



On the restoration of high diversity forests: 30 years of experience in the Brazilian Atlantic Forest

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ARTICLE INFO

Article history:

Received 15 September 2008

Received in revised form 1 December 2008

Accepted 7 December 2008

Available online 20 January 2009

Keywords:

Biodiversity conservation

Brazil

Public policies

Restoration practices

ABSTRACT

We present a review of more than 30 years of ecological restoration in the Brazilian part of the Atlantic Forest. Based on what has been done in this biome, we try to summarize the main findings and challenges for restoration in this highly threatened forest biome. We found that many past experiences did not result in self-perpetuating forests, for different reasons. Currently, most projects aim to construct self-sustaining communities and no longer see restoration as a deterministic process. We also found that the reconstruction of permanent forest with high diversity is feasible but it depends on the strategies applied and on the surrounding landscape. Although many new techniques have been created (e.g. seed rain management or promotion of natural regeneration), the most used one in the Atlantic Forest is still the planting of many native species from different functional groups. Native species are largely used and perform well even in highly disturbed environments. Today, many projects are trying to produce thousands of hectares of permanent forests and many technical advances are about to be incorporated. But restoration also faces some main challenges to become an effective and widespread means of conserving the Atlantic Forest which are, namely, reducing costs, planning restoration actions at landscape-level, and conforming to socio-political issues. The socio-political tools to overcome such barriers in practice have yet to be developed.

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1. The Brazilian Atlantic Forest: from deforestation to ecological restoration

Deforestation and forest degradation began 20,000 years ago and still persist in modern days (Brown and Brown, 1992; FAO, 2005). This has been no different in Brazil, where intense forest degradation started more than 500 years ago (Dean, 1995). The Atlantic Forest was the first biome to be affected and by the end of the last century, it had practically vanished. Only ca. 12% of the original extension remains (Ribeiro et al., 2009) and most of it corresponds to small, isolated, unprotected and/or severely altered forest fragments (Fonseca, 1985; Silva and Tabarelli, 2000). The high endemism level of the Atlantic Forest (fourth hottest biodiversity hotspot – Myers et al., 2000) suggests that many species have become extinct and that others will also meet the same fate owed to intense fragmentation (Whitmore and Sayer, 1992; Brooks and Balmford, 1996; Metzger et al., 2009).

But, there has been an increase in initiatives to lessen human damage, such as, ecological restoration (i.e. the process of assisting the recovery of ecosystems – SER, 2004), a main alternative to safe-

guard natural resources and to conserve biodiversity (Dobson et al., 1997; Young, 2000; Lamb et al., 2005). Restoration has, in some way, been practiced for centuries but only recently has it started to receive society's attention and the scientific support of a young discipline, restoration ecology (Cairns and Heckman, 1996; Palmer et al., 2006; Young et al., 2005). It takes place when the ecosystem fails to naturally recover from disturbances or when this process may take over centuries to occur (Parrotta et al., 1997; Chazdon, 2003; Martínez-Garza and Howe, 2003). Since its onset, restoration practice has greatly evolved from non-scientific, trial-and-error, forest plantations to projects based on many ecological concepts and theories that are now being put to the test (Palmer et al., 1997; Young et al., 2005). There has also been a great development of restoration techniques (Ashton et al., 2001; Mansourian et al., 2005). Today, more and more restoration projects are conducted worldwide (Sayer et al., 2004; Ruiz-Jaen and Aide, 2005) and specialized journals were created to publish the increasing amount of information produced.

However, there is still a lot of work to do, especially with regard to the development of a stronger theoretical base for ecological restoration (Palmer et al., 2006), although this is not always as easy as it seems. Restoration takes time, costs of monitoring are high, and the success of its methods is often hard to assess (Parker, 1997; White and Walker, 1997; Ruiz-Jaen and Aide, 2005). On

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the other hand, there are few well-designed projects that are old enough to support the needed fine-tuning between ecological theory, and restoration practice (Temperton, 2007; Weiher, 2007). Therefore, some important questions are still waiting for answers (Ehrenfeld and Toth, 1997; Palmer et al., 1997; Young et al., 2005) and among other forest sites the Brazilian Atlantic Forest represents a challenging opportunity for finding some of these answers. The most consistent definition available for the Atlantic Forest includes formations from lowland rain forests to mixed *Araucaria* forests (Oliveira-Filho and Fontes, 2000; Scarano, 2009). The use of this definition leads us to a huge challenge: restore forests spread over 1.5 million km², from the Equator to latitudes below 24°S (Morellato and Haddad, 2000).

In such a large area, great human, physical and biological complexity is inevitable. Over 110 millions of Brazilians live in more than 3000 centres built along the Atlantic Forest, ranging from small villages with simple socio-economical structures to some of the main conurbations of the world. Legal and cultural aspects related to the use and dependence on forests also vary from one region to the other (Young, 2003; Hobley, 2005). Consequently, a myriad of landscape contexts was created with different levels of forest fragmentation around the country (Morellato and Haddad, 2000). The physical environment is just as variable. Each region has its own peculiarities of climatic regime, geology, soils and topography. Consequently, there is great floristic segregation among Atlantic Forest formations (Oliveira-Filho and Fontes, 2000) that frequently have high species diversity and endemism levels (e.g. Martini et al., 2007).

Basic knowledge on forest composition, structure and dynamics, crucial to furnish conceptual guidelines for their restoration, is still limited for many Atlantic Forest formations (Morellato and Haddad, 2000; Gandolfi et al., 2007b). As with other highly diverse systems, the Atlantic Forest has enormous functional diversity (related to species reproductive biology, herbivory, competition and pathogen activity) which is extremely hard to manage or restore. Moreover, local socio-political issues greatly increase the complexity of any restoration project because they are related to the causes of degradation, and to the success of restoration at the same time (Silva and Tabarelli, 2000; Sayer et al., 2004; Hobley, 2005; Wuethrich, 2007).

