribute to spontaneous forest regeneration through an effective and significant seed rain? The

Table 1
Restoration actions recommended for each environmental situation found in projects of ecological restoration to be carried out in large sugarcane farms and in small mixed farms in the state of São Paulo, southeastern Brazil.

Environmental situations	Restoration methods
(I) Null or very low potential for autogenic restoration	Plantations of several native tree species covering the entire area (1666 seedlings/ha, 3 m × 2 m spacing), equally divided into species from the 'filling group' (fast-growing and wide canopy) and 'diversity group' (slow-growing and/or narrow canopy), according to the method described by Rodrigues et al. (2009). This method is similar to the so-called framework species method of Tucker and Murphy (1997) and Elliott et al. (2003); cf. Florentine and Westbrooke (2004)
(II) Poor potential for autogenic restoration	Active encouragement of natural regeneration by manual or chemical control of invasive grasses, plus plantation of several native tree species from the 'filling group' and 'diversity group', respectively, in the patches without natural regeneration and in the middle of natural regeneration areas (*ca.* 800 seedlings/ha)
(III) Fair potential for autogenic restoration, and presence of many pioneers in the regenerating community	Active encouragement of natural regeneration as described above in 'II', and planting of several native tree species from the 'diversity group' in the middle of natural regeneration areas (*ca.* 200 seedlings/ha). This plantation is mandatory in sites far from any forest fragments, and recommended in non-isolated sites, depending on results of monitoring
(IV) High potential for autogenic restoration	Natural regeneration is promoted to speed up the successional process, as described above in 'II'. In other words, invasive grasses are controlled but no tree planting is carried out, unless spontaneous increase of plant richness has not been observed over time (see item III)
(V) Highly degraded forest fragments	Site-specific management to restore diversity, structure, and functionality of this forest. This kind of fragment requires active control and management of superabundant native lianas and invasive non-native grasses, and supporting actions of various kinds intended to improve autogenic restoration, as described above in 'II', 'III' and 'IV'
(VI) Somewhat degraded forest fragments	Establishment of a protection zone to reduce border effects

classification of these remaining forest patches in terms of their conservation status is also important to estimate their potential to supply a large pool of native species to the restored site.

4. Description of ecological zones and recommended restoration methods

The most important ecological zones for restoration in Brazil are the riparian areas that were designated as permanent preservation areas (PPA) by the Brazilian Forest Code, established in 1965. PPA are land portions that must be set aside with the exclusive goal of conserving biodiversity and ecosystem services for society at large, and cannot be used for direct economic benefit by land owners. The width of the dual riparian corridors established by PPA depends on the width of the water course or size of water reservoirs, and a circular PPA with a radius of 50 m is required around all springs. Since the legislation has not been fully respected, most of the PPAs are now degraded and the majority of ecological restoration activities in Brazil are taking place in these riparian areas.

Based on the environmental situations found in these riparian PPA, and in the answers addressed in our decision-making framework, it was possible to identify, develop, and test the following six restoration methods for the six situations or contexts specified in the environmental zoning plan, as shown in Table 1.

5. Materials and methods

In order to apply the above-described two-step protocol for restoration planning in large agricultural areas, our Environmental Zoning Plan consists of the following steps: (i) photointerpretation of recent aerial photographs (1:25,000–1:30,000), or high resolution satellite images of varying scales, in which the limits of the PPA riparian areas were included in the maps, and their actual occupation was established – pasturelands, highly mechanized farm areas, less intensive agricultural areas, native forests, commercial forests, abandoned areas, anthropogenic wet fields created by siltation of water courses (normally occupied by the invasive cosmopolitan cattail *Typha angustifolia* and the Himalayan white ginger lily *Hedychium coronarium*), and many other categories – not all of which were included in the results presented here; (ii) field verification, in which the map produced by the previous step was checked in the field, and the diagnostic of the potential of autogenic restoration of the area was evaluated. This diagnostic was based on the amount of naturally regenerating native plants, especially trees, in the area, and in the proximity of the restored area from forest fragments (distances higher than 150 m are considered restrictive – Bertoncini and Rodrigues, 2008). Moreover, we also delimitated all the forest fragments inside and outside the riparian areas and determined their conservation status; (iii) correction of the maps based on field checking; (iv) final map construction with specific Geographic Information System software, in which the riparian areas, the different ecological zones present in these areas, and the forest type of each remnant are indicated in the final map by colored legends.

