

LONG-TERM DIAMETER GROWTH FOR TREES IN THE CINNAMON BAY WATERSHED

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ABSTRACT

From 1983 to 2008, the mean annual diameter growth (MAI) for 1,402 surviving stems of 62 species in the Cinnamon Bay watershed was 0.08 ± 0.002 cm yr⁻¹. Long-term MAI ranged from 0.02 cm yr⁻¹ for *Randia aculeata* to 0.23 cm yr⁻¹ for *Inga laurina*. Of the 30 species with ≥ 8 surviving stems, eight averaged ≥ 0.10 cm yr⁻¹. Hurricane Hugo in 1989, Hurricane Marilyn in 1995, and a severe drought in 1994 and 1995 were the major climatic events during the 25-year measurement period. Plot dbh measurements provide useful information about stand structure, composition and dynamics, and for silvicultural applications.

Key words: *Cinnamon Bay watershed, U.S. Virgin Islands; long-term monitoring; dbh increment.*

INTRODUCTION

The history of human activity on St. John, U.S. Virgin Islands dates back two millennia (Tyson 1987). During much of that time, the island's original forests survived largely intact; after 1600, however, the island was cutover for plantation agriculture. As with many other regions of the world, the cultural landscape seen today was fashioned as much by human activity as it was by natural processes.

In 1982, the Virgin Islands Resource Management Cooperative was established to carry out baseline research on numerous topics within the Virgin Islands National Park (Rogers and Teytaud 1988). As part of the research initiative, several collaborators representing the New York Botanical Garden, the Smithsonian Institution, the University of Wisconsin, the U.S. Department of the Interior Park Service, and the U.S. Department of Agriculture Forest Service began monitoring forest

plots at different sites on St. John (Weaver 2006a). The Institute of Tropical Forestry in Puerto Rico was well-prepared for the task with its previous experience in forest monitoring. During the 1940s, the Institute had established plots in several parts of the Luquillo Experimental Forest (LEF) and other parts of the island (Wadsworth 1947, 1953; Weaver 1983, 2009). During the mid-1950s, research was extended to Estate Thomas on St. Croix where experimental plantations of timber trees were set up in order to compare survival and growth with wetter sites in Puerto Rico (Weaver 2006b).

Forest monitoring provides a lot of useful information about forests, including data on stand structure and species composition, and the response of vegetation to normal climatic conditions and catastrophic events. The purpose of this report is to summarize long-term observations on dbh (i.e., diameter at breast height, or 1.4 m above the ground) growth in the Cinnamon Bay watershed.

SETTING – WATERSHED, CLIMATE, PAST USE

The Cinnamon Bay watershed, occupying 1.32 km² (2.5 percent of the island), ranges from sea level to about 300 m in elevation and is drained by two major arroyos. Steep slopes and narrow valleys filled with rocks and boulders characterize the landscape (Weaver 2006a). Geologically, about 85 percent of the Cinnamon Bay watershed is underlain by the Louisenhoj formation, which contains augite-andesite (i.e., volcanic minerals and rocks), volcanic breccia (i.e., fragments of rocks cemented together into a matrix) and tuff (i.e., consolidated volcanic ash) with minor conglomerate (i.e., sedimentary rocks made up of rounded fragments), all of Cretaceous age (i.e., a geologic period from 145 to 65 million years ago) (Donnelly 1966). The Water Island formation, comprised of quartz keratophyre (i.e., fine grained igneous rock of variable composition) flows and flow breccias of Lower Cretaceous age (i.e., period from 145 to 100 million years ago) occupies about 7 percent of the watershed at highest elevations along Centerline Road. Another 8 percent of the watershed along the shoreline is overlain by Quaternary (i.e., 2.5 million years ago until the present) alluvium (i.e., sand, gravel, silt, or clay deposited by running water). All of St. John is classified as Cramer Isaac soil association, characteristic of very steep mountainsides with steep slopes, and narrow alluvial fans (i.e., fan-shaped deposits formed where streams slow upon entering flat lands or plains) and flood plains (i.e., flat land formed where streams overflow their banks) (Rivera *et al.* 1966, 1970). The soils range from shallow to moderately deep, are well-drained, and lie over volcanic rock.

