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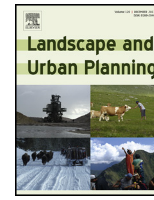

Research paper

Temporal dynamics of a subtropical urban forest in San Juan, Puerto Rico, 2001–2010

Joanna M. Tucker Lima[a,*], Christina L. Staudhammer[b], Thomas J. Brandeis[c], Francisco J. Escobedo[a], Wayne Zipperer[d]

[a] School of Forest Resources and Conservation, University of Florida, PO Box 110410, Gainesville, FL, USA
[b] Department of Biological Sciences, University of Alabama, PO Box 870344, Tuscaloosa, AL, USA
[c] USDA Forest Service, Southern Research Station, Knoxville, TN, USA
[d] USDA Forest Service, PO Box 11086, Building 164 Mowry Road, Gainesville, FL, USA

HIGHLIGHTS

- We examined structural and compositional dynamics of subtropical urban forests.
- Tree mortality rates were higher in San Juan than in temperate urban forests.
- San Juan forests experienced greater in-growth than temperate urban forests.
- Average tree growth rates in San Juan were higher than in temperate urban forests.
- Mortality (death and removal) was higher for invasive than non-invasive species.

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ABSTRACT

Several studies report urban tree growth and mortality rates as well as species composition, structural dynamics, and other characteristics of urban forests in mostly temperate, inland urban areas. Temporal dynamics of urban forests in subtropical and tropical forest regions are, until now, little explored and represent a new and important direction for study and management of these ecosystems. This study used permanent plots and statistical models incorporating tree and plot-level covariates to analyze mortality, in-growth, diameter growth, and species composition, as well the socioeconomic and urban morphology factors driving change in San Juan, Puerto Rico's subtropical coastal island urban forests over a nine year period. A total of 87 plots contained 482 trees in 2001 and 749 trees in 2010. Between 2001 and 2010 average tree densities increased, and average annual mortality rates were nearly 30%. Mortality was lower for larger, open-grown, non-leguminous trees and in higher income neighborhoods, but higher for street trees and larger population areas. The most widespread tree was invasive *Spathodea campanulata*, but overall, average mortality was higher for invasive than non-invasive tree species. In-growth of invasive species increased with human population, while higher tree densities corresponded with increased in-growth of native species. Overall mean diameter growth rate was 0.98 cm/yr, but remnant forest patch growth rates were 0.35 cm/yr. Higher diameter growth rates were associated with larger human populations, amounts of duff/mulch cover, and open-grown conditions. This study adds new insights to broaden our understanding of these emergent ecosystems in the Caribbean region.

1. Introduction

Urban forest structure, composition and spatio-temporal dynamics are intricately linked to the provision of ecosystem services and quality of life (Escobedo, Kroeger, & Wagner, 2011; Roy, Byrne, & Pickering, 2012). In tropical and subtropical regions, trees regulate the urban climate, and in particular, tree shade can reduce interior temperatures of buildings and homes, increasing human comfort (Heisler, 1986; Pandit & Laband, 2010). Natural and planted trees in tropical, coastal areas can affect air quality, sequester carbon, and mitigate tropical windstorm effects (Escobedo, Varela, Zhao, Wagner, & Zipperer, 2010; Nowak & Crane, 2002; Zhao et al., 2013). Trees also convey important esthetic and psychological value in urbanized environments as people form strong emotional and spiritual associations with trees, and their

* Corresponding author at: School of Forest Resources and Conservation, University of Florida, PO Box 110410, Gainesville, FL 32611, USA. Tel.: +1 352 870 6028.
E-mail addresses: jmtucker@ufl.edu, lima.joanna@gmail.com (J.M. Tucker Lima), cstaudhammer@ua.edu (C.L. Staudhammer), tjbrandeis@fs.fed.us (T.J. Brandeis), fescobed@ufl.edu (F.J. Escobedo), wzipperer@fs.fed.us (W. Zipperer).

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presence helps reduce stress for urban dwellers and increases property values (Escobedo et al., 2011; Roy et al., 2012; Wolf, 1998).

Several studies report tree growth rates, mortality rates, species composition, structural dynamics, and other characteristics of urban forests in mostly temperate, inland urban areas (Broshot, 2011; Iakovoglou, Thompson, Burras, & Kipper, 2001; McPherson et al., 1997; Nowak et al., 2011; Nowak, Kuroda, & Crane, 2004). Little work has focused on growth and mortality of trees in non-temperate urban landscapes with the exception of recent U.S. studies on subtropical forests in Florida and Texas (Lawrence, Escobedo, Staudhammer, & Zipperer, 2012; Staudhammer et al., 2011; Zhao, Escobedo, & Staudhammer, 2010) and others in Asia and Brazil (Dislich & Pivello, 2002; Jim & Liu, 2001; Nagendra & Gopal, 2010; Zhao et al., 2013), making basic information relatively scarce for tropical and subtropical urban forests, and in particular, island urban forests.