Based on the detailed description of land use and potential of autogenic restoration in riparian areas, and the conservation status of the remaining natural vegetation, the second step, our methods prescription consisted of selecting the most appropriate ecological method to develop a permanent forest under the prevailing socio-economic conditions and constraints in each area. Most of the methods were based on the approach developed by Rodrigues et al. (2009). This consists in organizing species from different successional groups of the target tropical forest into two functional groups for purposes of restoration, namely a 'filling group' (fast-growing and wide canopy species) and a 'diversity group' (slow-growing and/or narrow canopy species). These functional groups are planted in equal proportions, at the same time, in plantings covering the entire area.

The importance to restore degraded forest fragments within private lands is obvious when considering that more than 90% of the remaining fragments of the Atlantic Forest are located on private lands (Ribeiro et al., 2009). These fragments may also constitute an important source of propagules and biota to the neighboring restored sites over time. Therefore, forest restoration can play an important role for conserving biodiversity in human-modified tropical landscapes outside protected areas (Chazdon et al., 2009). The forest fragments on private lands in our study area were classified in two major categories. These were: (i) showing need for restoration when the forest has a discontinuous canopy completely covered by superabundant lianas, the borders heavily colonized by invasive African grasses, *e.g.*, *Brachiaria* spp. and *Panicum maximum*, and the forest core little more than a large and degraded gap also dominated by alien grasses and lianas. In this situation, the forest fragment will clearly not be able to restore itself in less than several decades, and active restoration interventions are needed to speed up the process; and (ii) showing good prospects for autogenic

Table 2
Contribution of different types of occupation of riparian areas (*sensu* permanent preservation areas according to the Brazilian forest code) in projects of ecological restoration carried out in large sugarcane farms (21 projects – total area 483,198 ha) and in small mixed farms[a] (11 projects – total area 44,784 ha) in the state of São Paulo, southeastern Brazil.

Land use	Large sugarcane farms		Small mixed farms		Z	P
	%-Mean ± standard deviation	Total area (ha)	%-Mean ± standard deviation	Total area (ha)		
Native vegetation	36.9 ± 16.7	15,073	18.3 ± 12.6	1150	2.9	<0.01
Highly mechanized agriculture	10.5 ± 4.9	5133	0.1 ± 0.2	0.79	4.3	<0.01
Low or non-mechanized agriculture	0.36 ± 0.5	164	15.3 ± 22.3	1256	4.5	<0.01
Pasturelands with low or null potential of autogenic restoration	11.6 ± 11.2	4251	38.6 ± 21.6	2930	3.1	<0.01
Pasturelands with adequate potential of autogenic restoration	0.9 ± 0.9	240	3.2 ± 4.2	317	1.2	0.21
Abandoned areas with low or null potential for autogenic restoration	10.4 ± 7.4	4401	4.0 ± 6.0	162	2.2	0.02
Abandoned areas with adequate potential for autogenic restoration	2.1 ± 2.9	1115	1.5 ± 1.0	72	0.2	0.81
Commercial reforestation with low or null potential for autogenic restoration	0.5 ± 0.9	209	1.6 ± 1.6	151	1.9	0.05
Commercial reforestation with adequate potential for autogenic restoration	0.2 ± 0.4	85	0.7 ± 1.2	31	0.8	0.39
Anthropogenic wet fields created by siltation of water courses	21.3 ± 13.7	10,478	11.9 ± 13.2	750	1.7	0.08
Exposed soils	0.1 ± 0.5	24	0.2 ± 0.3	17	0.2	0.82
Other situations	5.2 ± 4.5	2452	4.5 ± 3.4	277	0.2	0.85
Total	100.0	43,625	100.0	5.963		

[a] *Z* and *P* values for comparison of means in a row were obtained with the Mann–Whitney test.

restoration, when forest canopy is continuous, aggressive lianas do not cover most of the tree crown, epiphytes are present, and the forest core still stands with the understorey shaded and ongoing recolonization by various native species of trees and shrubs taking place.

