

Land-use history augments environment–plant community relationship strength in a Puerto Rican wet forest

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Summary

1. Environmental heterogeneity influences the species composition of tropical forests, with implications for patterns of diversity and species coexistence in these hyperdiverse communities. Many studies have examined how variability in soil nutrients and topography influence plant community composition, with differing results. None have quantified the relative contribution of environmental heterogeneity versus endogenous processes to variability in forest community composition over time and with respect to successional recovery.

2. Using five consecutive trees censuses of a forest plot in Puerto Rico, conducted between 1990 and 2011, we evaluated the influence of edaphic and topographic variability on community composition. The plot has a well-documented land-use history and is subject to periodic hurricane disturbance. Using multiple canonical distance-based redundancy analyses, we studied how spatial heterogeneity in soil nutrients and topography structure community composition over time, as the forest recovers from long-term land-use effects and two major hurricanes in 1989 and 1998.

3. For the entire plot, spatial variables (principle coordinates of neighbourhood matrices), representing the autocorrelation of tree species in the community, explained the majority (49–57%) of the variability in tree community composition. The explanatory power of spatial variables decreased over time, as forest structure recovered from hurricane damage and the stems in the understorey died. Soil nutrients and topography, collectively, explained a moderate portion (33–37%) of the species compositional variation and were slightly more robust in explaining compositional differences in areas of more intense past land use.

4. Areas of less-intense past land use showed weaker community–environmental trends overall, illustrating a tendency for stronger resource competition (i.e. light, water and soil nutrients) between species in these areas. This illustrates how environmental–plant community interactions are strengthened by the lasting effects of human land-use legacies, which persist for decades to centuries.

5. Synthesis. Our findings confirm past land use to be a fundamental driver of the structure and composition of secondary forests through its impacts on the tree community, the abiotic terrestrial environment and their interaction. Since the extent of second-growth tropical forests continues to increase, our findings highlight the importance of understanding the processes that determine the rate and nature of their succession.

Key-words: beta-diversity maps, land-use legacies, Luquillo, plant–soil (below-ground) interactions, soil resources, spatial autocorrelation, terrain ruggedness, topography, tropical forest, variance partitioning

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Introduction

A number of theories exist regarding how such high levels of tree species diversity are maintained in tropical forests, from negative density-dependent mechanisms (e.g. Janzen–Connell processes; Janzen 1970; Harms *et al.* 2000; Jansen *et al.* 2014) to dispersal-limited stochasticity (Hubbell 2001; see Wright 2002 for a complete review of theories). Studies also support local resource variation (i.e. soil nutrients, light and water), and other niche-related processes as key in maintaining diversity, especially in highly diverse tropical ecosystems (Hutchinson 1957, 1978; Ricklefs 1977; Booth *et al.* 1988; Paoli, Curran & Zak 2006). These processes shape observed forest communities by operating at multiple scales, over varying time periods, and in conjunction with natural or anthropogenic disturbance regimes.

Natural disturbances (e.g. hurricanes, floods and fire) and human land use (e.g. logging) induce changes in species composition and abiotic resource availability, accelerating ecosystem transformation (White 1979; Sousa 1984; Legendre & Fortin 1989). A number of studies have demonstrated that forest responses to human and natural disturbance depend on species-specific life-history trade-offs. Differences in survival and reproductive strategies among tropical tree species, specifically the initial competitive advantage and subsequent high mortality of early-successional pioneer species as the forest canopy recovers, determine the trajectory and rates of forest succession (Pacala & Rees 1998; Comita *et al.* 2010; Wright *et al.* 2010; Uriarte *et al.* 2012). As human activities continue to simplify and modify ecosystems (Chapin *et al.* 1997; Hautier *et al.* 2015), it is crucial to understand how land-use legacies influence the abiotic environment of tropical forests and how the impacts of these legacies play out over time.

Time since land-use abandonment, the land-use intensity and its duration are the main factors affecting soils and subsequent vegetation recovery rate and quality (e.g. forest structure, canopy height and biomass). For example, disturbance intensity was found to be more important than environmental variation in soil resources in determining structure and composition of regenerating forests in Hainan Island, China (Ding *et al.* 2012). Human land use reduced total organic carbon and nitrogen concentrations of soils in Mexican forests, with increases after land-use abandonment, but at different rates (Cram *et al.* 2015). Nitrogen and phosphorus have long been thought to trade-off as limiting nutrients in terrestrial systems and together may be used as indicators of soil fertility in the tropics (Tateno & Chapin 1997). The recovery of soil fertility and the organic humus layer in tropical forest, clay-derived soils (e.g. Oxisols vs. Ultisols) that have been strongly affected by past land use are likely to take decades to recover, illustrating the long-term effects of soil-based alteration via land use on vegetation composition and structure (Zimmermann, Papritz & Elsenbeer 2010).

Environmental heterogeneity in resources reflects the complex interaction of many biotic (e.g. herbivory and vegetation turnover) and abiotic processes (e.g. decomposition, lithology

and climate) that operate at a variety of spatial and temporal scales (Canham *et al.* 1994; Zimmerman *et al.* 1996; Wilson 2000; Tylianakis *et al.* 2008). Specifically, highly diverse tropical forests are known for their large spatial variability in soil chemical and texture, soil moisture, elevation, topography and temporal dynamism in soil moisture (related to rainfall and soil characteristics) and light conditions (e.g. light dynamics associated with canopy structure and gap creation or hurricane disturbance and recovery; Terborgh 1992; Holdridge *et al.* 1971; Brokaw & Busing 2000; Davies *et al.* 1998; Cleveland *et al.* 2011).