The dynamics of tropical and subtropical urban forests certainly differ from those of temperate ones. Due to limited information, growth and mortality rates associated with inland temperate urban trees are often used to assess structural change and carbon dynamics of urban forests in tropical, subtropical, and coastal areas (Escobedo et al., 2010). To improve estimates of ecosystem services, benefits, and the value of these urban forests, a clear understanding of tree growth and mortality in tropical and subtropical urban ecosystems is critical (Brandeis, 2009; Escobedo et al., 2011; Roy et al., 2012), and identification of factors driving growth rates and dynamics in urban forests is imperative (Seguinot Barbosa, 1996). In urban settings, tree growth rates vary due to anthropogenic disturbance, soil properties (Hagan et al., 2010; Iakovoglou et al., 2001), site conditions (Vrecenak, Vodak, & Fleming, 1989), disease, insects, and mechanical injury (Iakovoglou et al., 2001), and climate conditions (Lawrence et al., 2012). Even within the same climate, growth rates vary significantly according to land use/land cover, species, and site characteristics (Brandeis, 2009; Iakovoglou et al., 2001). We cannot accurately apply results from long-term studies of inland, temperate urban forests to trees found in subtropical urban areas due to different climate and urban characteristics (Escobedo et al., 2010; Roy et al., 2012; Zhao et al., 2010).

Urban forest dynamics in subtropical and tropical forests regions are, until now, little explored and represent a new and important direction for study and management of these ecosystems (Roy et al., 2012). Although studies of street tree dynamics (Nagendra & Gopal, 2010; Sklar & Ames, 1985) and urban forest ecosystem structure using multiple inventories or permanent plots are increasing (Broshot, 2011; Cumming, Twardus, & Nowak, 2008; Jo & McPherson, 1995; Lawrence et al., 2012; Nowak et al., 2004; Staudhammer et al., 2011; Thompson, Escobedo, Staudhammer, Matyas, & Qiu, 2011; Zhao et al., 2013), to our knowledge, research on the temporal dynamics of subtropical island urban forests is lacking. The goal of this study was to examine how tree mortality, in-growth (i.e., recruitment by growth or planting), diameter growth, and species composition of island, subtropical forests across San Juan, Puerto Rico's urban and peri-urban areas varied across a set of permanent plots between 2001 and 2010. We examine temporal changes in tree densities, diameter, basal area, and species composition, and compare these patterns within and across San Juan's land use/land cover types, including remnant upland secondary forest, mangrove forest, residential, vacant, and commercial/industrial/institutional/transportation covers. We further analyze how species endemicity, invasiveness, and other socioeconomic factors and urban morphology affect forest dynamics in this subtropical, island urban forest.

We hypothesized that urban forests in San Juan, Puerto Rico will have greater mortality and in-growth rates than those in temperate cities, due to the city's dense urban morphology, and predicted higher tree diameter growth rates due to favorable year-round growth conditions. The long-term nature of our study (2001–2010), analysis of 21 tree, plot, landscape scale covariates, and geographic location are novel to the urban forestry literature and will add important new insights to broaden our understanding of these emergent ecosystems in the Caribbean region.

2. Methods

2.1. Study area

Research was carried out across the 216.6 km^2 San Juan Bay Estuary (SJBE) watershed, which lies along the northeast coast of Puerto Rico. The watershed is contained within the highly dynamic and expanding San Juan metropolitan area, which has a total population of ~2.5 million (U.S. Census Bureau, 2010). The SJBE falls in the subtropical moist forest life zone (sensu Holdridge, 1967) with average temperatures of 23–27 °C and 1500–2300 mm of precipitation annually (Lugo, Ramos Gonzáles, & Rodriguez Pedraza, 2011). Geologically, the watershed is covered in alluvial deposits of sand, gravel, and clay except in the southern portion, where soils are derived from volcanic rocks and areas with outcroppings of exposed limestone (Lugo et al., 2011).

Historically, the watershed's natural vegetation was mangrove forest in the low-lying areas protected from the surf and wind and subtropical moist forest in upland areas. The mangrove forest, while reduced in overall area, remains along bays and lagoons, particularly in the eastern portion of the watershed that falls within the Piñones Commonwealth Forest. Upland secondary forests have been heavily impacted by human activities and remain as scattered forest patches fragmented by urban development (Grau et al., 2003). The introduction and establishment of many non-native tree species has further altered these forests and continues today as ornamental tree and shrub species from around the world are brought into the San Juan area.

2.2. Urban forest inventory sampling design

The SJBE watershed was first systematically sampled from July 2001 to February 2002 (hereafter referred to as 2001), using an intensification of the island-wide forest inventory sampling grid already established by the USDA Forest Service's Forest Inventory and Analysis (FIA) program (see Brandeis, 2003; Brandeis, Helmer, & Oswalt, 2007 for details). We resampled these plots from May 2010 to March 2011 (hereafter referred to as 2010). Sampling intensity was approximately one plot per 200 ha. After excluding sampling points that fell onto water, a total of 108 sampling points remained within the watershed boundaries.

Two plot designs were used, both with the same total sample plot area of 0.067 ha. In areas that met the Caribbean FIA criteria for forested land (i.e., a contiguous area > 0.4 ha or > 30 m wide with > 10% tree canopy coverage), crews installed an FIA subplot cluster consisting of four 7.3 m radius circular subplots to sample trees with diameter at breast height (DBH) ≥ 12.5 cm and 2.1 m radius nested microplots to sample trees with DBH ≥ 2.5 cm (USDA Forest Service, 2011) (see Bechtold & Scott, 2005; USDA Forest Service, 2006, 2007 for details). In urban and agricultural lands that failed to meet minimum requirements for forest, crews installed single 14.6 m radius circular plots using the Urban Forest Effects (UFORE) urban forest inventory methods, sampling all trees with DBH ≥ 2.5 cm (Nowak, Crane, Stevens, & Hoehn, 2005). In the interest of time, two densely vegetated plots were measured using a 0.01 ha quarter-plot (northeast quarter of the UFORE plot), and data was adjusted accordingly; plot level density measures were calculated using plot-specific areas and tree-level data were weighted by their plot's area. Small patches (>0.4 ha) of tree-covered land