For these reasons, the restoration of the Atlantic Forest was, for decades, considered an impossible task (Dean, 1995). Nevertheless, projects in the Atlantic Forest have started to develop in number, concepts and methods. Following the development of restoration worldwide, the increasing ecological knowledge of the Atlantic Forest and the results of past initiatives have deeply contributed to this development. Some of these projects have been more or less successful; however, many of these results have not been properly published or have not been published at all, making any synthesis difficult. Thus, our aim here is to review the practice of ecological restoration in the Brazilian Atlantic Forest. From different sources of information, we try to summarize the main results from past and recent restoration experiences. We consider historical features and conceptual issues in the attempt to enlighten the following questions: What has already been done? What went right and what went wrong? Are there any apparent determinants of success or failure? What is left to be improved? A practical example is used to illustrate how restoration is currently being done, and how practices have evolved to solve particular cases. Finally, we try to identify the main lessons, and the future challenges for the practice of restoration in the Brazilian Atlantic Forest.

2. Brief history of Atlantic Forest restoration: evolution of concepts, aims and methods

Concern about the intense deforestation of the Atlantic Forest already existed at the beginning of the 19th century (Dean,

1995), because of the first shortages in natural resources, agricultural plagues, and climatic changes. During this period the city of Rio de Janeiro was undergoing a serious crisis in water supply related to the conversion of forested areas to coffee plantations. To fight this crisis, the emperor of Brazil ordered what would become the first forest restoration project, at least in the tropics (Corlett, 1999): between 1862 and 1892, thousands of seedlings of native and exotic species were planted on the hills surrounding the city (area that today corresponds to the Tijuca National Park and Rio de Janeiro Botanical Garden – Atala et al., 1966).

Various restoration projects were conducted in the Atlantic Forest since this pioneer initiative. During this period, ecological restoration showed great evolution internationally (White and Walker, 1997; Young et al., 2005; Chazdon, 2008). The goals of restoration projects changed, new techniques were developed based on the available ecological theory and monitoring furnished new insights on the best practices in restoration. The restoration in the Atlantic Forest experienced a quite similar process. Therefore, it is possible to recognize phases of evolution in the restoration process that, although arbitrarily defined, are a useful simplification to understand this evolution. Often, ideas were conceived in one phase but were only incorporated as practices later on. Thus, a proposal for dividing the restoration process into phases is presented for the Brazilian Atlantic Forest, and may also be useful to understand the evolution of ecological restoration in an international perspective.

Phase 1 (until 1982) – Corresponds to the first restoration projects, so-called protection plantings, because of their intent to protect water, and soil resources rather than forest biodiversity (see examples in Kageyama and Castro, 1989). As cited above, this phase started in 1862 but became more pronounced after the 1970s. At first, mixed plantations without any experimental purposes did not allow any inferences to be drawn about species and techniques used. Only at the end of the 1970s, restoration ecology started to emerge as a formal line of research, with the first data on the performance of tree species and restoration models (e.g. Gurgel-Filho et al., 1982; Nogueira et al., 1982, 1983). Mainly conducted by government institutions, these first attempts were restricted to exotic (mainly *Pinus* and *Eucalyptus*) and native tree planting, pure or mixed (generally with low diversity), aiming to recreate a forest physiognomy, as inexpensively as possible, using traditional silvicultural practices. Ecological processes responsible for forest maintenance were largely ignored, and criteria for the selection of species were not established yet. Therefore, although some projects did result in permanent forests (e.g. Nogueira, 1977; Mariano et al., 1982; Fig. 1a), they often required long term maintenance activities (10–15 year), and greatly increased costs.

Phase 2 (1982–1985) – From this phase on, the planting of Brazilian native species became widespread, even though they were not always regionally native from the restored area. This phase marked the start of the incorporation of the increasing ecological knowledge on natural forest succession into restoration projects that selected and distributed species according to their ecological groups (*sensu* Budowski, 1965). But their main motivation was to rapidly recreate a forest structure with smaller maintenance costs. Very little was known on the majority of native species and their availability in nurseries was very low. Hence, projects started to use a small number of fast-growing species (maximum 30 species) planted in high density (low biological and functional diversity). The result was the reconstruction of forest physiognomies with lower costs but generally without any capacity of self-perpetuation. Pioneer species reached adult age and died quickly leaving allowing few time and non-favourable conditions for non-pioneer species establishment. So, many of these projects declined after 10–15 years (Fig. 1b, Barbosa et al., 2003). This phase also represented the beginning of large scale

