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ORIGINAL PAPER

Phytogeographic retrospective in ecotonal areas guided by soil attributes

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Abstract Re-establishing deforested ecosystems to pre-settlement vegetation is difficult, especially in ecotonal areas, due to lack of knowledge about the original physiognomy. Our objective was to use a soils database that included chemical and physical parameters to distinguish soil samples of forest from those of savannah sites in a municipality located in the southeastern Brazil region. Discriminant analysis (DA) was used to determine the original biome vegetation (forest or savannah) in ecotone regions that have been converted to pasture and are degraded. First, soils of pristine forest and savannah sites were tested, resulting in a reference database to compare to the degraded soils. Although the data presented, in general had a high level of similarity among the two biomes, some differences occurred that were sufficient for DA to distinguish the sites and classify the soil samples taken from grassy areas into forest or savannah. The soils from pastured areas presented quality worse than the soils of the pristine areas. Through DA analysis we observed that, from seven soil samples collected from grassy areas, five were most likely originally forest biome and two were savannah, ratified by a complementary cluster analysis carried out with the database of these samples. The model here proposed is pioneer. However, the users should keep in mind that using this technology, i.e., establishing a regional-level database of soil features, using soil samples collected both from pristine and degraded areas is critical for success of the project, especially because of the ecological and regional particularities of each biome.

Keywords Ecotone · Pristine forest soil · Soil database · Vegetation re-establishment

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Introduction

São Paulo State is the Brazilian region where the largest portion of the Brazilian gross internal product and largest fraction of the Brazilian population are concentrated. São Paulo also encompasses important parts of two important Brazilian biomes: the savannah and the Atlantic rain forest. During the last seven decades, a land cover shift has occurred that favored land-use for profit and many of the forest-related biomes were destroyed. There is a common understanding between governments, researchers and communities that some regions should be restored, but in some ecotonal regions, little is known about the original vegetation that were present (Gandolfi et al. 2007; Rodrigues et al. 2009). Methods aiming to identify the original vegetation are welcomed and may be useful in environmental recovery projects.

Land cover shifting, ecotones degradation and restoration

Land cover is defined by the features of the earth's land surface and immediate subsurface (Lambin et al. 2003). Land-use transition usually refers to land cover change through the substitution of original vegetation and, although land-use practices vary greatly across the world, their ultimate result is generally the same: the acquisition of natural resources for immediate human requirements, frequently at the expense of degrading environmental conditions (Foley et al. 2005). Land cover transition is one of the major driving forces that causes the loss the terrestrial biodiversity, although further degrading effects are also perceived, such as soil erosion, soil compaction, and disruption of several soil ecological interactions (Wolters et al. 2000; Lambin et al. 2003). One of the most common transitions is from forest or woodlands to grassy vegetation (Ellis 2011).

Two main tendencies exist currently: (a) stop the deforestation and conserve the remaining natural fragments, and (b) restore areas in strategic places. The aim of restoration projects may be to begin or speed the recovery of an ecosystem following disturbance (Vaughn et al. 2010). Inducing a process of secondary succession as similar as possible to natural processes is the most appropriate way to bring about this restoration (Reis et al. 2010). In this context, techniques are developed and used to promote the restoration of ecosystems that resemble intact habitat as closely as possible (Aronson and Alexander 2013; Liebenberg et al. 2013). The passive, natural regeneration is an alternative technique considered by some researches for the cases when the forest clearance has occurred relatively recently; where some seedling banks, residual trees, and soil seed stores composed of native species remain; as well as intact, biodiversity-rich native forests that are still present in the landscape surrounding the degraded area (Lamb et al. 2005).

However, passive regeneration usually takes decades (Jones and Schmitz 2009; Corbin and Holl 2012) and the assisted restoration methods are gaining momentum worldwide (Chazdon 2008). Two of the most common methods of assisted restoration are the re-establishment of vegetation by planting seedlings produced in nurseries (Byrne et al. 2011) and applied nucleation, which is a strategy that uses principles of colonization of non-forested landscapes by woody vegetation to restore forest cover by means of establishing small patches of shrubs and/or trees to serve as focal areas for recovery (Corbin and Holl 2012). Such methods are largely employed because of relatively good cost-to-benefit ratios (Chazdon 2008; Jones and Schmitz 2009; Corbin and Holl 2012).

Ecotones are areas of transition between ecological communities, ecosystems, or ecological regions. They take place at multiple spatial scales such as spatial shifts in elevation, climate, soil, and many other environmental factors (Kark 2011). Hence, for restoration projects in ecotonal areas, one important question arises: for a successful re-establishment of vegetation, choosing the correct plant species requires knowledge of the original vegetation in the area of interest.

When a restoration project starts, one generally verifies that the native vegetation was completely destroyed and, as a result, one of the main questions to be solved when planning a restoration project is what kind of vegetation is suitable for that area or for each condition of the degraded area, which allows inference that some of the project objectives will be achieved, such as the restoration of the local biodiversity, of a structurally and functionally self-sustainable community (SER 2004 in Gandolfi et al. 2007).

For example: in an ecotonal area formed by the junction of the savannah and forest biomes, which is now dominated by pastures, should species from the savannah or forest be chosen? Answering this question is critical because the biodiversity restoration patterns differ, and are difficult and time consuming to implement (Corbin and Holl 2012; Zahawi et al. 2013).

One way to verify the existing physiognomy of the pre-settlement ecotones is to consult aerial photographs of the region (Kettle et al. 2000; Gandolfi et al. 2007). However, there are many regions for which there is no photographic evidence of vegetation that was present decades ago. Another way is try to find local relations among the soil and vegetation.

Soil features and vegetation relationships

Soil features have been recognized as important determinants of vegetation and usually the vegetation also imprints significant characteristics in the underlying soils. Modifying the land cover results in modifications of soil chemical, physical and biological properties. Some modifications occur rapidly after the land cover shift, while others change gradually (Tavili and Jafari 2009). For altered landscapes, some edaphic features that change slowly may indicate the original physiognomy of that location (Bradshaw 1997). Thus, the changes in soil's physical features, highlighting bulk density, and chemical composition, especially those elements that drive changes in the cation exchange capacity (CEC) and organic matter concentration and composition, should be measured routinely and incorporated into the planning and evaluating of restoration projects (Schoenholtz et al. 2000; Heneghan et al. 2008). Existing edaphic features that suggest the vegetation that originally occurred in a given location should be included; they could be used to generate more definitive and useful guides for restoration (Vieira and Scariot 2006).

Discriminant analyses as a tool for restoration activities

Not only in the environmental sciences, but in several other situations, when a single variable is not capable of differentiating between two or more groups, discriminant analysis might be used. This analysis is a statistical procedure that is used to investigate differences between groups on the basis in their attributes, and indicates which attributes contribute most to group separation. It is a multivariate and descriptive technique that successfully identifies the linear combination of attributes that maximally contribute to a group separation (Burns and Burns 2008). If the groups are sufficiently distinct from one another through the use of Fisher's discriminant functions (FDA), new individuals can be classified in one of the identified groups (Ayres et al. 2007). This technique has been used in environmental research for a long time (Matthews 1979; Williams 1983). In soil science this method was used to evaluate the usefulness of soil properties for distinguishing between taxonomic units (Webster and Burrough 1974; Henderson and Ragg 1980). However, few studies have used this technique in projects regarding environmental reclamation (Piqueray et al. 2011).