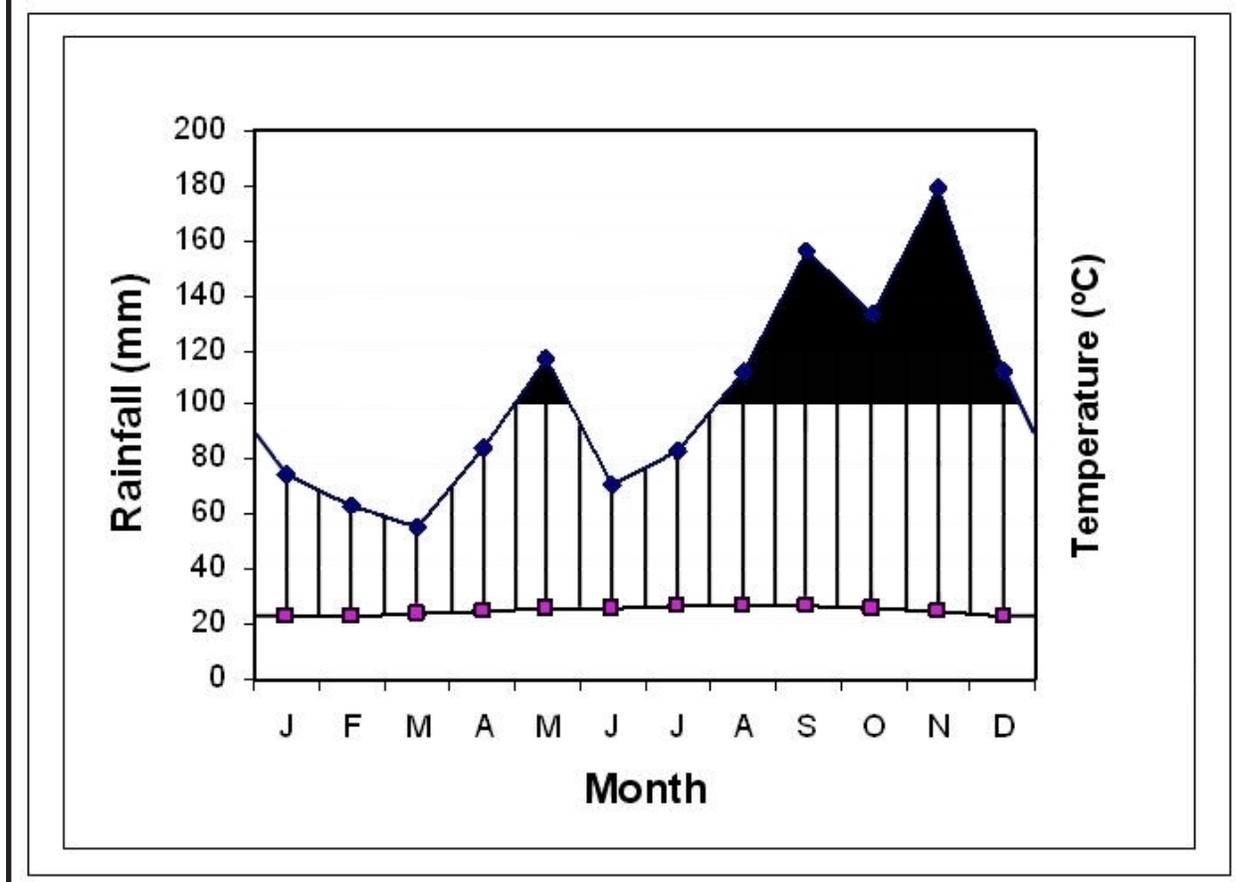
St. John has a tropical maritime climate and much of the rainfall is orographic (i.e., rainfall caused when air masses are lifted over mountains). Catherinberg, about 1 km west of the Cinnamon Bay watershed, receives an average of 1,240 mm yr⁻¹ (Southeast Regional Climate Center 2003). The January through April dry season receives about 20 percent of the annual total. The corresponding annual temperature normal is 24.8 °C (Fig. 1).

