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An integrated approach for measuring urban forest restoration success

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Abstract

Rapid urban growth has increased the importance of restoring degraded vegetation patches within these areas. In this study, we reforested a site that was previously dominated by exotic grasses within an urban area. The goal of this study was to evaluate restoration success in a reforested site using four variables of vegetation structure, five groups of organisms, and eight variables of ecosystem processes, and compare these values with a pre-reforested site and a forested reference site using the Subjective Bray Curtis Ordination. The change in vegetation structure provided arboreal habitats that increased species diversity and ecosystem processes in the reforested site. Specifically, the development of a vertical vegetation structure was associated with: (1) a decrease in herbaceous cover, which allowed the colonization of woody seedlings; (2) a change in microclimatic conditions, which enhanced the colonization of ants and amphibians; (3) colonization of arboreal reptiles and birds; and (4) an increase in litter production, which enhanced nutrient inputs. Moreover, the Subjective Bray Curtis Ordination demonstrated an overall recovery of approximately 70%. Planting woody species was sufficient to stimulate rapid recovery of many ecosystem attributes. Future restoration projects should include multiple variables that reflect important ecosystem attributes to determine the success of a project and to direct future management efforts.

Keywords: Ecological restoration; Ecosystem processes; Species diversity; Urban forest patches; Vegetation structure

Introduction

In Africa, Asia, and Latin America, the urban population is expected to increase from 1.9 billion in 2000 to 3.9 billion in 2030 (United Nations, 2002). This rapid urban growth is contributing to the loss of habitats, which often includes areas of high species diversity (Czech and Krausman, 1997; Ricketts and Imhoff, 2003). At the global scale, the area of agriculture activities (>30% of terrestrial systems) is much more extensive than urban areas (<5%), but when agricultural lands are abandoned natural systems can often recover (James et al., 2001). For example, in Puerto Rico the shift from agriculture to industry in the 1950s permitted forest to recover on abandoned lands, and forest cover increased from <10% to >30% (Aide et al., 2000; Rudel et al., 2000; Grau et al., 2003). In contrast to agriculture activities, urban land use is rarely reversible, and thus the remaining vegetation patches within urban environments are extremely important in providing habitat for fauna and flora (McKinney, 2002; Miller and Hobbs, 2002; Hostetler and Knowles-Yanez, 2003).

These vegetation patches within urban areas can maintain metapopulations of flora and fauna by serving as stepping-stones or corridors for dispersal (Pirnat, 2000; Rudd et al., 2002; Melles et al., 2003). For

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example, tree-lined streets provide alternative habitat for feeding and nesting for birds, and act as corridors between forest patches (Fernández-Juricic, 2000), which serve as habitat for native species (Jones and Bock, 2002; Shapiro, 2002). Riparian corridors can also play an important role in providing habitat and connectivity because they often traverse large urban areas (Forman, 1995; Bentley and Catterall, 1997).

Despite the importance of these remaining vegetation patches within urban areas, many of these patches are of low quality. One cause for the low quality is that during construction more land is cleared than is actually used, and these areas, which have been degraded, are often colonized by grasses (Jones et al., 2004). Although grass cover can reduce soil erosion, the biodiversity value of these sites is often low. These sites have a simple vegetation structure and can arrest forest succession by impeding the natural regeneration of woody species (Hooper et al., 2002).

To improve the quality of these sites, restoration efforts are often needed. Although the goal of restoration projects is to create an ecosystem that is self-supporting and resilience to perturbation (Urbanska et al., 1997; SER, 2004), the evaluation of restoration success is usually limited to plant colonization or growth (Ruiz-Jaén and Aide, 2005). The evaluation of restoration success should include variables of vegetation structure, species diversity, and ecosystem processes, which will help predict the recovery process (Elmqvist et al., 2003; Dorren et al., 2004). Furthermore, these variables need to be compared with values from reference sites to estimate the level of restoration success (Hobbs and Norton, 1996; Passell, 2000; Purcell et al., 2002; SER, 2004).

In this study, we reforested a riparian site dominated by exotic grasses with native woody species in the metropolitan area of San Juan, Puerto Rico. To evaluate the success of this project, we measured four variables of vegetation structure, five groups of organisms, and eight variables of ecosystem processes, and compared these variables with values from a pre-reforested site and a forested reference site. This multivariate approach provides a more complete evaluation of ecosystem restoration.

Methods

Study site

The study was conducted in the San Juan Metropolitan area (population density = 1254 km^{-2}) in Puerto Rico along a tributary of the Puerto Nuevo River (18°23′N, 66°06′W). The pre-reforested site is a riparian grassland dominated by *Paspalum fasciculatum* and *Pennisetum purpureum*, introduced grasses that grow to 2.0 m in height, and scattered shrubs of *Mimosa pellita* and *Ricinus communis*. The reforested site was similar to the pre-reforested site until it was reforested with 23 native species of trees and shrubs in August 1999 (Appendix A). The forested reference site is a close-canopy secondary forest that is approximately 40 years old. Common woody species in the forested reference site include both exotics (e.g., *Ardisia elliptica*, *Bambusa vulgare*, and *Spathodea campalunata*) and natives (e.g., *Casearia guianensis*, *Calophyllum brasilense*, and *Ocotea leucoxylum*). Although the forested reference site is a secondary forest, we selected it because it was the oldest secondary forest in this urban area with the same environmental conditions as the other two sites (i.e., riparian forests previously dominated by grasses).

The sites ranged from 0.75 to 1.0 ha, there was a minimum distance of 100 m between them and they occur along a small creek that traverses an urban matrix. A total of 200 m of transects were established in all sites. Specifically, the pre-reforested and reforested sites were sampled using a single transect of 200 m, and the forested reference site was sampled with two transects of 100 m. In all sites, transects were established systematically at least 5 m away from the edge and 20 m between each transect.

Vegetation structure

Ground cover

Ground cover was estimated in 20 1-m^2 plots every 10 m along the 200 m transect in each site in July 2002. Percent herbaceous, litter, and bare soil cover was determined in each plot. Herbaceous cover included grasses, vines, and herbs.

