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RESEARCH ARTICLE

Look down—there is a gap—the need to include soil data in Atlantic Forest restoration

Maiara S. Mendes[1,2,3], Agnieszka E. Latawiec[1,2,3,4,5,6], Jerônimo B. B. Sansevero[3,7], Renato Crouzeilles[1,2,8], Luiz F. D. Moraes[3,9], Ana Castro[1,2], Helena N. Alves-Pinto[1,2,8], Pedro H. S. Brancalion[10], Ricardo R. Rodrigues[11], Robin L. Chazdon[2,12], Felipe S. M. Barros[2], Juliana Santos[1,2], Alvaro Iribarrem[1,2], Stella Mata[3], Luisa Lemgruber[1,2], Aline Rodrigues[1,2], Katarzyna Korys[1,2], Bernardo B. N. Strassburg[1,2,8]

Consideration of soil quality indicators is fundamental for understanding and managing ecosystems. Despite the evidence regarding the importance of soil for provision of local and global ecosystem services, such as water regulation and carbon sequestration, soil remains an under-investigated and undermined aspect of the environment. Here we evaluate to what extent soil indicators are taken into account in restoration. We focused on the Brazilian Atlantic Forest, a highly fragmented biome and a global biodiversity hotspot. We conducted a systematic literature review and we showed that the majority (59%) of the studies on restoration did not consider any soil indicator. Studies that demonstrated the importance of soil indicators most commonly reported soil pH (71%, $n=44$), followed by potassium content (66%, $n=41$) and phosphorus (64.5%, $n=40$), while the least reported indicator was water retention (6.5%, $n=4$). Only 40% of the retrieved studies included information about reference sites or project baseline information. We complement our literature review with a case study on restoration in two areas of the Atlantic Forest. We found a relation between soil indicators such as soil organic matter, nitrogen, sodium and sand content, and aboveground indicators, confirming a necessity to include soil screening in restoration. Moreover, we found that prior to restoration none of these soil indicators were analyzed. This study highlights the gap that exists in soil data in restoration in studies on the Brazilian Atlantic Forest. We urge scientists and practitioners to include basic soil analysis to maximize the successful outcomes of restoration.

Key words: Atlantic Forest, forest landscape restoration, gap analysis, restoration, soil–restoration relationship, systematic review

Implications for Practice

- Understanding of soil impacts on restoration is fundamental for restoration success.
- Soil analysis needs to be performed routinely before and throughout any restoration project.
- By highlighting the gap that exists in soil data in restoration projects we urge stakeholders involved in restoration to include soil characteristics when planning and managing restoration projects.

Introduction

Deforested and fragmented landscapes compromise the provision of ecosystem services such as biodiversity conservation, water quality and quantity regulation, carbon storage, and soil protection (Gama-Rodrigues et al. 2008; Ditt et al. 2010). In response to land degradation and the need to recover services that ecosystems provide, such as biodiversity (Latawiec et al. 2016; Crouzeilles et al. 2017), carbon (Porter et al. 2009), or water (Ferraz et al. 2013), restoration has gained increased interest and has been promoted globally and locally (Aronson et al. 2011). For instance, the Bonn Challenge sets a goal to restore worldwide 150 million hectares of disturbed ecosystems and the 20x20 Initiative aims to bring 20 million hectares into restora-

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[1]Department of Geography and the Environment, Rio Conservation and Sustainability Science Centre, Pontifícia Universidade Católica, 22453900, Rio de Janeiro, Brazil
[2]International Institute for Sustainability, Estrada Dona Castorina 124, 22460-320, Rio de Janeiro, Brazil
[3]Escola Nacional de Botânica Tropical (ENBT), Rua Pacheco Leão, 2040-Solar da Imperatriz, Horto, 22460-036, Rio de Janeiro, Brazil
[4]Institute of Agricultural Engineering and Informatics, Faculty of Production and Power Engineering, University of Agriculture in Kraków, Balicka 116B, 30-149, Kraków, Poland
[5]School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich, NR4 7TJ, U.K.
[6]Address correspondence to A. E. Latawiec, email a.latawiec@iis-rio.org
[7]Department of Environmental Science, Federal Rural University of Rio de Janeiro (UFRRJ), Rodovia BR 465, Km 07, 23890-000, Seropédica, Rio de Janeiro, Brazil
[8]Programa de Pós Graduação em Ecologia, Universidade Federal do Rio de Janeiro, 68020, Rio de Janeiro, Brazil
[9]Brazilian Agricultural Research Corporation, Embrapa Agrobiology, Rodovia BR 465, Km 7, 23891-000, Seropédica, Rio de Janeiro, Brazil
[10]Departamento de Ciências Florestais, Universidade de São Paulo, Escola Superior de Agricultura Luiz de Queiroz, Av. Pádua Dias 11, 13.418-900, Piracicaba, SP Brazil
[11]Departamento de Ciências Biológicas, Universidade de São Paulo, Escola Superior de Agricultura Luiz de Queiroz, Av. Pádua Dias n. 11, 13.418-900, Piracicaba, SP Brazil
[12]Department of Ecology and Evolutionary Biology, University of Connecticut, Storrs, CT 06269, U.S.A.

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tion, both by 2020. The New York Declaration on Forests, endorsed by 190 countries and companies, establishes a global timeline to halve natural forest loss by 2020, and to end it by 2030.

In Brazil, according to the National Plan for the Recovery of Native Vegetation (Planaveg 2016), approximately 12.5 million hectares will have to be recovered in the next 20 years. Regionally, the Pact for the Restoration of the Atlantic Forest aims to restore 15 million hectares in the biome by 2050 in an attempt to recover ecosystem services compromised by historical deforestation for coffee and sugarcane plantations that caused dramatic modification and degradation of this biome (Calmon et al. 2011). Currently, more than 80% of Atlantic Forest remaining is composed of forest fragments smaller than 50 ha (Ribeiro et al. 2009) and this biome suffered degradation to more extent than any other Brazilian biome. Restoration in this biome therefore faces great opportunities and challenges.

Soil has been studied to lesser extent in the context of restoration than biodiversity, carbon, or water (Ohsowski et al. 2012) wherein both active planting and natural regeneration have been shown to impact the provision of these ecosystem services (Porter et al. 2009; Latawiec et al. 2016; Crouzeilles et al. 2017). Lack of adequate soil consideration has also been pointed out in the context of conservation, ecology, and carbon balance (Wardle 2002). Good soil quality promotes plant growth, regulates water distribution, and attenuates environmental degradation (Larson & Pierce 1991), and deforestation often leads to negative changes in soil chemistry, structure, and biota, impacting plant productivity and composition (Doran & Zeiss 2000; Centurion et al. 2001; Eviner & Hawkes 2008). Soil organic carbon affects important functional processes in soil like the storage of nutrients (mainly nitrogen), stability of aggregates, and water holding capacity (Silva & Sá Mendonça 2007). Nitrogen in soil is a key nutrient and the most required by plants and it is essential in assessments of soil quality. Soil texture is an important physical indicator and it is correlated with hydrological process such as run-off, erosion, infiltration rate, and water holding capacity. It is an indicator very stable through time, mostly independent of the soil management.