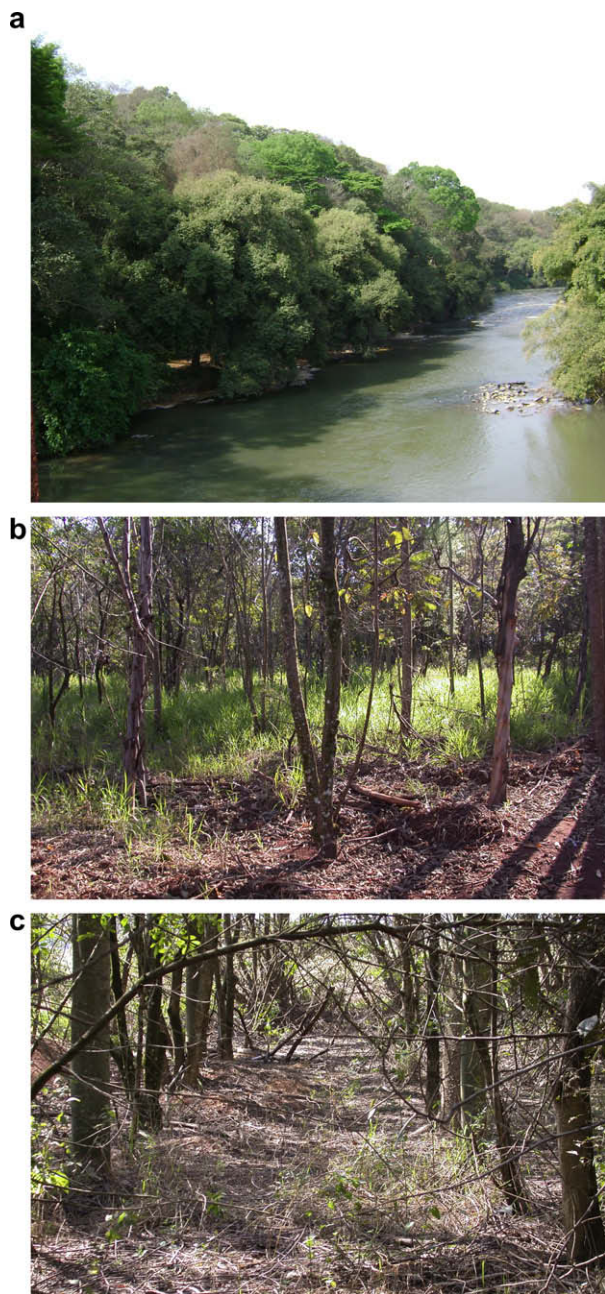


Fig. 1. Differences in results of restoration projects carried out in the Atlantic Forest, south-eastern Brazil: (a) 50-year-old example of a costly but highly succeeded riverine forest restoration initiative using native and exotic seedlings; (b) 7-year initiative using only pioneer species in high densities, suffering from weed invasion and lack of natural regeneration after the senescence of planted canopy individuals; and (c) a project of approximately 5-years old showing good and increasing canopy cover but little natural regeneration related to poor landscape context.

restoration projects, mainly surrounding dams of hydroelectric stations or for water supply.

Phase 3 (1985–2000) – Ecological studies on the Atlantic Forest during this period were generally only phytosociological descriptions of different forest types. Despite the existing knowledge of some forest processes (e.g. gap dynamics), these descriptions were the only ecological data available for Atlantic Forest restorationists and, therefore, nearby fragments started to be used as restoration targets (Joly et al., 2000; Rodrigues and Gandolfi, 1996). Thus, by the end of the 1980s, projects were carried out using ‘restoration recipes’: establishing mixed native species plantations that tried

to copy the composition and structure of natural forests. The most commonly used systems during this period, known as ‘modules of planting’, combined and distributed species according to their ecological groups into contiguous, fixed-area, modules of planting. As a positive consequence, restoration started to use higher species diversity (up to 140 species; see Vieira and Gandolfi, 2006), and to be seen not only as a way to guard ecosystem services but also as an alternative to *in situ* biodiversity conservation (Kageyama and Castro, 1989). In contrast to the results obtained in the previous phase, many projects carried out in this phase resulted in self-sustainability, at least regarding forest structure (Souza and Batista, 2004; Damasceno, 2005; Fig. 1c). The introduction of higher functional diversity, mainly in respect to species ecological groups and longevity, was an important change to enhance restoration success. However, the low availability of seedlings of regionally native species was still a hindrance to many projects. Riparian forest formations received special attention (Rodrigues and Gandolfi, 2000) and for the first time genetic issues started to be considered although not yet applied (Kageyama and Castro, 1986, 1989).

Phase 4 (2000–2003) – This phase brought important changes in the objectives of restoration that no longer aimed to ‘copy’ natural forests which experience had shown was a costly practice. There was still the concern with high species diversity, local floristics and species light requirements. However, the main focus was to restore the basic ecological processes of the forest by the stimulation and acceleration of natural succession, aiming to recover the forest ability to self-maintain. Thus, restoration was now seen as a non-deterministic process open to stochastic events that may not lead to a single pre-defined climax (Pickett et al., 1987; Parker and Pickett, 1999; Pickett and Cadenasso, 2005). Disturbances were incorporated as part of the process and phytosociology received little attention during species selection, which started to be influenced more by the increasing knowledge on the biology of species (e.g. dispersal syndrome and pollination system). High diversity (e.g. 80–90 tree species) was used to supposedly guarantee the restoration of some ecological processes, and was obtained through planting and/or alternative models used according to the condition of the area to be restored (Engel and Parrotta, 2001; Reis et al., 2003). Monitoring results of projects in this phase are presented below.

Phase 5 (2003 until today) – This phase comprises the current effort to fit in floristic and intraspecific genetic diversity that are key elements for the maintenance and evolution of any forest systems (Lesica and Allendorf, 1999). There is more care with seed origin and collection that is carried out as locally as possible (McKay et al., 2005). In some cases, seeds are collected in nearby forests and cultivated in local nurseries. Another strategy is to take advantage of the pre-existing genetic diversity by the management of pre-existing natural regeneration, such as soil seed banks and/or seedling transplantation (Rodrigues and Gandolfi 2000; Reis et al., 2003; Viani et al., 2007). The maintenance of this diversity in time is now considered in the spatial distribution of species, that try to respect their specifications on pollination and dispersal (Barbosa and Pizo, 2006; Castro et al., 2007). However, data on the reproductive biology of many native species are largely missing.

3. The use of ecological processes as restoration practices

There is a considerable amount of information and theories on the ecology, and succession of tropical forests. As reviewed elsewhere (Palmer et al., 1997; Parker and Pickett, 1999; Temperton and Hobbs, 2004; Young et al., 2005), many theories have direct or indirect influence on restoration practices. As a consequence, restoration practice has greatly developed conceptually and nowadays, there are many different approaches, and techniques

available (Mansourian et al., 2005). To illustrate how this practice has developed in the Brazilian Atlantic Forest, we present examples of projects conducted in the Brazilian part of this biome, mostly by the Laboratório de Ecologia e Restauração Florestal (LERF – www.lerf.esalq.usp.br) at the Universidade de São Paulo, some of them currently being monitored.

From various experiences since 1988 we have learned that restoration is the process of promoting or accelerating the recover of communities through direct and/or indirect actions, currently conducted based on three main principles (Rodrigues and Gandolfi, 2007): (i) reconstruct species-rich functional communities capable of evolving; (ii) stimulate any potential for self-recovery still present in the area (resilience) whenever this is possible; and (iii) plan restoration actions in a landscape perspective. Within these principles, projects generally have the following site-level goals: remove or minimize human impact; create or protect a forest structure capable of providing permanent shade; keep or increase the number of woody species, and favour the invasion of other life forms; provide shelter and food to permanently retain the local fauna; and manage invasive exotic species (e.g. *Brachiaria* spp., *Leucaena leucocephala*, and *Tecoma stans*).