St. John has two life zones and Cinnamon Bay watershed is classified within the subtropical moist forest (Ewel and Whitmore 1973). Steep slopes, however, facilitate rapid runoff and much of the watershed contains tree species characteristic of subtropical dry forest. In reality, the entire island might be best described as a transition between subtropical dry and subtropical moist life zones accompanied by typical associations in more humid sites bordering streams and in bottom lands. A survey of the vegetation, using a modified version of Beard's system to account for secondary and humid sites, classified the Cinnamon Bay watershed as basin moist forest at lower elevations, and either upland moist or galley moist forest at higher elevations (Beard 1949, Woodbury and Weaver 1987; Fig. 2). Later, ordinations based on the stratified sampling of the watershed (i.e., by elevation and topography) showed that tree species tended to survive and grow best in certain habitats (Weaver and Chinea-Rivera 1987).

Hurricanes occur periodically -- at least 20 storms passed over or near St. John before 1900 (Dookhan 1974, Lawaetz 1991) and 10 more during the 20th century (Colón-Dieppa *et al.* 1991, Forthun 2005). These included hurricanes of varying intensity in 1916, 1924, 1928, Connie (1955), David (1979), Hugo (1989), Marilyn (1995), Hortense (1996), Georges (1998), and Lenny (1999). In addition, seven severe or moderate droughts were experienced during the 20th century (Colón-Dieppa *et al.* 1991; Rogers and Reilly 1998), including moderate events in 1938-1942, 1945-1948, and 1959 and severe events in 1957, 1964, 1967-68, and 1994-1995. As is evident, hurricanes Hugo (1989) and Marilyn (1995) and the severe regional drought of 1994 and 1995 occurred during plot measurements.

About 2000 years ago, Indians from the Orinoco region of Venezuela arrived at Coral Bay and migrated to other sites on St. John, including the Cinnamon Bay area (Bullen 1962, Tyson 1987). Their use of the island through the arrival of Europeans was probably sporadic. In 1675, Denmark sent two men to St. John with provisions

FIGURE 1. Climatic diagram based on 30-year normals (1971-2000) for rainfall and temperature at Catherinberg, St. John, about 1 km west of the Cinnamon Bay watershed.



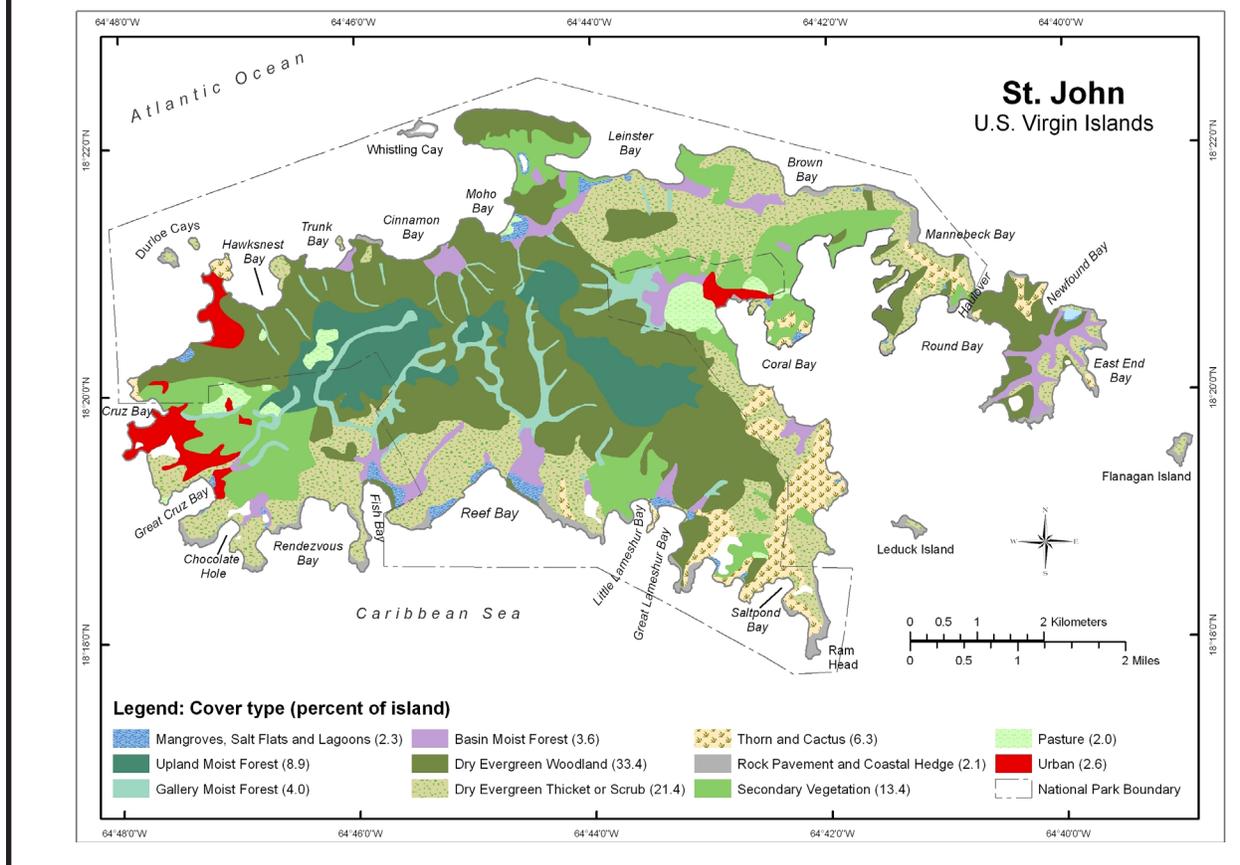
as a means to establish a territorial claim (Larsen 1986). By 1727, the shore of Cinnamon Bay was occupied for cotton production (Knight 1999). By the late 1730s, the aerial extent of agricultural activities at Cinnamon Bay plantation, including the sugar cane fields, was at its peak. By 1868, sugar cane production had largely disappeared, and the watershed was used for subsistence crops, grazing, and charcoal production (Haas 1940, Olwig 1980). In the 1880s, when Cinnamon Bay watershed was all in bush, residents began harvesting the berries and leaves of the Bay rum tree *Pimenta racemosa* to make perfumes and cosmetics (Hatch 1972). Bay rum production peaked around 1920 and remained the island's most important industry through the 1940s. In 1959, Virgin Islands National Park was created as a sanctuary of natural beauty (Robinson and Henle 1978). Subsequently, hunting, wood