Woody vegetation

Diameter at breast height (DBH) and height of all woody plants >1 cm DBH were sampled within 800 m^2 along the established transects in June 2002.

Microclimatic conditions

To understand how changes in vegetation structure alter microclimate conditions, we measured temperature and relative humidity. We expected that as forest structure in the restored site develops, microclimate conditions will stabilize and conditions would become more similar to the forested reference site. Temperature and relative humidity were measured at 20 cm above the forest floor using a HOBO Pro Series data logger in each site for a month. Each data logger was programmed to measure temperature and relative humidity every hour during July 2002. We also measured soil water content in July 2003 in 12 soil samples of 15 g taken from two depths: 0–10 and 10–20 cm.

Species diversity

We compared diversity and composition of woody seedlings, ants, reptiles, amphibians, and birds to sample species from different trophic levels. Woody seedlings were included as an estimate of natural regeneration. Ants, amphibians, reptiles, and birds are important components of the total animal biomass and food webs in Puerto Rico (Reagan and Waide, 1996; Torres and Snelling, 1997). Specifically, ants are the most abundant invertebrate in Puerto Rico (Levins et al., 1973; Barberena-Arias and Aide, 2003) and are fungivores, herbivores, granivores, and predators (Torres, 1984a). Amphibians and reptiles are the most abundant vertebrates in terrestrial ecosystems in Puerto Rico and are prey and predators (Reagan, 1996; Stewart and Woolbright, 1996), and birds are important seed dispersers, pollinators, and predators (Waide, 1996; Wunderle, 1997). Below are the methods used for each group.

Woody plant seedlings

Woody seedlings from 5 to 50 cm in height were counted and identified in 20 circular plots (1 m diameter) in March 2003 in each site. Plots were located every 10 m along the 200 m transect. Nomenclature followed Liogier (1982) and dispersal mode information followed Francis and Lowe (2000) and Carlo et al. (2003).

Ants

Ants were collected using leaf litter samples and pitfall traps in July 2002. Ten 1-m^2-leaf litter samples were collected every 20 m along the 200 m transect. In the field, litter was sifted using a 100-mm^2 mesh to eliminate large debris. The sifted litter samples were placed in Berlese funnels in the laboratory (Bioquip, 30.5 cm diameter, 35.6 cm height, 25 W bulb). Ants were removed from Berlese traps after 48 h. Ten plastic pitfall traps (7 cm diameter, 190 ml) were buried with the top of the trap flush with the ground surface. Traps were placed every 20 m along transects and left in the field for 48 h. Traps were partially filled with ethanol as a preservative and soap as trapping fluid. Similar sampling methods have been previously used for rapid assessment studies (Oliver and Beattie, 1996). Nomenclature followed Torres and Snelling (1997), and habitat preferences followed Torres (1984a, b), Holldobler and Wilson (1990), Brown (2000), and Barberena-Arias and Aide (2003).

Amphibians and reptiles

Composition and abundance of the herpetofauna were determined by one diurnal and one nocturnal visual and acoustic census in each of the three sites. The censuses were conducted along a $3 \times 100\,m^2$ transect ($300\,m^2$) in each site in July 2002. Diurnal censuses were conducted between 12:00 and 14:30 h, and nocturnal censuses were conducted between 19:30 and 22:00 h. On average, it took 2.5 h to complete a diurnal or nocturnal census in each site. Nomenclature followed Schwartz and Henderson (1991).

Birds

Five pre-dawn visual and acoustic censuses were conducted along two -100 m transects in each site to determine presence of birds species in July 2002. Each census took approximately 30 min. Nomenclature followed Biaggi (1997) and Raffaele et al. (1998).

Ecosystem processes

Earthworms

Earthworms play an important role in regulating decomposition of soil organic matter, and can increase soil fertility (Zou and Gonzalez, 1997; Liu and Zou, 2002). Earthworms comminute plant residues, incorporate organic matter, produce enriched casts, and enhance aggregate stability (Lavelle, 1988; Martin et al., 1990; Marinissen and Hillenaar, 1997), and thus they are good indicators of soil quality (Herrick, 2000). Earthworms were collected in 12 soil plots of $25 \times 25 \times 20\,cm^3$ every 15 m along the 200 m transect in July 2003. Each soil sample was separated into two profiles: 0–10 and 10–20 cm. The soil from each profile was placed on a cloth sheet, and earthworms were hand-sorted and stored in plastic bags in a cooler with ice. Earthworm fresh weight was measured after the worms were rinsed with water and dried with paper towels on the same day of sampling to determine earthworm biomass (Zou and Gonzalez, 1997).

Litter production

Litter production was estimated by collecting litter in 20 plastic buckets (area $0.071\,m^2\,bucket^{-1}$) in each site. Buckets were located on the forest floor every 10 m along the 200 m transect. Leaf litter was collected monthly from April 2003 to March 2004. Each litter sample was separated into leaves and miscellaneous (fruits, flowers, and twigs with a diameter less than 2 cm), oven dried at 70 °C for 72 h, and weighed.

Nutrient inputs

Total nutrient content of P, N, Ca, Mg, and K were measured in the monthly litterfall samples from the three sites. Nutrient content of monthly litterfall was used to determine potential nutrient inputs to each site. Potential nutrient inputs were determined by multiplying monthly values of litterfall with its corresponding nutrient content. All leaf material collected in a given month was combined to make a composite sample, thoroughly mixed, and ground for chemical analyses. Nitrogen concentration was analyzed using Kjeldahl procedure (Jackson, 1968). Phosphorus, calcium, potassium, and magnesium concentrations were determined by atomic absorption spectrometer with sulfuric and perchloric acid digestions (Murphy and Riley, 1962; Olsen and Sommers, 1982).