Finally, the floristic composition of the forest fragments was investigated to select the appropriate species to be used in restoration actions. In our floristic surveys, we used a method adapted from Ratter et al. (2000), in which the occurrence of tree and shrub species is evaluated in random walks of 15 min each. The sampling process is considered adequate when, in two consecutive intervals of 15 min each, no more than two new species are added to the list. Moreover, a bibliographic survey is carried out to complete the list of native species, eventually including species that have been driven locally extinct as a result of overexploitation or habitat degradation.

6. Data analysis

Each project considered in this work included dozens to hundreds of farms (81 ± 86 farms, $x \pm 1$SD). The results obtained in the environmental zoning and planning of different farms from a given project were then merged into a single dataset (as if the several farms of the project were part of a single farm), in such a way that each project was used as a replicate in the analysis to compare LLS and SLMF (treatments). A total of 21 projects in LLS (483,198 ha) and 11 projects in SLMF (44,784 ha) were analyzed. We used the Mann–Whitney test (Zar, 1984) to compare, between LLS and SLMF, the contribution of riparian areas in the total area of the project, the current occupation of these areas, the degradation status of the remaining forest fragments, and the relative importance of each prescribed method of ecological restoration.

7. Results

The environmental zoning showed that SLMF had higher portions of land that should be protected as PPA riparian areas (13.31 ± 4.13%, $x \pm 1$SD) than LLS (10.02 ± 2.94%) (Mann–Whitney test: $Z = 2.15$, $P = 0.03$). The methods used in the environmental zoning revealed that many situations could be observed in riparian areas in both land tenure categories, but that SLMF had a different pattern of riparian areas use than LLS. Large sugarcane farms had higher portions of riparian areas occupied by highly mechanized agriculture, abandoned fields and anthropogenic wet fields created by siltation, while in small mixed farms there was a predominance of low or non-mechanized agriculture and pasturelands (Table 2).

Reduced natural vegetation cover outside riparian areas was observed for both SLMF and LLS (Table 3). Additionally, most of the remaining forest patches were somewhat degraded, and consequently required active management actions and restoration-oriented interventions (Table 3). Despite this critical situation for biodiversity conservation, the remaining forest patches consistently showed high floristic richness in LLS (Table 4).

Despite differences in riparian use and occupation, reforestation with native species was by far the main restoration method indicated for both large sugarcane farms (76.0%) and small mixed farms (92.4%), in view of the low resilience of forests in the target areas. In other words, reduced forest cover, and a high degree of fragmentation, limited the potential for autogenic restoration through application of other, less costly methods (Table 5). To restore those areas where reforestation would not be necessary, *i.e.* forest remnants and areas with some degree of natural regeneration, a different set of methods was indicated (Table 5).

Table 3
Percentage of area cover by riparian and non-riparian native forests, as well the degradation level of the forest fragments, in projects of ecological restoration carried out in large sugarcane farms (21 projects – total area 483,198 ha) and in small mixed farms[a] (11 projects – total area 44,784 ha) in the state of São Paulo, southeastern Brazil.