Soil properties can influence tree canopy height, productivity and the rate of recovery of tropical forests following disturbance, especially in terms of species community richness (Ellis & Pennington 1992). High soil C: N, sand: clay, Al and P concentrations were associated with a more complex forest structure and increased diversity associated across a successional gradient in Brazil (Martins *et al.* 2015). Similarly, higher soil organic matter, higher nitrogen availability and lower bulk density of soils were the main factors facilitating forest regrowth and succession in highly degraded areas of China (Duan *et al.* 2008). Despite a number of studies on this topic, results vary greatly across the tropics, and it remains unclear how soil resources influence plant community composition in forests recovering from land use or other disturbance.

Although plant community diversity is generally greater at high precipitation and lower elevation, at any particular time, differences in physical environment can only weakly explain patterns of alpha-diversity within tropical forest communities (Laliberté, Zemunik & Turner 2014; Laliberté *et al.* 2013). Therefore, to understand environmental–community relationships, we must first understand community composition in terms of beta-diversity or compositional differences between forest areas. Globally, beta-diversity in tree species increases with increasing topographic variation (De Cáceres *et al.* 2012). It is equally useful to evaluate the how topographies influence community composition at more localized scales within tropical forests. In a 20-ha permanent forest dynamics plot (FDP) in south-western China, topography was shown to play a significant role in controlling distributions of a number of tree species, especially at early life stages (e.g. saplings and immature trees; Lan *et al.* 2011). Other studies have documented the strong effects of topographic-related habitat-filtering of juvenile trees, showing a trend of decreasing strength of filtering as trees mature (Kanagaraj *et al.* 2011; Puchi-Manage *et al.* 2013; Hu *et al.* 2012; Zemunik *et al.* 2016).

Here, we examine the role of topography and soil resources in structuring a Neotropical plant community that was affected by land use in the past of different intensities within a permanent 16-ha forest dynamics plot in Puerto Rico. In this study, however, we do not seek to differentiate the direct or indirect effects of land use on plant community–soil interactions, but rather examine how the interactions change over time and with the recovery of the forest from the land use and the compound effect of two hurricane disturbances

(Hurricane Hugo in 1989 and Hurricane Georges in 1998). Using multivariate redundancy analysis to partition the variability in plant community beta-diversity into spatial, edaphic and topographic portions, we ask:

1 How well does variation in soil resources and topography explain patterns of plant diversity composition with respect to land-use legacies? We predicted soil resource and topographic variables would have less explanatory power in structuring plant communities with more intense land use (i.e. weaker habitat association). The explanation could be that either the land use has homogenized soil resource distributions, or plant species distributions have been affected by the effects of past land use. Alternatively, weak species–environment associations could reflect a compound effect of the two processes, resulting in a decoupling of the relationships between the abiotic environment and forest community composition.

2 To what degree do environmental–plant community relationships change over time and in response to hurricane disturbances and with respect to land-use history? We expect the strength of plant community–environmental relationships to increase with time following hurricane disturbances as the effect of the hurricane damage diminishes and the plant community reflects the environment. We hypothesize environmental relationships to be strongest in less-disturbed areas, because there was less of a decoupling effect associated with past low-intensity land-use pressure in these areas.

Materials and methods

SITE DESCRIPTION AND TREE CENSUS METHODS

The Luquillo Forest Dynamics Plot (LFDP) [18°20' N, 62°49' W] is a permanent forest monitoring plot located in the montane wet forest of north-eastern Puerto Rico. The forest type is described as *tabonuco* forest, named after a dominant species *Dacryodes excelsa* Vahl. (Wadsworth 1951). The forest canopy is uniform, lacking canopy emergents, in primary tabonuco forest with an average canopy height of about 30 m and with few trees exceeding 2 m diameter at breast height (dbh, diameter at 1.3 m above the ground surface; Brokaw *et al.* 2004). Topographic variability within the LFDP is large with elevation ranging between 333 and 428 masl. and slopes averaging 17%, but ranging from 3% to 60% (Weaver 2000; Thompson *et al.* 2002; Harris *et al.* 2012). Mean annual rainfall is 3685 mm (1975 to present) and temperature ranges from 20.5 to 22.8 °C (Ramírez & Melendez-Colom 2003; Thompson *et al.* 2004).

Soils in the LFDP are clay, comprised of deeply weathered Oxisols and Ultisols developed in marine sedimentary lithology of volcanic origin. These soils orders are typical of lowland tropical forests world-wide; however, soil fertility in the LFDP is higher than much of the continental lowland tropics (Soil Survey Soil Staff 1995; Beinroth 2010). The plot has been censused five times at approximately 5-year intervals between 1990 and 2011. Due to Puerto Rico being a medium-sized island located at a moderate distance from continental land masses, species richness is relatively low when compared to other tropical forests, ranging from 43 to 54 species·ha⁻¹ (Lawrence 1996). In the most recent (2011) tree census, 123 species were recorded in the whole LFDP (Hogan 2015).

In the 16-ha (320 m × 500 m) LFDP, all free-standing wood stems ≥1 cm dbh are mapped, measured and identified to species.

Tree measurement protocols follow those employed by the Center for Tropical Forestry Science (CTFS) and large forest dynamics plots across the globe (Condit 1998; Anderson-Teixeira *et al.* 2015). The LFDP was established in 1990, soon after Hurricane Hugo, which heavily damaged the forest (Scatena & Larsen 1991; Zimmerman *et al.* 1994). A second hurricane, Georges, passed over the forest in 1998, but caused much less damage. Land-use legacies resulting from settlement, coppicing and charcoal production prior to the 20th century have emerged as a key driver of forest succession within the northern LFDP. The LFDP is made up of three areas of secondary forest of differing past land-use intensity (all three areas ≤80% forest cover in 1936 aerial photographs; Foster, Fluet & Boose 1999), which were combined to form one heterogeneous patch of secondary forest that we refer to as the high land-use intensity area in the north of the plot (Thompson *et al.* 2002; Uriarte *et al.* 2009). This area was completely cut over at some point prior to 1934 (Thompson *et al.* 2002). The southern third of the plot contains relatively well-conserved area of *tabonuco* forest, which harboured > 80% canopy cover in historical aerial photographs, and was only subjected to minor selective logging in the 1940s for tests of release thinning around individual trees (Frank Wadsworth, personal communication). Following major hurricanes in 1928 and 1932, it is believed that farming died out in the area and stopped entirely in 1934 when the forest service bought the land (Gerhart 1934; Weaver 2012), creating a land-use legacy gradient, of four distinct forest patches, that directly relates to forest successional stage across the plot (Fig. 1).