To assess whether forest restoration projects are feasible, monitoring of environmental quality, including soil analysis, and baseline assessment prior to monitoring are fundamental (Rocha et al. 2015). Soil chemical indicators are important when considering soil capacity to maintain nutrient cycling, plant biomass, organic matter, and for sustaining forest production and sustainability (Schoenholtz et al. 2000). The most important chemical indicators to be assessed are pH, available P, K, Cu, Fe, Mn, and Zn (Idowu et al. 2008). In addition, different native species often present symptoms of deficiency, if certain nutrients are not present in the soil (Sorreano et al. 2012). However, despite the importance of soil for the provision of crucial ecosystem services and although restoration efforts may fail if they do not consider the limitations of soil conditions, soil data are rarely reported in restoration projects (Ehrenfeld et al. 2005). Furthermore, few studies monitor the processes of recovery of the physical and chemical attributes of soil throughout restoration process. Some authors claim that restoration is "phytocentric" and underestimates belowground environment and soil ecological knowledge (Callaham et al. 2008; Kardol & Wardle 2010; Ohsowski et al. 2012).

Our systematic literature review investigates to what extent soil indicators are assessed within restoration projects in the Brazilian Atlantic Forest. In addition, we analyzed a case study to explore the relationship between soil indicators and vegetation structure (basal area and tree height) within two areas restored in the Atlantic Forest. The overarching aim of this study was to verify whether a soil data gap exists in restoration projects. The results of this study may ultimately help scientists and decision-makers to plan restoration more effectively.

Methods

Systematic Literature Review

We conducted a systematic literature review (Table S1, Supporting Information) on soil data in restoration projects in the Brazilian Atlantic Forest. The search for the studies was carried out in Web of Science, Scopus, Scielo, Capes, and Google Scholar databases, and was not restricted by publication date. Both peer-reviewed journal articles and theses were included in our database. While searching the articles and theses, the following key words were used: *Restoration & soil, natural regeneration & soil, Restoration Ecology & Atlantic Forest, Atlantic Rainforest & Restoration & Soil, Restoration & Soil, Natural Regeneration & Soil, Ecological restoration & Soil, Atlantic Forest & Restoration & Soil*. These words were searched both in English and Portuguese. Two criteria were used to include the studies in the database: (1) restoration studies in which soil variables were available; and (2) the study area should be within the Brazilian Atlantic Forest biome.

From the selected articles and theses, when available, we collected data on: (1) characteristics of restoration projects (e.g. latitude and longitude, age, and total restored area); (2) type of restoration (active or passive—as defined in each study); (3) soil indicators (e.g. carbon, pH, nitrogen, phosphorus, potassium, water retention, cation exchange capacity, aluminium, iron, C/N ratio, granulometry, and soil biota; Table S2); and (4) forest indicators (e.g. basal area, canopy height; Table S3), species and diversity species richness, and diversity of restored forests and reference areas. We differentiated reference area as either positive or negative (e.g. Benayas et al. 2009). The positive reference area was characterized by old-growth forest, well-developed forests or in very advanced stages of succession. The negative reference was represented by degraded areas (e.g. degraded pastureland) in which restoration was implemented.

Case Study

Case Study Area. The restoration project based on our case study (Mutirão de Reflorestamento, in Portuguese) was initiated in 1984 in various parts of the municipality of Rio de Janeiro. It was led by the local government in order to control disorderly occupation on hillsides, marginal areas, and areas with a high risk of landslides and fires. The project acted in 150 sites and