However, it is not easy to start any on-the-ground project from scratch nor is it straightforward to decide the best restoration strategy for a particular area. In practice, there will always be one or more suitable strategies for each specific situation as each area has its own disturbance history, degree of resilience, reference information, and surrounding landscape, as well as the applicable legal and socio-economic background (White and Walker, 1997; Holl et al., 2000; Ashton et al., 2001; Maginnis and Jackson, 2007). Therefore, a dichotomous key was developed to assist the identification of the most suitable strategy, aiming to reduce costs, time, and enhance restoration effectiveness. Before using the key a diagnosis is performed at the landscape-level to assess soil aptitude with regard to plant development, to evaluate the resilience of the degraded area (i.e. presence and condition of advanced regeneration, soil seed bank and/or resprouts), and the likelihood of its colonization by species from surrounding forest fragments. Aerial photographs are used to identify landscape features such as land-use patterns, types of forest formations, and the connectivity among fragments.

Eventually, the key is applied as many times as needed to divide the landscape into zones according to the strategy to be put into practice. Therefore, as different zones require different strategies, detailed diagnoses are crucial to plan and optimize landscape restoration, which can be attained with different costs and practices (see practical example in Busato et al., 2007). As shown in Table

1, there is more than one possible strategy for a single situation. Therefore, the restorationist must be capable of interpreting the prescription, and providing a ‘menu’ of technically and economically suitable actions that individually or combined will solve particular cases (Parrotta et al., 1997; Holl et al., 2000). For example, although estimates vary greatly, planting seedlings (planting spacing: 2×3 m) or hydroseeding are unrealistic for many smallholders (estimated costs of 3000–4500 and 20,000 US\$ ha⁻¹, respectively; 1 US\$ = 1.65 R\$ in 23/06/2008). In such cases, the restorationists may suggest cheaper techniques such as direct seed sowing (Engel and Parrotta, 2001: 760–1450 US\$ ha⁻¹), topsoil transposition (Jakovac, 2007: 2180 US\$ ha⁻¹) or nucleation techniques (Bechara, 2006: around 2200 US\$ ha⁻¹), that can be even cheaper depending on the technologies applied.

Frequent and severe disturbances radically reduce the ability of a site to recover naturally (Chazdon, 2003; Silva and Matos, 2006). Often, other landscape features such as the distance and/or degradation of the existent forest fragments hold back the dispersal of new species and consequently restraining forest regeneration (Holl, 1999, 2007). This is the general scenario of the Atlantic Forest where forests have been converted and intensively used for agriculture for many decades (Morellato and Haddad, 2000; Ribeiro et al., 2009). In such cases the most effective site-level strategy is to sow seeds and/or plant seedlings to promote environmental conditions favourable for the invasion of other species (Montagnini et al., 1995; Engel and Parrotta, 2001; Martínez-Garza and Howe, 2003). As for other sites worldwide (Ruiz-Jaen and Aide, 2005), this strategy has been the most common one for the Atlantic Forest.

In such context, LERF developed its own succession-based model which consists of ‘filling’ and ‘diversity’ planting lines. In the ‘filling’ line, 15–30 fast-growing species are planted to promote fast soil coverage, and improve environmental conditions near the ground. As the main goal is the rapid suppression of exotic weeds, typical pioneers with poor soil coverage (e.g. *Cecropia* spp. and *Rapanea* spp.) are often included in the diversity line and not in the ‘filling’ line. On the other hand, the ‘diversity’ line receives 70–80 tree species (late secondary, climax or poor coverage pioneers) that, distributed in proper densities, will promote the long term development and self-maintenance of the forest structure, and introduce more functional diversity into the system (full details and a discussion on the model performance are provided in Nave and Rodrigues, 2007).

Although still under development and evaluation, preliminary experiences using this model (planting spacing: 2×3 m) provided interesting results with reduced costs. Soil coverage is attained (i.e. values of coverage >100%) after 2 and 3 years of planting the

Table 1

Simplified outcome examples of the decision making key developed to identify suitable restoration strategies according to the potentials of self-recovery (resilience) and seed arrival from surrounding fragments. Actions of each possible strategy are presented in the order that they should be implemented. The decision to implement the following actions, however, should be preceded by monitoring the previous one, which can be more or less successful than expected. An estimated scale of relative costs of each strategy from 1 (most expensive) to 10 (least expensive) was developed to help decision making processes (superscript numbers). Adapted from Rodrigues and Gandolfi (2007).

| Potential of self-recovery | Potential of seed dispersal from surrounding forest fragments | | | |
|----------------------------|---|----------------------------|--------------------------|------------------------|
| | Absent | Small | Medium | High |
| Absent | A + H ¹ | A + D/H ⁴ | A + B + G ⁶ | A + B ⁹ |
| Small | A + D/E/F/G/H ² | A + D/E/F/G/H ² | A + B/E/F/G ⁷ | A + B/E/G ⁸ |
| Medium | A + E + F + G ³ | A + E + F + G ³ | A + B/E/F/G ⁷ | A + B/C/E ⁹ |
| High | A + C/E + G ⁵ | A + C/E/F/G ⁷ | A + E/G ⁸ | A ¹⁰ |

A = Isolation of the area and removal of degradation causes (pre-requisite).

B = Management of seed rain and dispersal (e.g. seed rain collection and transference from surrounding fragments, perches, planting bird, and bat-attracting pioneer species).

C = Induction of seed germination from local soil seed bank.

D = Transference of litter and soil seed bank from nearby forest fragments.

E = Management of advanced natural regeneration (e.g. seedlings and sprouts).

F = Density-improvement tree planting through seed sowing or seedling (trans)planting.

G = Enrichment planting through seed sowing or seedling (trans)planting.

H = Dense tree planting of several species through seed sowing or seedling (trans)planting.

filling and diversity lines, respectively (L.S. Araujo et al., unpublished data; Nave and Rodrigues, 2007), almost 2 years faster than other planting models (R.A.G. Viani et al., unpublished data). Also, the inclusion of all ecological groups at the beginning of the project assures species regeneration for longer periods and avoids costs related to future enrichment plantings (cf. Lamb et al., 2005). In a 5-year-old area restored using this model, undergoing research addressing plant-pollinator networks and floral resources also showed interesting results compared to an abandoned area of the same age. Although both areas had plant-pollinator networks composed of generalist species and high variance in floral resource availability, the restored area had different plant and animal compositions with higher species richness, and higher floral abundance (Vosgueritchian and Buzato, 2007a). Interestingly, such positive features of the restored area were insufficient to promote higher functional diversity because the floral types were basically the same in both areas, and only 50% of the flowering species received visits in the restored area (Vosgueritchian and Buzato, 2007b). Such features however may change with time assuming that many species take more than 5 years to flower.

