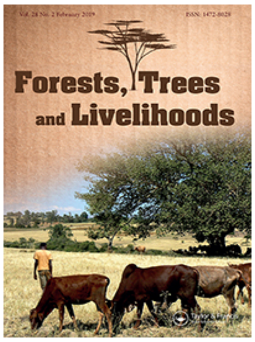

Forests, Trees and Livelihoods

ISSN: 1472-8028 (Print) 2164-3075 (Online) Journal homepage: https://www.tandfonline.com/loi/tftl20

Potential of second-growth Neotropical forests for forestry: the example of Puerto Rico

Jimena Forero-Montaña, Humfredo Marcano-Vega, Jess K. Zimmerman & Thomas J. Brandeis

To cite this article: Jimena Forero-Montaña, Humfredo Marcano-Vega, Jess K. Zimmerman & Thomas J. Brandeis (2019) Potential of second-growth Neotropical forests for forestry: the example of Puerto Rico, Forests, Trees and Livelihoods, 28:2, 126-141, DOI: 10.1080/14728028.2019.1579673

To link to this article: https://doi.org/10.1080/14728028.2019.1579673

Published online: 26 Feb 2019.

FORESTS, TREES AND LIVELIHOODS
2019, VOL. 28, NO. 2, 126–141
https://doi.org/10.1080/14728028.2019.1579673

ARTICLE

Potential of second-growth Neotropical forests for forestry: the example of Puerto Rico

Jimena Forero-Montaña[a], Humfredo Marcano-Vega[b], Jess K. Zimmerman[c] and Thomas J. Brandeis[b]

[a]Department of Biology, University of Puerto Rico-Rio Piedras, San Juan, PR, USA; [b]Forest Inventory and Analysis, Southern Research Station, North Carolina, NC, USA; [c]Department of Environmental Science, University of Puerto Rico-Rio Piedras, San Juan, PR, USA

ABSTRACT

The development of appropriate strategies towards the sustainable management of tropical second-growth forests is essential for human well-being and climate change mitigation. The well-documented process of forest recovery in Puerto Rico offers a unique opportunity to evaluate the potential of second-growth tropical forests for forestry. Here, we combined 10 years of forest inventory data with ethnobotanical information to determine trends in forest cover, stand structure, and timber volume, as well as the suitability of useful tree species for timber and non-timber forest products. We observed a period of stability in the process of forest recovery. Even though the forests are still too young for extensive forestry, they are rich in useful species and contain high densities of trees suited for timber and several non-timber forest products. These results suggest that Puerto Rico's forests have substantial capability for forestry and research on silvicultural practices. Today, numerous government programs encourage reforestation in private forests. However, lack of markets for local forest products and services is a major limitation for sustainable forest management. Therefore, it is worthwhile to support local enterprises of artisans and sawyers and create innovative incentives for forestry, rather than mainly focus on subsidizing landowners to plant trees.

KEYWORDS

Ethnobotany; forest inventory; forest transition; non-timber forest products; tree density; tree volume; sustainable forestry; timber uses

Introduction

Interest in second-growth tropical forests has grown with increasing awareness of their role in the global carbon cycle and importance to human well-being (Chazdon 2014). Second-growth forests regenerating after human disturbance currently represent more than 70% of all remaining tropical forests (FAO 2010), and are predicted to continue expanding as result of socioeconomic processes that lead to deforestation of primary forests and forest transition (i.e. forest regrowth) on abandoned agricultural fields (Chazdon 2014). Given their extensive area and fast growing properties, second-growth tropical forests represent a major global sink of carbon (Brown and Lugo 1990). These ecosystems can harbour more biodiversity than agriculture or other habitats under more intense land uses (Barlow

CONTACT Jimena Forero-Montaña forero.jimena@gmail.com

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/tftl.

et al. 2007), and have valuable ecological characteristics that benefit a large proportion of the population (about 300 million people, which live close to forests (ITTO 2002) specially in less developed countries (FAO 2010). In economic terms, second-growth forests are sources of a wide variety of products such as medicine, food, timber, and fuel (Chazdon and Coe 1999) and provide essential ecosystem services such as watershed protection, biodiversity conservation, and climate change mitigation (Guariguata and Ostertag 2001).

Given that substantial areas of second-growth tropical forests exist close to human settlements, the sustainable management of these ecosystems represents a major opportunity to enhance their economic and environmental value (ITTO 2002). The economic potential and management prospects of second-growth forests depend on the ecological characteristics (floristic composition, structure, and phase of succession), and socioeconomic context in which succession takes place (Enao et al. 2015). Silvicultural experience throughout the lowland Neotropics has demonstrated that the management of second-growth forests presents good possibilities from a technical point of view, but poor governance, policy failures, and lack of markets for forest products are often major limitations for the sustainable use of forest resources in less developed countries (De Las Salas 2002; Enao et al. 2015). Nonetheless, land use studies have shown that when socioeconomic changes lead to agriculture abandonment forest regeneration occurs (Rudel et al. 2005), and under these conditions long term management for the sustainable production of forest products becomes possible (FAO 2014; Enao et al. 2015).

Monitoring forest change provides a sound basis for policy, investment, and management decision-making at the national, regional, and global levels (FAO 2016). National forest inventories, however, are scarce in the tropics because ground-based forest inventories require many trained personnel and are expensive across whole nations (Mollicone et al. 2007). This information is important to comprehensively understand the management and conservation potential of second-growth forests and to formulate appropriate forest management strategies for forest products and ecosystem services. In this study, we combined 10 years of data from the Forest Inventory and Analysis (FIA) program of the United States Department of Agriculture (USDA) Forest Service with ethnobotanical information to examine the potential for forestry in the archipelago of Puerto Rico, an unincorporated territory of the United States of America in the Caribbean. In doing so, we addressed the following questions: 1) What are the current trends in forest cover, stand structure, and timber volume on timberland (the area with potential for commercial timber production and not reserved from harvest by law or statute)? and 2) What is the suitability of useful tree species in the second-growth forests of Puerto Rico?.

Methods

Study area

The archipelago of Puerto Rico comprises the islands of Puerto Rico, Culebra, Vieques, Mona, and other smaller islands in the Caribbean. This is a good place to evaluate the potential of Neotropical second-growth forests for forestry because forest recovery following hurricanes and on previous agricultural lands have been extensively studied. Spatial and temporal changes in forest cover have been investigated during the last seven decades (Thomlinson et al. 1996; Grau et al. 2003; Lugo and Helmer 2004; Parés-Ramos et al. 2008; Wang et al. 2017). The main island has been inventoried six times between 1980 and 2014 (Birdsey and Weaver 1982, 1987; Franco et al. 1997; Brandeis et al. 2007; Brandeis and Turner 2013; Marcano-Vega 2017), and the archipelago's flora including tree taxonomy, ecology, and ethnobotanical uses are well described in the literature (Longwood 1961; Little et al. 1974–1988, 1977; Francis and Lowe 2000).