The FDA may be an easy, fast tool to help identify the past vegetation in areas currently occupied by anthropogenic land cover, by means of the construction of a database with soil features of samples collected in places with different categories of vegetation and as well as places where we want to implement the restoration program. This is important, because although restored forests might recover essential ecosystem services and increase biodiversity conservation, if the activity is not well planned, the outcome will not match the structure and composition of the primal forest cover (Gandolfi et al. 2007).

Considering this information, research was carried out during 2011 and 2013 in Iperó–SP, Brazil to test our hypothesis: soils from the forest and savannah can be numerically distinguished by using an edaphic database. Hence, we examined some physical, chemical and isotopic properties of the soil samples taken from areas with three different categories of land cover (forest, savannah and pasture) within an ecotonal region, to determine the class of vegetation (forest or savannah) that was originally present on the landscape, and through the Fisher's discriminant analysis, determine what was the original vegetation in areas currently in pasture.

Materials and methods

The study site

São Paulo State has many ecotonal regions, one of which is located near the Iperó Municipality (Fig. 1). Iperó is in southeastern São Paulo State. The average annual temperature is 21.6 °C, and the average annual rainfall is 1,240 mm (Alvares et al. 2013). Iperó encompasses an area of 170 km^2 and includes 28,300 inhabitants, 60 % living in urban settlements (IBGE 2013). It is essentially rural, with three main land cover categories that cover almost 90.7 % of the area: Atlantic forest (33.3 %), savannah (27.8 %), and pasture (29.6 %) (Fig. 2). Other land cover categories include: crops (0.7 %), urban areas (2.7 %), water bodies (1.7 %), bare soil (4.1 %), and others (0.1 %).

A part of the Ipanema National Forest (Brazilian National Park) is in the southern region of Iperó. Land there has been mostly converted to agricultural proposes and is predominantly pasture. In pasture areas, the most common grass is *Brachiaria* spp. In Brazil, pastures do not receive soil amendments; fire is the "tool" widely used for years to manage the land cover, although its use has diminished in recent years.

Two soil orders are found within this region: (a) Ultisols are soils that are highly weathered and leached, with a clayey B horizon, base saturation <50 %, are acidic, and are generally found in humid areas of the tropics and subtropics (FAO 1992; Palm et al. 2007). They occur in 40.3 % of our study area (Oliveira et al. 1999); (b) Oxisols, present in the remaining 59.7 % of the land area, are highly weathered soils with little variation in texture with depth. Soils in the study area, either Ultisols or Oxisols, tended to have a sandy clay loam texture.

The region is a zone of ecological tension between two biomes: Atlantic forest and savannah. For the Atlantic forest biome, some common tree species are: *Tibouchina pulchra* (Cham.), *Eugenia glazioviana* (Kiaersk), *Chomelia ribesioides* (Benth), *Cupania vernalis* (Camb). In the savannah biome, common tree species include: *Austroplenkia populnea* (Reiss), *Copaifera langsdorfii* (Desf), *Anadenanthera falcata* (Speg). Species such as *Machaerium vestitum* (Vog) and *Pterogyne nitens* (Tul) occur in the both physiognomies (Albuquerque and Rodrigues 2000).

Sampling and laboratory analyses

All soil samples were collected in October 12, 2011. Collecting all samples in a single day was a strategy adopted to eliminate variations in the soil water content; the day chosen was one that had been preceded by five days without rainfall. Sampling points were selected using a stratified random sampling design that would capture the heterogeneity of land cover (Vasenev et al. 2013). In the field, the vegetation physiognomy (forest, savannah and grass) was distinguished using expert visual recognition. Intact soil cores were collected from each of the 25 sampling points at the 0–20 cm depth, using a 250 cm^3 steel ring. Just to the side of where the core was collected, an additional sample was taken in the same depth with a Dutch auger.

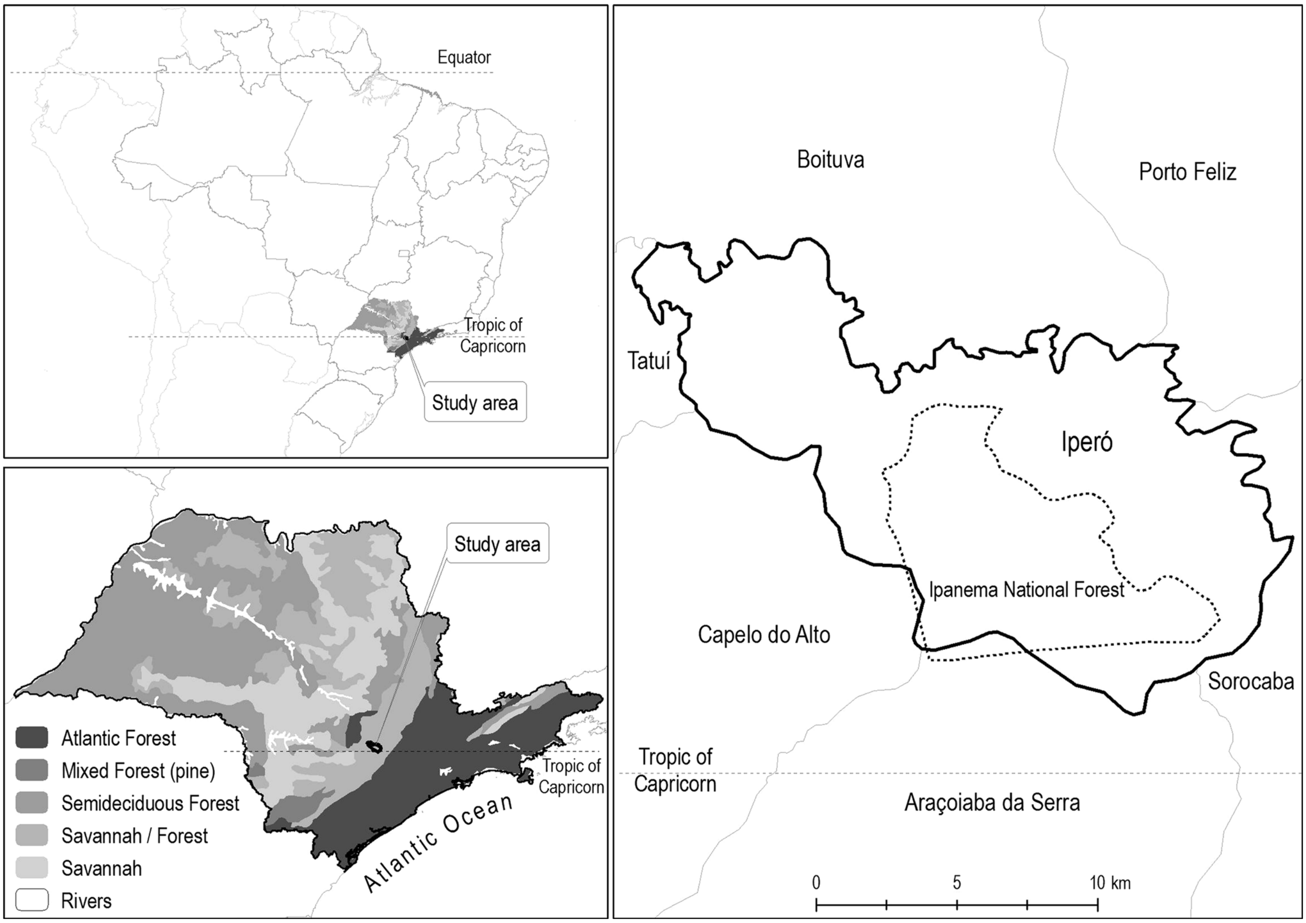
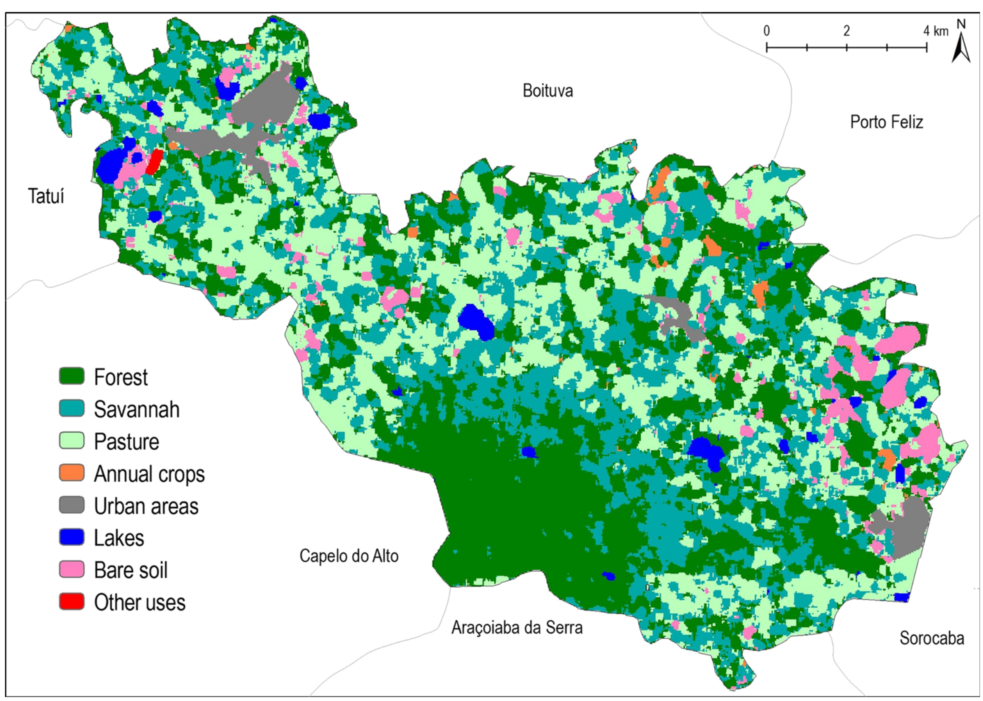