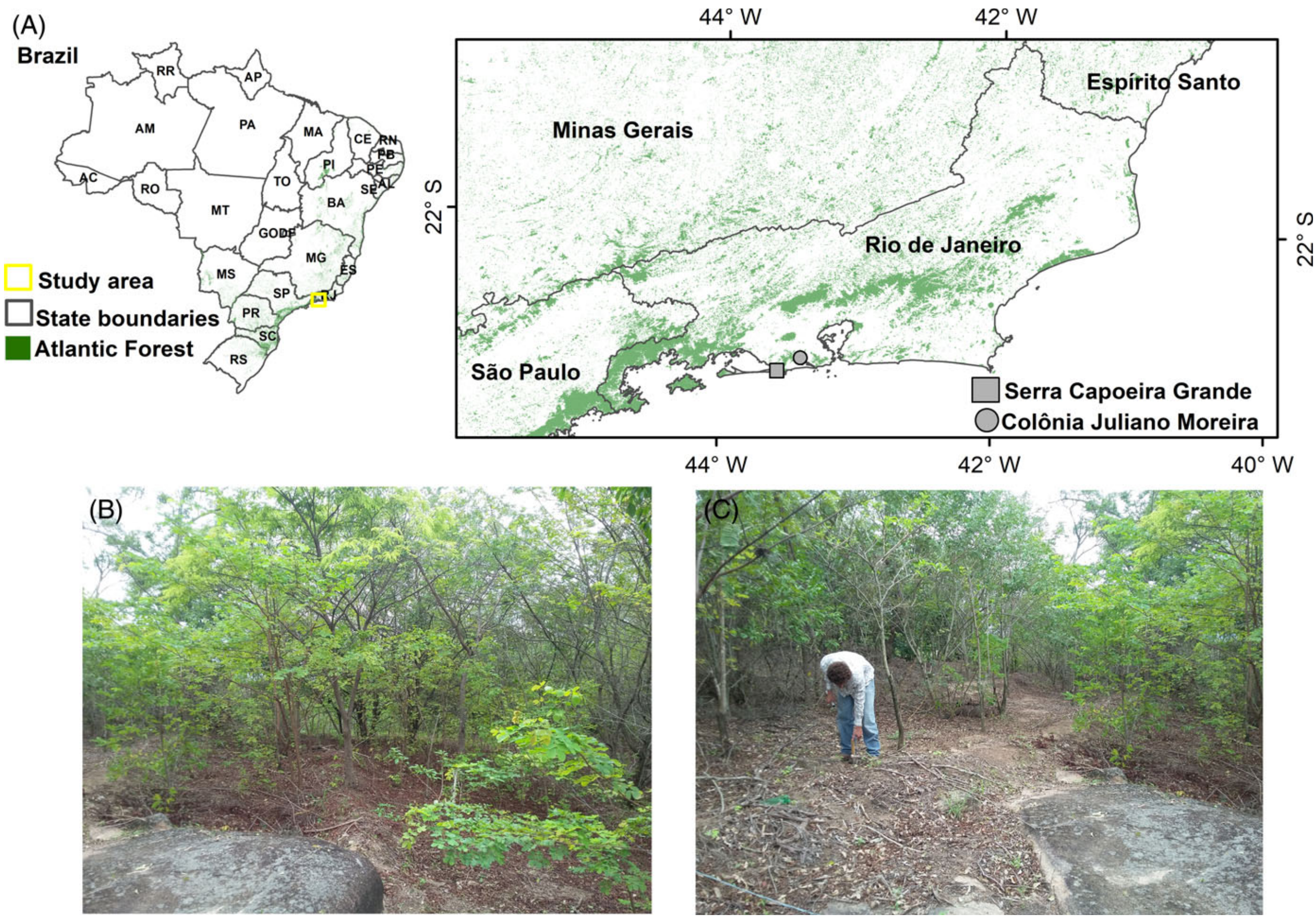

Figure 1. Location of the case study: Atlantic Forest biome (A); The community Colônia Juliano Moreira (Entre Rios) and Serra Capoeira Grande (B); Serra Capoeira Grande site 7 years after being restored (C); soil sample collection in Serra Capoeira Grand site in June of 2016 (D). Photo can be credited: Maiara Mendes.

restored about 3,000 hectares of the Atlantic Forest. We selected two sites for our analysis, both in the western zone of Rio de Janeiro (Fig. 1). Site 1: Colônia Juliano Moreira (also called “Entre Rios”)—22°56′13.44″S and 43°24′26.25″W and Site 2: Serra Capoeira Grande—22°59′14.53″S and 43°38′31.32″W (Fig. 1).

These two sites present a similar history of land use, where initially there was intense sugarcane and coffee cultivation, subsequently replaced by citrus production (Patzlaff 2007; Souza 2013; Muler 2014). The sites differ with respect to soil type (Table 1). The project started in both areas in 2009, completing 7 years of project implementation at the time of sampling for this research (June 2016). Both projects were implemented following the same methodological procedures (native tree species plantations) and maintenance frequency (Mata 2017). The species used in the restoration of Site 1 were defined by the Atlantic Forest Fiocruz Campus (research foundation), which allowed the planting only of species of natural occurrence in that region (Maciço da Pedra Branca, personal communication with forestry engineer responsible for the restoration project in this area; Miranda 2017). Table 2 presents the mean height and basal area of species evaluated in both sites.

Soil Sampling, Vegetation, and Analyses in the Case Study. At each site, 20 permanent experimental plots of $100\,m^2$ (10 × 10 m) were established with a minimum distance of 20 m between each other. Experimental plots totaled 0.2 ha/site, and the mean of soil attributes and vegetation structure are presented in Tables 1, 2, and S4. Soil sampling for chemical and physical analysis was performed with a probe. We collected 10 samples of soil per plot at a depth of 0–20 cm, and then mixed them to form a single composite sample (Tables S5 & S6). These samples were analyzed for pH, pF curve 15 atm (%), pF curve 0.1 (%), moisture (%), total N (g/kg), total P (mg/dm^3), total K (mg/dm^3), total Na (mg/dm^3), total Mg ($cmol/dm^3$), Ca ($cmol/dm^3$), Al ($cmol/dm^3$), H + Al ($cmol/dm^3$), Fe (mg/dm^3), Mn (mg/dm^3), and Cu (mg/dm^3). Soil pH was measured in water. Nitrogen was determined using the Kjeldahl method. Phosphorus and potassium were analyzed using a Mehlich-1 extractor (0.05 mol/L HCl and 0.0125 mol/L H_2SO_4) while total Mg was measured using a 1 mol/L KCl solution. To determine organic matter (OM) content, $Na_2Cr_2O7 + H_2SO_4$ 10 N oxidation was applied. Carbon content (C) was calculated as C = OM/1.724 and subsequently the C/N ratio was determined. Iron, manganese, and copper were analyzed using a Mehlich-1

Table 1. Results of nutrient content and soil texture in the plots of the case study of the Mutirão de Reflorestamento project in the Capoeira Grande site, Rio de Janeiro.

		P-Resin	*N*	*P*	*Na*	*H + Al*	*O.M*	*P.rem*	*Fe*	*Mn*	*Silt*	*Sand*
Site	*pH*	*mg/dcm*	*g/kg*	*mg/dm³*		*cmol/dm³*	*dag/kg*	*mg/L*	*mg/dm³*		*dag/kg*	
Entre Rios	4.1	10.7	1.67	7.31	31.4	12.8	1.39	23.59	231.6	16.75	14.35	68.2
Capoeira Grande	5.16	5.62	1.71	2.44	32.06	2.89	1.65	40.65	58.88	41.6	19.15	62.95

Table 2. Mean height and mean basal area of species, sampled in the case study of the Mutirão de Reflorestamento in the Entre Rios and Capoeira Grande sites, Rio de Janeiro.

Sites	*N Plots*	*Height*	*Basal Area*
Entre Rios	20	6.56	14.49
Capoeira Grande	20	4.8	6.27

extractor (in relation to soil extractor 1:10). The potential cation exchange capacity (CEC) was measured as the sum of the base cations Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+} in addition to Al^{3+} and H^{+} (cmol/kg). The effective CEC was defined as the sum of base cations in addition to Al^{3+} (determined using a 1 mol/L KCl solution). To investigate soil water properties, pF curves were calculated by a Richards pressure chamber. Analysis of the soil moisture and retention curve was based on the methodology described by Klute (1986) and for the analysis of the texture we used the sedimentation fractionation methodology described by Gee and Bauder (1986). Basal area and height were measured for all plants with diameter at breast height (DBH) greater than or equal to 5 cm in the same plots where soil data were collected (Table S4). We chose to measure the basal areas as an indicator of success of the restored areas because the basal area is highly correlated with the aboveground biomass and carbon (Clark & Clark 2000).

Statistical Analysis

We ran a series of generalized linear mixed-effect models (GLMMs; "lme4" package—R program; R Core Team 2013) to detect if soil variables influenced vegetation structure and to evaluate which variables are more important to explain height and basal area of the trees in the restored areas. All data were transformed using logarithm transformation, except for silt and sand content to which we applied arcsine of square root transformation. We used the "area" variable of each site as a random factor to minimize the experimental error. First, we performed a model with all explanatory variables (pH, P.resin, N, P, Na, H.Al, OM, P.rem, Fe, Mn, silt, and sand), then we identified the lower significance variable and removed it from the analysis, and continued to do so systematically in order of lower significance. As each removed variable corresponded to a new model, we evaluate the significance of the different model's combinations with an analysis of variance (ANOVA) (see Table S7). The model where all variables were significant or marginally significant with p-value less than 0.05 was classified as the plausible model (Tables 3 & 4). We compared the GLMMs using the maximum likelihood method (ML) and to perform the final models we used the restricted maximum likelihood method (REML). We then scaled the significant variables to calculate regression standardized coefficients and ranked the significant variables according to the magnitude of the difference. We calculated the conditional and marginal R squared values of the models using the "MuMIn" package of the R software, where the marginal values are those associated with fixed effects, and the conditional ones are those of fixed effects plus the random effects.