Types of forests and degradation level of fragments	Large sugarcane farms		Small mixed farms		Z	P
	%-Mean ± standard deviation	Total area (ha)	%-Mean ± standard deviation	Total area (ha)		
Riparian forests	3.5 ± 1.9	14,352	2.9 ± 1.8	1228	1.0	0.32
Non-riparian forests	4.3 ± 2.6	20,825	6.0 ± 5.4	2790	0.3	0.72
Total forest cover	7.9 ± 3.3	35,176	8.9 ± 6.7	4018	0.2	0.79
Forest fragments with need for restoration (highly degraded)	2.0 ± 5.1	6091	1.8 ± 2.4	1003	0.5	0.60
Forest fragments with possibility of restoration (somewhat degraded)	6.5 ± 5.1	29,085	7.1 ± 6.9	3015	0.6	0.52

[a] *Z* and *P* values for comparison of means in a row were obtained with the Mann–Whitney test.

Table 4
Plant richness of tree and shrub species found in fragments of different forest types included in large sugarcane farms (21 projects – total area 483,198 ha) in the state of São Paulo, southeastern Brazil. The number of species shown for each forest type was obtained by primary data.

Forest type	Number of species	
	Mean	SD
Cerrado	152.4	63.6
Seasonal semideciduous forest	169.3	104.1
Seasonal deciduous forest	23.4	19.6
Riparian forest	65.0	45.5
Swamp forest	39.6	31.4
Plant richness from primary data	242.0	57.3
Plant richness from secondary data	269.0	96.0
Total plant richness (primary data merged to secondary data)	349.5	158.1

8. Discussion

To achieve large-scale restoration of tropical forests, we first need to know what should be restored (*i.e.* which forest types and species pool), where restoration will take place, and how it will be carried out. The proposed Program of Restoration can contribute to answer these questions, and to establish a plan of action to put the program into practice. This plan of action will include purchase or production of seeds and seedlings, organization of community groups or hiring private restoration companies to implant restoration, the quantification of costs involved in the process and, above all, the definition of strategies to work with different types of land use and socio-economic contexts. If different reasons motivate landowners to restore degraded portions of their farms, it is important to know how much productive area will be set aside for restoration and how much financial capital will be required. This organizational approach may be key to move restoration efforts from local to regional scales. In general, the proposed method of environmental zoning has proven to be adequate for choosing appropriate methods of ecological restoration to each site-specific situation, both within large and small landholdings (see Table 5).

This environmental diagnostic procedure described here may also help identify the sources of anthropogenic impacts over riparian areas. For instance, increased occupation of riparian areas in LLS with mechanized agriculture for production of sugarcane may lead to increased erosion and, consequently, to the expansion of anthropogenic wet fields created by siltation (see Table 2), while riparian areas of SLMF were predominantly occupied by non-mechanized agriculture and pasturelands, with just a small number of abandoned areas. The higher proportion of abandoned areas in the LLS was probably due to the higher pressure applied by law enforcement for legislation compliance in this agricultural sector than in the SLMF, which in turn resulted in the abandonment of riparian areas after sugarcane harvest.

Although a range of ecological restoration methods had been envisaged, reforestation was by far the main restoration method required both on LLS (76.0%) and SLMF (92.4%). Indeed, the forest cover of LLS and SLMF was, respectively, 7.87% and 8.89% (Table 3), and most of these remnants were somewhat degraded (Table 5), while the mean forest cover of the municipalities where LLS and SLMF projects were inserted was 7.5% and 13.1%, respectively (SIFESP, 2010). In such unfavorable conditions for tropical forest restoration, active restoration is needed to restore a tropical forest in a presently degraded area, and different restoration methods have been proposed for it.

Several researchers have shown that a diverse understorey of native species can develop under the canopy of pure tree plantations in tropical areas (*e.g.*, Barbosa et al., 2009a; Butler et al., 2007; Lamb, 1998, and references therein), which indicates that this type of reforestation can be used to catalyze secondary succession in degraded areas. However, context is everything. In highly fragmented forest landscapes, where propagules of the plant species still present in the scarce, degraded forest patches are not dispersed into the sites to be restored, single species or low diversity tree plantations will certainly not be sufficient to catalyze forest restoration (Kanowski et al., 2003; Larjavaara, 2008). The general absence of fauna in these areas further aggravates the problem (Silva and Tabarelli, 2000).