Fig. 1 Location of the Iperó municipality in São Paulo State

Fig. 2 Land cover map for Iperó-SP. Source: Monteiro and Silva (2011)



Eighteen sampling points from the 25 were collected in pristine locations, i.e., local vegetation was uninjured and completely free from dirt or contamination; there were nine each of forest and savannah sampling sites. Within Brazil, the Cerrado savannah biome encompasses a series of vegetation forms from open grasslands to dense, low canopy woodlands (Durigan and Ratter 2006), and in Iperó the Cerrado is dominated by this woody vegetation, thus all savannah samples were collected from sites representing this vegetation biome. Another seven samples were collected in pastures, which were also free of dirt or contamination.

In the laboratory, all samples were air-dried. The ring samples were used to determine bulk density (BD) (EMBRAPA 1997). The auger samples were sieved through a 2-mm sieve, and then divided into two portions. One portion was sent to the Department of Soil Science laboratory (ESALQ/USP-Piracicaba, Brazil) for analysis of potential acidity (H + Al) and pH (both by means of the Shoemaker–McLean–Pratt (SMP) solution), extractable P, K, Ca, and Mg (using ion exchange resin), sum of bases (SB) and CEC (Raij et al. 2001; Ruggiero et al. 2002). The second portion was sieved again to 0.35 mm and was sent to Center of Stable Isotopes of the Biosciences Institute (UNESP-Botucatu, Brazil) for the determination of C and N concentrations and $\delta^{13}C$ and $\delta^{15}N$ (Amundson et al. 2003; Silva et al. 2009). The C and N analyses were performed by dry combustion using a Finnigan Delta Plus mass spectrometer (Thermo Fisher Scientific, http://www.thermofisher.com). Isotopic measurements were included in this study since the savannah woodland ecosystem contained a large portion of grass vegetation, which could significantly alter the isotopic signature of the soil C ($\delta^{13}C$) (Carvalho et al. 2010) when compared to that of the forest soils.

Statistical analyses

First, the Kruskal–Wallis test was used for each parameter to verify the level of significance of the differences among the three land cover categories. Non-parametric correlation tests (Spearman) were also conducted. For both tests, $P = 0.05$ was used for determining the minimum level of significance. Further, Fisher's Discriminant Analysis (FDA) was carried out to evaluate whether soils from the different categories of original land cover (forest and savannah) could be numerically distinguished by using the edaphic database.

Complementary cluster analyses were conducted to show the distinction among the sampling points from pasture areas that were classified as either forest or savannah through the use of discriminant analysis. The criterion/options considered were: (a) Ward's method, (b) Euclidean distance, and (c) standardization of the variables. All analyses were conducted using the freeware Bioestat 5.0 provided by the Mamiraua Institute for Sustainable Development (http://www.mamiraua.org.br/downloads/programas).

Results and discussion

Descriptive analysis of soil attributes

Most of variables presented a large range of values and consequently high coefficients of variation (Table 1). None of the sampling point taken in pasture sites was in the 1st quartile of BD measurements, while there were no samples from the savannah represented in the 4th quartile. All the BD data indicated that the soils were not critically compacted in terms of limiting the development of plant root systems.

The $\delta^{15}N$ data were all positive and higher than 2.8 ‰. Only one sampling point from a pasture and two from forests had $\delta^{15}N$ values significantly lower than the mean value. On the other hand, only two savannah sites were significantly above the average. The mean total N concentration was 1.8 g kg^{-1}, with most of the pasture sites having values below the mean. Samples with simultaneously high $\delta^{15}N$ values and low total N values indicate that the edaphic system is highly susceptible to external influences and is not sustaining the N in the soil, meaning that the soil N is being lost either to the atmosphere and/or to hydrologic pathways (Boeckx et al. 2005; Hobbie and Ouimette 2009).

The $\delta^{13}C$ data showed that some soil organic matter (SOM) samples were strongly influenced by organic material from C_3 plants (most negative values) and some samples were influenced by organic material from C_4 plants (for our case: grassy areas, less negative values). All C:N ratio values regarding can be considered low, indicating that the SOM that was present had a medium–high degree of humification and are values commonly found in soils from this region (São Paulo State countryside). Only two sampling points, from pasture sites, had C:N values significantly lower than the overall mean. Although materials with both high C:N ratios and lignin contents, such as grasses, generally favor nutrient immobilization, organic matter accumulation and humus formation (FAO 2005), this trend was not apparent in our data, i.e., all correlation values among C:N and P, K, Ca, Mg, SB and CEC were not significant at $P = 0.05$.