Puerto Rico is frequently cited as an example of forest transition in emergent economies, where a major shift in the economy from agriculture to manufacturing in the middle 20th century led to extensive forest recovery in abandoned agricultural fields (Grau et al. 2003; Rudel et al. 2005). During this process forests increased from covering less than 6% of the islands in the 1930's to more than 54% in 2014 (Marcano-Vega 2017). Earlier assessments of the status of second-growth forests in Puerto Rico (1980 and 1990) indicate little opportunity for industrial wood production, but demonstrate a positive trend towards forest recovery and colonization with well-formed saplings suitable for potential timber production in abandoned coffee shade stands (Birdsey and Weaver 1982, 1987; Franco et al. 1997). Every year Puerto Rico imports about $ US 246 million in a wide variety of solid wood products, including raw wood for construction and carpentry, as well as numerous manufactured solid wood products such as furniture, joinery, tools, crates and boxes, wooden frames, string instruments, tableware, and marquetry (Forero-Montaña 2015). On the other hand, locally grown woods are harvested and processed by small private sawmills and mainly used by local artisans for furniture and traditional handicrafts (Forero-Montaña et al. 2018). Recovery of the forestry industry has valuable economic, social, and environmental benefits as the production of sustainable harvested forest products can substantially increase the value of timber and non-timber forest products (NTFPs), create jobs, and serve as a land use option that maintains essential ecosystem services (Wadsworth 2009). Therefore, at this time, 35 years after the first systematic forest inventory of Puerto Rico, it is pertinent to revisit current trends in the regeneration of useful tree species to evaluate the potential for a forestry industry on the archipelago.

Forest inventory data

We used the results of the last three FIA forest inventories of Puerto Rico (Brandeis et al. 2007; Brandeis and Turner 2013; Marcano-Vega 2017) to quantify useful tree species and evaluate trends in forest area, tree size distribution, and timber volume increment from 2004 to 2014 in the timberland (i.e the region with commercial forestry potential). Previous forest inventories were not included in the analyses because substantial changes in the FIA methods in 2004 do not allow direct comparisons of forested area and merchantable volume increment. For details on the changes see Brandeis (2003).

The forest inventory in Puerto Rico comprises 480 permanent plots out of 13,191 photointerpretation points of a 2,400 ha hexagonal grid in all forest types found in the archipelago of Puerto Rico (mainland, Mona, Vieques, and Culebra) (Brandeis et al. 2007). Each inventory plot consists of a cluster of four circular adjacent subplots of 7.3 m radius, which correspond to a total sampled area of 0.067 ha. Every five years, field crews visit each sample area to identify and measure all trees > 12.5 cm in stem diameter at breast height (dbh). In addition, they identify and measure all saplings

≥ 2.5 cm dbh and identify and count all seedlings with height > 30 cm within a 2.1 m radius microplot nested within each subplot. The species are identified in the field using the nomenclature of the PLANTS database of the Natural Resources Conservation Service (NRCS) (NRCS 2018), but in this study we used Axelrod (2011), which is the most recent revision of the taxonomy of Puerto Rico's vascular plants. For more details on FIA survey design and methods in Puerto Rico see Brandeis et al. (2007) and Brandeis and Turner (2013).

Timberland is currently defined by FIA as forest land that is producing or capable of producing 1.4 m^3 ha^{-1} of wood per year or more at culmination of mean annual increment. Timberland excludes reserved lands, which are defined as those forest lands where management for the production of wood is prohibited through statute or administrative designation. Examples include national forest wilderness areas and national parks and monuments (Bechtold and Patterson 2005). In this study timberland was defined based on the current FIA definition in conjunction with the environmental extremes considered by Birdsey and Weaver (1982) for characterizing forest lands with potential for commercial timber production in Puerto Rico. Thus, state forests, mangroves, dry forests, slopes better suited for agriculture (≤ 20) or very steep (≥ 60%), and areas with high rainfall (≥2500 mm yr^{-1}) or poor rainfall (<1000 mm yr^{-1}) were excluded from the analyses. Tree species composition was presented in terms of relative frequency of live trees, which include all live trees ≥ 2.5 cm dbh, and growing stock trees or trees ≥ 12.5 cm dbh that meet minimum merchantability standards. In general for a tree to be considered growing stock it must have at least one solid section of 3.6 m or two solid sections of 2.4 m reasonably free of form defects. Tree size distributions were presented by size classes, including, saplings (2.5 to 12.4 cm dbh), pole timber trees (12.5 to 27.5 cm dbh), and saw timber trees (> 27.5 cm dbh).

The net volume of live trees ≥ 12.5 cm dbh was estimated using tree volume equations developed by Brandeis et al. (2005) and Brandeis et al. (2007) for some tree species and forest types of Puerto Rico. Average annual net growth of merchantable bole volume was calculated as $((Vt_2 - Vt_1/datet_2 - datet_1) \times 365)$, where V is volume, subscripts refer to FIA surveys, and time is measured in days. The volume of trees that die from human or natural causes between time t_1 and time t_2 was estimated based on tree size at the midpoint of the measurement interval. Likewise, the volume of trees removed by cultural operations such as timber harvest or stand improvement, land clearing, or changes in land use during the inter survey period was estimated based on tree size at the midpoint of the measurement interval.

Tree attributes such as tree volume per hectare, were estimated using the ratio of means methodology described by Bechtold and Patterson (2005). Net tree volume estimates for different diameter size classes were derived indirectly. First the parameter is calculated by summing the tree level attribute of interest (i.e. net tree volume) for all trees in the condition class (i.e. size class) and then dividing by the area of the plot covered by the condition.

$$y_{ik} = \frac{\sum_{j}^{4} \sum_{t} y_{ijkt}}{\sum_{j}^{4} a_{oijk}}$$

Where, Y_{ijkt} = net volume of tree *t* in subplot or microplot *j* covering condition *k* on plot *i*, and a_{oijk} = area used to observe the attribute of interest on the subplot or microplot *j* covering condition *k* on plot *i*. Total values on timberland forest presented here are the result of mean per hectare estimates derived from forest inventory data and the forest area estimates derived from photointerpretation, both with independent variance estimates.

The forest inventory data is available online and was downloaded from the FIA database (FIADB) (https://www.fia.fs.fed.us/tools-data/), which provides a consistent data processing, formatting, and storage tool for the FIA Program nationwide (Woudenberg et al. 2010) by using EVALIDator Version 1.6.0.00 for estimates of timberland area, stand structure, timber volume, and species composition (Miles 2015). Sampling errors were computed by dividing the estimate into the square root of its variance, and presented as a percent of the estimate within a 68% confidence interval. Differences among forest inventories in number of individuals and stand structure were examined using contingency tables to compare the proportions of saplings, pole timber, and saw timber trees in the three FIA surveys.