cutting, and grazing within park boundaries were gradually eliminated (Olwig 1980).

METHODS

Sixteen plots measuring 50 x 10 m were established in June of 1983 (Weaver and Chinea-Rivera 1987). The plots were set up in five groups of three (i.e., on ridge, slope and ravine topography) at elevations of 60, 120, 180, 210, and 240 m. The final plot was located near the watershed summit at 290 m. Ridge plots were located on convex topography, slope plots on relatively uniform slopes, and ravine plots on concave topography. All stems ≥ 4 cm were identified to species and permanently tagged for future measurements (Fig. 3). Dbh was measured to the nearest 0.1 cm with a tape. Subsequently, the plots were re-

FIGURE 2. Map of forest types on St. John, U.S. Virgin Islands, using a modification of Beard's (1949) classification system (Woodbury and Weaver 1987).



measured at 5-year intervals between 1988 and 2008 when ingrowth (i.e. new stems reaching the minimum dbh class) and mortality were also tallied.

Long-term dbh increment was determined by species with ≥ 8 surviving stems. Species with ≤ 6 stems were analyzed as a group. Vandalism of tags precluded the identification of individual stems on 3 of the 16 plots. Therefore, the vandalized plots were omitted from this study.

RESULTS

Survey of 13 plots in 2008 showed that 1,402 stems had survived since the 1983 measurements. Their mean annual dbh increment (MAI) was 0.08 ± 0.002 cm yr⁻¹ (Table 1). *Inga laurina* had the most rapid MAI at 0.23 cm yr⁻¹ and *Randia*

aculeata had the slowest MAI at 0.02 cm yr⁻¹. Only eight species averaged ≥ 0.10 cm yr⁻¹. The greatest majority of the growth rates averaged ≤ 0.15 cm yr⁻¹ and occurred on stems ≤ 10.0 cm in dbh in size (Fig. 4). MAI (cm yr⁻¹) for all species combined varied by measurement date, as follows: from 1983-88, 0.073; 1988-93, 0.067; 1993-98, 0.081; 1998-2003, 0.072; and from 2003-08, 0.099.

The mean of minimum dbh growth rates by species ranged from 0 to 0.03 cm yr⁻¹ (Table 1); moreover, dbh rates for a few individual stems were negative during the measurement period (Fig. 5). In comparison, the means of maximum growth rates by species ranged from 0.07 to 0.62 cm yr⁻¹. From 18 to 235 years was the minimum amount of time estimated for the most rapidly growing individual stems of each species to grow through its sampled range of dbhs (Table 1).