QUANTIFYING ENVIRONMENTAL VARIABLES WITHIN THE LFDP

Field soil collection took place in 2011. Soil samples were taken from 0 to 10 cm depth in the mineral soil across a 40-m grid within the LFDP following methodology in John *et al.* (2007), with additional samples taken at 2 m and 8 m in random directions from selected regular sample points to estimate local variability in soil chemistry. Soil pH was determined in both deionized water and 10 mM CaCl₂ in a 1:2 soil to solution ratio using a glass electrode. Concentrations of ammonium and nitrate were determined by extraction of fresh soils in the field in 2 M KCl, with detection by automated colorimetry on a Lachat Quikchem 8500 (Hach Ltd, Loveland, CO, USA). Plant-available phosphorus was estimated by extraction of air-dried and sieved (< 2 mm) samples by Bray-1 solution, with detection of phosphate by automated molybdate colorimetry. Exchangeable cations, including aluminium, calcium, iron, magnesium, manganese and sodium, were extracted from air-dried soils in 0.1 M BaCl₂ (2 h, 1:30 soil to solution ratio), with detection by ICP-OES spectrometry on an Optima 7300 DV (PerkinElmer Inc, Shelton, CT, USA; Hendershot, Lalonde & Duquette 2008). Total exchangeable bases (TEB) were calculated as the sum of calcium (Ca), potassium (K), magnesium (Mg) and sodium (Na); effective cation exchange capacity (ECEC) was calculated as the sum of aluminium (Al), Ca, iron (Fe), K, Mg, manganese (Mn) and Na; base saturation was calculated by (TEB/ECEC) × 100. Values were kriged to obtain soil cation estimates at the 20 × 20-m scale.

Topographic variation within the LFDP is more variable than in most other permanent forest dynamics plots (Losos & Leigh 2004). The CTFS method for measuring topographic variability in large FDPs is at the 20-m, or quadrat, scale (Condit 2012). Using previously surveyed elevations for quadrat corners within the LFDP (16 columns × 25 rows; see Thompson *et al.* 2002), finer-scale topographic variation was measured at the 5-m scale using clinometers to

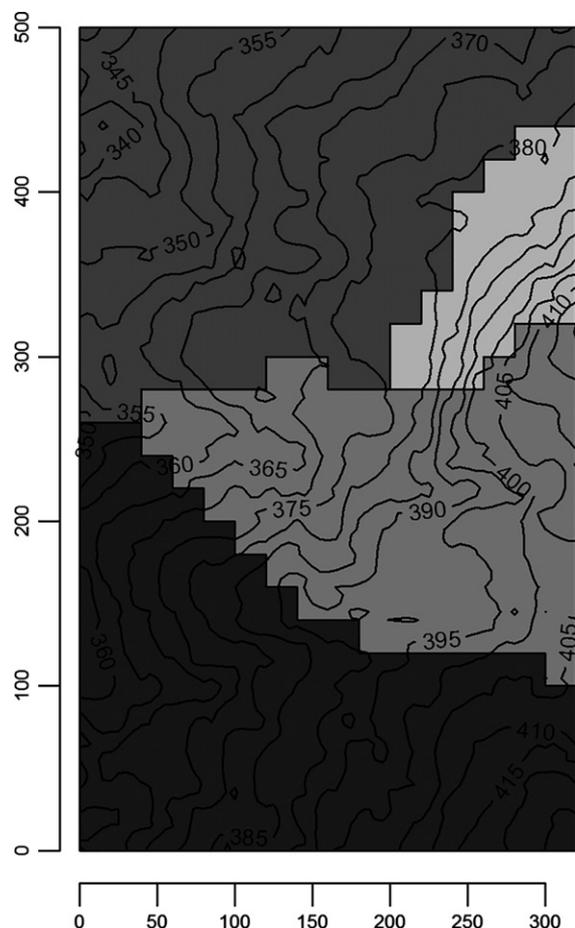


Fig. 1. Historical land-use demarcations within the LFDP (Thompson *et al.* 2002), based on the amount of forest canopy in 1936 aerial photographs (Foster, Fluet & Boose 1999). Per cent forest cover in 1936, in order from lightest to darkest: 0–20%, 20–50%, 50–80% and 80–100%. The low land-use intensity area is shown in the darkest shade, and the three lightest shaded areas, together, make up the high land-use intensity portion of the plot.

measure the elevation of 5×5 m grid points delineating the subplots and was used to calculate topographic variation. Elevation throughout the LFDP is shown in Fig. 1, with the most elevated areas towards the south-eastern plot boundary and the lowest elevations in the north-west corner.

Topographic variables included slope, convexity, aspect and terrain ruggedness. We incorporated a unique topographic variable, terrain ruggedness, which is a quantifiable measure of terrain heterogeneity. Slope was calculated using the CTFS method, where 4 planes are drawn through all possible, unique combinations of 3 quadrat corners at 5-m intervals within a $20 \text{ m} \times 20 \text{ m}$ plot and subsequently averaged (Condit 2012). Convexity was calculated using the mean elevation of each quadrat relative to the mean of its eight orthogonal neighbours (Condit 2012). Aspect was decomposed into east–west and north–south orientations using sine and cosine, respectively (Lin *et al.* 2013). The terrain ruggedness index, quantified for at the 20-m scale, was implemented as defined by Riley (1999) and calculated in GRASS (Grass Development Team 2012) using the 5-m scale topographic variation within the LFDP. We refer to environmental variables, hereafter, as the complete set of the kriged soil nutrient estimates and topographic variables, excluding spatial variables.