Data analysis

Given that treatments (i.e., pre-reforested, reforested, and forested reference) were not replicated, statistical analyses are not included. Nevertheless, we determined restoration success with the Subjective Bray Curtis Ordination analysis using PC-Ord version 4 (McCune and Mefford, 1999). The Subjective Bray Curtis Ordination was used to compare overall restoration success and recovery rates among variables. The Subjective Bray Curtis Ordination places points in relationship to selected reference sites (i.e., endpoints). Specifically, the data from the reforested site were arrayed relative to the endpoints (i.e., pre-reforested and forested reference sites) along a horizontal axis by using the Sorensen coefficient of similarity as the distance measure (Bray and Curtis, 1957; McCune and Grace, 2002). The position of the reforested site along this axis indicates the percent of restoration success relative to the endpoints. In contrast to other commonly used ordination methods (e.g., NMS, PCA, DCA, and CCA), the Subjective Bray Curtis Ordination is specific for evaluating data with conceptual references points (McCune and Grace, 2002).

To determine overall restoration success we used four variables of vegetation structure (herbaceous cover, litter cover, maximum plant height, and basal area), two variables of species diversity (ants and reptiles), and five variables of ecosystem processes (earthworm density, nutrient content of P, Ca, Mg, and K in leaf litter). For variables of vegetation structure and ecosystem processes, we used the average values of each site. For species diversity, we used total species richness of each site. A general relativization transformation was used to standardize values between 0 and 1. We did not include the variables that have values in the reforested site outside (i.e., lower or higher) the range of the endpoints (e.g., pre-reforested and forested reference sites). The variables that were excluded from this analysis were: woody seedling richness, amphibian richness, bird richness, earthworm biomass, annual litter production, and nutrient content of N in leaf litter.

We also used the Subjective Bray Curtis Ordination to determine recovery rates of individual variables. For the analyses of vegetation structure, the data for each variable (e.g., herbaceous cover, litter cover, woody plant height, and DBH size classes) were divided into classes to better reflect the overall distribution of the values. Abundance data were used for the analyses of woody seedlings and herpetofauna. For ants, presence and absence data were used to avoid the spatial clumping of their distribution due to nesting behavior (Longino, 2000). For birds, we used presence and absence data for comparison among sites. For earthworm density, the densities of all samples within a site were divided into classes to better reflect the within-site variation. To determine the change in litter nutrient quality, we used the mean values of P, N, Ca, Mg, and K from three sample periods from each site. Earthworm biomass and annual litter production were not analyzed because values in the reforested site were outside of the endpoints.

Results

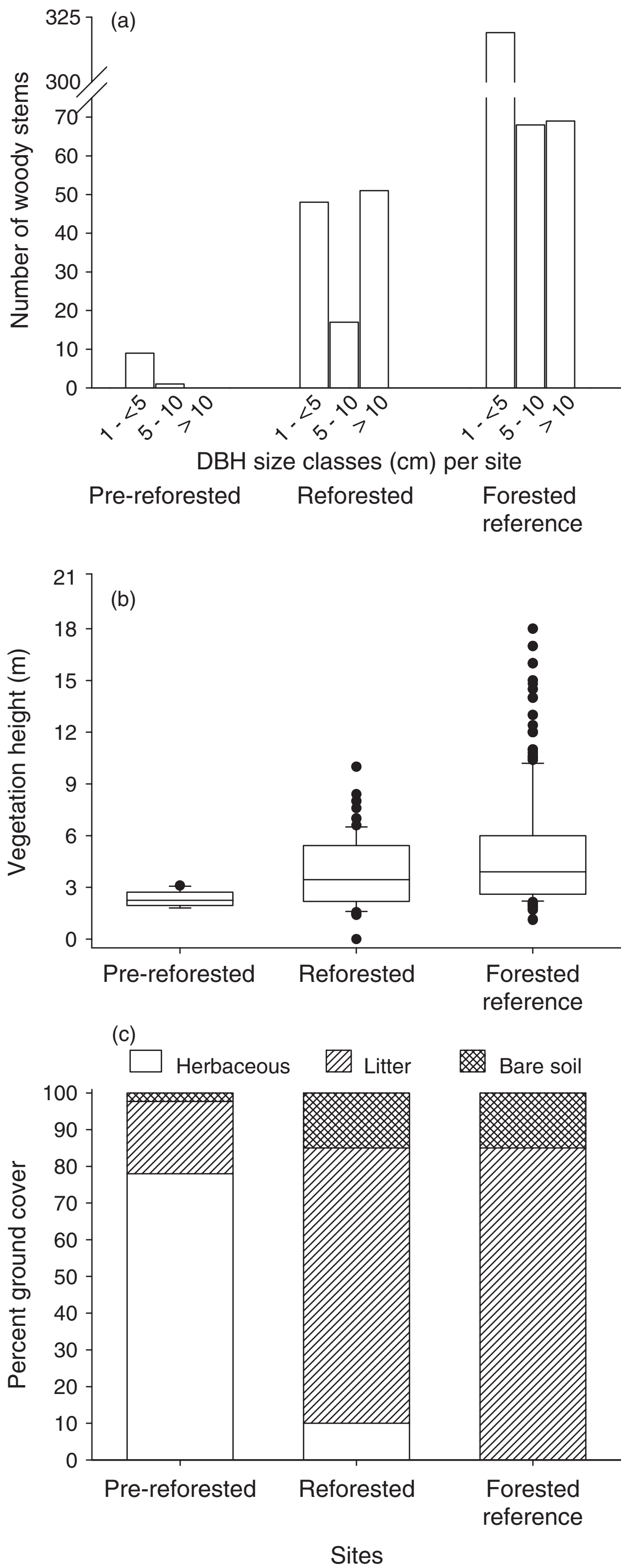
Vegetation structure

The growth of woody stems in the reforested site created a diverse vegetation structure (Fig. 1). The reforested site had fewer stems in all DBH classes in comparison with the forested reference site, but there were 50 stems greater than 10 cm DBH (Fig. 1a). Vegetation height in the reforested site ranged from 1.4 to 10 m with a mean height of approximately 4.0 m (Fig. 1b). Even though the vertical structure in the reforested site increased, the forested reference site had a greater range of tree height (e.g., 1.4–18 m). The tallest trees in the reforested site were the planted pioneer species *Citharexylum fructicosum*, *Hura crepitans*, and *Thespesia grandiflora*.