FIGURE 3. Typical plots within the Cinnamon Bay watershed. Each plot has been visited six times on a 5-year cycle since their establishment in 1983.



DISCUSSION

Disturbance

Recurrent hurricanes and droughts during centuries have had an impact on the understory vegetation within the Cinnamon Bay watershed. During pre-hurricane visits in 1983 and 1988, the understory was open and easy to traverse; in comparison, after hurricanes Hugo and Marilyn, dense regeneration, broken branches, and fallen trees occupied the understory through 1998, and to a much lesser extent, until 2003. By 2008,

tree canopy had recovered completely and the understory was similar to pre-hurricane conditions. Near the end of the 1994 and 1995 drought, much of the island's forest canopy had a brownish cast and noticeably more light reached the forest floor (Weaver 2006a). Also, the floor was covered with dry leaves analogous to un-nailed shingles on a rooftop. Walking uphill was actually "slippery" and more difficult than usual. The drought, the severest of the century, ended with a hurricane showing that vegetation on low-lying tropical islands may face dramatic changes in weather from one moment to the next (Weaver 2006a).

TABLE 1. Twenty-five year diameter growth rates for species with ≥ 8 survivors in the Cinnamon Bay watershed.

Species	Mean dbh growth cm/yr \pm SE (No.) ¹	Max-min ² growth (cm/yr)	Dbh range ³ (cm)	Max ⁴ Mean	Minimum ⁵ (years)
<i>Andira inermis</i> (W. Wt.) DC.	0.09 \pm 0.023 (9)	0.20-0.02	4.6-48.2	2.2	218
<i>Ardisia obovata</i> Desv. ex Hamilton	0.06 \pm 0.005 (69)	0.18-0.01	4.1-9.7	3.0	31
<i>Bursera simaruba</i> (L.) Sarg.	0.09 \pm 0.012 (30)	0.30-0.00	9.1-52.5	3.3	145
<i>Capparis baduicca</i> L.	0.10 \pm 0.032 (8)	0.28-0.02	5.8-35.1	2.8	105
<i>Capparis cyanophallophora</i> L.	0.04 \pm 0.007 (29)	0.16-0.00	4.1-13.9	4.0	61
<i>Casaria guianensis</i> (Aublet) Urban	0.07 \pm 0.012 (22)	0.23-0.00	4.4-14.4	3.3	43
<i>Chionanthes compacta</i> Swartz	0.08 \pm 0.013 (8)	0.12-0.03	4.5-11.4	1.5	58
<i>Chrysophyllum pauciflorum</i> Lamarck	0.08 \pm 0.015 (32)	0.45-0.00	4.1-18.5	5.6	32
<i>Citharexylum fruticosum</i> L.	0.06 \pm 0.009 (14)	0.11-0.00	5.4-16.3	1.8	99
<i>Cordia rickseckeri</i> Millsp.	0.07 \pm 0.013 (24)	0.19-0.00	4.2-23.4	2.7	101
<i>Cordia sulcata</i> DC.	0.07 \pm 0.028 (10)	0.25-0.00	7.7-37.5	3.6	119
<i>Erothroxylum rotundifolium</i> Lunan	0.07 \pm 0.013 (13)	0.18-0.03	4.4-8.8	2.6	24
<i>Eugenia procera</i> (Swartz) Poiret	0.08 \pm 0.006 (46)	0.18-0.00	4.3-13.2	2.2	49
<i>Faramea occidentalis</i> (L.) A. Rich.	0.06 \pm 0.003 (99)	0.18-0.01	4.1-9.0	3.0	27
<i>Guettarda elliptica</i> SW.	0.04 \pm 0.004 (55)	0.13-0.00	4.1-13.0	3.2	68
<i>Guapira fragrans</i> (Dum.-Cours.) Little	0.10 \pm 0.007 (158)	0.59-0.00	4.2-73.2	5.9	117
<i>Guettarda scabra</i> (L.) Vent	0.06 \pm 0.008 (44)	0.29-0.00	4.4-16.0	4.8	40
<i>Inga laurina</i> (Sw.) Willd.	0.23 \pm 0.031 (27)	0.62-0.02	4.3-41.3	2.7	60
<i>Krugiodendron ferreum</i> (Vahl) Urban	0.05 \pm 0.011 (15)	0.13-0.00	5.2-12.4	2.6	55
<i>Maytenus laevigata</i> (Vahl) Grisebach	0.07 \pm 0.003 (272)	0.22-0.00	4.1-32.0	3.1	127
<i>Melicoccus bijugatus</i> Jacquin	0.12 \pm 0.027 (13)	0.34-0.02	4.4-43.4	2.8	115

TABLE 1. Twenty-five year diameter growth rates for species with ≥ 8 survivors in the Cinnamon Bay watershed. (continued).