BETA-DIVERSITY MAPS

To visually examine variation within the forest community across the LFDP, species diversity maps were generated using floral gradient analysis (Thessler *et al.* 2005). Using Bray–Curtis dissimilarities, non-metric multidimensional scaling (NMS) ordinations for each census at the quadrat scale (20×20 m) were constrained to three axes. Ordination axes scores, or their position in the 3-dimensional ordination space, were translated to hexadecimal colour values for red, blue and green, respectively. The resulting maps display diversity differences in community composition chromatically (Baldeck *et al.* 2013). Quadrats with colours of similar shades between quadrats represent similar species composition, whereas colours of different shades show areas where tree species composition is more different. Within each census, redder shades were standardized within each census to show areas where compositional make-up was most similar. NMS and colour standardization was done separately for each tree census; therefore, maps created using this method cannot be interpreted in relation to one another (i.e. across censuses).

REDUNDANCY ANALYSIS/VARIANCE PARTITIONING

We used canonical distance-based redundancy analysis (db-RDA; Legendre & Anderson 1999), to examine the amount of variance explained by environmental differences related to soil resources, topography and space (Fig. 3; Peres-Neto *et al.* 2006). Redundancy analysis, an extension of canonical correspondence analysis, is a method of multivariate linear predictive models for a combination of response variables (in our case, community composition) from a set of predictor variables (in our case, space, topographic and soil nutrient variables; Quinn & Keough 2002; McCune, Grace & Urban 2002). We chose to use RDA to test how well environmental predictor variables, including space, could predict community composition as a direct test for plant community–environment relationships. Hellinger-transformed species abundance counts within quadrats made up the set of response variables (Legendre & Gallagher 2001; Dray, Legendre & Peres-Neto 2006).

Due to the autocorrelated nature of tree species distributions, space must be explicitly incorporated into the RDA (Legendre 1993). Principle coordinates of neighbourhood matrices (PCNM) is currently the most appropriate tool for this (Borcard & Legendre 2002; Dray, Legendre & Peres-Neto 2006), because it incorporates the spatial structure in species response data at the most relevant species–environmental scale. PCNM decomposes the spatial structure present in the community data into distance-based Moran's Eigenvector Maps (db-MEM; Borcard *et al.* 2004; Borcard & Legendre 2002). The db-MEM comprised the set of all spatial variables. The PCNM was computed in the *R* statistical environment (ver. 3.1.1; R Development Core Team 2014) with the 'PCNM' package (Legendre *et al.* 2010).

We expanded the set of environmental variables to permit for non-linear relationships and increase model flexibility, by calculating second- and third-order polynomials of all variables, except for aspect, prior to their forward selection (Legendre *et al.* 2009). Forward selection of variables is one of the simplest data-driven model building approaches, where explanatory variables are added to a model separately and successively until no variables can be further added to improve model fit or flexibility. Prior to variance partitioning, explanatory variables were standardized and selected at the 95% confidence interval using forward selection in the 'packfor' package (Dray, Legendre & Blanchet 2007; Blanchet, Legendre & Borcard 2008). Three-way variance partitioning of response variables with

respect to spatial, topographic and edaphic variables was carried out using the 'vegan' package (Oksanen *et al.* 2008).

PERMUTATIONAL ANALYSIS OF VARIANCE AND NON-METRIC MULTIDIMENSIONAL SCALING BI-PLOTS

Differences in of the community beta-diversity with respect to past land use were further explored by quantifying the magnitude of difference between quadrat groups of varying land-use intensity across the LFDP (as determined by 1936 aerial photographs, Fig. 1) using permutational multivariate analysis of variance (PERMANOVA) and ordinating them using non-metric multidimensional scaling (NMS). PERMANOVA was performed in the 'vegan' R package using the community species counts from the most recent (2011) tree census and the a priori land-use classifications (Thompson *et al.* 2002). PERMANOVA *P*-values were Bonferroni-adjusted to correct for multiple comparisons. For the NMS, forward-selected explanatory variables from RDA models were overlain as environmental vectors on the ordination, using 0.100 as the coefficient of determination cut-off to allow for weak to moderate environmental variable relationships (McCune, Grace & Urban 2002). Axis 1 in the ordination was rotated with respect to land-use intensity and therefore can be directly interpreted as an explanatory axis for land use. Visually, this allows for the display of environmental–community relationships across the entire plot. NMS ordinations were completed in PC-ORD 6 (McCune, Grace & Urban 2002; McCune & Mefford 2011).

Results

BETA-DIVERSITY MAPS

Quadrats of similar species composition consistently grouped together for each census in relation to past land-use intensity. Quadrats in the northern portion of the LFDP, subject to more intense land use, were clearly similar in community composition, as were quadrats in the southern portion where land use was less intense. A second area of high community compositional similarity was on the ridge at the western edge of plot ($\sim x = 100$ m, $y = 200$ m), and compositional differences were captured along the elevation gradient from the upper left corner (north-west LFDP) to the bottom right corner of the maps (south-east LFDP; Fig. 2; see Appendix S1 of Supporting Information). Most notably, the dominant colours in the beta-diversity maps changed greatly for census 2 (1995). Redder shades (lowest compositional variability between quadrats) became less prominent in the high land-use intensity portion (north) of the plot in 1995 due to the widespread recruitment of understory pioneer species in the high-intensity past land-use secondary forests following damage caused by Hurricane Hugo and then switched back to more-red colours and more compositional variability, recorded in the 2000 census, as mortality in the understory occurs as the canopy recovers (Hogan 2015).