Ethnobotanical information

Information on the use of tree species was gathered from the literature (Longwood 1961; Little et al. 1974–1988, 1977; Francis and Lowe 2000) and from a former survey based on semi-structured interviews that we conducted among 271 artisans and 14 sawyers from April 2012 to May 2013 to characterize the current use of forest products in the local handicraft market of Puerto Rico. For details on the survey methods see Forero-Montaña (2015) and Forero-Montaña et al. (2018). Tree species were classified in 15 categories of use including NTFPs such as food, fuel, medicine, bee keeping, fodder, and tannins; as well as timber uses such as construction, carpentry, furniture, crates and boxes, flooring, tool handles, veneer and plywood, paper, poles, and handicrafts. This last included musical instruments, carving, turning, toys, and other typical handicrafts from Puerto Rico. The classification system takes into account that one species can have multiple uses.

Results

Trends in timberland area, stand structure, and timber volume

In 2014 timberland area (as defined in this study) in Puerto Rico comprised 204,265 ha (SE 8.25), which corresponds to 43% of the total forest cover and about 23% of the archipelago's area. Sixty three percent of the timberland area was located in subtropical moist forest and 37% in wet subtropical forest. Twenty six percent of the timberland was on steep slopes greater than 50%. Timberland area increased by 10,795 ha (5.04%) from 2004 to 2009, while it decreased by 10,162 ha (4.7%) from 2009 to 2014, indicating that forest cover has remained relatively steady during the last ten years in the commercial area of Puerto Rico (Figure 1).

Typesetters: Insert Figure 1Live trees >2.5 cm dbh totalized more than 536 million individuals with a total net volume of 17,336,051 m^3 in 2014. Most of the live trees (88%) were saplings, while pole timber and saw timber trees represented 9% and 3% of the live trees, respectively (Figure 2). The number of live trees decreased by 46,077,288

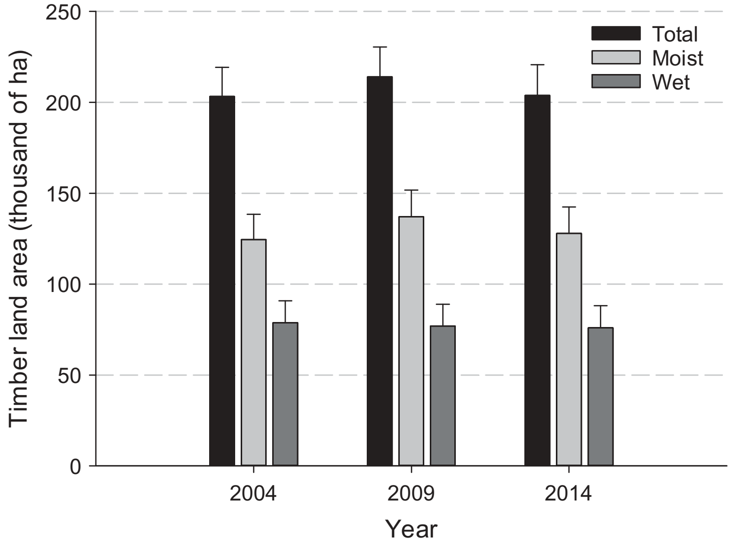

Figure 1. Timberland area by forest type group with sampling errors for the 2004, 2009, and 2014 forest inventories in Puerto Rico.

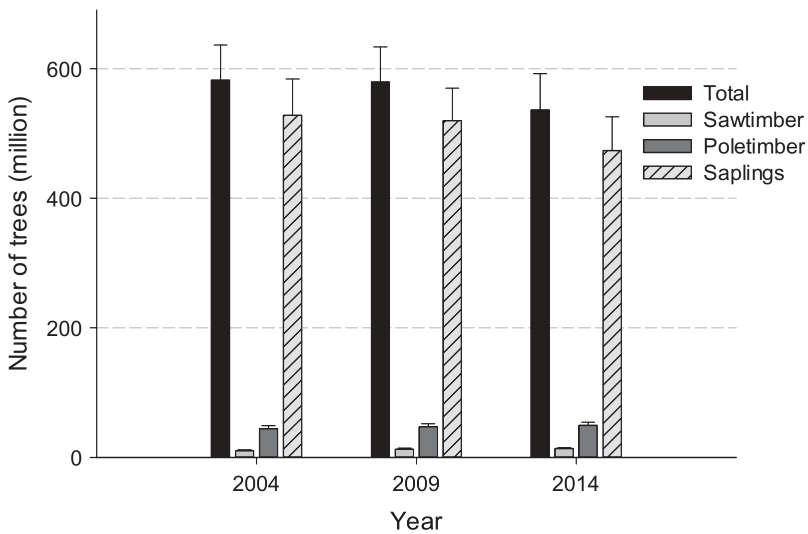

Figure 2. Number of live trees (≥2.5 cm dbh) by tree size class with sampling errors for the 2004, 2009, and 2014 forest inventories on the timberland of Puerto Rico. Saw timber: trees >27.5 cm dbh, Pole timber: trees 12.5 to 27.5 cm dbh, Saplings: trees 2.5 to 12.4 cm dbh.

individuals (8%) over the study period, annual net growth decreased by 141,698 m^3 yr^{-1} (26%), whereas total net volume increased by 2,979,081 m^3 (20%) (Table 1). In addition, average annual removals and mortality increased to 47,116 m^3 yr^{-1} (SE 81.54) and 394,271 m^3 yr^{-1} (SE 29.59), respectively. These values, however, barely correspond to 0.2 and 2.3% of the total net volume of live trees (Table 1).

Table 1. Puerto Rico's timberland area and statistics from 2004 to 2014 for live trees (≥2.5 cm dbh) and growing stock trees (≥12.5 cm dbh) that meet minimum merchantability standards showing sampling errors (SE) as a percent of the estimate within a 68% confidence interval.

Timber land characteristics	2004	SE 2004	2009	SE 2009	2014	SE 2014
Area (ha)	203,222	7.87	214,003	7.71	204,265	8.24
Number of live trees	582,267,419	10.28	579,206,980	9.36	536,190,131	10.44
Total net volume of live trees (m^3)	14,356,970	9.92	17,177,764	13.39	17,336,051	11.29
Average annual net growth of live trees (m^3 yr^{-1})			535,969	26.73	394,271	30.85
Average annual removals of live trees (m^3 yr^{-1})			0.1	83.90	47,116	81.54
Average annual mortality of live trees (m^3 yr^{-1})			292,323	19.26	507,453	29.59
Number of growing stock trees ≥	16,284,082	14.76	12,066,052	14.39	4,174,761	15.71
Total net volume of growing stock trees (m^3 yr^{-1})	4,245,977	18.96	4,805,285	17.76	1,874,965	14.53
Average annual net growth of (m^3 yr^{-1})			166,614	44.12	−42,971	118.39
Average annual removals of growing stock trees (m^3 yr^{-1})					9,795	69.64
Average annual mortality of growing stock trees (m^3 yr^{-1})			95,400	30.11	125,558	38.85