Results

Systematic Review

In total, 152 published works were retrieved: 95 theses in Portuguese and 57 scientific articles in English. If the thesis was also published as a scientific paper, we considered the scientific paper only in our systematic review. Less than half of the studies reported any soil data (41%; 62 of 152; Table S1) (Fig. 2). Of those, 32 (34%) were reported in theses and 30 (53%) were reported in published papers. Noteworthy, only 40% ($N = 25$) of the retrieved studies included information about reference sites or project baseline information. Of the articles that reported reference sites, 30% ($n = 8$) did not report the age of the restored forest. Most of the studies were located in southeastern Brazil (Rio de Janeiro, São Paulo, Minas Gerais, and Espírito Santo; 31%, $n = 19$; 27%, $n = 17$; 16%, $n = 9$; and 11%, $n = 7$ studies, respectively). Six studies failed to provide information on the coordinates of the study areas, giving only the municipality name. Sixty-four percent of the studies provided information about the time of soil sampling (whether at the beginning or the end of restoration project, or throughout).

Soil pH was the most common soil indicator reported (71%, $N = 44$), followed by potassium content (66%, $N = 41$) and phosphorus (65%, $n = 40$). Least reported variables were water retention (6.5%, $N = 4$), iron content (11%, $N = 7$), and C/N (14%, $N = 9$) (Fig. 2A). Forty-six studies presented information on the soil classes where studies were conducted, of which 48% ($N = 22$) appeared in theses and 52% ($N = 24$) appeared in the articles (Fig. 2B). The majority of studies occurred in oxisols (50%, $N = 23$) followed by ultisols (44%, $N = 22$) and 30% ($N = 14$) in inceptisols.

A total of 48 papers presented information on forest variables in their studies (remaining 14 studies included only descriptive information and/or photo documentation). Regarding type of restoration, 30 of 50 reported active restoration and 20 presented

Table 3. The regression standardized coefficients for nitrogen and organic matter variables. $^{**}p \leq 0.05$.

	Value	*SE*	*DF*	t-*Value*	p-*Value*
Intercept	−5.576359	0.8291311	36	−6.725545	0.0000
Nitrogen	2.694649	1.0908373	36	2.470258	0.0184**
Organic matter	−1.384249	0.5565486	36	−2.487201	0.0176**

Table 4. The regression standardized coefficients showed for Na and sand variables. $^{**}p \leq 0.05$; *marginally significant.

	Value	*SE*	*DF*	t-*Value*	p-*Value*
Intercept	0.1443113	0.6539226	36	0.2206857	0.8266
Na	0.1376518	0.0736292	36	1.8695262	0.0697*
Sand	1.1747422	0.4557393	36	2.5776625	0.0142**

passive restoration (natural regeneration). All studies reported information focused on species composition (100%, $N = 48$), 98% ($N = 46$) reported other variables such as seed bank, while 83% ($N = 40$) informed about species richness. Least reported variables were total area restored (65%, $N = 31$), diversity (42%, $N = 20$), and basal area (46%, $N = 22$). For details on the age of restoration, see Appendix S1.

Out of the studies that had reference sites ($N = 25$) all presented soil information. Phosphorus and pH are the most cited soil indicators in restoration projects that provide the information on reference site, being cited 14 times each (56%), followed by carbon (52%; $N = 13$), potassium (48%; $N = 12$), nitrogen (44%; $N = 11$), aluminium (31%; $N = 8$), edaphic fauna (20%; $N = 5$), CEC (16%; $N = 4$), and iron (12%; $N = 3$). Information on soil water properties, the least reported indicator, was included in only one paper (of 25). Ten studies (40%) that provided information about reference area included also information regarding time of soil sampling (whether in the beginning or the end of restoration), of which five were theses and eight were articles.

Case Study

We found a relationship between selected soil indicators and tree structure in the restored areas. Basal area was positively correlated with nitrogen while negatively with organic matter content. Tree height showed a positive correlation with sodium and sand content ($p < 0.005$; Tables 3 & 4; Fig. 3). For the first model that we considered the basal area as a response variable the conditional R squared (R^2c) and marginal R squared (R^2m) were 0.7483 and 0.0553, respectively. For the second model, where the height of the trees was the response variable the R^2c and R^2m were 0.8113 and 0.0251, respectively.

Discussion

Systematic Review

Soil evaluation through relevant indicators is fundamental because it allows to directly analyze the environmental quality (Araújo et al. 2012). Quality indicators can be measured and their attributes can be monitored in a variety of ways via remote sensing, monitoring of field observations, sample collection, selection of pre-existing data, or the combination of all these methods (Arshad & Martin 2002). Failures in restoration projects can often be attributed to site-specific indicators that were not taken into account during planning and execution of restoration (Wassenaar et al. 2007).

The results of this work demonstrate a soil data gap within the restoration projects in the Brazilian Atlantic Forest. Less than half of the studies included in the systematic review reported any soil data. Moreover, we observed that even if a study includes information about soil properties, such information is frequently added "bureaucratically" without appropriate consideration of these data in the context of the performed study and evaluation of the patterns stemming from such a data. Most studies presented analyses of pH and macronutrients, but other important properties of the soil (e.g. water retention capability, cationic exchange capacity, microorganisms) were rarely reported. Even though soil pH was the most commonly reported soil indicator, found in 44 studies, 29% of the restoration projects did not provide this indicator. Soil pH, a measure of soil acidity, is fundamental to consider in restoration. It influences chemical reactions in soils, nutrient availability, and plant productivity (Harris et al. 1996). Doran and Parkin (1994) suggested that soil pH should be reported as a basic and key indicator of soil quality, especially since it can easily be inexpensively measured.