Species	Mean dbh growth cm/yr \pm SE (No.) ¹	Max-min ² growth (cm/yr)	Dbh range ³ (cm)	Max ⁴ Mean	Minimum ⁵ (years)
<i>Myrcia citrifolia</i> (Aublet) Urban	0.07 \pm 0.006 (52)	0.22-0.01	4.1-11.6	3.1	34
<i>Myciaria floribunda</i> (West ex Willdenow) Berg	0.08 \pm 0.004 (96)	0.18-0.01	4.1-26.1	2.2	122
<i>Nectandra coriacea</i> (Sw.) Grisebach	0.11 \pm 0.026 (14)	0.40-0.01	4.1-11.3	3.6	18
<i>Pimenta racemosa</i> (Miller) J.W. Moore	0.12 \pm 0.014 (44)	0.37-0.01	4.3-18.6	3.1	39
<i>Pisonia subcordata</i> Sw.	0.10 \pm 0.018 (16)	0.26-0.01	5.8-29.0	2.6	89
<i>Quararibea turbinata</i> (Swartz) Poiret	0.06 \pm 0.010 (26)	0.22-0.01	4.3-11.0	3.7	30
<i>Randia aculeata</i> L.	0.02 \pm 0.008 (8)	0.07-0.00	4.8-16.9	3.5	173
<i>Sabinea florida</i> (Vahl) DC.	0.10 \pm 0.007 (55)	0.25-0.00	5.0-20.9	2.6	64
<i>Tabebuia heterophylla</i> (DC.) Britton	0.03 \pm 0.008 (18)	0.12-0.00	4.6-32.8	4.0	235
32 remaining species ⁶	0.10 \pm 0.012 (76)	----	4.1-68.5	---	---
Totals/Means	0.08 \pm 0.002 (1402)	----	4.1-73.2	---	---

¹SE = standard error and No. = number of stems.²Max-min = maximum and minimum 25-year (i.e., 1983-2008) dbh growth rates.³Dbh range in 1983 at beginning of study.⁴Maximum dbh growth divided by mean dbh growth.⁵Estimate of years required for fastest growing tree to grow through listed dbh range.⁶Species with ≤ 6 surviving stems.

Hurricane Hugo had different impacts on trees according to species (Weaver 1994, 1998). *Pimenta racemosa* was very resistant to wind damage. Only one tree of the 157 found on the plots succumbed during the 1988-1993 measurement period that included Hurricane Hugo; moreover, it is uncertain that Hugo was responsible for the loss. Other well-known tree species that were highly resistant to damage were *Maytenus elliptica*, *Inga laurina*, and *Bursera simaruba*. In comparison, all of the sampled *Clusia rosea* and 23 percent of the *Nectandra coriaceae* on the plots died as a result of the storm. Another important factor regarding tree damage is their location within the watershed (Weaver 1998). Among the important watershed variables were elevation, topography (i.e., ridge, slope, valley, or summit), aspect, and slope. In general, tree damage in the Cinnamon Bay watershed was greater at:

- higher elevations (>180 m) than at lower ones (<180 m)
- in ravines and on the summit than on slopes or ridges
- on northern aspects as opposed to either east or west aspects
- on slopes ≤ 5 percent than on slopes ≥ 20 percent

The relationship of dbh growth rates to disturbance events is somewhat speculative. The greatest variation in MAI among the 5-year measurement periods for all species combined was only 0.027 cm. The growth rates before and immediately after Hurricane Hugo (1983 to 1993), were among the lowest. The next period (1993 to 1998), which included the regional drought and Hurricane Marilyn, were only slightly higher, followed by a slight decrease (1998 to 2003). The last period (2003 to 2008) had the most rapid MAI. With three major events concentrated in only 6 years, responses to any particular event are confounded by others. However, in 2003, about 8 years after all major disturbances, plot stem density averaged near its lowest (Weaver 2006). In other words, the watershed had been thinned by nature. Subsequently, the amount of light reaching many

tree crowns was comparatively high, and MAI of survivors on the plots at a maximum for the 25-year period of measurement.