Growing stock trees, or trees ≥ 12.5 cm dbh that meet minimum merchantability standards, merely represented 0.7% of the live trees (i.e. more than 4 million trees) and accounted for 10% of the total net volume (1,874,965 m^3, SE 14.53). Sixty percent of the growing stock trees were pole timber, while saw timber trees represented 40% of growing stock trees but accounted for 70% of their net volume. Even though the number of growing stock trees decreased by 74% in the last forest inventory, the proportions of saw timber and pole timber trees were similar among the three FIA inventories ($\chi^2 = 0.488$, df = 2, $p > 0.05$), indicating that stand structure held steady over the study period (Figure 3). In addition, total net volume of growing stock trees decreased by 2,930,320 m^3 (61%) and their average annual net growth to −42,971 m^3 yr^{-1} (SE 118.39), while average annual removals and mortality increased to 9,795 m^3 yr^{-1} (SE 69.6) and to 125,558 m^3 yr^{-1} (SE 38.85), respectively (Table 1). These values, however, corresponded to less than 0.1% of the total net volume of growing stock trees.

Species richness and uses

A total of 182 woody species in 48 botanical families were found on the timberland area, of these 138 were native, 36 introduced, and eight unknown. Many species, however, were encountered very infrequently such that just 12 species represented 50% of the live trees (Annex A, supplemental material). Trees with identified uses represented 69% of the taxa (125 species) and 60% of the live trees. Half of the useful species were found in only nine families, which composed 45% of the sampled taxa. The family Fabaceae contained the largest number of useful species (18), followed by Rubiaceae (9 spp.), Lauraceae (7 spp.), and Myrtaceae (7 spp.), while the remaining families had five or less useful species. Many species had multiple uses, such that 55% of the taxa were timber species that also produced a type of NTFP (Annex A). Timber was the use category with the largest number of species (98), followed by fuel (58 spp.), medicine (48 spp.), beekeeping (43 spp.), food (22 spp.), fodder (12 spp.), and tannins (8 spp.).

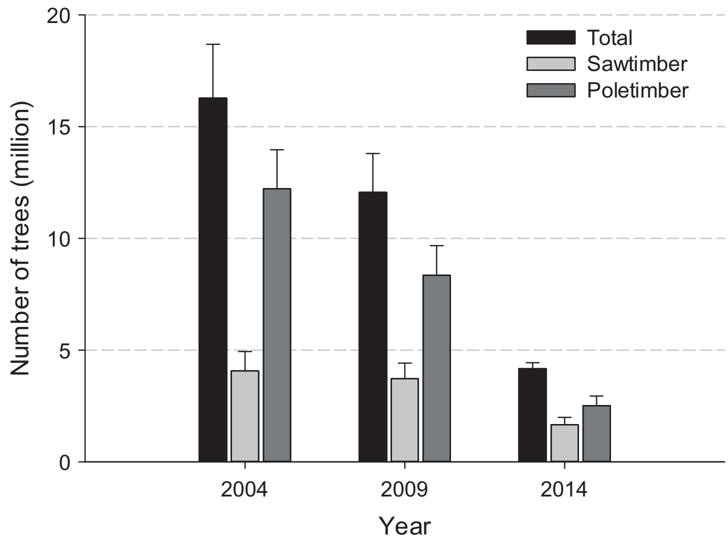

Figure 3. Number of growing stock trees (≥ 12.5 cm dbh) that meet minimum merchantability standards with sampling errors by tree size class for the 2004, 2009, and 2014 forest inventories on timberland in Puerto Rico. Saw timber: trees > 27.5 cm dbh, Pole timber: trees 12.5 to 27.5 cm dbh.

Timber presented the highest relative abundance with 1,819 trees ha^{-1}, followed by medicine (1,006 trees ha^{-1}), fuel (1,003 trees ha^{-1}), and beekeeping (815 trees ha^{-1}), while the other categories had less than 295 trees ha^{-1} (Figure 4). The most important timber use category in terms of volume was carpentry with a net volume per area of 69 m^3 ha^{-1}, followed by handicraft (68 m^3 ha^{-1}), construction (50 m^3 ha^{-1}), and furniture (44 m^3 ha^{-1}), while the other timber use categories had less than 35 m^3 ha^{-1} (Figure 5). In contrast, the most important timber use category among growing stock trees was handicraft with (7.17 m^{3}ha^{-1}), followed by carpentry (6.9 m^{3}ha^{-1}), construction (5.2 m^{3}ha^{-1}), and furniture (5.1 m^{3}ha^{-1}), while the other timber use categories had less than 3.1 m^{3}ha^{-1} (Figure 5).

The ten most abundant species, which represented almost 50% of the live trees, included in order of importance *Guarea guidonia, Spathodea campanulata, Casearia sylvestris, C. guianensis, Tabebuia heterophylla, Syzygium jambos, Ocotea leucoxylon, Andira inermis, Leucaena leucocephala*, and *Ardisia obovata* (Annex A). Only five species, *S. campanulata, G. guidonia, Cecropia schreberiana, Mangifera indica*, and *T. heterophylla*, represented 50% of the total net volume of live trees (Annex A). The timber species with the greatest average annual net growth were *G. guidonea* (100,641 m^3 yr^{-1}), *C. schreberiana* (50.880 m^3 yr^{-1}), and *T. heterophylla* (33,742 m^3 yr^{-1}). All the species mentioned above, except *C. guianensis* and *A. obovata*, were suited for multiple timber uses and NTFPs (Annex A). For example, the wood of the introduced *S. campanulata*, is light, easy to work, and suitable for handicrafts and carpentry works of moderate durability such as crates and frames for construction (Francis 2000). It is resistant to fire, which makes it appropriate for objects and structures exposed to high temperature. In the west coast of Africa, from where it originates, several parts of the tree are used for traditional medicine (Francis 2000). The wood of *C. scheberiana* is light and suitable for

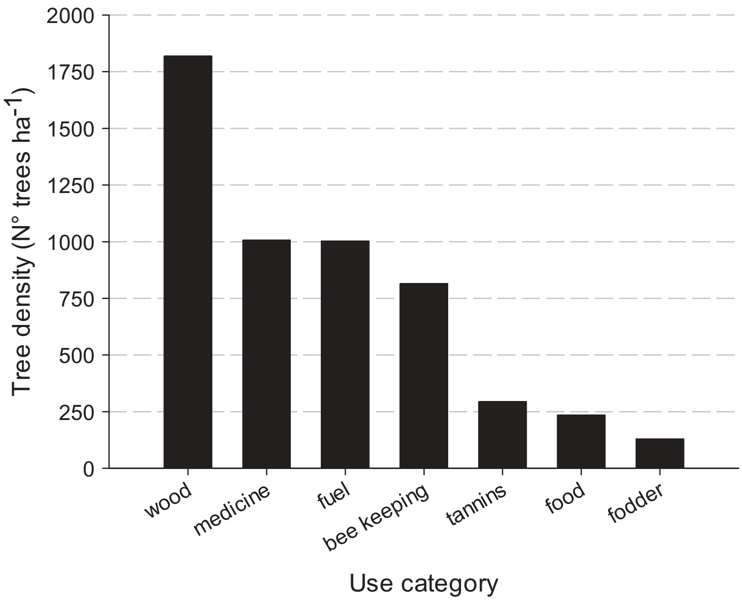

Figure 4. Tree density by use category based on the 2014 FIA data base for the timberland of Puerto Rico.