Regarding macronutrients, potassium and phosphorus contents, even though these nutrients appeared on the top of the list of reported indicators, similarly to soil pH they were cited in a minority of the reviewed works. Nutrient content and cycling is a basic indicator to assess soil fertility and stability (Mitchell et al. 2000) and it should routinely be monitored in restoration. Soil organic matter is also a fundamental indicator used to measure crucial ecosystem services, such as carbon sequestration, yet few studies reported it. Carbon was reported to a greater extent in articles rather than in theses and appeared more in studies that reported reference area. Soil pH and macronutrients such as P and K were shown to be the most commonly reported soil indicators also at the global scale. Bünemann et al. (2018) show that more than 80% of reviewed

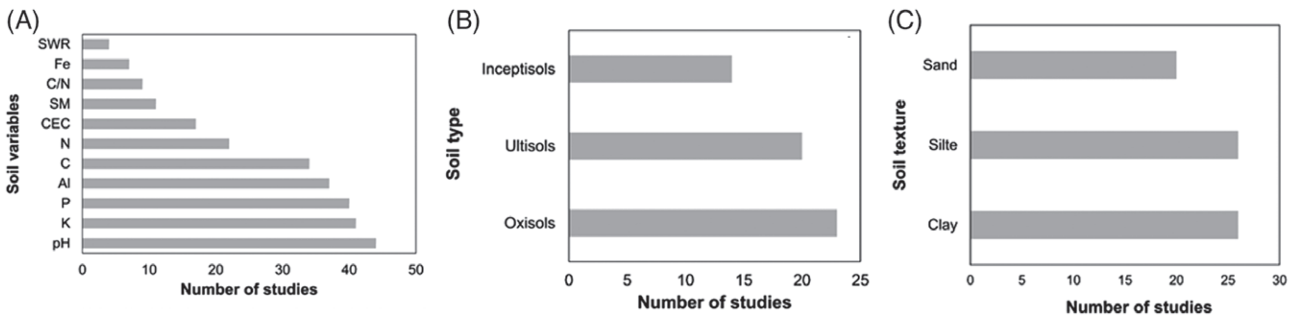

Figure 2. Indicators retrieved from systematic literature review on restoration in the Atlantic Forest ($N = 62$). Soil indicators reported in the reviewed studies (A), where pH is an indicator of soil acidity, K is potassium, P is phosphorus, Al is aluminum, C is carbon, N is nitrogen, CEC is cation exchange capacity, SM is soil biota, C/N is carbon to nitrogen ratio, Fe is iron, and SWR is soil water retention. Soil type in retrieved studies (B); the majority of studies occurred in oxisols (deep soils, well drained, and weathered) that have the largest geographical representation in Brazil. Ultisols and Inceptisols were two other types of soils that occurred in the reviewed studies. Soil texture (C) with clay and silt content being measured in the majority of the reviewed studies.

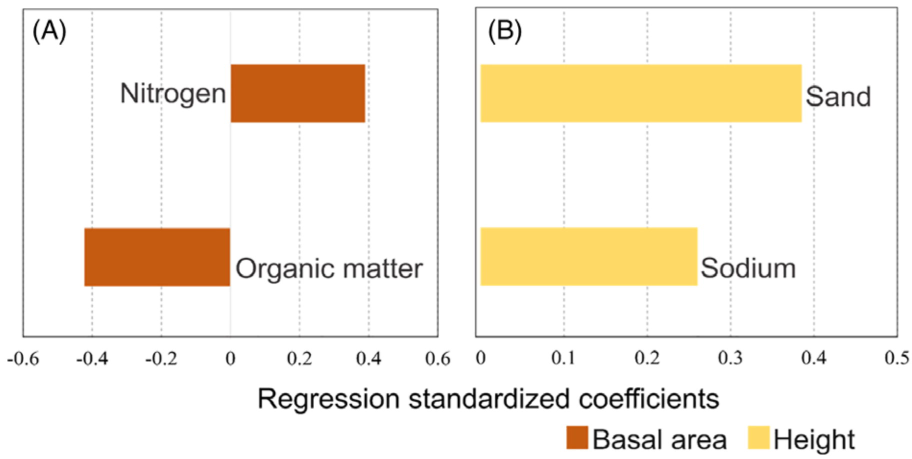

Figure 3. Regression standardized coefficients responses for soil variables. In red are marked coefficients for basal area and in yellow for tree height.

studies related to soil reported soil pH. However, in their study, soil organic matter/carbon content was the most commonly reported indicator (found in 91% of the studies). Regarding micronutrients, even less commonly found in restoration literature, native species may present great sensitivity to unbalanced micronutrient levels (Sorreano et al. 2012).

Another important data gap was observed with respect to soil texture. Only 40% of the studies reported any property related to soil texture (Fig. 2C). Soil texture is one of the most stable soil properties, being slightly modified by cultivation and other practices that end up causing the mixing of different layers (Arshad et al. 1996). Texture is a key, easy, and inexpensive soil quality indicator that is the most fundamental soil physical property. Soil texture impacts soil water properties, nutrients, and oxygen exchange, retention, and uptake.

The soil fauna component is rarely assessed in studies of forest restoration (18%, $N = 11$). Soil biota is paramount for soil functions and processes like decomposition, nutrient cycling, fertilization, soil restructuring, and bioturbation (Brussaard et al. 1997) thereby maintaining a flow of ecosystem services. Both short- and long-term changes in soil biological characteristics are one of the most rapidly observed consequences of altered ecosystems (Ducatti 2002). In the case of extensive ecosystem change, appropriate studies using bioindicators and biological monitoring are good indicators of environmental degradation and potential for regeneration (Sautter & Santos 1991; Curry & Good 1992). Although other authors have repeatedly highlighted the fundamental role of microorganisms for forest restoration and ecosystem services, this is still a rarely measured and/or reported indicator (Doran & Zeiss 2000; Anderson 2003; Bardgett & Wardle 2003; Van de Heijden et al. 2008). Considering soil microorganisms and carbon soil carbon feedback is paramount for increasing production and carbon storage especially in disturbed ecosystems, such as the Atlantic Forest (Ojima et al. 1993; Cairns 2000).

The least reported soil indicator found in our review was water retention (6.5%, $N = 4$), which highlights another important soil data gap in restoration projects. In the Atlantic Forest and worldwide, restoration is often performed to recover water ecosystem services and schemes of Payments for Ecosystem Services in the Atlantic Forest are principally focused on water recovery through restoration (Lima 2016). Water stress in soil is also one of the most critical factors associated with tree seedling mortality in restoration projects (Grossnickle 2012).

We also found that the majority of the studies did not include the information about reference area or baseline. The presence of data on the restoration site and the reference site makes it possible to compare data between the two areas and verify which variables responded better to the restoration and the impact of this on the success of the restoration. Furthermore, most of the studies reviewed here did not report any information regarding whether soil sampling was done in the beginning or at the end of the restoration. The continuous collection of soil samples has fundamental importance within a restoration project to monitor the chemical and physical evolution of the soil throughout the project. This monitoring of soil fertility, depending on the type of restoration (active or passive), helps to evaluate the survival rate of the seedlings and helps to verify the behavior of the species in the field. Soil analysis before the planting is also essential for the possible application of soil correction to facilitate or indeed enable tree growth (Boletim Técnico 100 1997; Sorreano et al. 2012).