REDUNDANCY ANALYSIS/VARIANCE PARTITIONING

Across the entire LFDP, over half of the variability in tree species community composition was related to spatial

(db-MEM) and environmental variables (Fig. 3; see Appendix S2). Although environmental fractions (i.e. those related to either soil or topography) were explanatory to some degree, the portion of variability explained by spatial variables accounted for most of the variance explained by RDA models. Generally, there was a decreasing trend in explanatory power over time for all RDA models, both at the whole-plot level (Fig. 3) and with respect to past land-use intensity (i.e. north vs. south; Figs. 4 and 5). Additionally, RDA models had greater explanatory power in areas of more intensive past land use (the northern part of the LFDP; see Figure S1 of Supporting Information). For the high land-use intensity part of the plot, environmental and spatial variables explained from 57% to 44% of community composition over time (Fig. 4). In contrast, the low land-use intensity area of *tabonuco* forest (i.e. the southern part of the LFDP) had weaker environmental–community relationships, with models explaining only 38–44% of variation in community composition (Fig. 5).

In all models, spatial variables accounted for the majority of variation in community composition, explaining between 38% and 57% of the variability in community composition. For the entire LFDP, soil cation concentrations and topographic variables only explained 30–33% and 11–14% of variation, respectively (Fig. 3). The explanatory power of environmental fractions was similar in magnitude, but more variable for the high land-use intensity areas of the LFDP (Fig. 4). However, in forest areas with low levels of previous land-use, soil nutrients and topographic variation explained less of the difference in community composition than in the high land-use intensity areas, ranging between 23% and 27% and between 14% and 16%, respectively (Fig. 5).

PERMANOVA AND NMS BI-PLOT

Community composition differed across the land-use gradient present in the LFDP, as shown in the beta-diversity maps (Fig. 2). These differences have persisted over the 21 year study period and were found to be statistically significant (PERMANOVA, $P < 0.01$) for both the high versus low land-use intensity comparison and also when comparing all four land-use intensities separately (Table 1; see Appendix S3). In the NMS of the most recent tree census (Fig. 6; 3-dimensional solution based on 125 iterations with a final stress of 14.89 using Bray–Curtis distance measure), a slight separation of the communities can be seen, with the high land-use intensity quadrats mainly clustering out more to the left hand side of axis 1 (land-use intensity), and with the lower land-use intensity quadrats tending towards the right side of the ordination. Convex hulls, or a polygons containing all the sites within each land-use category, were overlain on the ordination to display a tendency for more compositional variability in forest community across the area of more intense past land use in the LFDP. Axis 2 can be interpreted as a catena effect (convexity) from high (ridge) to low (valley) going from bottom to top of the axis. Base saturation of soil (BS) decreased along the catena (axis 2).

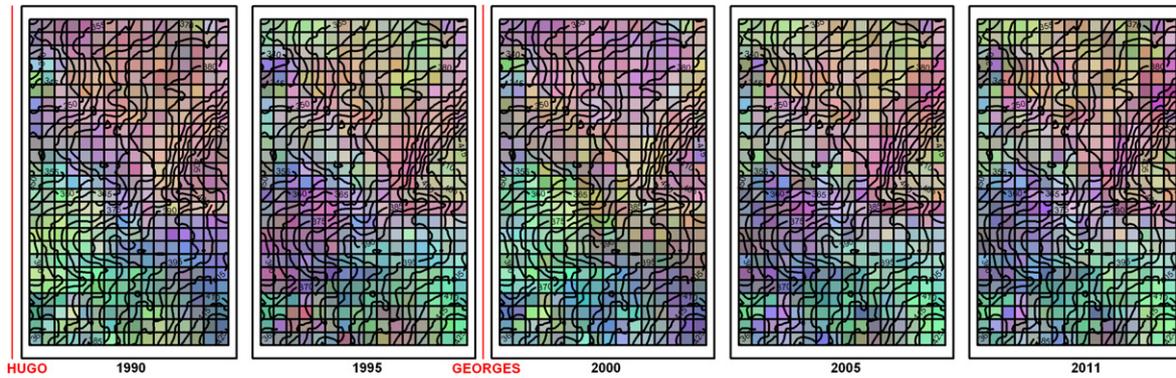


Fig. 2. Beta-diversity maps for the LFDP, created using floral gradient analysis (Thessler *et al.* 2005) for each of the five tree censuses. Colour represents the degree of compositional similarity (raw interpretation of Bray–Curtis dissimilarities) of tree species community composition between 20-m quadrats; quadrats of similar colour represent communities with similar species composition. Redder shades were standardized to areas of greatest community compositional similarity for that census. Notably, maps cannot be compared across censuses as the method compares compositional similarity between 20-m quadrats for each census separately. Red vertical lines show the hurricane occurrences (Hugo in September 1989 and Georges in September 1998).