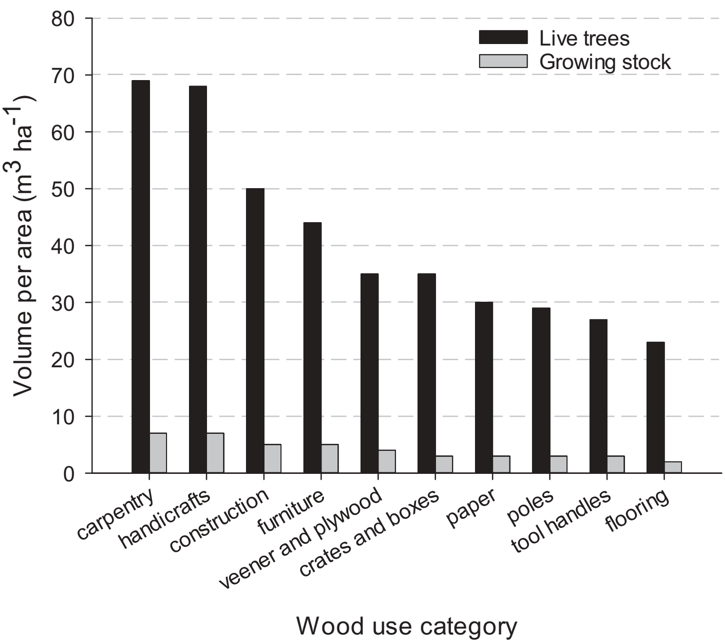

Figure 5. Net volume per area by wood use category for live trees (≥2.5 cm dbh) and growing stock trees (≥12.5 cm dbh) or trees that meet minimum merchantability standards based on the 2014 FIA data base for the timberland of Puerto Rico.

toys, crates and boxes, carpentry, and paper (Longwood 1961,) but currently it is mainly used to make the *cuatro*, the national string instrument (Forero-Montaña 2015). The leaves, bark, and latex of several species of the genus *Cecropia* are used by indigenous tribes in the Amazon basin, as well as traditional healers in Cuba, Central and South America as medicine for several diseases (Silander and Lugo 2000). *G. guidonea, T. heterophylla, A. inermis*, and *O. leucoxylon* are good native quality woods with fair attractiveness and durability mainly suitable for handicrafts, furniture, carpentry, and construction (Longwood 1961). *G. guidonea* and *T. heterophylla* are frequently used by local artisans in Puerto Rico (Forero-Montaña 2015). *A. inermis* and *T. heterophylla* are melliferous species suited for bee keeping (Little et al. 1977). *M. indica* is a naturalized tree, native to tropical Asia (Little et al. 1977). It is one of the most popular tropical fruit trees, and its wood is suitable for fuel, furniture, carpentry, construction (Little et al. 1977), and handicrafts (Forero-Montaña 2015). In addition, it is a melliferous species and is used for traditional medicine in India, Philippines, west of Africa, and Central America (Parrotta 2000).

Discussion

In this study small fluctuations in timberland area, number and volume of live trees, and stand structure indicate a period of stability in the process of forest recovery in Puerto Rico. In contrast previous FIA inventory analyses show a significant trend towards forest recovery and structural maturation from 31.3% of forest cover in 1980 to 52.8% in 2004 (Birdsey and Weaver 1982, 1987; Franco et al. 1997; Brandeis et al. 2007). The slight decrease in number of live trees accompanied by relatively small increments in tree volume and mortality, observed here, may be related to a general pattern of self-thinning during the process of forest succession shown in other studies in Puerto Rico (Aide et al. 1995, 1996) and the Dominican Republic (Rivera et al. 2000). On the other hand, growing stock trees exhibited a significant decrease in number and volume. These changes, however, likely result from differences in the accuracy of tree classification by field crews in each survey, rather than from significant increments in tree mortality or removals of trees with potential for commercial wood production. During the study period no severe hurricanes affected Puerto Rico to cause significant mortality. In addition, removals of growing stock trees were insignificant and represented less than 0.1% of their total net volume. Under current FIA methods, only trees with specific dimensions and free of form defects are classified as growing-stock (Marcano-Vega 2017). In Puerto Rico few trees meet minimum merchantability standards because the Caribbean forests are frequently affected by hurricanes and tropical storms that create trees with multiple epicormic sprouts and imperfections (Anderson et al. 1982). Thus, well-formed trees are much less common in these forests and the percentage of total volume in growing stock is too low when compared to other forests. However, FIA guidelines for the classification of growing stock seem too restrictive for meaningful application in Puerto Rico and not an accurate reflection of how much usable volume is out there. New approaches to record the general quality of a tree according to the context of the market are necessary. Efforts to salvage wood after hurricane Maria have demonstrated that saw timber-sized logs ranging from 1.2 to 3.5 m in length are valuable for the market, and even those less than 1.2 m long are useful to artisans (USD A Caribean Climate Hub 2017).

Lands well-suited for forestry (i.e timberland, as defined in this study) comprised 204,265 ha, nearly a half of the total forest cover and a quarter of the archipelago's area. A characterization of the lands of Puerto Rico for agriculture, forestry, and conservation by Wa et al. (2017) with similar criteria to classify suitable lands for forestry, but that excludes slopes greater than 50%, identifies 169,125 ha suitable for timber production, about 19% of the archipelago. However, they consider that land uses are not mutually exclusive, so lands over slopes greater than 50% have potential for forestry while maintaining ecosystem functions and conservation values. Likewise, if we exclude 52,438 ha of timberland over steep slopes >50 < 60%, the land suitable for forestry would correspond to 151,827 ha, about 17% of the archipelago's area. Our results support the findings of Wa et al. (2017), which suggest that in a broad context the forestry lands of Puerto Rico are suited for production of timber, NTFPs, and agroforestry such as shade-grown coffee and cacao, apiculture, and silvopastoral systems. We show that second-growth forests in Puerto Rico are rich in useful species and contain high densities of trees suited for timber, medicine, fuel, beekeeping, and other NTFPs. However, it is important to note that the ethnobotanical information presented here only includes direct observations for handicrafts as the current commercial use of local forest products is restricted to the handicraft sector, while most of the food and timber products that are consumed in Puerto Rico are imported (Forero-Montaña 2015). Moreover, a survey by Alvarado-Guzmán et al. (2009) showed that some trees in the *Citrus* genus have significant use as medicinal plants in southeast Puerto Rico, but they also point that ethnopharmacological knowledge is decreasing. Thus, most of the data on tree uses presented in this study represent potential uses and further research on the ethnobotany of NTFPs based on direct observations is necessary to understand the demands and expectations of the people in relation to these forests.