These limitations for tropical forest restoration have been observed in different regions throughout South and Central America. For instance, seed availability has proved to be an important limiting factor for tropical forest recovery and succession on abandoned pastures in Costa Rica (Holl, 1999; Wijdeven and Kuzee, 2000), Puerto Rico (Zimmerman et al., 2000), Colombia (Aide and Cavalier, 1994), Panama (Hooper et al., 2005a), and Brazil (Nepstad et al., 1990). To overcome this limitation, human assistance is now required to recover forest structure, species composition, and species interactions typical of mature tropical forests worldwide (Chazdon, 2003). In one study, in Veracruz, Mexico, the manual introduction of propagules of native species was recommended to accelerate forest restoration (Muñiz-Castro et al., 2006).

Table 5
Prescribed methods of ecological restoration for each situation found in the environmental zoning of projects of ecological restoration carried out in large sugarcane farms (21 projects – total area 483,198 ha) and in small mixed farms[a] (11 projects – total area 44,784 ha) in the state of São Paulo, southeastern Brazil. (I) Plantations of fast-growing, middle and late successional native tree species covering the entire area (1666 seedlings/ha, 3 m × 2 m spacing); (II) active encouragement of natural regeneration, plus plantation of early and middle/late successional native tree species, respectively, in the patches without natural regeneration and in the middle of natural regeneration areas (ca. 800 seedlings/ha); (III) active encouragement of natural regeneration, and planting of several middle and late successional native tree species in the middle of natural regeneration areas (ca. 200 seedlings/ha); (IV) only active encouragement of natural regeneration; (V) site-specific management of highly degraded forest fragments; and (VI) implantation of a protection zone to reduce border effects. In all situations, the removal of degrading factors is mandatory before applying the described methods of ecological restoration.

Ecological restoration method	Large sugarcane farms		Small mixed farms		*Z*	*P*
	%-Mean ± standard deviation	Total area (ha)	%-Mean ± standard deviation	Total area (ha)		
Riparian areas not covered with native forest						
I	76.0 ± 20.5	14,290	92.4 ± 6.5	3549	2.0	0.05
II	14.8 ± 13.1	4560	6.8 ± 5.7	292	1.8	0.07
III	5.2 ± 7.3	1032	0.0 ± 0.0	0	2.6	<0.01
IV	4.0 ± 10.1	790	0.8 ± 2.6	6	0.3	0.76
Total	100.0	20,672	100.0	3847		
Native forests in general (inside and outside riparian areas)						
V	22.2 ± 30.4	6091	20.0 ± 25.5	1003	0.3	0.72
VI	77.7 ± 30.0	29,085	80.0 ± 25.5	3015	0.5	0.59
Total	100.0	35,176	100.0	4018		

[a] *Z* and *P* values for comparison of means in a row were obtained with the Mann–Whitney test.

Another approach to restoring high-diversity tropical forests in a degraded area with low or nil levels of potential seed dispersal, and low overall resilience, is to reforest from the outset using a large pool of native species. In this approach, the composition and functioning of restored forests will largely depend on what is planted, as observed in old reforestations from São Paulo state (Bertoncini and Rodrigues, 2008; Rodrigues et al., 2009; Souza and Batista, 2004). However, once the planted species reach reproductive age, they contribute with 'internal' seed dispersal and spontaneous regeneration at restored site commences, even if few propagules from the neighboring forests reach the area.