Despite the evidence from the previous studies that demonstrated the importance of considering soil indicators in restoration and their scarcity in published papers (Falk et al. 2006), the gap of including soil data in restoration projects persists. Our study demonstrates a gap that exists in soil data in restoration projects in the Brazilian Atlantic Forest. The systematic literature review enabled us to identify the most reported indicators (pH, K, and P) yet these indicators appeared in the minority of retrieved studies related to restoration in the Atlantic Forest. Other important indicators such as water retention and biological activity were rarely reported. We complemented our systematic review with a case study that showed not only soil data scarcity (e.g. the soil data were not collected before restoration started) but also confirmed that different soil indicators and different planting compositions correlate with fundamental restoration success indicators such as basal area and height.

Case Study

Based on the soil sampling performed after 7 years of restoration, we observed a relationship between nitrogen and the basal area, and nitrogen is one of the principal nutrients required by plants (Siddique et al. 2008). Apart from biological fixation, soil organic matter is the main source for the supply of nitrogen, especially in forest ecosystems (Cole 1995). However, our results show that the relative importance of soil organic matter and of nitrogen was similar (regression coefficients of approximately 0.4) but had opposite effects on basal area. This result was somewhat surprising. The dynamics of carbon and nitrogen in the soil is interrelated in a way that, for the accumulation of carbon in the soil, the nitrogen availability in the system is essential (Resende et al. 2005). In general, a lower C:N ratio, common in soils under native forests, indicates high biological nitrogen fixation and intense organic matter deposition, and nutrient cycling (Parrota 1999; Macedo et al. 2008). According to Pulito (2009), total nitrogen content can be considered as a good indicator of the availability of nitrogen in the soil. On the other hand, low soil C:N ratio (lower than 10–12:1) may suggest low stability of the system, low quality of soil organic matter, and may indicate higher mineralization of the organic matter; and again, a failure to recovery of forest structure and soil organic matter contents. One of the possible explanations for the inverse correlation between basal area and organic matter may be the presence of invasive grasses in the restoration areas that may be responsible for the higher carbon content. Exotic grasses are very efficient and aggressive competitors in relation to native species, and their abundant presence facilitates the occurrence of fires and makes forest regeneration difficult (D'Antonio & Vitousek 1992). Grass species can compensate for initial losses with high growth rates and rapid accumulation of carbon in biomass (Fernandes et al. 1997). Soil organic matter, apart from being a source of highly available organic carbon, provides the system with other advantages such as greater capacity to retain nutrients, greater capacity to retain water and immobilize elements that may have some degree of toxicity. Soil organic matter is important because it interferes with the physical, chemical, and biological properties of the soil and is considered by some authors as the most relevant indicator of soil quality and the predictor of restoration success (Parrota et al. 1997; Bolinder et al. 1999; Mummey et al. 2002; Moraes 2005). Another explanation may be the low contribution of tree species to litter formation and a rate of decomposition of this litter that does not contribute to the accumulation of soil carbon. It is, however, very difficult to precisely establish which patterns are cause or consequence and it may, at least partially, explain why few scientists dedicate to study soil processes and relations in restoration. In the case of Atlantic Forest literature, even if soil analysis was performed, it is rather limited to tentative descriptions of patterns rather than soil-restoration feedback.

In relation to tree height, we found a positive relationship between sodium and sand contents and the tree height. A possible explanation is that sandy soils are better drained and are characterized by lower nutrient retention. In such conditions, roots have more feasibility to penetrate through the soil resulting in more development of the roots and higher individuals. Regarding sodium, in healthy soils sodium is uncommon and its presence is an indicator of salinization (by irrigation or because of elevated water table or due to inadequate fertilization). Differences in height values observed between plantations of the same age can also be attributed to the different composition of species used in plantations. Restoration sites showed similar values of species richness (Site 1: 40 species/0.2 ha; Site 2: 38 species/0.2 ha) but shared only 30% of species composition. It should be noted that these are possible explanations and further studies into soil, species, and landscape features should be performed to better understand these relations. Interestingly, in our parallel ongoing field study we also found sodium and carbon contents as the primary soil indicators that differed between different restoration models (active planting vs. natural regeneration) (Korys et al. in preparation).

Overall, the analysis of the case study and the gap-analysis emphasize the importance of soil data in restoration projects in the Atlantic Forest. For example, indicators such as carbon and sand contents correlated with the indicators of restoration success, yet they were considered in the minority of the studies retrieved in our systematic review. We highlight the need to include all soil indicators discussed here and strongly encourage continuous monitoring over the duration of a restoration project. We strongly reinforce the importance of soil analysis before planting to enable possible soil correction before possible negative soil-associated factors occur during restoration process. The timing is also favorable as recent spotlight focuses on the role of soil in ecosystems such as the IPCC "4 per 1000" initiative (https://www.4p1000.org/) that fosters concerted effort to include soil data in environmental assessments. Soil should be routinely incorporated for evaluating and planning restoration projects as these projects often fail due to inadequate consideration of local conditions (Heneghan et al. 2008; Grossnickle 2012). Given that the important soil indicators such as pH, soil texture, nitrogen, organic matter, and water content are relatively easy and cheap to measure and have profound and direct effect on crucial ecosystem services such as carbon sequestration and water regulation, we urge to include these indicators routinely in restoration projects.

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LITERATURE CITED

Anderson T (2003) Microbial eco-physiological indicators to assess soil quality. Agriculture, Ecosystems and Environment 98:285–293

Araújo EA, de Ker JC, Neves JCL, Lani JL (2012) Qualidade do Solo: conceitos, indicadores e avaliação. Pesquisa Aplicada & Agrotecnologia 5:187–196

Aronson J, Durigan G, Brancalion PHS (2011) Conceitos e definições correlatos à ciência e à prática da restauração ecológica. IF Série Registros 44:1–38

Arshad MA, Lowery B, Grossman B (1996) Physical tests for monitoring soil quality. Pages 123–141. In: Doran JW, Jones AJ (eds) Methods for assessing soil quality. Soil Science Society of America, Madison, Wisconsin, (SSSA special publication, 49)

Arshad MA, Martin S (2002) Identifying critical limits for soil quality indicators in agro-ecosystems. Agriculture, Ecosystems and Environment 88:153–160

Bardgett RD, Wardle DA (2003) Herbivore-mediated linkages between aboveground and belowground communities. Ecology 84:2258–2268

Benayas RJM, Newton AC, Diaz A, Bullock JM (2009) Enhancement of biodiversity and ecosystem services by ecological restoration: a meta-analysis. Science 325:1121–1124

Boletim Técnico 100 (1997) Recomendações de adubação e calagem para o Estado de São Paulo. Instituto Agronômico (SP). http://www.iac.sp.gov.br/publicacoes/boletim100/versaoimprenssa.php (accessed 3 June 2018)