The close proximity of forest fragments (distances < 100 m) greatly affects the speed and trajectory of forest recovery, as well as the reestablishment of critical ecological interactions (e.g. dispersal, pollination and herbivory – Holl, 2007). Therefore, when there are nearby forest fragments, allied to some self-recovery potential, strategies other than tree planting should be used alternatively or complementarily (see Rodrigues and Gandolfi, 2007 for details). Some of these practices are: the stimulation of pre-existing advanced regeneration (seedlings and/or tree sprouts protection and conduction), management of seed dispersal (e.g. artificial perches), and enrichment through soil seed bank, seed rain and/or seedling transference (McClanahan and Wolfe, 1993; Simões and Marques, 2007; Viani et al., 2007). Recent research in the Atlantic Forest has provided some interesting results regarding these techniques, even in relatively large area restoration projects. Jakovac (2007), for instance, obtained 150 species of various life forms and a significant density increase using topsoil transposition (but see Nave, 2005). With lower costs than traditional seedling plantations, Bechara (2006) reintroduced 148–180 species of different life forms using nucleation techniques (i.e. an alternative method which involves the spatial combination of soil seed bank and wood debris transposition, collection and transposition of seed rain, establishment of artificial perches, and clustered tree planting – details in Reis et al., 2003). Other interesting results regard the significant increase of seed inputs using perches (Melo, 1997), and seed rain transference (Aquino, 2006).

After project implementation, monitoring, another important restoration phase, must be carried out. This is the periodic assessment of indicators capable of telling whether the restoration targets are likely to be accomplished in the near future or not, allowing the adoption of corrective actions, if necessary (SER, 2004). In the Atlantic Forest monitoring is a recent practice that still lacks a clear definition of which indicator should be evaluated, and how often it should take place. As with other sites (Ruiz-Jaen and Aide, 2005), studies in the Atlantic Forest generally monitor the vegetation structure and plant species diversity (Souza and Batista, 2004; Martins and Kunz, 2007; Melo and Durigan, 2007). Monitoring activities carried out by LERF mainly evaluate richness, composition and biomass of planted and regenerating individuals, mortality of planted individuals, and the proportion of soil coverage by tree crowns and exotic grasses. More complete examinations also evaluate the regeneration modes (Siqueira, 2002; Sorreano, 2002; Barbosa and Pizo, 2006; Vieira and Gandolfi, 2006). Animal species are rarely monitored (Reay and Norton, 1999; Jansen, 2005), and some recent and preliminary results in

the Atlantic Forest involve soil fauna (Damasceno, 2005; Moraes, 2005).

4. Public policies shaping forest restoration

Legal and political changes were and are the most effective driving forces to shape restoration in the Atlantic Forest. For example, laws regulating the use of native forests have existed in Brazil since 1965 but have rarely been respected. Only from the 80s on, did the increasing social concern for the Atlantic Forest pressured governments to enforce these laws more rigorously. Recently, international market mechanisms (i.e. certification systems, implementation of the Kyoto Protocol) also started to stimulate restoration (Ferretti and Britez, 2006). As a consequence, the encouragement of restoration initiatives is now a government priority in some Brazilian states (Barbosa et al., 2003).

However, the knowledge and infrastructure available were insufficient to support effective Atlantic Forest restoration. Governments are currently fostering the discussion and publication of good restoration practices and incorporating them into their own laws. In São Paulo state, for example, many political instruments were developed between 1998 and 2007 in a joint venture between government and research agencies. As a result, a recent and complete state decree furnishes details such as the minimum number of species to be used, their proportions and some basic monitoring indices. It also provides a menu of techniques other than planting trees, and a list of potential species according to each state region. Consequently, this decree has become the most important tool to orient restorationists, and to inspect restoration projects in each state.

Another main role of public policies is the capacity of stimulating restoration over large areas. Although recent and not fully established, the federal government restoration fund was instituted in 2006 to encourage projects and research in the Atlantic Forest. The increase in seedling production and diversity, one of the main bottle-necks of Atlantic Forest restoration (Barbosa et al., 2003), was stimulated and regulated by federal laws after 2003. Moreover, the São Paulo state government launched a riverine forest restoration program with the ambitious aim to increase in one million hectares the state forested area (Wuethrich, 2007). To catalyze this process, landowners can register their lands since 2007 on a state government database created to publish riverine areas available for mandatory or volunteer restoration by third parties.

Although many political advances were achieved, we strongly believe that public policies should be more intensively used as a tool to stimulate large scale restoration efforts, and to enhance their chances of success. Besides direct government financial and tax incentives, the consideration of socio-economical issues must become an explicit part of all future restoration policies. Because restoration in Brazil is virtually always part of a legal and compulsory process, all investments are of landowner's liability (it's not clear yet if and how public funding will be used in this circumstances), and they generally are economically unfeasible to many landowners. Unless direct or indirect incentives and tangible benefits are provided to local communities and landowners, the success of restoration will be reduced (Cairns and Heckman, 1996; Sayer et al., 2004). Therefore, legal or political instruments must be urgently developed to make restoration more attractive (e.g. linking restoration and forest products: ITTO, 2002; see examples below). Another important consideration involves training government agents, scientists and local associations to support the intended growth of Atlantic Forest restoration.

And perhaps more importantly, public policies should be seen more and more as a way to consolidate restoration ecology as well.

For instance, more detailed requirements on how to monitor restoration success and how to obtain reference information must be included in the existing policies (Ruiz-Jaen and Aide, 2005). If this is accomplished, restoration projects with more standardized designs could provide data for analysis over large geographical areas (Block et al., 2001). This is an important, but commonly overlooked tool to put results together to answer broader questions about restoration.