As woody vegetation increased in the reforested site, there was a decrease in herbaceous cover and an increase in litter cover (Fig. 1c). Herbaceous cover decreased from 78% in the pre-reforested site to 10% in the reforested site, while in the forested reference site there was no herbaceous cover. In contrast, litter cover increased from 20% in the pre-reforested site to 75% in the reforested site, and 85% in the forested reference site. Litter cover in the reforested site was dominated by the pioneer species, *Helicteres jamaicensis*, *Hura crepitans*, and *Thespesia grandiflora.*

Microclimatic conditions

The presence of woody species changed the microclimatic conditions in the reforested site. At 20 cm above the forest floor, temperatures in the reforested and forested reference sites fluctuated between 23 and 32 °C, while in the pre-reforested site temperature fluctuated between 21 and 44 °C (Fig. 2a). Differences in relative humidity among sites were less dramatic (Fig. 2b), but the pre-reforested site still had the highest variability (range: 35–100%), while the reforested (range: 50–96%) and forested reference sites (range: 66–98%) were less variable. Differences in temperature and relative humi-



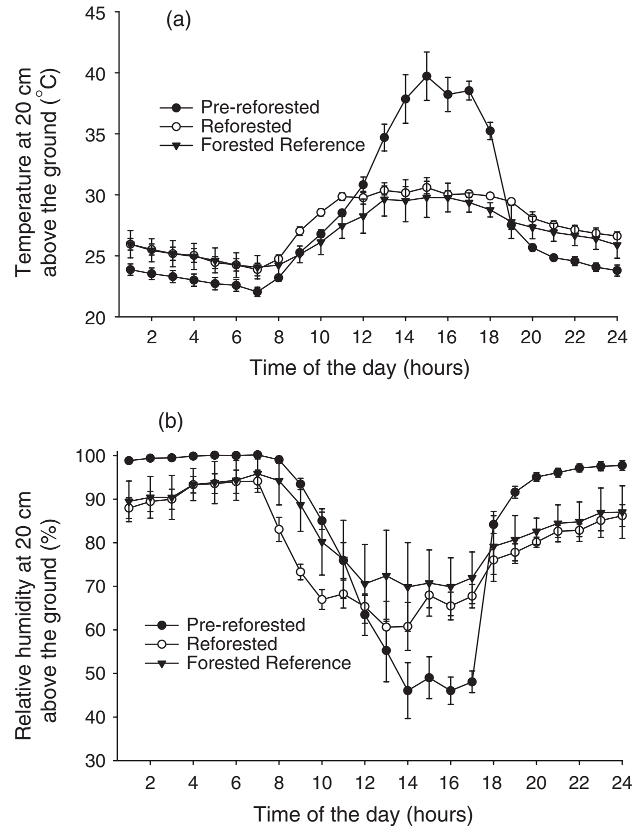


Fig. 2. (a) Temperature and (b) relative humidity during July 2002 in the pre-reforested, reforested, and forested reference sites. Values are the mean and standard deviations ($n = 30$ days).

dity were less pronounced during the night. Soil water content was highest in the pre-reforested (29.8%) followed by the reforested site (24.6%) and forested reference site (18.8%; Table 1).

Species diversity

The development of a more complex vegetation structure in the reforested site changed the microhabitat and facilitated the colonization of other plant species (Table 2). For example, once herbaceous cover decreased, woody seedling richness increased from one species in the pre-reforested site to 21 species in the reforested site, and 18 in the forested reference site

Fig. 1. Recovery of vegetation structure in the reforested site in comparison with the pre-reforested and forested reference sites: (a) distribution of DBH size classes of woody stems; (b) vegetation height (m) of woody stems (boxes represent 25–75 percentiles, lines within boxes represent the median value, and bars indicate the 90th and 10th percentiles, and black dots are outliers); and (c) percent of ground cover (herbaceous, litter, and bare soil).

Table 1. Density and biomass of earthworms, and soil water content at two soil depths in the pre-reforested, reforested, and forested reference sites

Sites	Soil profiles (cm)	Earthworms		Soil
		Density (individuals m^{-2})	Biomass ($g\,m^{-2}$)	Water content (%)
Pre-reforested	0–10	154.7±173.3	21.4±26.2	31.0±4.0
	10–20	100.0±164.6	21.2±33.0	28.7±3.4
Reforested	0–10	196.0±273.2	33.1± 57.0	24.8±5.0
	10–20	57.3±89.1	27.8± 41.0	24.5±3.6
Forested reference	0–10	253.3±125.8	46.5±25.5	18.9±3.7
	10–20	25.3±26.8	5.6±7.3	18.6±4.6

Values are means and standard deviations.

Table 2. Woody seedlings density (individuals m^{-2}) and dispersal mode in the pre-reforested, reforested, and forested reference sites

Scientific name	Dispersal mode	Pre-reforested	Reforested	Forested reference
Ricinus communis[a]	Wind	0.34	0.08	
Calophyllum brasiliense	Bats/birds		2.63	8.74
Bambusa vulgaris[a]	Animal/water		2.04	1.78
Ocotea leucoxylon	Birds		0.34	1.53
Solanum torvum	Birds		0.25	
Spathodea campalunata[a]	Wind		0.25	1.70
Citharexylum fruticosum	Birds		0.17	
Delonix regia[a]	Autochorus		0.17	
Helicteres jamaicensis	Explosive		0.17	
Mimosa pellita	Autochorus		0.17	
Andira inermis	Bats		0.08	
Cecropia schreberiana	Bats/birds		0.08	0.08
Mangifera indica[a]	Humans		0.08	
Mutingia calabura[a]	Birds		0.08	
Ochna mossambicensis[a]	Birds		0.08	
Piper hispidum	Bats		0.08	0.34
Hura crepitans	Explosive		0.08	
Swietenia mahagoni[a]	Wind		0.08	
Tabebuia heterophylla	Wind		0.08	
Thespesia grandiflora	Autochorus		0.08	
Ardisia elliptica[a]	Birds			5.86
Ocotea floribunda	Birds			1.61
Nectandra patens	Birds			0.85
Syzygium jambos[a]	Birds/water			0.76
Guarea guidonea	Birds			0.59
Casearia guianensis	Birds			0.25
Piper jacquemontianum	Bats			0.17
Hippocratea volubilis	Wind			0.08
Murraya exotica[a]	Birds			0.08
Ocotea coriaceae	Birds			0.08
	Total number of species	1	20	16

[a]Represents exotic species.