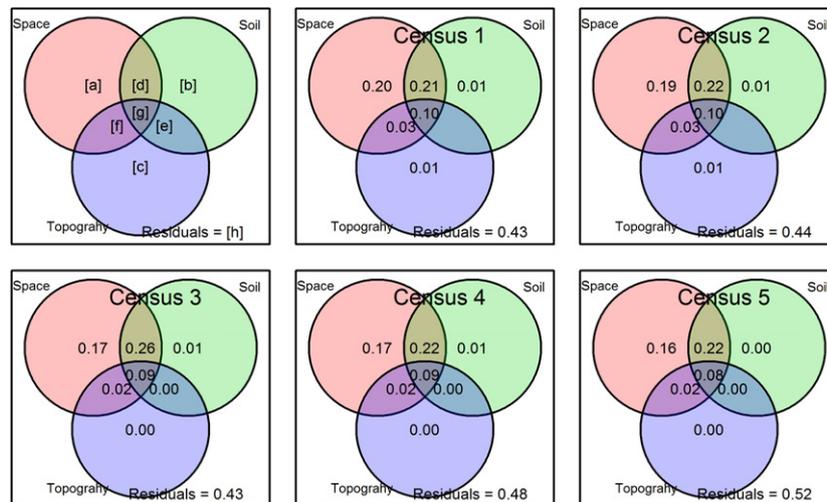


Fig. 3. Variance partitioning diagram (upper left panel) and results for the entire LFDP by tree census. Census 1 (top-middle panel) took place from 1990 to 1992, and subsequent censuses occurred at approximately 5-year intervals with census 5 (lower right panel) occurring in 2011. Numerical values represent the per cent of variance explained by distance-based RDA models for their respective fractions (values <0 not shown). Spatial variables (principle coordinates of neighbourhood matrix (Dray, Legendre & Peres-Neto 2006)) are presented in red, edaphic variables in green and topographic variables in blue. Fraction a = the pure spatial component (space | environment). Fractions b + d = the proportion explained by soil after accounting for topography (soil | topography). Fractions c + f = the proportion explained by topography after accounting for soil (topography | soil). Fractions e + g = the topographically structured soil component (soil and topography). Fractions d + f + g = the spatially structured environmental component (space and environment). Fractions a + d + f + g = the proportion of variation explained by spatial variables (PCNM) alone (space). Fractions b + d + e + g = the proportion explained by only soil nutrients. Fractions c + e + f + g = the proportion explained by topographic variables solely. Fractions b + c + d + e + f + g = the proportion explained by the environmental variables (soil resources and topography). Total explanatory power of db-RDA models = the percentage of variability explained by all spatial and environmental variables combined (a + b + c + d + e + f + g, or 100 – residuals (h)).

In 2011, all soil nutrient concentrations, and topographic convexity, were key in explaining differences in environmental–forest community relationships with respect to past land-use intensity, and were positively correlated with amount of canopy cover present in the 1936 historical aerial photographs (i.e. past land-use intensity). For example, concentrations of exchangeable K, Na, Ca, Mg, Fe and Mn were greater in less-disturbed sites. Total exchangeable bases

(TEB) and effective cation exchange capacity (ECEC) were also greater in these areas. Aluminium, soil bulk density and soil pH were the main notable exceptions, which appeared on NMS bi-plots perpendicular to axis 1 (land use), meaning that they had no noticeable relationships with past land-use intensity. Similarly, topographic variables were neutrally or weakly negatively related to past land use when examined across the entire LFDP (Fig. 6).

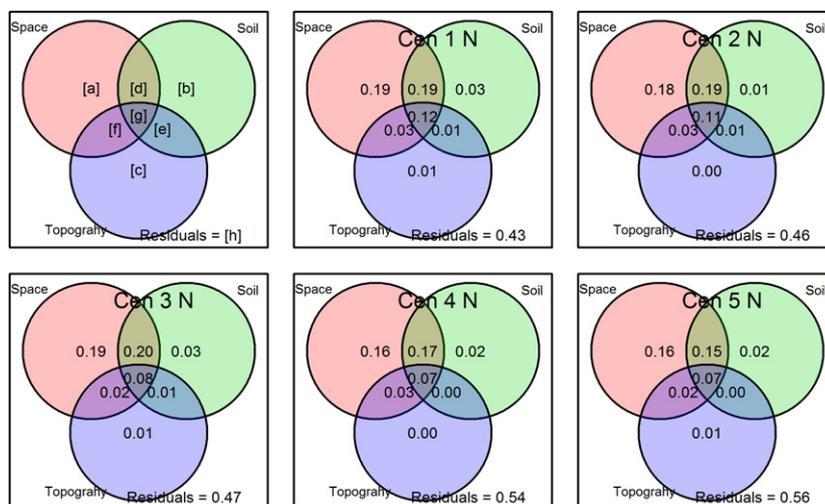


Fig. 4. Variance partitioning diagram (upper left panel) and results for the higher land-use intensity portion (northern) LFDP by tree census. Numerical values represent the per cent of variance explained by distance-based RDA models for their respective fractions. Figure panels and their partitioned fractions are identically labelled with respect to Fig. 3a.

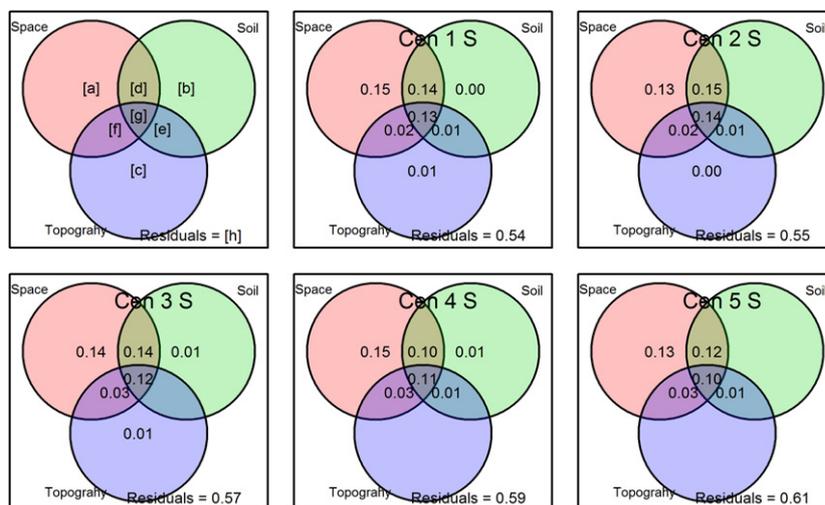


Fig. 5. Variance partitioning diagram (upper left panel) and results for the low land-use intensity portion (southern) LFDP by tree census. Numerical values represent the per cent of variance explained by distance-based RDA models for their respective fractions (Values <0 not shown). Figure panels and their partitioned fractions are identically labelled with respect to Fig. 3a.