Bolinder MA, Angers DA, Gregorich EG, Carter MR (1999) The response of soil quality indicators to conservation management. Canadian Journal of Soil Science 79:37–45

Brussaard LVM, Behan-Pelletier DE, Bignell VK, Brown W, Didden P, Folgarait C, et al. (1997) Biodiversity and ecosystem functioning in soil. Ambio 26:563–570

Bünemann EK, Bongiorno G, Bai Z, Creamer RE, de Deyn G, de Goede R, et al. (2018) Soil quality – a critical review. Soil Biology and Biochemistry 120:105–125

Cairns J (2000) Setting ecological restoration goals for technical feasibility and scientific validity. Ecological Engineering 15:171–180

Callaham MA Jr, Rhoades CC, Heneghan L (2008) A striking profile: soil ecological knowledge in restoration management and science. Restoration Ecology 16:604–607

Calmon M, Brancalion PH, Paese A, Aronson J, Castro P, Silva SC, da Rodrigues RR (2011) Emerging threats and opportunities for large-scale ecological restoration in the Atlantic Forest of Brazil. Restoration Ecology 19:154–158

Centurion JF, Cardoso JP, Natale W (2001) Physical and chemical properties of an oxisol in different agroecosystems. Revista Brasileira de Engenharia Agrícola e Ambiental 5:416–424

Clark DB, Clark DA (2000) Landscape-scale variation in forest structure and biomass in a tropical rain forest. Forest Ecology and Management 137:185–198

Cole D (1995) Soil nutrient supply in natural and managed forests. Plant and Soil 169:43–53

Crouzeilles R, Ferreira MS, Chazdon RL, Lindenmayer DB, Sansevero JBB, Monteiro L, Iribarrem A, Latawiec AE, Strassburg BBN (2017) Ecological restoration success is higher for natural regeneration than for active restoration in tropical forests. Science Advances 3:1–8

Curry JP, Good J (1992) A soil faunal degradation and restoration. Advances in Soil Science 17:171–215

D'Antonio CM, Vitousek PM (1992) Biological invasions by exotic grasses, the grass–fire cycle, and global change. Annual Review of Ecology and Systematics 23:63–87

Ditt EH, Mourato J, Knight J (2010) Forest conversion and provision of ecosystem services in the Brazilian Atlantic Forest. Land Degradation & Development 21:591–603

Doran JW, Parkin TB (1994) Defining and assessing soil quality. Pages 3–21. In: Doran JW, Coleman DC, Bezdicek DF, Stawart BA (eds) Defining soil quality for a sustainable environment. ASA/SSSA, Madison, Wisconsin (special publication, 35)

Doran JW, Zeiss MR (2000) Soil health and sustainability: managing the biotic component of soil quality. Applied Soil Ecology 15:3–11

Ducatti F (2002) Fauna Edáfica em fragmentos florestais e em áreas reflorestadas com espécies de Mata Atlântica. MSc dissertation. Pós- Graduação em Recursos Florestais – Universidade de São Paulo Escola Superior de Agricultura "Luiz de Queiroz", Piracicaba, Brazil [in Portuguese]

Ehrenfeld JG, Ravit B, Elgersma K (2005) Feedback in the plant–soil system. Annual Review of Environment and Resources 30:75–115

Eviner VT, Hawkes CV (2008) Embracing variability in the application of plant–soil interactions to the restoration of communities and ecosystems. Restoration Ecology 16:713–729

Falk D, Palmer M, Zedler JB (eds) (2006) Foundations of restoration ecology. Island Press, Washington D.C.

Fernandes ECM, Motavalli PP, Castilla C, Mukurumbira L (1997) Management control of soil organic matter dynamics in tropical land-use system. Geoderma 79:49–67

Ferraz SFB, Lima WP, Rodrigues CB (2013) Managing forest plantation landscapes for water conservation. Forest Ecology and Management 301:58–66

Gama-Rodrigues AC, Gama-Rodrigues EF, Barros NF (2008) Balanço de carbono e nutrientes em plantio puro e misto de espécies florestais nativas no sudeste da Bahia. Revista Brasileira de Ciências do Solo, Viçosa 32:1165–1179

Gee GW, Bauder JW (1986) Particle-size analysis. Pages 383–411. In: Methods of soil analysis. Part 1. 2nd edition. American Society of Agronomy, Madison, Wisconsin

Grossnickle SC (2012) Why seedlings survive: influence of plant attributes. New Forests 43:711–738

Harris RF, Karlen DL, Mulla DJ (1996) A conceptual framework for assessment and management of soil quality and health. In: Doran JW, Jones AJ (eds) Methods for assessing soil quality. Science Society of America, Special publication, 49:61–82

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. Restoration Ecology 16:608–617

Idowu OJ, van Es HM, Abawi GS, Wolfe DW, Ball JI, Gugino BK, Moebius BN, Schindelbeck RR, Bilgili AV (2008) Farmer-oriented assessment of soil quality using field, laboratory, and VNIR spectroscopy methods. Plant and Soil 307:243–253

Kardol P, Wardle DA (2010) How understanding aboveground-belowground link-ages can assist restoration ecology. Trends in Ecology & Evolution 25:670–679

Klute A (1986) Water retention: laboratory methods. Pages 635–686. In: Methods of soil analysis. Part 1. 2nd edition. American Society of Agronomy, Madison, Wisconsin

Korys KA, Mendes M, Latawiec AE, Iribarrem AS, Sansevero JB, Rodrigues AF, Strassburg BBN, Dib V, Lino E. Does type of restoration impact soil ecosystem services? The evidence from the Atlantic Forest, Brazil. Ecosystem Services: in preparation for submission

Larson WE, Pierce FJ (1991) Conservation and enhancement of soil quality. 175–203

Latawiec AE, Crouzeilles R, Brancalion PHS, Rodrigues RR, Sansevero JB, Silvera dos Dantos J, Millis M, Nave AG, Strassburg BB (2016) Natural regeneration and biodiversity: a global meta-analysis and implications for spatial planning. Biotropica 48:844–855

Lima APM (2016) Estado da Arte do Monitoramento de Iniciativas de Pagamentos por Serviços Ambientais Hídricos no Brazil. Graduação (Geography and Environment) Pontifícia Universidade Católica do Rio de Janeiro, Rio de Janeiro, Brazil

Macedo MO, Resende AS, Garcia PC, Bobbey RM, Jantalia CP, Urquiaga S, Campello EFC, Franco AA (2008) Changes in soil C and N stocks and nutrient dynamics 13 years after recovery of degraded land using leguminous nitrogen-fixing trees. Forest Ecology and Management 255:1516–1524