More than just supplying seeds to assist secondary succession, high-diversity reforestations have several other advantages for tropical forest restoration as well (Larjavaara, 2008). Basically, restored forests with high tree diversity are desirable: (1) to increase resource supply for frugivores, pollinators, and herbivores (Bascompte et al., 2006; Janzen, 1970; Vehviläinen et al., 2007; Wunderle, 1997); (2) to create niche diversity for understorey regeneration of trees and establishment of other plant life forms, such as epiphytes and lianas (Gandolfi et al., 2007; Kanowski et al., 2003; Nicotra et al., 1999; Muñoz et al., 2003); (3) to increase micro-organism abundance and diversity (Lambais et al., 2006; Mitchell et al., 2010); (4) to favor the functional connectivity of the landscape, since the presence of several species typical of mature forest may facilitate biological fluxes (Tabarelli et al., in press); (5) to stimulate the use of endangered species in restoration actions; (6) to constitute a kind of 'ecological insurance' against unpredictable anthropogenic and human-mediated disturbances, including violent storms and climate change (Larjavaara, 2008; Loreau et al., 2001); (7) to reduce the synchronicity of canopy trees death, which is necessary to avoid understorey invasion by aggressive grasses (Rodrigues et al., 2009); and, finally, to optimize ecosystem functioning as the restored forest matures (Chase, 2010; Hooper et al., 2005b; Loreau et al., 2001; Wright et al., 2009).

This approach of high-diversity reforestation as a means of ecological restoration fits well within the – biodiversity – ecosystem functioning framework to restoration science proposed by Wright et al. (2009). Our results show that it is possible – but not necessarily easy – to plan for restoration of biodiversity *and* ecosystem services in the highly human-modified landscapes of the Brazilian Atlantic Forest biome (Rodrigues et al., 2009; Wuethrich, 2007). Moreover, the use of low or high-diversity reforestations will not affect cost because seedling price do not vary among species in the nurseries present in the biome.

The costs involved in the implementation of the restoration projects described in this work can shed light on the economics of large-scale restoration in our study area at the present time. Considering the number of seedlings required by each method of restoration described here (see Table 1), and the total area to be restored by these methods in the projects under evaluation (see Table 5), approximately 34 million seedlings of native species will be required just to restore riparian areas. Considering that average seedling price is US$0.45 per unit ($1.00 = R$1.82 in June 2010) in the nurseries of São Paulo state, seedling acquisition would cost approximately $15 million. The cost to plant and take care of each seedling for two years in the field is estimated at $3, which results in an additional cost of $102 million to implement restoration, totaling $117 million. Up-scaling to the whole biome, the Atlantic Forest Restoration Pact should estimate to invest between $49 billion ($3315 per ha) and $77 billion ($5216 per ha), to restore 15 millions ha over 41 years (Calmon et al., 2009). The wide range of estimated cost is related to the options available for carrying out the operations, *i.e.* hiring regional community-based services will be less expensive than hiring private restoration companies. Although the estimated cost is thus quite high, it will be distributed over time and there could and should be opportunities to offset these costs through carbon offsets, biodiversity banking, habitat banking, REDD+ payments, and payments for ecosystem services in general. Additionally, the Atlantic Forest Restoration Pact aims to amortize part of these expenses by carrying out high-diversity reforestations for timber and non-timber forest products exploitation in areas not suitable for agriculture, which are currently occupied by low-yielding pastures on steep slopes (Preiskorn et al., 2009). Economic analysis of these reforestations has show the possibility to earn at least $265 ha/year using only native timber species, considering the conservative prices prevailing today, no additional value of certification, and no wood processing (Fasiaben, 2010). This is more than twice the amount that farmers are currently earning through cattle ranching in these degraded areas, though other economic incentives will be necessary given that farmers must wait 10–15 years until the first harvest of timber.

9. Policy implications of the data collected in the field

In the projects under investigation, there were two main motivations for ecological restoration, namely market requirements associated with mandatory compliance with legislation, and voluntary government programs providing incentives as a means of orientation and encouragement of ecological restoration on private lands. The market requirement results primarily from the need for environmental certification of the production process to increase access to foreign markets. In the last 10 years, the main demand for restoration efforts in LLS was the need of environmental certification of the means of production, especially of sugar. On the other hand, SLMF did not follow this market trend, but were supported instead by the state environmental secretariat in the process of organizing land use and implementing restoration.