Discussion

To examine the direct effect of past land-use intensity in environmental niche structuring of plant communities, the variance partitioning results from the LFDP can be compared to those of five other larger FDPs; BCI in Panama, Huai Kha Khaeng in Thailand, Korup in Cameroon, Pasoh in Malaysia and Yasuni in Ecuador (Baldeck *et al.* 2013). In these plots, both soil resources and topography explained about the same amount of variation in plant community composition (9–34% and 5–29%, respectively), and soil resources and topography together explained 13–39% of compositional variation (Baldeck *et al.* 2013). In addition, these large FDPs (≥ 50 ha each), which all largely lack previous well-documented land use, were divided into half to aid in comparison with smaller FDPs, such as the LFDP. Differences between the north and south of the LFDP were greater than the other plots, especially following hurricane disturbances (i.e. census 1 in 1990 following Hurricane Hugo and census 3 in 2000 following

Hurricane Georges). Difference between the total explanatory power of RDA models for five FDP halves in the Baldeck *et al.* (2013) study averaged 0.04. Differences in RDA total model explanatory power for the northern and southern halves of the LFDP were 0.12, 0.08, 0.10, 0.04 and 0.06, for tree census 1 through 5 respectively, indicating that differences between plant communities in the LFDP tended to be greater than those in other large plots largely lacking the effects of past land use and hurricane damage.

The beta-diversity maps clearly showed the northern portion of the LFDP to be distinct in species composition. This area is the high land-use intensity portion of the plot, with three distinct areas of differing canopy cover, all less than 80% in the historical 1936 aerial photographs (Foster, Fluet & Boose 1999; Thompson *et al.* 2002). Historical land-use intensity varies across the three distinct areas, with some areas having been largely cut over, and others having been dominated by either agricultural practices or small subsistent human settlements (Thompson *et al.* 2002; Thompson, Lugo

Table 1. Results for permutational multivariate analysis of variance (permanova) for Bray–Curtis dissimilarities for the 2011 (census 5) tree community within the LFDP in relation to the land-use intensity (i.e. the amount of canopy cover in 1936 aerial photographs). DF = degrees of freedom, SS = sum of squares, Pseudo- $F = F$ value by permutation. Bold face indicates statistical significance ($P < 0.05$); P -values are based on 999 permutations (i.e. the lowest possible P -value is 0.001).

Land-use Intensity Comparison (percentage canopy cover in 1936)	DF	SS	Pseudo- F	R^2	P -value	Bonferroni-adjusted P -value
80–100% vs. 50–80%	1	8.916	64.887	0.194	0.001	0.006
80–100% vs. 20–50%	1	6.289	45.782	0.167	0.001	0.006
80–100% vs. 0–20%	1	4.536	35.099	0.182	0.001	0.006
50–80% vs. 20–50%	1	2.195	15.502	0.061	0.001	0.006
50–80% vs. 0–20%	1	1.643	12.108	0.067	0.001	0.006
20–50% vs. 0–20%	1	0.929	6.877	0.052	0.001	0.006
< 80% vs. \geq 80%	1	10.367	71.687	0.152	0.001	0.001

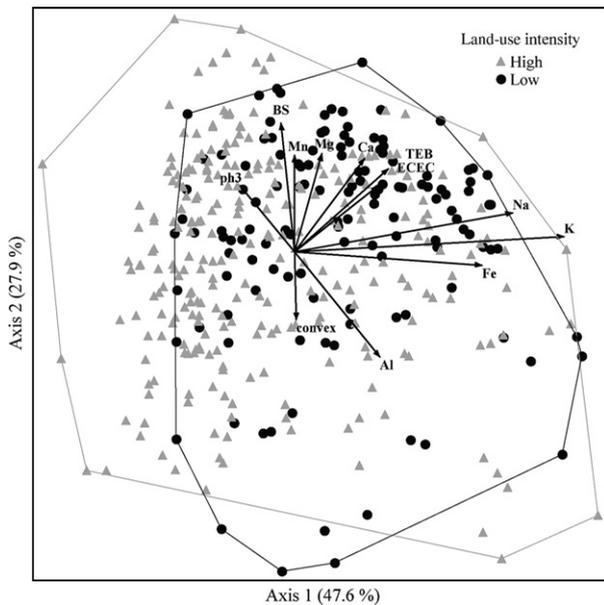


Fig. 6. Non-metric multidimensional scaling (NMS) ordination of tree communities of the LFDP for the most recent tree census (2011). Black circles indicate low-intensity land-use quadrats (80–100% forest cover in 1936), while grey triangles show quadrats in the high-intensity land-use portion of the LFDP. A three-dimensional solution was achieved with an average plot stress of 14.89 after 125 iterations; axes 1 and 2 are shown. Overlain vectors for forward-selected explanatory environmental variables (either topographic or edaphic) from RDA models with an r^2 value ≥ 0.100 are shown. The length of the vector is proportional to the strength of the environmental–community relationship for that variable. Axis 1 was oriented with respect to land-use strength from high intensity to low intensity going from left to right.

& Thomlinson 2007). Land-use legacies are reflected in a structurally younger forest where secondary forest species with lower wood density are more abundant (Thompson *et al.* 2002; Uriarte *et al.* 2009) and canopy structure allows more light through (Comita *et al.* 2010; Hogan 2015). These areas were more affected by hurricanes (Zimmerman *et al.* 1995; Canham *et al.* 2010; Uriarte *et al.* 2012) and have resulted in

secondary forests that have faster dynamics driven by greater light availability in the understory after hurricane damage. The beta-diversity maps likely capture distance-restricted dispersal and recruitment within high-intensity land-use areas, leading to greater similarity in community composition at census 2, with community differences increasing over time as shrub and pioneer species densities thin under a recovering canopy (Hogan 2015). These results are similar to responses measured in nearby USDA Forest Service plots, in terms of similarity of community composition along successional trajectories in time after hurricane disturbance (Heartsill Scalley *et al.* 2010).