Mata S (2017) Florestas em processo de restauração ecológica na Mata Atlântica: o caso das florestas urbanas do Rio de Janeiro. MSc dissertation. Escola Nacional de Botânica Tropical, Instituto de Pesquisas Jardim Botânico, Rio de Janeiro, RJ, Brazil

Miranda BC (2017) Projetos de restauração ecológica: percepção ambiental e interação de comunidades urbana. MSc dissertation. Escola Nacional de Botânica Tropical, Instituto de Pesquisas Jardim Botânico, Rio de Janeiro, RJ, Brazil

Mitchell RL, Auld MHD, Le Duc MG, Marrs RH (2000) Ecosystem stability and resilience: a review of their relevance for the conservation management of lowland heaths. Perspectives in Plant Ecology, Evolution and Systematics 3:142–160

Moraes LFD (2005) Indicadores da Restauração de Áreas Degradadas na Reserva Biológica de Poço dasAntas, RJ. PhD dissertation. Instituto de Agronomia, Universidade Federal Rural do Rio de Janeiro, Rio de Janeiro, Seropédica, Brazil

Muler AE (2014) Avaliação de uma Floresta Atlântica urbana em restauração: da ecologia às questões sociais. MSc dissertation. Escola Nacional de Botânica Tropical, Instituto de Pesquisas Jardim Botânico do Rio de Janeiro, RJ

Mummey DL, Stahl PD, Buyer JS (2002) Microbial biomarkers as an indicator of ecosystem recovery following surface mine reclamation. Applied Soil Ecology 21:251–259

Ohsowski BM, Klironomos JN, Dunfield KE, Hart MM (2012) The potential of soil amendments for restoring severely disturbed grasslands. Applied Soil Ecology 60:77–83

Ojima DS, Dirks BO, Glenn EP, Owensby CE, Scurlock JO (1993) Assessment of C budget for grasslands and drylands of the world. Water, Air, and Soil Pollution 70:95–109

Parrota JA (1999) Productivity, nutrient cycling, and succession in single and mixed-species plantations of *Casuarina equisetifolia*, *Eucalyptus robusta* and *Leucaena leucocephala* in Puerto Rico. Forest Ecology and Management 124:45–77

Parrota JA, Knowles OH, Wunderle JM Jr (1997) Development of floristic diversity in 10-year-old restoration forests on a bauxite mined site in Amazonia. Forest Ecology and Management 99:21–42

Patzlaff RG (2007) Estudo etnobotânico de plantas de uso medicinal e místico na comunidade da Capoeira Grande, Pedra de Guaratiba, Rio de Janeiro, RJ, Brazil. MSc dissertation. Escola Nacional de Botânica Tropical, Instituto de Pesquisas Jardim Botânico do Rio de Janeiro, RJ, Brazil

PLANAVEG (2016). Plano nacional de recuperação da vegetação nativa. http://www.mma.gov.br/images/arquivo/80049/Planaveg/PLANAVEG_20-11-14.pdf (accessed 10 November 2016)

Porter J, Costanza R, Sandhu H, Sigsgaard L, Wratten S (2009, 2009) The value of producing food, energy and ecosystem services within an agro-ecosystem. Ambio 38:186–193

Pulito AP (2009) Resposta à fertilização nitrogenada e estoque de nitrogênio biodisponível em solos usados para plantações de Eucalyptus. Dissertação de mestrado. Universidade de São Paulo, Piracicaba, Brazil [in Portuguese]

R Core Team (2013) Description: R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria

Resende M, Curi N, Ker JC, de Rezende SB (2005) Mineralogia de solos brasileiros: interpretação e aplicações. UFLA, Lavras, Brazil 192 p

Ribeiro MC, Metzger JP, Martensen AC, Ponzoni F, Hirota MM (2009) Brazilian Atlantic forest: how much is left and how is the remaining forest distributed? Implications for conservation. Biological Conservation 142:1141–1153

Rocha JHT, Santos AJM, Diogo FA, Melo AGC, Borelli K, Godinho TO (2015) Reflorestamento e Recuperação de atributos químicos e físicos do solo. Floresta e Ambiente 22:299–306

Sautter KD, Santos HR (1991) Recuperação de solos degradados pela mineração de xisto, tendo como bioindicadores insetos da Ordem Collembola. Revista do Setor de Ciências Agrárias 11(1/2):85–91

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

Siddique I, Engel VL, Parrota J, Lamb D, Nardoto G, Ometto J, Martinelli L, Schmidt S (2008) Dominance of legume trees alters nutrient relations in mixed species forest restoration plantings within seven years. Biogeochemistry 88:89–101

Silva IR, Sá Mendonça ES (2007) Matéria orgânica do solo. Pages 275–374. In: Novais RF, Alvarez VVH, Barros NF, Fontes RLF, Cantarutti RB, Neves JCL (eds) Fertilidade do solo. Sociedade Brasileira de Ciência do Solo, Viçosa, Brazil

Sorreano MCM, Rodrigues RR, Boaretto AE (2012) Guia de Nutrição – para Espécies Florestais Nativas. Oficina de textos, São Paulo, Brazil

Souza M (2013) Do “sertão” à Urbanização do bairro Campo Grande – Rio de Janeiro: uma análise dos impactos socioambientais Resumo Resumen. Reencontro de sabares territoriales latinoamericanos. http://www.egal2013.pe/

Van der Heijden MG, Bardgett RD, van Straalen NM (2008) The unseen majority: soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. Ecology Letters 11:296–310

Van der Heijden MGA, Klironomos JN, Ursic M, Moutoglis P, Streitwolf-Engel R, Boller T, Wiemken A, Sanders IR (1998) Mycorrhizal fungal diversity determines plant biodiversity, ecosystem variability and productivity. Nature 396:69–72

Wardle D (2002) Communities and ecosystems: linking the aboveground and belowground components. Princeton University Press, Princeton, New Jersey

Wassenaar TD, Ferreira SM, Van Aarde RJ (2007) Flagging aberrant sites and assemblages in restoration projects. Restoration Ecology 15:68–76

Supporting Information

The following information may be found in the online version of this article:

Table S1. Literature reviewed that composed the database of systematic literature review.
Table S2. Soil indicators data taken from theses and articles.
Table S3. Forest indicators taken from theses and articles.
Table S4. Botanical species, mean height, and mean basal area, sampled in the case study of the Mutirão de Reflorestamento in the Entre Rios and Capoeira Grande sites, Rio de Janeiro.
Table S5. Results of nutrient content and soil texture in the plots of the case study of the Mutirão de Reforestation project in the Entre Rios site, Rio de Janeiro.
Table S6. Results of nutrient content and soil texture in the plots of the case study of the Mutirão de Reflorestamento project in the Capoeira Grande site, Rio de Janeiro.
Table S7. ANOVA analysis for all performed models.
Appendix S1. Age of restoration.

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