The extractable P concentration ranged from 6.0 to 113.0 mg kg^{-1}, with a mean of 26.9 mg kg^{-1}. Only one sampling point, from a pasture area, had a value higher than 50.0 mg kg^{-1}. This same sample also had the highest

Table 1 Descriptive statistics for soil properties measured in the study area within the Iperó region of São Paulo State, Brazil ($n = 25$)

Soil attribute	Min	Max	Range	Median	1st quartile (25 %)	3rd quartile (75 %)	Mean	Coefficient of variation (%)
Bulk density (g cm^{-3})	0.75	1.59	0.83	1.15	1.02	1.26	1.16	15.7
δ^{15}N (‰)	2.8	8.4	5.6	5.9	4.2	6.8	5.6	26.8
N (g kg^{-1})	0.2	5.1	4.9	1.6	1.2	2.1	1.8	57.8
δ^{13}C (‰)	−27.6	−14.8	12.8	−24.8	−26.3	−22.6	−23.3	17.6
C (g kg^{-1})	2.6	51.0	48.4	18.6	12.2	22.8	20.5	57.4
C:N ratio	7.2	15.8	8.6	11.7	9.9	12.8	11.5	17.6
pH	3.7	6.5	2.8	5.1	4.6	5.4	5.0	12.4
P (mg kg^{-1})	6.0	113.0	107.0	20.0	14.0	34.0	26.9	83.5
K (mg kg^{-1})	1.1	11.5	10.4	4.3	2.0	5.6	4.6	65.1
Ca (mg kg^{-1})	7.0	690.0	683.0	58.0	45.0	80.0	100.6	147.2
Mg (mg kg^{-1})	3.0	90.0	87.0	17.0	11.0	28.0	22.4	83.9
H + Al (mg kg^{-1})	10.0	79.0	69.0	27.0	24.0	40.0	33.0	51.8
Sum of bases (cmol kg^{-1})	11.3	783.3	772.0	86.8	58.5	115.3	127.5	130.2
Cation exchange capacity (cmol kg^{-1})	55.3	793.0	737.7	111.8	99.7	150.2	160.5	98.9

H + Al value. For the cases when the pH is <5.5, the plant available P in soil was increasingly tied up as aluminum phosphates. On the other hand, when the pH > 5.5 the majority of the phosphates react with Ca, forming calcium phosphates (Brady and Weil 2008). In our study, the extractable P and H + Al concentrations were significantly and negatively correlated ($P = 0.001$). Hence, in our study area, for most of the sampling points, the P was complexed with Al.

The pH values ranged from 2.6 to 6.5 with a median value of 5.1 (Table 1). Soil pH plays a critical role in the availability of the elements included in the CEC measurement (Schoenholtz et al. 2000). For our study, pH was not correlated with extractable K, however there was a significant positive correlation ($P < 0.001$) with Ca and Mg and a significant negative correlation ($P < 0.001$) with H + Al. The two sampling points with pH > 5.5, which were from forested sites, also had the highest Ca and Mg concentrations and the lowest H + Al concentrations.

The saturation of bases (V) is the relation [(SB/CEC)*100] (Ronquim 2010), and with values ranging from 20.4 to 98.8 % and a mean of 69.2 %. Only three sampling points had values lower than 50 %, pH < 4.4, and were classified as dystrophic; two of them were from pastures and one from the forest areas. Base saturation values were highly correlated with pH ($r = 0.94$, $P < 0.001$).

Description of influence of soil order and land cover

Although the soil orders Ultisol and Oxisol usually have different morphological as well as some physical and chemical features, reacting differently to management activities (Palm et al. 2007), no significant differences occurred among the soil attributes when the data were separated according to soil orders (Table 2). This means that for our study region the soil order is not a critical factor for differentiating the near-surface soil attributes. The similarity of the soil texture is one of the drivers for bulk density, aggregation, and various chemical properties. The high similarity between the texture of the two soil orders support the non-significant statistical differences between the soil orders for all measured soil properties.

On the other hand, significant differences were observed in 4 out of 15 soil attributes (δ^{15}N, δ^{13}C, Ca, and SB—Table 3) when grouped by land cover. The soil properties that were not significantly different trended to poorer quality in the pasture soils as compared to the pristine areas, except P and K. The total C and N concentrations were, respectively, about 30–40 % lower, the bulk density was approximately 12 % higher, and the pH was 11 % lower. The SB was roughly 35 % lower and H + Al around 40 % higher. The V was 53.1 % for pasture and significantly lower than that of the pristine forest and savannah, at 73.7 and 77.2 %, respectively.

The H + Al contribution to the CEC was 11.8 % for forest, 21.3 % for savannah and 46.2 % for pasture. The δ^{13}C values were significantly different between the land cover categories ($P = 0.05$), although total C concentrations were not. Thus different kinds of cover, while not significantly altering the amount of SOM, modify its quality.

The δ^{15}N was significantly different between the savannah and pasture ($P = 0.05$), with the highest mean value observed for pasture. Smaller concentrations of some nutrients, e.g. extractable Ca and Mg, jointly with the enrichment of δ^{15}N indicate that the pasture ecosystems

Table 2 Mean and coefficients of variation (CV) for physical, chemical, and isotopic soil properties grouped by soil order

Soil attribute	Soil class (number of sampling points)			
	Ultisoils (5)		Oxisoils (20)	
	Mean	CV (%)	Mean	CV (%)
Bulk density (g cm^{-3})	1.16	18.8	1.15	15.5
$\delta^{15}N$ (‰)	5.4	15.3	5.7	29.0
Total N (g kg^{-1})	2.0	50.9	2.0	59.4
$\delta^{13}C$ (‰)	−23.6	18.7	−23.3	17.8
Total C (g kg^{-1})	28.0	54.7	19.0	56.1
C:N ratio	12.3	18.9	11.4	17.4
pH	5.3	14.0	4.9	11.8
Extractable P (mg kg^{-1})	23.6	44.3	27.7	89.2
Extractable K (mg kg^{-1})	4.3	86.9	4.7	61.9
Extractable Ca (mg kg^{-1})	141.2	122.2	90.5	159.8
Extractable Mg (mg kg^{-1})	28.2	69.3	21.0	90.0
H + Al (mg kg^{-1})	27.2	57.7	34.4	50.8
Sum of bases (cmol kg^{-1})	173.6	110.0	116.0	140.2
Cation exchange capacity (cmol kg^{-1})	200.9	90.7	150.5	103.6

For all soil properties, there were no significant differences using the Kruskal–Wallis test ($P = 0.05$)

had become more open, and were more susceptible to external influences than the native ecosystems (Amundson et al. 2003; Boeckx et al. 2005; Viani et al. 2011a). The mean ratios of Ca:Mg:K was 45:8:1 for forest, 14:4:1 for savannah and 8:3:1 for pasture.

Fisher's linear discriminant and cluster analyses

First, we verified the distinction between the sampling points in the forest and savannah ecosystems that was the result of the FDA procedure (Fig. 3). Two sampling points from the forested areas were positioned far from the main group, most likely because these samples were from riparian zones. After the initial separation of the soil data, the software displayed the two FDA derived from the dataset. Next the seven pasture sampling points were analyzed, using the same measured soil attributes. Five of them were classified as forest and two as savannah.