(Fig. 1c and Table 2). Seedlings in the reforested site included native species, but there were also exotic species. Animal dispersed species were only present in the reforested and forested reference sites, and most of the animal dispersed species in the reforested site were not planted (Appendix A). An exception was *Calophyllum brasilense*, a bat-dispersed species, which was planted, but these individuals have not begun to reproduce; therefore, the high abundance of seedling is due to dispersal.

Table 3. Ant capture frequency (frequency of captures in 20 traps) and habitat preference in the pre-reforested, reforested, and forested reference sites

Scientific name	Habitat preference	Pre-reforested	Reforested	Forested reference
Wasmannia auropunctata	Generalist	0.71	0.29	0.46
Paratrechina steinheili	Generalist	0.25	0.29	0.17
Solenopsis geminata	Generalist	0.25	0.04	0.25
Monomorium ebeninum	Grass/agricultural land	0.17	0.17	0.04
Brachymyrmex heeri	Generalist	0.17	0.17	0.08
Pheidole moerens	Forest	0.13	0.29	0.21
Solenopsis corticalis	Forest	0.04	0.50	0.50
Odontomachus ruginodis	Generalist	0.17		0.13
Cyphomyrmex minutus	Ground	0.08		0.17
Pheidole sp1	Ground/rotten wood		0.17	0.46
Pheidole sp2	Ground/rotten wood		0.17	
Strumigenys rogeri	Leaf litter		0.08	
Mycocepurus smithii	Ground			0.13
Hypoponera opaciceps	Generalist			0.13
Tapinoma melanocephalum[a]	Arboreal			0.08
	Total number of Species	9	10	12

[a]Represents exotic species.

Ant species richness was similar in all sites, but the composition and capture frequency varied among sites (Table 3). For example, *Wasmannia auropunctata* was most common in the pre-reforested site (0.71 capture frequency) and was less common in the reforested (0.29 capture frequency) and forested reference (0.46 capture frequency) sites. In contrast, the frequency of *Solenopsis corticalis* increased with an increase in vegetation structure from a capture frequency of 0.04 in the pre-reforested site to 0.50 in the reforested and forested reference sites. Even though, most ant species were present in all sites, *Hypoponera opaciceps*, *Mycocepurus smithii*, and *Tapinoma melanocephalum* were only present in the forested reference site.

Amphibian species richness was highest in the reforested site ($n = 5$), followed by the forested reference site ($n = 4$), and the pre-reforested site ($n = 3$). Three native species were present in all sites and they accounted for $>90\%$ of the total abundance in each site (Table 4). These species varied in densities among sites. *Eleutherodactylus coqui*, the most abundant species in all sites, increased in density from the pre-reforested site to the reforested and forested reference sites (Table 4). In contrast, densities of *Eleutherodactylus antillensis* decreased from the pre-reforested site to the reforested and forested reference sites.

Reptile species richness increased from two species in the pre-reforested site to five species in the reforested and forested reference sites (Table 4). The reforested site shared species with the pre-reforested and forested reference sites. For example, *Anolis krugii* decreased in density from the pre-reforested site to the reforested and forested reference sites (Table 4). In contrast, densities of *Anolis pulchellus* increased from the pre-reforested site to the reforested site; however, it was not present in the forested reference site. *Anolis cristatellus* was only present in the reforested and forested reference sites. Similarly, *Anolis stratulus* was only found in the reforested and forested reference sites, but at low densities.

Three bird species were observed in the pre-reforested site, 11 species in the reforested site, and 10 species in the forested reference site (Table 5). In the reforested site, two species were exotics and nine were native. Most of the native species are very common in urban areas in Puerto Rico (e.g., *Quiscalus niger* and *Tyrannus dominicensis*) (Table 5). One of the native species in the reforested site is an endemic, while the forested reference site has three endemics. Moreover, the aquatic species *Butorides virescens* and *Egretta caerulea* were present in the reforested site.

Ecosystem processes

Earthworm density and biomass did not varied among sites, but earthworm density was higher in 0–10 cm soil profile (201.33 individuals m^{-2}) than in the 10–20 cm soil profile (60.89 individuals m^{-2}) in all sites (Table 1).

Litterfall production and nutrient inputs varied among the three sites (Fig. 3). Litterfall production was highest in the reforested site (15.52 Mg ha^{-1} yr^{-1}) followed by the forested reference site (12.86 Mg ha^{-1} yr^{-1}), and pre-reforested site (1.68 Mg ha^{-1} yr^{-1}; Fig. 3a). Phosphorus inputs varied from 1.35 kg ha^{-1} yr^{-1} in the pre-reforested site to 10.14 kg ha^{-1} yr^{-1} in the reforested site, while the forested reference site had 6.97 kg ha^{-1} yr^{-1} (Fig. 3b). Similarly, nitrogen inputs varied from 22.90 kg ha^{-1} yr^{-1}

Table 4. Amphibian and reptile density (individual ha^{-1}) and habitat preference in the pre-reforested, reforested, and forested reference sites

Group/scientific name	Habitat preference	Pre-reforested	Reforested	Forested reference
Amphibians				
Eleutherodactylus coqui	Arboreal/herbs	1900	2000	2733
Eleutherodactylus antillensis	Herbs/grasses	1333	600	200
Leptodactylus albilabris	Ground	100	433	67
Bufo marinus[a]	Ground		67	
Eleutherodactylus cochranae	Arboreal		167	
Rana catesbeiana[a]	Aquatic			33
	Total density	3333	3267	3033
	Total number of species	3	5	4
Reptiles				
Anolis krugii[b]	Grass/bush	3700	3100	1500
Anolis pulchellus	Herbs/grasses	1300	2900	
Anolis cristatellus	Arboreal		3367	3433
Anolis stratulus	Arboreal		100	133
Sphaerodactylus macrolepis	Leaf litter		67	
Anolis evermanni[b]	Arboreal			900
Ameiva exsul	Ground			133
	Total density	5000	9533	6100
	Total number of species	2	5	5

[a]Represents exotic species.
[b]Represents endemics.