However, independently of the above-described situation, the important role of, and need for, well-established and conservationist legislation is undeniable, *e.g.*, The Brazilian Forest Code. The integration of ecological restoration within the context of environmental certification is an important strategy in large landholdings of monoculture-based and export-oriented agro-industry companies. Concurrently, government must support ecological restoration efforts in the SLMF, which do not operate in the same market context as the LLS. Other motivations, such as payment for ecosystem services (Wunder, 2006) and agro-forestry systems with native tree species (Schroth et al., 2004) may also help provide economic incentives and rewards for small landowners who are obliged to invest in restoration on portions of their land.

The need for a different approach to ecological restoration in small farms is also reinforced by the larger portions of riparian areas occurring there than on the much larger sugarcane farms. Most flat and therefore attractive areas for intensive agriculture have historically been acquired by large agro-industry companies and wealthy farmers, and only areas considered marginal or unsuitable for mechanized agriculture have remained available for SLMF. This implies that different strategies of ecological restoration are needed to reconcile restoration to the socio-economic interests of small farmers (Lamb et al., 2005). Moreover, outreach programs of the state secretariat of agriculture would be important to compensate the production previously obtained in riparian areas by higher productivity in other areas suitable for agriculture. The lower proportion of riparian forests in SLMF may also be an indirect result of the low income of farmers, which tends to stimulate intentional deforestation in order to expand production areas as an attempt to increase income. Therefore, farmers' subsistence can and should be integrated with forest conservation and restoration goals in order to reduce deforestation and degradation of natural forest remnants (Knoke et al., 2009; Lamb et al., 2005).

The implementation of large-scale high-diversity restoration through the proposed plan of action will require the involvement of professionals and private companies from different professional areas – from seed harvesting to restoration monitoring – and their progressive integration into the rapidly emerging market for restoration services. This underlines the importance of on-the-job training and capacity-building to help meet the growing demand for workers and professionals. This is an aspect that will certainly have key importance in the future for the success of putting restoration in practice, especially at large scales (Clewell and Aronson, 2007). Additionally, we need urgent research advances to improve forest restoration in developing countries, where most of the world's biodiversity is concentrated, but only a tiny portion of research on restoration ecology has been carried out to date (Aronson et al., 2010).

To illustrate how public policies can induce biodiversity reestablishment through restoration efforts integrated with the market, the state of São Paulo has created legislation to guide ecological restoration. Amongst different recommendations to support the creation of high-diversity, and self-perpetuating restored forests, this legislation established the need to reach a minimum of 80 tree/shrub species at the end of the restoration process when the goal is to restore originally high-diversity forests, where 80 species represent less than half of richness found in conserved forests. This legislation and the increasing demand for ecological restoration in the state of São Paulo resulted in the creation of a prominent market for ecological restoration practitioners and providers of nursery stock of native trees. Literally thousands of professionals are currently involved in furnishing these services in the state today. This can be appreciated when analyzing the production of seedlings of native species to be used in ecological restoration projects. The production of seedlings of native tree species in 2003, when the effects of the above-mentioned legislation started to be observed, reached 13,000,000 seedlings in 55 nurseries, primarily from a mere 30 species. In 2008, production attained 33,000,000 seedlings in 114 nurseries, from more than 80 species in most of the nurseries involved in this emerging service industry (Barbosa et al., 2009b). It is important to highlight that the cost of seedlings do not differ among species, so that there is no plausible justification nowadays to avoid using high-diversity of native species while restoring the Atlantic Forest in São Paulo state (Brancalion et al., 2010)

There is of course discussion and controversy on this topic (see Durigan et al., 2010). But as noted above, the larger economic issues, including government incentives and national and international opportunities for payments for biodiversity protection and enhancement of ecosystem services provided by restored tropical ecosystems need to be clarified before coming to final conclusions about how to move forward with the planned restoration of 15 million ha of the Atlantic Forest. Yet the organizers and members of the Pact are determined to move ahead.

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