5. Lessons from the Atlantic Forest restoration

Using the analogy that restoration is similar to human medicine (Temperton, 2007), one important lesson from the Atlantic Forest is related to the treatment (i.e. restoration strategy) prescribed for each specific disease (i.e. degree of degradation and fragmentation). In the beginning, Atlantic Forest restorationists rarely made proper diagnoses and often prescribed the same treatment to different diseases. This certainly was the main cause of the 'death' of many patients (i.e. degraded lands) that fortunately is not irreversible as in medicine. Today, precise diagnoses are the critical step to assist the determination of different diseases, their degree of severity, the patient individual history, and the selection of the feasible medicines (i.e. restoration actions), which are now more numerous and may be combined in cocktails to heal specific cases (Rodrigues and Gandolfi, 2007). Another important lesson is that often the best strategy is not the more 'ecological' one. This may frustrate the more avid restorationists but the inclusion of socio-economic, and political issues in restoration are determinant, being cited as the new paradigm shift in restoration (Temperton, 2007).

Past experiences on ecological restoration of the Atlantic Forest are difficult to compare or summarize. Many methods and models have been applied, making some comparisons somewhat speculative, but, considering that self-sustainability has been the common goal, there are some lessons that can be learned from these experiences. First, the most important step is to create a forest structure capable of keeping the soil permanently shaded, especially in grass-dominated fields. Faster soil coverage means lower costs on weed management and better environments for the establishment and growth of other life forms (Holl et al., 2000). Past experience has shown that this type of coverage can be rapidly attained (3–5 years) by combining regional indigenous species with the appropriate techniques, even in severely degraded sites, in contrast to other authors' suggestions (Corlett, 1999; Ashton et al., 2001; Lamb, 2005). Currently, exotic species (i.e. green manure) are mostly used in the Atlantic Forest to recover soil properties or to generate income (e.g. Jakovac, 2007).

Another major lesson from Atlantic Forest restoration is that higher diversity (>50 species) was shown to be more efficient to restore permanent forests (Siqueira, 2002; Barbosa et al., 2003). The reason for this is not yet fully understood. Most likely, higher species diversity inserted higher functional diversity influencing long term forest functioning (e.g. keystone species, ecological engineers; Jones et al., 1997; Hooper et al., 2005). The remaining issue is to find which and how many species are really needed to start community development and guarantee its future functioning, and under which circumstances (Dobson et al., 1997). In this sense, at least 50 species may be a costly overestimation if particular combinations are more important than the number of species itself (Lamb et al., 2005; Mansourian et al., 2005). Also, this issue becomes more important because studies in other countries are using or suggesting the use of fewer species (e.g. Holl et al., 2000; Hooper et al., 2002; Young et al., 2005), an approach that makes restoration more practical (i.e. seedling are more easily found in nurseries and may be cheaper).

A common result of many of these recent monitoring studies in the Atlantic Forest is the failure of new native plant species to in-

vade restored isolated areas, even where restoration is 20-years old. Highly fragmented and defaunated landscapes are one of the main restraints to this invasion. What strategy should be used to accelerate this invasion is still unclear (cf. Holl, 2007), especially in the highly fragmented Atlantic Forest. Another major issue related to this landscape feature is finding quality reference information to set parameters for comparison and the acceptable amount of variation from them (Cairns and Heckman, 1996; White and Walker, 1997; Parker and Pickett, 1999). This is a common problem that is undervalued in many Atlantic Forest restoration projects. Frequently, severely altered forest fragments (if present at all) are used as site references, making it difficult to assess to what extent the evaluation of success of many Atlantic Forest projects may have been overestimated (White and Walker, 1997).

Moreover, it seems that the traditional, monitoring-based, static parameters (e.g. vegetation structure and diversity) have provided few insights so far. Primarily, many of the existing studies on monitoring have failed to control the effects of environment heterogeneity (mainly soil and climate) and post-implementation management (e.g. weed control). But also, restoration has not been monitored in terms of the rate of change of parameters, the influence of the landscape and historical processes (Parker, 1997; Parker and Pickett, 1999; Holl, 2007). Therefore, restorationists usually have little information to conduct proper adaptive management, a key tool to enhance restoration activity success (Block et al., 2001). In addition, other approaches should be used to evaluate restoration outcomes, as a replacement to the standard structural aspects of biodiversity (Forup and Memmott, 2005; Vosgueritchian and Buzato, 2007b). Even so, one key lesson involves the need for maintenance of the restored area, at least in the first 2 years. This is particularly true for the control of exotic grasses that can seriously compromise the restoration process (Holl et al., 2000). Mechanical or chemical control of grasses, as well as the use of fertilizers, increases costs but is critical for not putting the invested resources at risk (Souza and Batista, 2004).

With regard to floristic and genetic diversity of restoration, there are some recent and successful initiatives in the Atlantic Forest that can be reproduced elsewhere. In different regions of São Paulo state, several individuals (at least 10 per species) of more than 800 native tree species were tagged and mapped for genetic diversity improvement during seed collection and production. Distribution and many other species information (e.g. phenology, seed storage, and seedling production) are currently being freely divulged over the internet. The establishment of regional nurseries has been stimulated to avoid the negative impacts related to the introduction of exotic genotypes (Lesica and Allendorf, 1999; McKay et al., 2005). Another effort to improve genetic diversity has been the exchange of seeds from different species among nurseries, and the mixture of seed lots within regions to assure multiple-origin of seeds. In addition, the transference of seedlings or entire individuals (in the case of epiphytes and herbs) from natural forest fragments proved to be successful to increase floristic and probably genetic diversity of nurseries (Nave, 2005; Viani et al., 2007). This last technique has often been applied where vegetation suppression is inevitable.

6. Challenges for the future

Many ecological restoration projects aiming to produce thousands of hectares of high diversity forests in the Atlantic Forest are under way (e.g. Ferretti and Brites, 2006). In São Paulo state, for instance, 98 restoration projects restored an area of approximately 2500 ha (Barbosa et al. 2003). But there is still an enormous extent of degraded areas to be restored. Considering only areas where restoration is needed to meet federal law requirements

(e.g. riparian forest formations), estimates show that there are millions of hectares of degraded forest areas waiting to be restored. Expanding the rate of restoration in the Atlantic Forest is thus the greatest challenge of all. This enormous area is split into more than hundreds of thousands of private properties, which means that the stimulation of the Atlantic Forest restoration depends directly on private initiative that must start to see restoration as an activity coherent to its own interests (Lamb et al., 2005; Tabarelli et al., 2005). Although restoration may be part of a legal obligation in Brazil and other countries (Ruiz-Jaen and Aide, 2005), highly altered lands associated with high implantation and monitoring costs, provides little motivation, especially to smallholders (Dudley et al., 2005).