Even though direct comparisons with other ethnobotanical studies on second-growth forests are difficult because of differences in sampling designs and measurements, the information gathered in this study support the findings of Chazdon and Coe (1999), Redondo et al. (2001), and Vílchez-Alvarado et al. (2008) in the Atlantic lowlands of Northeastern Costa Rica, Duchelle (2007) in the Eastern Andes of Ecuador, and Burgos-Hernández et al. (2014) in the central region of Veracruz, Mexico, which show that second-growth forests are important sources of timber, medicine, food, fuel, and other NTFPs for local communities. Forest structure analyses have demonstrated that second-growth forests accumulate species at relatively rapid rates during forest succession, such that within a period of 80–100 years the number of species approaches that of mature forests (Guariguata and Ostertag 2001). Although the species composition of second-growth forests may never resemble that of mature forests, these forests can provide a large range of products and environmental services (Chazdon 2014). In addition, given their accessibility to human settlements, rapid tree growth, and relatively uniform structure and composition; second-growth stands regenerating though natural processes might be better suited to severing local communities and environmental needs than old growth forests or monoculture plantations of exotics (Wadsworth 1997).

Our results indicate that promising stands are developing and that Puerto Rico's forests have substantial capability for sustainable timber production, especially for handicrafts. Timber species suitable for handicrafts comprised 47% of the individuals and 93% (13,966,828 m^3 or 68 m^3 ha^{-1}) of the total net volume of live trees. However, *S. campanulata* alone represented 27% of the total net volume suitable for handicrafts. Even though this tree is suited for multiple timber uses and traditional medicine (see above), in Puerto Rico it is considered invasive by farmers and the wood is in general not desired for any use (Forero-Montaña 2015). Species composition is often a limitation for forestry in second-growth forests, but their economic value can be increased through management strategies that facilitate the growth of commercially valuable native hardwoods (Weaver and Birdsey 1986). For example, poor quality trees can be removed to liberate promising trees and enrichment planting (i.e. planting target species under canopy gaps or along cleared strips) implemented to improve the stock of timber species (Lamb et al. 2005; Piotto 2007). Large canopy openings in second-growth tropical forests, however, may lead to serious invasion of weeds and vines that can drastically reduce productivity (Wadsworth 1997). Therefore, to foster forestry in Puerto Rico it is essential to study the responses of *S. campanulata* forests to silvicultural treatments, explore how to use its wood for handicrafts, and estimate costs and profitability of the operations. New research on silvicultural treatments in novel forests dominated by introduced species has opportunely started. Preliminary results of enrichment planting treatments carried out two months before hurricane Maria hit Puerto Rico in 20 September 2017 show satisfactory results with 90% of seedling survival a year after the hurricane (O.J. Abelleira per. comm. 4 September 2018).

Sustainable forest management of second-growth forests in general aims at increasing the forest's capacity to yield products for farmers and ranchers, as well as provide important environmental and social services for a wide range of stakeholders on a long-term basis. The rationale behind this is that the local people are more prone to protect the forests if they perceive essential utilities from these ecosystems. Currently, in Puerto Rico a variety of government programs provide economic incentives and technical assistance through 10 years agreements to help private forest owners to implement sustainable forestry practices (CEDES EAA UMET 2008). Emphasis is made on reforestation and conservation, but the programs are not market based or integrated with programs to assist local forest industries. An independent program, The Arts and Crafts Development Program, helps local artisans to develop microenterprises (Law 64 of 20 June 2016). But, the local handicraft sector is so poorly developed that artisans and sawyers have low levels of productivity, yield, and profits (Forero-Montaña et al. 2018). In addition, farmers face severe competition from cheaper imported products (Comas Pagán 2015) and markets for specialty agroforestry products such as shade-grown coffee are still undeveloped (Borkhataria et al. 2012). Until now, just 2,939 ha of private farms have management plans certified by the Forest Stewardship Program (DNER 2018 unpublished data). Moreover, the public sector is currently the only source of finance for forestry, and apart from a tax exemption program "*Bosques Auxiliares*" for private forest owners who are committed to conserve and sustainably manage their forest (Law 133 of 1 July 1975), long term incentives for forestry have not been developed. Hence, land owners today heavily depend on government subsidies to implement and maintain the practices, which makes the forestry programs unsustainable on the long term.

The significance of developing forest management programs within a market framework for forest products and services is increasing in light of growing concerns on the current economic bankruptcy and vulnerable food sovereignty. Management of Puerto Rico's second-growth forests for commodities and ecosystem services is especially important in the wake of hurricane Maria. Rural areas were particularly hard-hit and their recovery, both in terms of infrastructure and stopping people's emigration will depend on providing viable livelihoods. Carefully planned silvicultural treatments could encourage the growth of commercially valuable timber species that naturally have high wind resistance because of their dense wood (Zimmerman et al. 1994), and hence create forested landscapes that are more resilient to climatic disturbances. Given that markets for local forest products and services are currently undeveloped, immediate efforts should be focused on assisting local forest enterprises of artisans and sawyers to increase their capacity to add value to their products and meet globalized markets demands (Forero-Montaña et al. 2018). Also, there is a need to attract private investments to forestry and create funding mechanisms to provide long term incentives for forestry.

Conclusions

Second-growth forests in Puerto Rico, like in other Neotropical landscapes, are rich in useful species and contain high densities of trees suited for timber and several NTFPs. Puerto Rico is politically stable, has secure land tenure, and a long history of forest research. These characteristics provide important opportunities for sustainable forestry and research on silvicultural practices. However, lack of institutional experience to effectively implement a market based policy for forest products and services is a major limitation for the development of forestry in Puerto Rico. Revitalization of the forestry industry can serve to increase the economic and ecological value of second growth forests and encourage more sustainable forest management practices. Puerto Rico has the potential to become a leader in sustainable forestry by demonstrating how to increase forestry production in second-growth forests while generating social benefits and maintaining essential ecosystem services. This effort will need to involve the effective participation of numerous partners including government agencies, non-governmental organizations, educational institutions, and the private sector to enhance the capacity of small enterprises to produce and trade sustainably harvested forest products. A process of action learning will be necessary. Numerous approaches will need to be tried to find the most appropriate strategies to develop a sound business environment for environmental services and small forest enterprises of cabinet makers, carpentry products, and crafts in Puerto Rico.

Acknowledgments

We thank. J.J. Fumero and two anonymous reviewers for their valuable comments and criticism, which improved the manuscript.