Due to the difficulty of visually distinguishing the internal differences and similarities within land cover groups, a cluster analysis was conducted to help visualize the differences among and between sampling points from the three ecosystems. The dendrogram developed from the cluster analysis (Fig. 4) showed that two sampling points from the pasture soils were classified as originally being in

Table 3 Mean and coefficient of variation (CV) for physical, chemical, and isotopic soil properties grouped by land cover (LC) categories from the Iperó region of São Paulo State, Brazil

Soil attribute	LC categories (no. of sampling points)					
	Forest (9)		Savannah (9)		Pasture (7)	
	Mean	% CV	Mean	% CV	Mean	% CV
Bulk density (g cm^{-3})	1.18	16.8	1.06	15.3	1.24	11.7
$\delta^{15}N$ (‰)	5.8a, b	24.5	4.6a	26.8	6.7b	18.8
Total N (g kg^{-1})	2.0	54.2	2.0	60.2	1.2	41.1
$\delta^{13}C$ (‰)	−24.6a	5.3	−26.5b	2.0	−17.5c	16.1
Total C (g kg^{-1})	23.0	65.1	22.0	53.4	16.0	42.8
C:N ratio	11.3	18.1	10.8	18.4	12.8	13.1
pH	5.2	15.9	5.2	4.9	4.6	10.0
Extractable P (mg kg^{-1})	2.5	49.0	2.7	62.9	2.9	131.7
Extractable K (mg kg^{-1})	4.0	90.7	5.4	30.2	4.3	84.2
Extractable Ca (mg kg^{-1})	178.1a	129.9	73.1a, b	41.2	36.4b	44.5
Extractable Mg (mg kg^{-1})	31.4	88.1	20.0	47.7	13.9	52.6
H + Al (mg kg^{-1})	28.4	52.4	26.8	19.2	46.7	49.2
Sum of bases (cmol kg^{-1})	213.5a	121.0	98.4a, b	40.0	54.4b	48.7
Cation exchange capacity (cmol kg^{-1})	241.9	102.3	125.2	31.7	101.1	33.0

For the soil attributes that did not receive letter(s) in the cells, there were no significant differences using the Kruskal–Wallis test ($P = 0.05$). For soil attributes with letters in the cells, a different letter within a row indicates significant difference ($P = 0.05$) according to the Kruskal–Wallis test

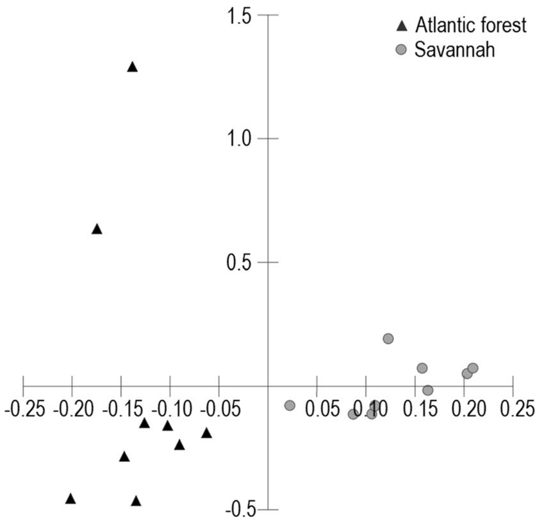


Fig. 3 Discriminant analysis ordination plot of the soil physical and chemical properties according to the type of vegetation

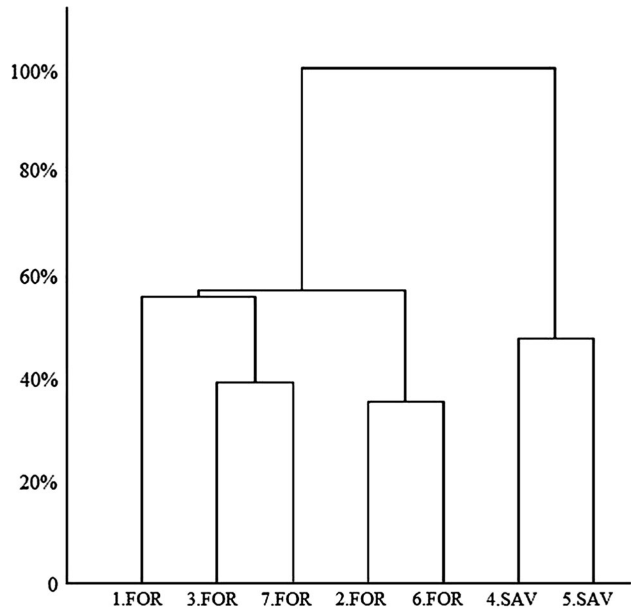


Fig. 4 Dendrogram developed using cluster analysis from the pasture soil data (Table 4). In the baseline, for example, 2. FOR corresponds to the sampling point #2 in Table 4 that was classified as forest by discriminant analysis. The vertical axis is the level of dissimilarity among the sampling points

savannah in one separated group and the other five sampling points were classified as forest with distinct levels of dissimilarity. Through this analysis, we suggest that the pasture samples #4 and #5 were completely different from the pasture other samples.

Interpretation of soil attributes and influence of the soil and land cover

The primary land cover transformation in Iperó has been a shift from forest or savannah to pasture (Monteiro and Silva 2011). Although statistical tests of the soil attribute data revealed that most variables had no significant differences, it is clear that land cover changes has driven modifications in the certain soil characteristics, especially regarding the SOM quality.

The last Brazilian agricultural census revealed that Iperó has a population of 2,772 cattle (IBGE 2013). Dividing this value by the area of pasture (5,032 ha) indicates that the density is 0.55 cattle ha^{-1}. Of course cattle are not uniformly spread in the pasture areas. However, the calculated value is below the average density for São Paulo State and suggests that the pastures are below the carrying capacity for the region.

If well managed, such pastures could help to improve the soil quality, bringing benefits to the local people, such as increasing biomass production, soil biological activity and plant residues and roots that provide organic matter (FAO 2005). A soil characteristic that could be managed is the level of acidity, especially since acid soils are usually more prone to weed and insect invasion, increased erosion and nutrient run-off into waterways, reduced microbial activity, and diminished farm income (NSW 1999).

Soil acidification is an ongoing natural process which can be enhanced by human activities, such as use of fertilizer amendments. This process should be controlled independently of soil classification (Ultisols and Oxisols), since the two soil orders tend to be acidic and have low nutrient capital (Palm et al. 2007). Since SOM is a critically regulator of the soil acidity and nutrient cycling (FAO 2005) and SOM accumulation depends essentially on tillage methods, root development, and residue management practices (Kong et al. 2009).

Many Ultisols and Oxisols in the tropics are under natural forest and once the land is cleared for cultivation, they rapidly lose SOM and fertility. Unless such land is used for tree-based cropping systems, they require intensive fertilization and liming (FAO 2005). Due to the similarity of these soil orders in response to conversion from native vegetation to agronomically managed systems, the grouping of the data according to soil orders did not permit us to distinguish between forest and savannah areas.

While some variables showed no significant differences among land covers, we could depict some local, ecological trends. The lack of significant differences in bulk density may be a consequence of low density of cattle and/or the lack of soil textural differences. For similar reasons, the pattern of soil aggregation probably is not significantly altered by land cover shifts.