Hence, reducing costs, as well as joining economic activities to the restoration process (with due respect to legal restrictions; Rodrigues and Gandolfi, 2007), is especially needed to stimulate Atlantic Forest restoration (Engel and Parrotta, 2001; Maginnis and Jackson, 2007). Some initiatives have been carried out but still need to be expanded and become an indivisible part of restoration planning (Temperton, 2007), particularly in poorer rural areas. Examples in the Atlantic Forest come from the management of commercial plantations (Carneiro and Rodrigues, 2007) and from the selection of native commercially attractive species (Parrotta and Engel, 2000; Martins and Kunz, 2007). Mixed plantation of timber species is a good example to provide landowners some eco-

nomical insurance and catalyze successional processes at the same time (Lamb et al., 2005; Fig. 2). Another example is the combined use of economic species (e.g. bean and pea) capable of fertilizing the soil, and generating income to stakeholders during the 1 years of restoration.

Conversely, encouraging the production of seeds and seedlings with high floristic and genetic diversity is crucial to support any future increases in Atlantic Forest restoration rates (Lesica and Allendorf, 1999; Barbosa et al., 2003). This production is vital for the Atlantic Forest where the highly fragmented landscape makes full-area implantation the most common restoration strategy (Dobson et al., 1997; Engel and Parrotta, 2001), and may also be a good way to generate extra income in rural areas. Good examples come from the training and organization of smallholders into community cooperatives to provide restoration services such as seed collection, seedling production and planting to companies or others stakeholders (e.g. Cooplantar (www.bioatlantica.org.br); Ecoar Florestal (www.ecoarflorestal.org.br)).

As reported elsewhere (Dudley et al., 2005; Lamb et al., 2005), most restoration projects in the Atlantic Forest have been carried out at a small scale where any ecological and economic consequences have been relatively small. Although much more complex, planning restoration on a broader scale, and involving many more social actors (stakeholders, government, and NGOs) may be a good way to suit multiple environmental and socio-economical needs

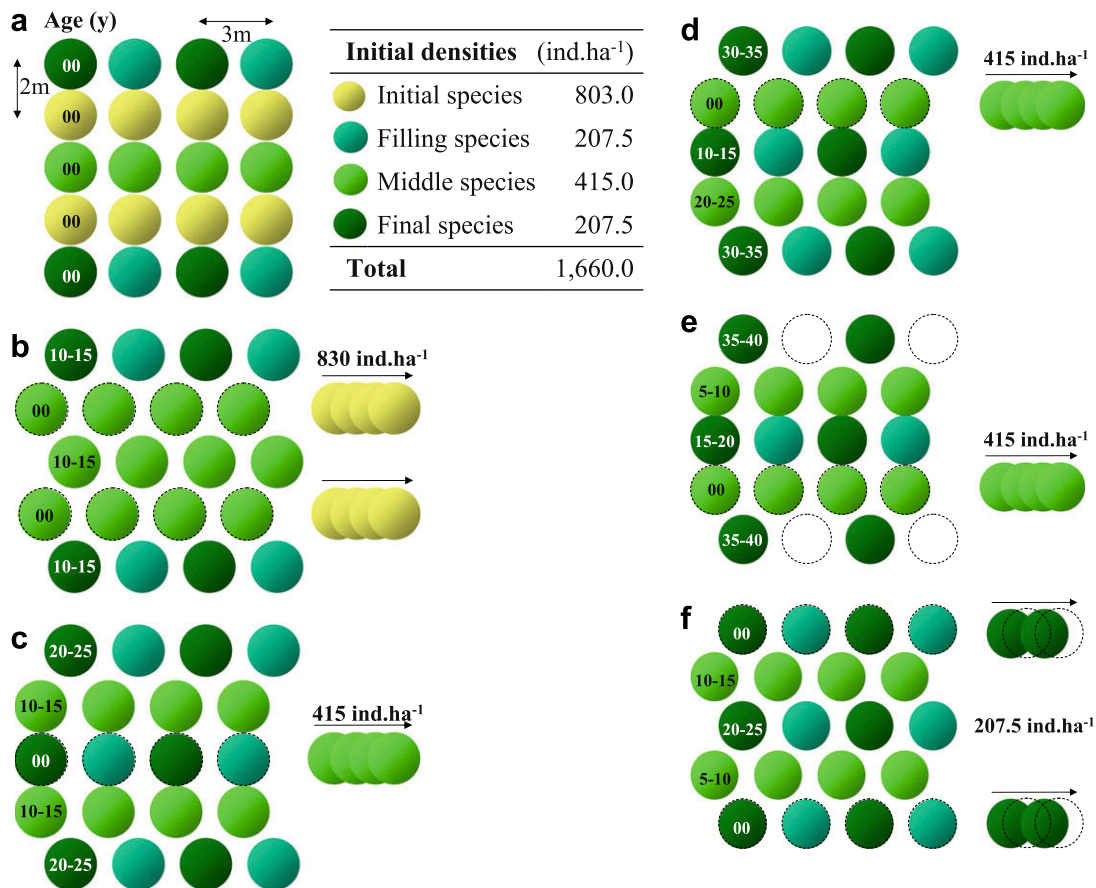


Fig. 2. Example of a restoration model using commercial wood species currently being tested in the Atlantic Forest. (a) Planting is planned according to the rate of growth and commercial value of the species. Management is cyclical, alternating harvesting and reintroduction of individuals every 5–10 year within 80–85 year cycles. Harvesting intensity is planned to keep a minimum of 75% of canopy cover with regard to Brazilian laws. Fast growing species (initial species) provide initial conditions for other species' growth and (b) can be harvested for fuel production in 10–15 year. These species will be then substituted by more valuable wood species (middle species) that (c, d and e) can be harvested in 20–25 year and used for rustic carpentry. Final hardwood species, used for luxury and finished carpentry, (f) can be harvested in 40–45 year, and so on. At the end of a harvesting cycle (80–85 year), 20–35, 767–1438 and 176–314 m³ ha⁻¹ of wood are expected to be produced for initial, middle and final species, respectively (wood volume estimated based on diameter growth rate of 1.5–2 cm year⁻¹ and trunks of six meters). Medicinal and food species can also be used to generate extra income between harvesting activities.