RDA models decreased in explanatory power over time. Despite these changes, variance partitioning results were stable over time, when compared to changes in stem densities, stem diameter size distributions (i.e. forest structure) or species diversity (i.e. compositional change) within the forest (Hogan 2015). The better explanatory power of RDA models in areas of more intense past land use in the LFDP points to the large magnitude of change, and persisting effects of anthropogenic land-use disturbance, within forest communities. This trend is well documented in vegetation succession of tropical forest systems (Aide *et al.* 1995; Foster, Motzkin & Slater 1998; Chazdon 2003; Holz, Placci & Quintana 2009). Clear differences between RDA models for areas of high and low land-use intensity were observed. RDA models had greater explanatory power in areas more intense past land-use history within the LFDP, most likely due to stronger successional responses to hurricane damage in these areas. In other words, areas more impacted by previous land use had greater plant community–environmental relationships, because they respond disproportionately to hurricanes, at least with respect to recruitment of understory pioneers (Hogan 2015). Such pioneer species often have considerably shorter life spans than their primary forest counterpart species and, therefore, can more closely track successional changes related to spatial environmental variation (i.e. light availability; Uriarte *et al.* 2009, 2012), providing an explanation for why RDA models had increased explanatory power in areas of more intensive past land use.

Separation of quadrats within the LFDP with respect to past land use and as the forest recovers from Hurricane Hugo, which affected the forest in 1989, and to a much lesser degree Hurricane Georges which passed over the LFDP in 1998, can still be seen via community ordination. There is a greater clustering of quadrats, as community composition between areas of differing past land-use pressure converge in community composition, with the widespread recruitment of pioneers across the whole plot. In community ordinations for all five LFDP tree censuses, compositional differences attributed to land-use legacies peaked at census 3 in 2000, with land-use legacies explaining 58.6% of the plot-wise compositional variation. This trend is congruent with the pattern of the magnitude of land-use legacies within the LFDP, explored using statistical techniques that quantify the contribution of past land use to changes in community composition over time (Hogan 2015).

Environmental–community relationships within tropical forests are difficult to detect and are strongest in well-conserved areas that exhibit high levels of environmental heterogeneity (Paoli, Curran & Zak 2006). In this study, we investigated the interactive effects of past land use and hurricane disturbance in altering environmental relationships. The results supported our hypothesis that associations between plant community compositional and the environment would be stronger following hurricane damages to the forest (Introduction – Question 2). Despite this, environmental niche partitioning (i.e. topographic and soil niche) was greatest in the areas of more intense past land-use pressure, recorded in the census immediately following Hurricane Hugo, providing evidence that land use alters abiotic and biotic variables within the forest. Alteration of the abiotic environment by land use selects for species suited for these conditions (e.g. secondary successional and pioneer species) to allow for competitive advantages for anthropogenically associated species (e.g. species commonly associated with human settlement or other land-use activity). Such altered forest communities can persist for decades or longer following land-use abandonment, as shown via the lasting land-use legacies within the LFDP. Although these findings are not new (Foster, Motzkin & Slater 1998; Thompson *et al.* 2002), the possible explanatory mechanisms deserve further research.

We clearly were incorrect in expecting weaker plant community–environmental relationships in areas of higher past land-use pressure (Introduction – Question 1). Contrary to our expectation, environmental–plant community structuring was greater in areas of more intense past land use, probably due to decreased competition in these areas when compared to old-growth tabonuco forest. A similar study (Bachelot *et al.* 2016) found below-ground biotic factors (e.g. soil fungi and microbes) to be more important in affecting community composition in the high land-use areas of the LFDP, suggesting that land-use legacies not only alter soil fertility and structure, but also biotic communities within them, providing an insight into mechanisms for the lasting effects of land-use legacies on forest species composition via soils. This research is important because a widespread forest regrowth continues to

take place in the tropics as land-use patterns change (Mather 1992; Rudel, Bates & Machinguashi 2002; Meyfroidt & Lambin 2009; Chazdon 2014). Regenerating tropical forests may resemble their old-growth counterparts in some metrics (e.g. structure), but it may take centuries or longer to recover old-growth species composition and interactions (Chazdon 2003; Lugo & Helmer 2004; Wright 2005; Lindenmayer, Laurance & Franklin 2012).

In complex tropical forests, identifying environmental drivers that organize plant communities is extremely difficult. Many signals tend to be weak and confounded with other factors, such as disturbance. Despite this, when comparing two areas of forest with differing previous land-use histories within the LFDP, environmental relationships were stronger in areas of more intense past land-use pressure. These findings provide a mechanistic understanding of the possible role that abiotic conditions associated with land-use legacies play in altering the successional dynamics of recovering secondary tropical forests. That mechanism is through the direct anthropogenic alteration of forest composition and structure via human land-use practices, likely providing competitive advantages to secondary forest, or oftentimes anthropogenically selected species due to the more rapid turnover and stronger spatial interactions present in second-growth tropical forests.

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Data accessibility

Tree census data for the Luquillo Forest Dynamics Plot are available for download through the Smithsonian Tropical Research Institute ForestGEO (formerly The Center for Tropical Forest Studies) data portal: http://ctfs.si.edu/Public/plot_dataaccess/index.php.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Variance Partitioning Barplots: Results from distance-based Redundancy Analysis (db-RDA) models shown in barplot form for the entire (a), the high land-use intensity area (b), and the low land-use intensity area of the Luquillo Forest Dynamics Plot (LFDP). Bar Fractions correspond to the variance partitioning diagram shown in Figs 3–5.

Appendix S1. Literate Statistical Document outlining the exploration of beta-diversity variability within the LFDP.

Appendix S2. Literate Statistical Document showing the transformation of response variables, forward selection of predictor variables, and db-RDA.

Appendix S3. Literate Statistical Document containing the PERMANOVA results shown in Table 1.