Table 5. Bird presence and absence in the pre-reforested, reforested, and forested reference sites

Group/scientific name	Pre-reforested	Reforested	Forested reference
Lonchura cucullata[a]	X	X	
Lonchura punctulata[a]	X	X	
Tiaris bicolor	X	X	
Chlorostilbon maugaeus[b]		X	X
Coereba flaveola		X	X
Margarops fuscatus		X	X
Turdus plumbeus		X	X
Tyrannus dominicensis		X	X
Butorides virescens		X	
Egretta caerulea		X	
Quiscalus niger		X	
Brotogeris versicolurus[a]			X
Melanerpes portoricensis[b]			X
Mimus polyglottos			X
Spindalis portoricensis[b]			X
Zenaida aurita			X
Total number of species	3	11	10

[a]Represents exotic species.
[b]Represents endemics.

in the pre-reforested site to 140.42 kg $ha^{-1} yr^{-1}$ in the reforested site, while the forested reference site has 97.27 kg $ha^{-1} yr^{-1}$ (Fig. 3c). Calcium and magnesium also had the highest values in the reforested site; followed by the forested reference site, and much lower values in the pre-reforested site (Figs. 3d and e). In contrast, potassium had the highest values in the pre-reforested site (35.61 kg $ha^{-1} yr^{-1}$), followed by the reforested site (23.50 kg $ha^{-1} yr^{-1}$), and the forested reference site had the lowest value (19.25 kg $ha^{-1} yr^{-1}$; Fig. 3f).

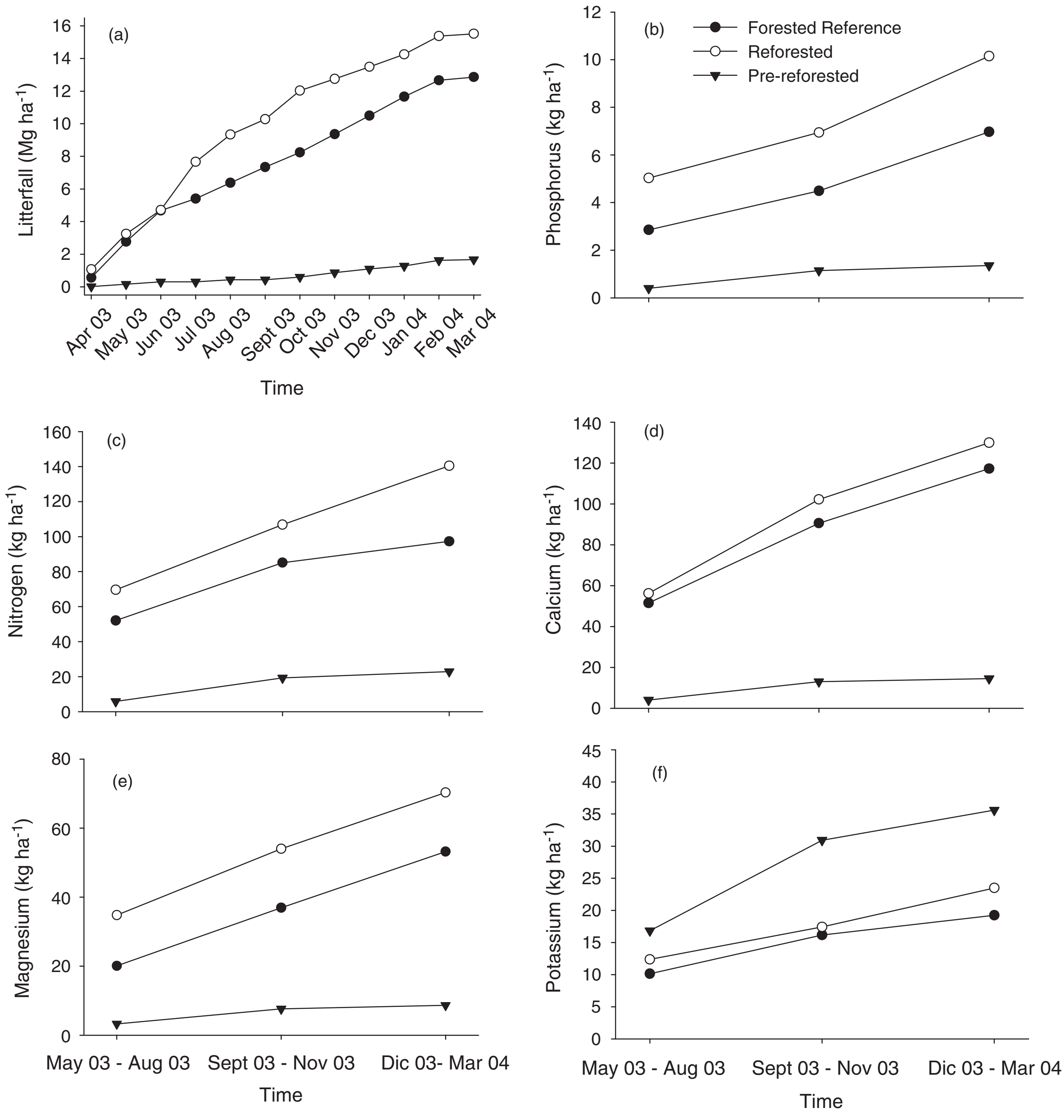


Fig. 3. Cumulative curves of: (a) litterfall production (mean monthly litter production), and nutrient inputs of (b) phosphorus, (c) nitrogen, (d) calcium, (e) magnesium, and (f) potassium. Values for nutrients were obtained by multiplying nutrient concentration by the litter produced during each period in the pre-reforested, reforested, and forested reference sites. Values of litterfall include leaves and twigs with a diameter less than 2 cm.