Disclosure Statement

The authors declare that they have no competing interests

Funding

This work was supported by the Center for Applied Tropical Ecology and Conservation (CREST-CATEC) under the Grant [HRD 0734826]; and the Luquillo LTER Program under the Grant [DEB-1546686] to University of Puerto Rico.

References

[CEDES/EAA/UMET] Centro de Estudios para el Desarrollo Sustentable de la Escuela de Asuntos Ambientales de la Universidad Metropolitana. 2008. Compendio de incentivos y programas para la conservación de los recursos naturales en Puerto Rico. Bayamón (Puerto Rico). Spanish.

[FAO] Food and Agriculture Organization of the United Nations. 2010. Global forest resources assessment 2010. Rome.

[FAO] Food and Agriculture Organization of the United Nations. 2014. State of the world's forests. In: Enhancing the socioeconomic benefits from forests. Rome.

[FAO] Food and Agriculture Organization of the United Nations. 2016. Global forest resources assessment 2015. In: How are the world´s forests changing? Rome.

[ITTO] Iternational Tropical Timber Organization. 2002. ITTO guidelines for the restoration, management and rehabilitation of degraded and secondary tropical forests. Yokohama (Japan): [ITTO] International Timber Organization.

[USDA] United States Department of Agriculture Climate Hub. 2017 Oct. How to salvage fallen trees after hurricane Maria. San Juan, PR: [IITF] International Institute of Tropical Forestry.

Aide TM, Zimmerman JK, Herrera L, Rosario M, Serrano M. 1995. Forest recovery in abandoned tropical pastures in Puerto Rico. For Ecol Manag. 77:77–86.

Aide TM, Zimmerman JK, Rosario M, Marcano H. 1996. Forest recovery in abandoned cattle pastures along an elevational gradient in northeastern Puerto Rico. Biotropica. 28:537–548. doi:10.2307/2389095.

Alvarado-Guzmán JA, Gavillán-Suárez J, Germosén-Robineau L. 2009. TRAMIL ethnopharmacological survey: knowledge distribution of medicinal plant use in the southeast region of Puerto Rico. Puerto Rico Health Sci J. 28(4):329–339.

Anderson RL, Birdsey RA, Barry PJ 1982. Incidence of damage and cull in Puerto Rico's timber resource, 1980. New Orleans (LA): United States Department of Agriculture, Forest Service, Southern Forest Experiment Station. Resource Bulletin SO-88.

Axelrod FS. 2011. A systematic vademecum of the vascular plants of Puerto Rico. Fort Worth (TX): BRIT Press.

Barlow J, Gardner TA, Araujo IS, vila-Pires TCA, Bonaldo AB, Costa JE, Esposito, M.C., Ferreira, L.V., Hawes, J., Hernandez, M.I., Hoogmoed, M.S. 2007. Quantifying the biodiversity value of tropical primary, secondary, and plantation forests. Proc Natl Acad Sci USA. 104(7):18555–18560. doi:10.1073/pnas.0703333104.

Bechtold WA, Patterson PL 2005. The enhanced forest inventory and analysis program - national sampling design and estimation procedures. Asheville (NC): United States Department of Agriculture Forest Service, Southern Research Station. General Technical Report SRS-80.

Birdsey RA, Weaver PL 1982. The forest resources of Puerto Rico. New Orleans (LA): Unite States Department of Agriculture Forest Service Southern Forest Experiment Station. Resource Bulletin SO-85.

Birdsey RA, Weaver PL 1987. Forest area trends in Puerto Rico. New Orleans (LA): United States Department of Agriculture Forest Service Southern Forest Experiment Station. Research Note SO 331

Borkhataria R, Collazo JA, Groom MJ, Jordan-Garcia A. 2012. Shade-grown coffee in Puerto Rico: opportunities to preserve biodiversity while reinvigorating a struggling agricultural commodity. Agricul Ecosys Environ. 149:164–170.

Brandeis TJ. 2003. Puerto Rico's forest inventory: adapting the forest inventory and analysis program to a Caribbean island. J For. 101(1):8–13.

Brandeis TJ, Helmer EH, Oswalt SN 2007. The status of Puerto Rico's forests, 2003. Asheville (NC): United States Department of Agriculture Forest Service, Southern Research Station. Resource Bulletin SRS-119.

Brandeis TJ, Kuegler O, Knowe SA 2005. Equations for merchantable volume for subtropical moist and wet forests of Puerto Rico. Asheville (NC): United States Department of Agriculture Forest Service Southern Research Station. Research Paper SRS-39.

Brandeis TJ, Turner JA2013. Puerto Rico's Forests, 2009. Asheville (NC): United States Department of Abriculture Forest Service, Southern Research Station, Resource Bulletin SRS-191.
Brown S, Lugo AE. 1990. Tropical secondary forests. J Tropl Ecol. 6:1–32.
Burgos-Hernández M, Castillo-Campos G, Vergara Tenorio M. 2014. Potentially useful flora from the tropical rainforest in central Veracruz, Mexico: considerations for their conservation. Acta Botánica Mexicana. 109:55–77. Spanish. doi:10.21829/abm109.2014.195.
Chazdon RL. 2014. Second growth: the promise of tropical forest regeneration in an age of deforestation. Chicago: The University of Chicago Press.
Chazdon RL, Coe FG. 1999. Ethnobotany of woody species in second-growth, old-growth, and selectively logged forest of Northeastern Costa Rica. Conserv Biol. 13:1312–1322.
Comas Pagán M. 2015. Plan de seguridad alimentaria para Puerto Rico. San Juan, PR: Departamento de Agricultura del Estado Libre Asociado de Puerto Rico.
De Las Salas G. 2002. Los bosques secundarios de América tropical: perspectivas para su manejo sostenible. Bois et Forêts des Tropiques. 272(2):63–73. Spanish.
Duchelle AE. 2007. Observations on natural resource use and conservation by the Shuar in Ecuador's Cordillera del Cóndor. Ethnobotany Res Appl. 5:5–23.
Enao E, Ordóñez Y, de Camino R, Villalobos R, Carrera F 2015. El bosque secundario en Centroamérica. Un recurso potencial de uso limitado por procedimientos y normativas inadecuadas. Turrialba (Costa Rica): Centro Agronómico Tropical de Investigación y Enseñanza. Boletín técnico no. 77. Spanish.
Forero-Montaña J. 2015. Potential of subtropical secondary forests for sustainable forestry in Puerto Rico. Rio Piedras, Puerto Rico, USA: University of Puerto Rico.
Forero-Montaña J, Zimmerman JK, Santiago LE. 2018. Analysis of the potential of small-scale enterprises of artisans and sawyers as instruments for sustainable forest management in Puerto Rico. J Sustainable For. 37(3):257–269. doi:10.1080/10549811.2017.1406372.
Francis JK. 2000. Spathodea campanulata Beauv. Tulipán africano, African tulip tree. In: Jk F, Lowe CA, editors. Bioecología de los árboles nativos y exóticos de Puerto Rico y las Indias Occidentales. Reporte Técnico General IITF-15. Rio Piedras (Puerto Rico): Departamento de Agricultura de los Estados Unidos, Servicio Forestal, Instituto de Dasonomía Tropical. 484–487. Spanish.
Francis JK, Lowe CA (editors). 2000. Bioecología de los árboles nativos y exóticos de Puerto Rico y las Indias Occidentales. Reporte Técnico General IITF-15. Rio Piedras (Puerto Rico): Departamento de Agricultura de los Estados Unidos, Servicio Forestal, Instituto de Dasonomía Tropical. Spanish.
Franco PA, Weaver PL, Eggen-Mcwentosh S 1997. Forests resources of Puerto Rico, 1990. Asheville (North Carolina): [USDA] United States Department of Agriculture Forest Service, Southern Forest Experiment Station. Resource Bulletin SRS-22.
Grau HR, Aide TM, Zimmerman JK, Thomlinson JR, Helmer EH, Zou X. 2003. The ecological consequences of socioeconomic and land-use changes in postagriculture Puerto Rico. Biosci. 53:1159–1168.
Guariguata MR, Ostertag R. 2001. Neotropical second grown forest succession: changes in structural and functional characteristics. Forest Ecol Manag. 148:185–206.
Lamb D, Erskine PD, Parrotta JA. 2005. Restoration of degraded tropical forest landscapes. Science. 310(5754):1628–1632.
Little EL, Wadsworth FH, Marrero J. 1977. Árboles comunes de Puerto Rico y las Islas Vírgenes. Barcelona: Editorial Universitaria Universidad de Puerto Rico. Spanish.
Little EL, Woodbury RO, Wadsworth FH. 1974–1988. Arboles de Puerto Rico y Las Islas Virgenes. In: Segundo Volumen. Agriculture handbook No. 449-S. Washington (DC): [USDA]United States Department of Agriculture Forest Service. Spanish.
Longwood FR. 1961. Puerto Rican Woods: their machining, seasoning and related characteristics. Washington (DC): USDA. Agriculture Handbook 205.
Lugo AE, Helmer E. 2004. Emerging forests on abandoned land: Puerto Rico's new forests. Forest Ecol Manag. 190:145–161.