There are different processes that might impact the ^{15}N patterns in soil profiles. For instance, burning surface layers

Table 4 Physical, chemical, and isotopic values for the seven sampling points collected from pasture areas and classified according to FDA

Soil attribute	Sampling points from pastures							Means for Sampling Points	
	1	2	3	4	5	6	7	1, 2, 3, 6, 7	4, 5
Bulk density (g cm^{-3})	1.14	1.06	1.28	1.44	1.33	1.37	1.1	1.19	1.39
$\delta^{15}N$ (‰)	7.8	7.7	7.0	4.1	7.0	7.1	6.1	7.1	5.6
N (g kg^{-1})	2.1	1.0	1.6	0.7	0.7	1.1	1.5	1.5	0.7
$\delta^{13}C$ (‰)	−14.8	−16.2	−15.8	−16.0	−20.1	−22.7	−17.2	−17.3	−18.1
C (g kg^{-1})	26.9	11.1	22.8	11.2	9.1	12.2	18.6	18.3	10.2
C:N ratio	12.8	10.8	14.1	15.8	12.6	11.4	12.4	12.3	14.2
pH	4.5	4.1	5.0	4.6	3.9	4.6	5.2	4.7	4.3
Extractable P (mg kg^{-1})	11.3	2.4	1.4	1.2	0.6	1.4	1.7	3.6	0.9
Extractable K (mg kg^{-1})	6.0	1.2	11.5	1.8	1.2	4.4	4.3	5.5	1.5
Extractable Ca (mg kg^{-1})	54.0	22.0	53.0	23.0	16.0	37.0	50.0	43.2	19.5
Extractable Mg (mg kg^{-1})	23.0	6.0	23.0	9.0	6.0	16.0	14.0	16.4	7.5
H + Al (mg kg^{-1})	79.0	42.0	30.0	27.0	77.0	48.0	24.0	44.6	52.0
Sum of bases (cmol kg^{-1})	83.4	28.9	87.4	33.4	22.7	57.2	67.9	65.0	28.1
Cation exchange capacity (cmol kg^{-1})	162.8	71.1	117.9	60.8	99.7	105.1	92.1	109.8	80.3
Classified as	Forest	Forest	Forest	Savannah	Savannah	Forest	Forest	–	–

often eliminates the most ^{15}N-depleted portion of the soil profile, and other practices such as windrowing or clear-cuts can also enrich the soil profiles with ^{15}N, due to modifications in the rates of loss of ^{15}N-depleted fractions through hydrologic pathways and alterations in the microbial community responsible for N mineralization processes (Hobbie and Ouimette 2009).

Fire is a factor that periodically occurs in the savannah and pasture areas, especially during the dry season. Thus it would be expected that savannah and pasture areas would be significantly different from forested sites and other land cover categories. However, statistical analysis revealed a different situation: savannah and pasture are significantly different from each other, while the forest sites were not significantly different from the other two. Hence, for our sites, it appears that climatologic features may be more important than anthropogenic activities as the primary driving force in the N fractionation processes (Robinson 2001; Hobbie and Ouimette 2009).

For the elements that constitute the cationic exchangeable bases, the differences reported here agrees with the findings reported by Viani et al. (2011b), who also researched differences in the soil attributes amongst varying vegetation types. They found significant differences in the Ca, K and Mg concentrations in soils covered with semidecidual forest versus savannah located at an ecological station located in São Paulo State, which is a region with similar ecological characteristics to our study site, with higher mean element concentrations in forest versus savannah soils. They found the mean concentration of extractable K 13 times higher in forest as compared to savannah soils, and extractable Ca and Mg were 29 and 7 times higher in the forest soil, respectively.

Discriminant analyses: strengths and weaknesses

Use of multiple soil attributes is more likely to result in successful guidelines for restoration of a pastured area. The FDA classified the pasture sampling points #4 and #5 (see Table 4) as being originally in savannah vegetation, with the other pasture points as originally in forest. Analyzing the data in Table 4, we perceived that sampling point #2 had several soil property values similar to savannah, however, the FDA indicated that it was likely to be originally in forest cover. Such statistical techniques are available in most statistical packages and include a prediction option. The variables evaluated were pH, P, K, Ca, Mg, SB, CEC and *V* are relatively easy to quantify and such analyzes are available from most commercial soil laboratories, as they are important markers for soil fertility (Mekaru and Uehara 1972).

For projects that aim to re-establish an ecosystem with native vegetation in ecotones, soil information from pristine ecological areas will be critical (Heneghan et al. 2008; Corbin and Holl 2012). Within this study, the locations where forest appeared to be the original vegetation, we suggest planting species of the Atlantic forest biome, and for those identified as savannah, the relevant savannah biome plant species should be used.

It is difficult to provide a precise estimate of the worldwide land area covered by ecotonal zones, but it is a significant, and many ecotonal areas have been degraded due to conversion to managed systems (Evett et al. 2012).

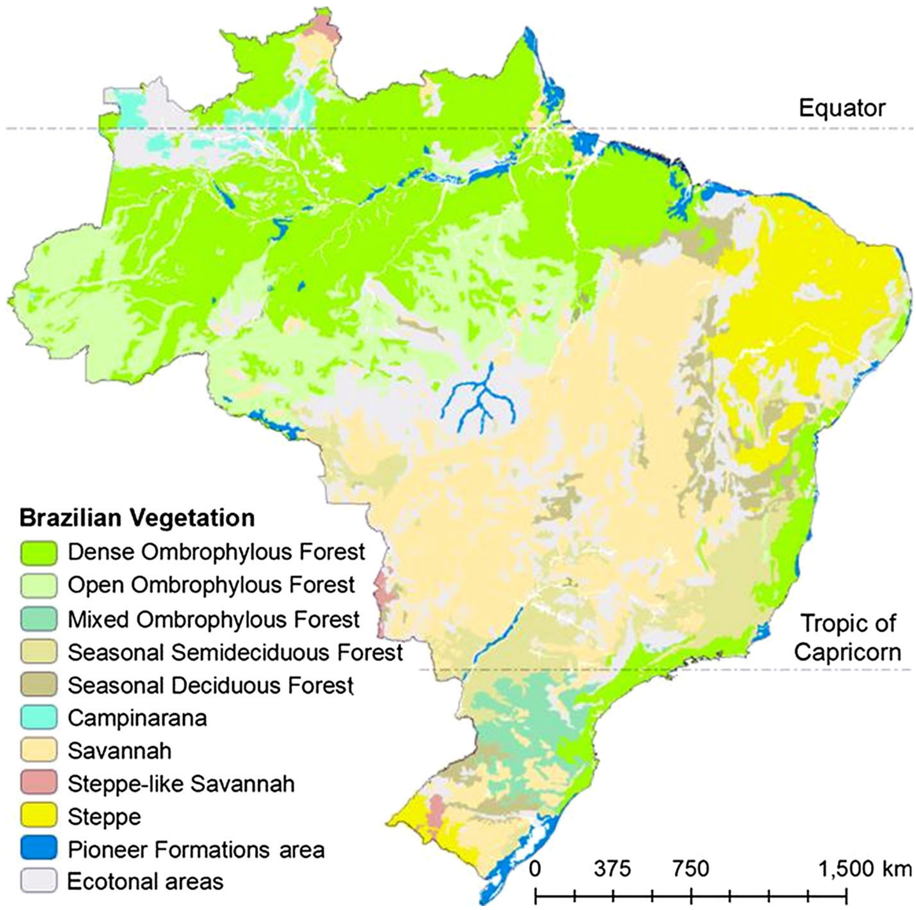


Fig. 5 Brazilian national map of Biomes. Modified from IBGE (2004)

In Brazil, there are enormous ecotonal areas between the large number of diverse biomes (Fig. 5), and there is a demand for services to re-establish the native vegetation and restore many of these areas (Silva et al. 2007; Rodrigues et al. 2011). However, Brazil, while a tropical country of continental dimensions, is not a unique case. These ecotonal zones exist worldwide, with a majority being degraded (Cheng-quing and Xing 1999; Possley et al. 2009). Thus, the demand for ecotonal–ecosystem restoration services is high and pre-established models, such as the one put forth in this study, should be considered.