Dbh increment

The 25-year MAIs (Table 1) are similar to the previously reported 20-year measurements where 1,742 survivors on all 16 plots averaged 0.07 ± 0.002 cm yr⁻¹ (Weaver 2006b). Maximum and minimum 25-year MAIs show the considerable variability possible within a species (Table 1). Many factors are involved in MAI differences, including species characteristics (i.e., maximum tree size and specific gravity of the wood) and environmental conditions (i.e., available light, topographic position and variable soil moisture and fertility) (Grubb 1977, Weaver 2009). Trees that naturally achieve greater size are likely to have larger crowns and grow at more favorable dbh rates for longer periods of time. Some of the most rapid MAIs were attained by relatively large species such as *Inga laurina* and *Melicoccus bijugatus*. Although negative MAIs are uncommon, they may occur for slow-growing species in dry habitats. Short-term negative MAIs may result from severe drought; in comparison, long-term negative MAIs may be due trunk damage during hurricanes. Also, a few trees may die slowly in competition with surrounding vegetation, gradually shrinking in dbh during the process.

Foresters often question why certain timber trees grow much faster than others (Wadsworth 1953). The most rapidly growing trees are most likely a function of genetics, habitat, and time. They probably inherit a favorable genetic constitution, regenerate in appropriate habitats (i.e., with regard to elevation and topography), begin growing at appropriate times (e.g., post-disturbance when growing space is available to rapidly develop full crowns), and survive intact numerous potentially damaging events (e.g., hurricanes and droughts). In comparison, most trees with typical dbh growth rates have experienced a less fortunate life cycle.

MAI measured in Puerto Rico's Luquillo Mountains, about 70 km west of Cinnamon Bay,

FIGURE 4. Reversed J-shaped curve showing the distribution of 1,402 stems by dbh class for plots within the Cinnamon Bay watershed.