(Martínez-Garza and Howe, 2003; Sayer et al., 2004) and therefore to stimulate Atlantic Forest restoration. During such planning, costs and benefits must be carefully considered to identify who will be affected by forest restoration impacts and how (Hobley, 2005). It is also important to consider that forested landscapes are exceptions in the modern Atlantic Forest and the livelihood dependence on forests has been substituted by large scale industrialized agriculture in the past decades. The assessment of social issues has rarely been carried out in the Atlantic Forest, although it is important to set socio-environmental trade-offs that in the long term will certainly influence restoration success (Lamb et al., 2005).

Recent research in the Brazilian Atlantic Forest indicates some new and exciting technical advances to be incorporated in restoration practices. Within the ongoing process of evolution of its practice, such advances may be seen as new phases in the history of Atlantic Forest restoration. To begin with, there is a clear tendency to increase the number of species and life forms in restoration projects. Despite past efforts to create species-rich restored forests, species richness in natural Atlantic Forests is at least two times bigger (e.g. Martini et al., 2007). In addition, the exclusive use of tree species may not be enough to properly restore tropical forest biodiversity (Gentry and Dodson, 1987). For instance, life forms such as herbs, lianas and epiphytes are important to supply resources to animals that can be provided in different seasons, with shorter time intervals or are much better vertically distributed than trees (Morellato, 1991; Andrade, 2006; Bonnet and Queiroz, 2006). This is more critical for areas with no nearby forest fragments to furnish seeds of other life forms. Some preliminary studies have shown promising results after reintroducing epiphytes (A.C.C. Jakovac et al., unpublished data), shrubs and lianas (Nave, 2005; Jakovac, 2007).

In Atlantic Forest restoration projects, species were traditionally selected and distributed with respect to their light requirements. Currently, the challenge is the selection of species based on their importance at the community-level (Parker, 1997; Hooper et al., 2005). Special focus ought to be given to species reproductive biology such as phenology, mating systems, pollination and dispersal syndromes, and the ability of vegetative reproduction (Martínez-Garza and Howe, 2003; Castro et al., 2007; Simões and Marques, 2007). But species can be selected and combined according to their potential to play specific or complementary roles (e.g. Barbosa and Pizo, 2006; Vieira and Gandolfi, 2006) that are sometimes capable of creating particular regeneration microhabitats (Jones et al., 1997; Gandolfi et al., 2007a). This type of selection can be done concerning features such as species growth habit, crown architecture, deciduousness, litter production, arrangement of roots, ability to fix nitrogen, potential of root hydraulic redistribution, and phytoremediation (Guariguata et al., 1995; Montagnini et al., 1995; Dobson et al., 1997; Oliveira et al., 2005). Studies trying to identify the functional importance of Atlantic Forest species should be encouraged, as well as those assessing the performance of these species in restored environments (Young et al., 2005).

Another promising field refers to restoration of ecosystem-level processes (Ehrenfeld and Toth, 1997), including the evaluation of nutrient cycling, litter decomposition, allelochemistry, and soil physicochemical properties, among others. In the Atlantic Forest this evaluation still depends on results of practically nonexistent studies (Montagnini et al., 1995; Nogueira-Júnior, 2001; Oliveira et al., 2005; also see Janos, 1996; Davidson et al., 2007) but which are fundamental to tell if restoration is able to recover ecosystem processes that greatly influence community development in the long term. Many other issues remain unexplored in the Atlantic Forest. Despite recent studies, long term monitoring of forests restored using different models and under different landscape situations are still needed (Holl, 2007), especially those able to control

environment and management variations experimentally. Studies with more variables, treatments, and non-obvious experimental designs are important as well (Weiher, 2007). Additionally, since the current Atlantic Forest restoration methods were developed for rainforests, and seasonal forests, it is hard to state if and how much these methods are valid for mixed *Araucaria* forests, deciduous forests, *Restinga* forests, and mangrove forests (cf. Ellison, 2000; Bechara, 2006; Zamith and Scarano, 2006; Vieira and Scariot, 2007). Lastly, projects focusing on animals are practically nonexistent in the Atlantic Forest.

7. Conclusions

Information is still meagre and many specific studies have yet to be undertaken, but the existence of high diversity permanent forests as the result of different initiatives proves the feasibility of restoring the Atlantic Forest. Although the restored forests may be far from the original complexity of this biome, they are moving in this direction. Also, there is an increasing political will to restore the Atlantic Forest (Wuethrich, 2007). Some remarkable results from recent research indicate the great increase in our potential to restore the diversity of the Atlantic Forest in the near future. The current challenge is, therefore, to translate the new scientific advances into simple restoration strategies able to produce self-sustaining diverse forests at suitable costs (Burke and Mitchell, 2007). That said, restoration ecology in the Atlantic Forest still needs great improvement to support future restoration activities with more solid scientific bases (Weiher, 2007). Political and socio-economic constraints, often the more frequent and restricting ones (Meli, 2003; Maginnis and Jackson, 2007), should be less and less underrated in order to speed up the restoration process, and increase its chances of success (Temperton, 2007). In this sense, the questions that remain are: what political, financial, and legal instruments should be created to stimulate Atlantic Forest restoration? And, how could restoration also work as a good socio-economic alternative to stakeholders aiming to restore their properties? A general guideline to answer these questions was already developed by Lamb et al. (2005) but we still lack practical socio-political tools to solve these issues in practice. Lastly, highly succeeded restoration experiences must be properly studied and divulged (Palmer et al., 2006), aiding the development of restoration and consequently the conservation of the highly threatened Atlantic Forest.

Acknowledgements

We are thankful for Karen Holl and Jean-Paul Metzger for their valuable comments on earlier versions of this manuscript. We are also in debt to Fabiana Basso and Ingo Isernhagen who provided recent estimates on restoration costs.

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