The methodology proposed in our study holds the potential to be a successful tool in restoring degraded areas by identifying the original native vegetation present in the ecotones before they became degraded through the use of soil attributes and statistical procedures. Many and more detailed studies are needed and new variables should be tested, because the database we developed was small and for use in a region of $<200\ km^2$, and developed using locally obtained information.

Each region and biome have their own ecological uniqueness. Hence, a comprehensive regional soil database that includes chemical, physical, and isotopic features, among other attributes is critical, and should include high-quality pristine areas. Other kinds of information, such as aerial images, should be included when available.

Conclusion

This study demonstrated the use of soil property data and multivariate analysis to develop a guideline for ecotonal restoration projects. Soil order classification was an environmental feature that did not have significant influence over the results. On the other hand, some soil variables were significantly different between the ecologically pristine areas (forest or savannah) and pastured areas. However comparisons between the forest- and savannah-covered lands were generally not significant, except for $\delta^{13}C$.

Although ecosystem restoration is not a substitute for good conservation goals, it is recognized globally as a key component in conservation programs and essential to the quest for the long-term sustainability of ecosystems (Aronson and Alexander 2013). The method presented here has the potential to be an effective tool for identification of the original native vegetation present before ecotones became degraded and can to be used in restoring degraded areas.

In the case of Iperó, some lists of plant species both for forest and savannah are already available (e.g. Albuquerque and Rodrigues 2000). For regions where the species composition has not yet been surveyed, we recommend beginning with a plant community survey, as well as an expansion of the local soil database, including both the pristine and degraded areas.

If the method of restoration chosen is the soil seed bank enrichment, seed rain and/or seedling transference (for details, see Rodrigues et al. 2009), we recommend collecting material (soil and/or forest litter, for details of this technique, see Reis et al. 2010) from forest areas and putting such material in areas indicated as forest, and the same for savannah. However, an expansion of the soil database, especially for key soil properties that distinguish between the primary pristine ecosystems of interest within the region of interest is critical.

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References

Albuquerque GB, Rodrigues RR (2000) A vegetação do Morro de Araçoiaba, Floresta Nacional de Ipanema, Iperó (SP). Sci For 58:145–159

Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM (2013) Modeling monthly mean air temperature for Brazil. Theor Appl Climatol 113:407–427

Amundson R, Austin AT, Schuur EAG, Yoo K, Matzek V, Kendall C, Uebersax A, Brenner D, Baisden WT (2003) Global patterns of the isotopic composition of soil and plant nitrogen. Glob Biogeochem Cycles 17:1031–1040

Aronson J, Alexander S (2013) Ecosystem restoration is now a global priority: time to roll up our sleeves. Restor Ecol 21:293–296

Ayres M, Ayres Jr M, Ayres DL, Santos AA (2007) Bioestat 5.0-Users Manual. Federal University of Pará–Belém, PA, Brazil

Boeckx P, Paulino L, Oyarzun C, Cleemput O, Godoy R (2005) Soil δ^{15}N patterns in old-growth forests of southern Chile as integrator for N-cycling. Isotopes Environ Health Stud 41:249–259

Bradshaw A (1997) Restoration of mined lands using natural processes. Ecol Eng 8:255–269

Brady NC, Weil RR (2008) The nature and properties of soils, 14th edn. Prentice-Hall, Upper Saddle River

Burns R, Burns R (2008) Business research methods and statistics using SPSS. Extra chapter (number 25: Discriminant Analysis), Sage. http://www.uk.sagepub.com/burns/website%20material/Chapter%2025%20-%20Discriminant%20Analysis.pdf. April 2013

Byrne M, Stone L, Millar M (2011) Assessing genetic risk in vegetation. J Appl Ecol 48:1365–1373

Carvalho JLN, Raucci GS, Cerri CEP, Bernoux M, Feigl BJ, Wruck FJ, Cerri CC (2010) Impact of pasture, agriculture and crop-livestock systems on soil C stocks in Brazil. Soil Tillage Res 110:175–186

Chazdon RL (2008) Beyond deforestation: restoring forests and ecosystem services on degraded lands. Science 320:1458–1460

Cheng-quing Y, Xing W (1999) Degradation problems of the land/water ecotones in China and their ecological impact to water systems. J Environ Sci 11:247–251

Corbin JD, Holl KD (2012) Applied nucleation as a forest restoration strategy. For Ecol Manag 265:37–46

Durigan G, Ratter JA (2006) Successional changes in cerrado and cerrado/forest ecotonal vegetation in western Sao Paulo State, Brazil–1962–2000. Edinb J Bot 63:119–130

Ellis EC (2011) Anthropogenic transformation of the terrestrial biosphere. Philos Trans R Soc A 369:1010–1035

EMBRAPA (1997) Brazilian Enterprise of Agricultural Research. Manual de métodos de análise de solos. 2nd edn. Rio de Janeiro-RJ, Brazil

Evett RR, Dawson A, Bartolome JW (2012) Estimating vegetation reference conditions by combining historical source analysis and soil phytolith analysis at Pepperwood Preserve, northern California Coast Ranges, USA. Restor Ecol 21:64–473

FAO (1992) Food and Agriculture Organization of the United Nations Soil classification and characterization. Technical Paper 1. http://www.fao.org/wairdocs/ilri/x5546e/x5546e04.htm#1.2. Accessed April 2014. Soils and their classification

FAO (2005) Food and Agriculture Organization of the United Nations The importance of soil organic matter. FAO's Soil Bulletin 80. Rome, Italy. http://www.fao.org/docrep/009/a0100e/a0100e.pdfAccessed April 2014

Foley JA, DeFries R, Asner GP et al (2005) Global consequences of land use. Science 309:570–574

Gandolfi S, Joly CA, Rodrigues RR, Martins S (2007) Forest restoration: many views and objectives. High diversity forest restoration in degraded areas. Nova Science Publishers, New York, pp 3–26

Henderson R, Ragg JM (1980) A reappraisal of soil mapping in an area of Southern Scotland: part II. The usefulness of some morphological properties and of a discriminant analysis in distinguishing between the dominant taxa of four mapping units. J Soil Sci 31:573–580