Restoration success

The Bray Curtis analysis showed that the overall restoration success of the project based on four variables of vegetation structure, two variables of species diversity, and five variables of ecosystem processes was approximately 70% (Fig. 4). For vegetation structure, the Bray Curtis analysis showed that the reduction of herbaceous cover and recovery on the abundance of woody stems in DBH size classes were the variables that recovered fastest, followed by woody plant height and litter cover (Fig. 4). For species diversity, the Bray Curtis showed that ants had the fastest recovery, followed by seedlings, reptiles, and birds. Amphibians

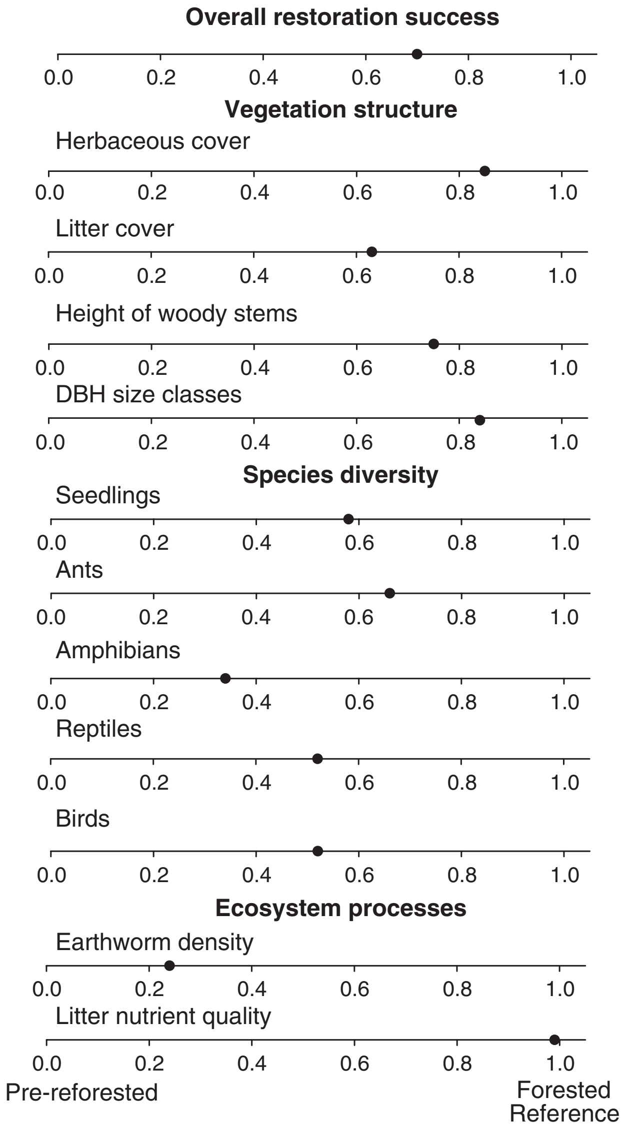


Fig. 4. The overall restoration success and recovery rates of individual variables based on the Subjective Bray Curtis Ordination. The overall restoration success was based on four variables of vegetation structure, two variables of species diversity, and five variables of ecosystem processes. In each ordination, the value indicates the relative position of the reforested site in comparison of the pre-reforested and forested reference sites.

were the slowest group to recover (Fig. 4). For ecosystem processes, the Bray Curtis showed that litter nutrient quality recovered very fast; in contrast, earthworm density will take longer to reach the values of the forested reference site.

Discussion

As vegetation structure developed in the reforested site, microclimate conditions stabilized and became similar to the forested reference site. The reforested site has reached similar values of vegetation structure in comparison with the forested reference site, due to fast growing pioneer species (*Helicteres jamaicensis*, *Hura crepitans*, and *Thespesia grandiflora*). This rapid growth of pioneers has created a closed canopy over most of the reforested site. The development of a closed canopy has reduced light levels in the understory causing a reduction in herbaceous cover. This reduction of herbaceous cover after only 4 years, normally occurs during the first 10 years of secondary forest succession (Aide et al., 1995). The reforested site had lower plant density than other secondary forests (Aide et al., 2000; Rivera et al., 2000), but we expected that this difference in plant density will decreased as seedling recruitment increases in the reforested site.

The woody seedlings that are recruiting into the reforested site included exotic and native species. The presence of exotic species (e.g., *Delonix regia*, *Mangifera indica*, *Mutingia calabura*, and *Spathodea campalunata*) is mostly explained by the proximity of the reforested site to a residential park that has exotic ornamental species and by the presence of invasive exotics in Puerto Rican landscapes (Lugo, 2004). Nevertheless, native species are also colonizing the reforested site. These native species included both wind dispersed (*Ricinus communis*) and animal dispersed species (e.g., *Andira inermis*, *Calophyllum brasilense*, *Cecropia schreberiana*, *Ocotea leucoxylum*, *Piper hispidum*, and *Solanum torvum*). The presence of wind-dispersed species in the reforested site is not a surprise, because these are often the first species to colonize abandoned lands (Aide et al., 2000; Zimmerman et al., 2000). For these species, the major limitation for colonization is competition with grasses (Holl et al., 2000). In contrast, the colonization of animal dispersed species is always limited in open areas (Nepstad et al., 1996; Zimmerman et al., 2000) because there are few resources to attract frugivorous birds and bats (Holl, 1998). Planting woody species has facilitated plant recruitment by reducing herbaceous cover and providing perches for animals dispersers.

Most ant species in the reforested site were generalists, a common pattern in urban forest fragments (Gibb and Hochuli, 2002). Nevertheless, ant species composition changed with the development of vegetation structure. *Monomorium ebeninum* decreased greatly with the development of vegetation structure, which reduced air temperature in the understory (Table 3 and Fig. 1a). This result supports the observations that *Monomorium ebeninum* forages more actively at higher temperatures and are common in grass-dominated areas (Torres, 1984b). In contrast, *Solenopsis corticalis* increased as vegetation structure developed, as was observe in a forest chronosequence study in Puerto Rico (Barberena-Arias and Aide, 2003).