Marcano-Vega H 2017. Forests of Puerto Rico, 2014. Asheville (NC): USDA Forest Service, Southern Research Station. Resource Update FS–121.
Miles PD. 2015 Dec 8–10. Batch reporting of forest inventory statistics using the EVALIDator. In: Stanton SM, Christensen GA, editors. ushing boundaries: new directions in inventory techniques and applications: Forest Inventory and Analysis (FIA) symposium. Portland (Oregon): USDA Forest Service, Pacific Northwest Research Station. p. 78–883.
Mollicone D, Freibauer A, Schulze ED, Braatz S, Grassi G, Federici S. 2007. Elements for the expected mechanisms on 'reduced emissions from deforestation and degradation, REDD' under UNFCCC. Environ Res Lett. (2):045024. doi:10.1088/1748-9326/2/4/045024.
(NRCS) Natural Resources Conservation Service U.S. Department of Agriculture. 2018. The PLANTS Database. Greensboro (NC): National Plant Data Team. http://plants.usda.gov.
Parés-Ramos IK, Gould W, Aide TM. 2008. Agricultural abandonment, suburban growth, and forest expansion in Puerto Rico between 1991 and 2000. Ecol Society. 13(2):1.
Parrotta JA. 2000. Mangifera indica L. Mango. In: Francis JK, Ca L, editors. Bioecología de los árboles nativos y exóticos de Puerto Rico y las Indias Occidentales. Rio Piedras (Puerto Rico): Departamento de Agricultura de los Estados Unidos, Servicio Forestal, Instituto de Dasonomía Tropical. p. 33–343.
Piotto D. 2007. Growth of native tree species planted in open pasture, young secondary forest and mature forest in humid tropical Costa Rica. J Tropical Forest Sci. 19(2):92–102.
Redondo A, Vílchez B, Chazdon RL. 2001. Estudio de la dinámica y composición de cuatro bosques secundarios en la región Huetar Norte, Sarapiquí, Costa Rica. Revista Forestal Centroamericana. 36(1):20–26. Spanish.
Rivera LW, Zimmerman JK, Aide TM. 2000. Forest recovery in abandoned agricultural lands in a karst region of the Dominican Republic. Plant Ecol. 148:115–125.
Rudel TK, Coomes OT, Moran E, Achard F, Angelsen A, Xu J, Lambin, E. 2005. Forest transitions: towards a global understanding of land use. Global Environ Change. 15:23–31.
Silander SR, Lugo EA. 2000. Cecropia schreberiana Miq. Yagrumo hembra, trumpet-tree. In: Francis JK, Lowe CA, editors. Bioecología de los árboles nativos y exóticos de Puerto Rico y las Indias Occidentales. Rio Piedras (Puerto Rico): Departamento de Agricultura de los Estados Unidos, Servicio Forestal, Instituto de Dasonomía Tropical. p. 484–487. Spanish.
Thomlinson JR, Serrano MI, López T, Aide TM, Zimmerman JK. 1996. Land use dynamics in a post-agriculture Puerto Rican landscape (1936–1988). Biotropica. 28:525–536.
Vílchez-Alvarado B, Chazdon RL, Milla Quesada V. 2008. Dinámica de la regeneración en cuatro bosques secundarios tropicales de la región Huetar Norte, Costa Rica. Su valor para la conservación o uso comercial. Recursos Naturales y Ambiente. 55:118–128. Spanish.
Wa G, Wf H, Quiñones M, Sj F, Álvarez-Berríos NL. 2017. Land use, conservation, forestry, and agriculture in Puerto Rico. Forests. 8:242. doi:10.3390/f8070242.
Wadsworth FH. 1997. Forest production for tropical America. Washigton (DC): USDA Forest Service. Agriculture Handbook 710.
Wadsworth FH. 2009. Conserva a Puerto Rico con bosques maderables. Acta Científica. 23:73–80. Spanish.
Wang C, Yu M, Gao Q. 2017. Continued reforestation and urban expansion in the new century of a tropical island in the Caribbean. Remote Sens. 9(9):731. doi:10.3390/rs9070731.
Weaver PL, Birdsey RA. 1986. Tree succession and management opportunities in coffee shade stands. Turrialba. 36(1):47–58.
Woudenberg SW, Conkling BL, O'Connell BM, LaPoint EB, Turner JA, Waddell KL. 2010. The forest inventory and analysis database: database description and user's manual version 4.0 for phase 2. Fort Collins (Colorado): USDA Forest Service, Rocky Mountain Research Station.
Zimmerman JK, Everham III EM, Waide RB, Lodge DJ, Taylor CM, Brokaw N. 1994. Responses of tree species to hurricane winds in subtropical wet forest in Puerto Rico: implications for tropical tree life histories. J Ecol. 12(1):911–922.