Heneghan L, Miller SP, Baer S, Callaham MA, Montgomery J, Pavao-Zuckerman M, Rhoades CC, Richardson S (2008) Integrating soil ecological knowledge into restoration management. Restor Ecol 16:608–617

Hobbie EA, Ouimette AP (2009) Controls of nitrogen isotope patterns in soil profiles. Biogeochemistry 95:355–371

IBGE (2004) Brazilian Institute for Geography and Statistics Mapa de vegetação do Brasil. Scale 1:5,000,000, 3rd edn. IBGE, Rio de Janeiro-RJ, Brazil

IBGE (2013) Brazilian Institute for Geography and Statistics Demographic Sense 2010. http://www.censo2010.ibge.gov.br/en/resultados. Accessed March 2013

Jones HP, Schmitz OJ (2009) Rapid recovery of damaged ecosystems. PLoS One 4(5):e5653

Kark S (2011) Ecotones and ecological gradients. In: Leemans R (ed) Ecological systems—selected entries from the encyclopedia of sustainability science and technology. Springer, New York

Kettle WD, Rich PM, Kindscher K, Pittman GL, Fu P (2000) Land-use history in ecosystem restoration: a 40 year study in the prairie-forest ecotone. Restor Ecol 8:307–317

Kong XB, Dao TH, Qin J, Qin H, Li C, Zhang F (2009) Effects of soil texture and land use interactions on organic carbon in soils in North China cities' urban fringe. Geoderma 154:86–92

Lamb D, Erskine PD, Parrotta JA (2005) Restoration of degraded tropical forest landscapes. Science 310:1628–1632

Lambin EF, Geist HJ, Lepers E (2003) Dynamics of land-use and land-cover change in tropical regions. Annu Rev Environ Resour 28:205–241

Liebenberg D, Claassens S, Van Rensburg L (2013) Insights and lessons learned from the long-term rehabilitation of an iron ore mine. Int J Environ Res 7:633–644

Matthews JA (1979) A study of the variability of some successional and climax plant assemblage-types using multiple discriminant analysis. J Ecol 67:255–271

Mekaru T, Uehara G (1972) Anion adsoption in ferruginous tropical soils. Soil Sci Soc Am J 36:296–300

Monteiro T, Silva AM (2011) Análise da fragmentação da vegetação do município de Iperó-SP-subsídios para programas de recuperação de áreas degradadas. 10th Brazilian Congress of Ecology—proceedings, São Lourenço–MG, Brazil

NSW (1999) New South Wales Pastures and acid soils. Acid Soil Action Program of the Australian Department of Agriculture, leaflet number 6, 4 p. http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0005/167261/acid-soil-pastures.pdf. Accessed September 2013

Oliveira JB, Camargo MN, Rossi M, Calderano Filho B (1999) Mapa Pedológico do Estado de São Paulo-Legenda Expandida. Instituto Agronômico de Campinas and EMBRAPA–Solos, Rio de Janeiro–RJ–Brazil

Palm C, Sanchez P, Ahamedi S, Awiti A (2007) Soils: a contemporary perspective. Ann Rev Environ Resour 32:99–129

Piqueray J, Bottin G, Delescaille LM, Bisteau E, Colinet G, Mahy G (2011) Rapid restoration of a species-rich ecosystem assessed from soil and vegetation indicators: the case of calcareous grasslands restored from forest stands. Ecol Indic 11:724–733

Possley J, Maschinski J, Rodriguez C, Dozier JG (2009) Alternatives for reintroducing a rare ecotone species: manually thinned forest edge versus restored habitat remnant. Restor Ecol 17:668–677

Raij B, Andrade JC, Cantarella H, Aquaggio JA (2001) Análise química para avaliação da fertilidade de solos tropicais. Instituto Agronômico de Campinas, Brazil, p 284

Reis A, Bechara FC, Tres DS (2010) Nucleation in tropical ecological restoration. Sci Agric 67:244–250

Robinson D (2001) ^{15}N as an integrator of the nitrogen cycle. Trends Ecol Evol 16:153–162

Rodrigues RR, Lima RAF, Gandolfi S, Nave A (2009) On the restoration of high diversity forests: 30 years of experience in the Brazilian Atlantic Forest. Biol Conserv 142:1242–1251

Rodrigues RR, Gandolfi S, Nave AG, Aronson J, Barreto TE, Vidal CY, Brancalion PH (2011) Large-scale ecological restoration of high-diversity tropical forests in SE Brazil. Forest Ecol Manag 261:1605–1613

Ronquim, CC (2010) Conceitos de fertilidade do solo e manejo adequado para as regiões tropicais. Boletim de Pesquisa & Desenvolvimento 8. Brazilian Enterprise of Agricultural Research (Embrapa), Campinas–SP, Brazil. http://www.cnpm.embrapa.br/publica/download/bpd_8.pdf. Accessed in April 2014

Ruggiero PGC, Batalha BA, Pivello VR, Meirelles ST (2002) Soil-vegetation relationships (Brazilian savannah) and semi deciduous forest, Southeastern Brazil. Plant Ecol 160:1–16

Schoenholtz SH, Miegroet HV, Burger JA (2000) A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities. Forest Ecol Manag 138:335–356

Silva AM, Nalon MA, Kronka FJN, Alvares CA, Camargo PB, Martinelli LA (2007) Historical land-cover/use in different slope and riparian buffer zones in watersheds of the State of São Paulo, Brazil. Sci Agric 64:325–335

Silva AM, Nogueira DP, Ikematsu P, Silveira FM, Bomback M, Alves SH, Paula FP, Camargo PB (2009) Carbon stocks and isotopic composition of the organic matter in soils covered by native vegetation and pasture in Sorocaba, SP, Brazil. Int J Environ Res 3:435–440

Tavili A, Jafari M (2009) Interrelations between plants and environmental variables. Int J Environ Res 3:239–246

Vasenev VI, Stoorvogel JJ, Vasenev II (2013) Urban soil organic carbon and its spatial heterogeneity in comparison with natural and agricultural areas in the Moscow region. Catena 107:97–102

Vaughn J, Porensky LM, Wilkerson ML, Balachowski J, Peffer E, Riginos C, Young TP (2010) Restoration ecology. Nat Educ Knowl 3:66

Viani RA, Rodrigues RR, Dawson TE, Oliveira RS (2011a) Functional differences between woodland savannahs and seasonally dry forests from south-eastern Brazil: evidence from ^{15}N natural abundance studies. Austral Ecol 36:974–982

Viani RA, Rodrigues RR, Dawson TE, Oliveira RS (2011b) Savanna soil fertility limits growth but not survival of tropical forest tree seedlings. Plant Soil 349:341–353

Vieira DLM, Scariot A (2006) Principles of natural regeneration of tropical dry forests for restoration. Restor Ecol 14:11–20

Webster R, Burrough PA (1974) Multiple discriminant analysis in soil survey. J Soil Sci 25:120–134

Williams BK (1983) Some observations of the use of discriminant analysis in ecology. Ecology 64:1283–1291

Wolters V et al (2000) Effects of global changes on above-and below ground biodiversity in terrestrial ecosystems: implications for ecosystem functioning. Bioscience 50:1089–1098

Zahawi RA, Holl KD, Cole RJ, Reid JL (2013) Testing applied nucleation as a strategy to facilitate tropical forest recovery. J Appl Ecol 50:88–96