The dominant amphibians species were the same in all sites. These species forage at night when there is little difference in relative humidity among sites (Fig. 1b). Amphibians are more likely to respond to moisture rather than to vegetation structure due to their physiological requirements (Stebbins and Cohen, 1995; Schlaepfer and Gavin, 2001; Fredericksen and Fredericksen, 2004). Nevertheless, species density changed with changes in vegetation structure. The density of the forest species *Eleutherodactylus coqui* increased almost 40% from the pre-reforested site to the forested reference site. In contrast, the density of *Eleutherodactylus antillensis*, a grass-dominated species, decreased approximately 80% from the reforested site to the forested reference site (Schwartz and Henderson, 1991). The presence of an arboreal species, *Eleutherodactylus cochranae*, in the reforested site, suggested that some amphibian species could serve as indicators of forest recovery.

The density of reptiles in the reforested site was higher than the density in the pre-reforested and forested reference sites. The higher density of reptiles in the reforested site could be explained by the conditions of vegetation structure. The vegetation structure of this site offered both herbaceous and arboreal habitats for different species requirements. For example, *Anolis krugii*, a grass/herb species (Schwartz and Henderson, 1991), was the most abundant reptile in the pre-reforested site; it was also very abundant in the reforested site, but the density in the forested reference site was much lower. In contrast, *Anolis cristatellus*, an arboreal species (Schwartz and Henderson, 1991), was the most abundant species in both reforested and forested reference sites, while it was absent in the pre-reforested site. Clearly, the reforested site offered suitable habitat for both herb/grass and arboreal species to co-occur. Surprisingly, the arboreal species, *Anolis stratulus*, that forages exclusively in the canopy had colonized the reforested site, suggesting that the fast growth of trees in the reforested site are already offering sites for arboreal specialists.

The presence of both herbaceous cover and woody vegetation in the reforested site increased bird species richness. The reforested site shared species with the pre-reforested and the forested reference sites, as has been observed in other studies of birds in urban areas (Crooks et al., 2004). Although there was an increase in species richness in the forested sites, the majority of the species are generalists. These species are associated with urban areas where their densities increase (Donelly and Marzluff, 2004). For example, *Quiscalus niger* and *Turdus plumbeus* are very abundant in urban areas and often forage in human garbage (Raffaele et al., 1998). Similarly, *Tyrannus dominicensis* takes advantage of insects attracted by streetlights (Raffaele et al., 1998). In addition to these generalist species, specialist species such as *Butorides virescens*, an aquatic predator, also colonized the reforested site once the vegetation structure provided perches for foraging (Raffaele et al., 1998).

The similarity in earthworm density and biomass among sites was mostly explained by the high variability within sites (Table 1). Another reason may be that the overall litter quality was the same in all sites. Litter quality rather than quantity have been reported to affect earthworm densities (Zou, 1993; Zou and Gonzalez, 1997). Nevertheless, earthworm density was highest in the upper soil layer (0–10 cm), possibly due to a higher concentration of roots and organic matter in this soil layer (Martinez and Sanchez, 2002).

Litterfall and nutrient inputs were highest in the reforested sites in comparison with both the pre-reforested and forested reference sites. Litterfall production was highest in the reforested site because *Helicteres jamaicensis*, *Hura crepitans*, and *Thespesia grandiflora* dominated the litter composition. These species are pioneers with short-lived leaves that senesce rapidly and produce abundant leaf biomass. In contrast, the forested reference site is dominated by shade tolerant species that allocate their energy to long-lived leaves and wood development. The difference in nutrient inputs was mainly due to differences in litterfall production, because there was little difference in litter nutrient quality among sites. Nutrient input in the reforested site was within the range of moderately fertile soils of other tropical ecosystems (Montagnini and Jordan, 2002).

Conclusion

The rapid recovery of vegetation structure contributed to four major changes in the urban reforested site: (1) the decrease in herbaceous cover allowed for the natural colonization of woody seedlings; (2) the changes in microclimatic conditions enhanced the colonization of species or increased their abundance (e.g., ants, amphibians); (3) the colonization of arboreal species of reptiles and birds, which contributed to the diversification of the natural food web; and (4) the increase in litter production enhanced nutrient input. Although the native species that colonized the reforested site were generalists with wide habitat tolerance (MacNally and Brown, 2001; Crooks et al., 2004), the presence of a forest patch within a high-density urban area offers potential sites for colonization of a diversity of species that do not occur in grass-dominated areas.

Although we measured restoration success after only 4 years, most legal evaluations of restoration projects are done for periods less than 5 years. Most of the variables included in this study showed a rapid recovery. The variables used in restoration projects will depend on the ecosystem and the overall objective of the project.

Nevertheless, it is important to include at least two variables of each major ecosystem attribute (e.g., vegetation structure, species diversity, and ecosystem processes; Ruiz-Jaén and Aide, 2005). Moreover, it is highly recommended to compare these variables with pre-reforested and forested reference sites to estimate restoration success.

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Appendix A. The number and percent of woody species planted in the reforested site in August 1999

Woody species	Total number planted	Percent planted
Andira inermis	49	6.00
Ardisia obovata	30	3.67
Byrsonima spicata	15	1.84
Calophyllum brasiliense	31	3.79
Ceiba pentandra	22	2.69
Citharexylum fruticosum	31	3.79
Clusia rosea	3	0.37
Cordia alliodora	4	0.49
Eugenia monticola	7	0.86
Guapira fragans	6	0.73
Guarea guidonia	2	0.24
Helicteres jamaicensis	201	24.60
Hura crepitans	25	3.06
Inga fagifolia	11	1.35
Manilkara bidentata	125	15.30
Petitia domingensis	78	9.55
Picramnia pentandra	3	0.37
Prunus occidentalis	4	0.49
Pterocarpus officinalis	2	0.24
Roystonea borinquena	10	1.22
Stahlia monosperma	2	0.24
Tabebuia heterophylla	80	9.79
Thespesia grandiflora	76	9.30
Total	817	100

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