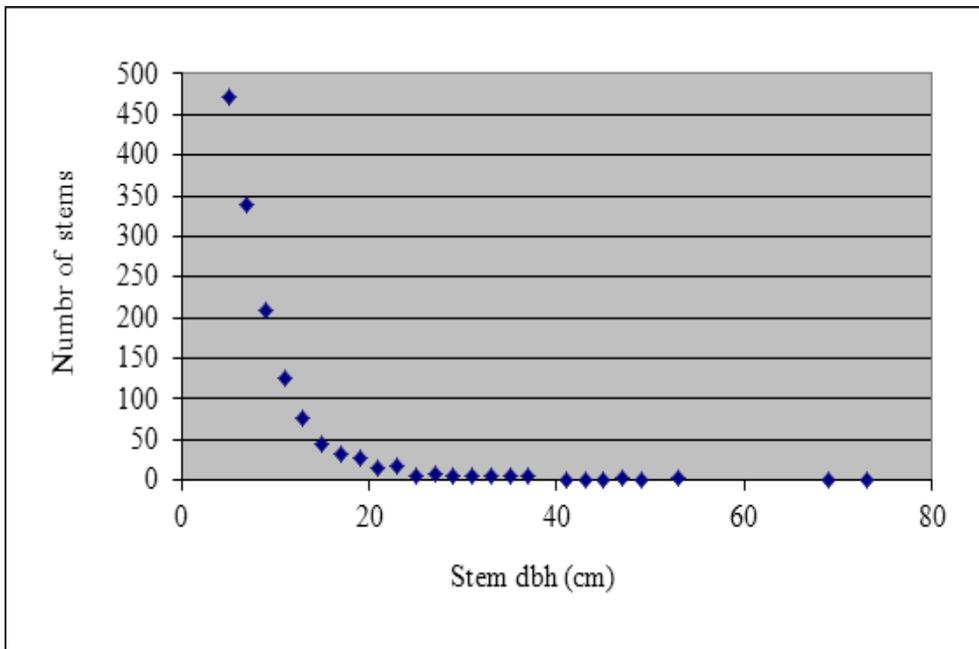
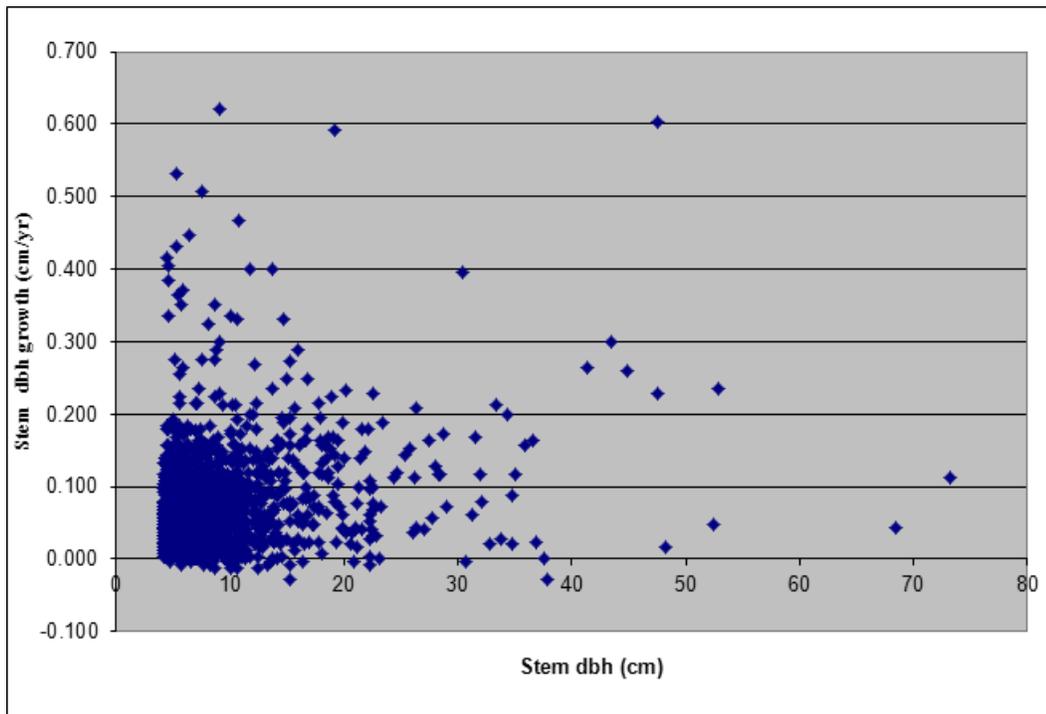


FIGURE 5. Mean annual diameter increment (MAI) for all 1,402 stems that survived the 25-year measurement period in the Cinnamon Bay watershed.



varied by species, forest type, and stage of maturity, and showed positive differences after hurricanes and thinning (Crow 1980; Crow and Weaver 1977; Wadsworth 1947, 1953; Weaver 1983). The MAI in mature stands for periods between 5 and 28 years ranged from 0.03 cm yr⁻¹ in dwarf forest at the mountain summits to 0.10-0.20 cm yr⁻¹ in lower montane, montane, and palm brake forests at lower elevations. Thinned lower montane forest showed MAIs averaging between 0.25 to 0.74 cm yr⁻¹ for potential crop trees of several different species over an 18-year period (Crow and Weaver 1977). In general, the long-term MAI in humid forests of the Luquillo Mountains is slightly greater than that of the dry forest at Cinnamon Bay, except for the dwarf forest. Moreover, typical differences between secondary and mature forest species are apparent.

Value of dbh measurements

Tropical foresters have measured dbh growth rates on permanent plots for more than a century but they are rarely reported in ecological literature. Dbh data from permanent plots remain one of the easiest measurements to record and one of the most versatile for determination of other useful ecological information. For example, dbh plot data may provide useful information regarding (Weaver 1983, 1994, 1996, 2009):

- **Stand characteristics** – tree density, species composition and richness, information on rare or endangered species, typical and maximum tree dimensions, and stand basal areas, volumes, and biomass; information for determination of site indices (i.e., growth curves for timber production).
- **Gradient information** – species-site relationships or species' changes according to environmental variables, i.e., aspect, elevation, topography (ridge, slope, or ravine), and exposure.
- **Dynamics** – stand density changes due to differential tree survival, ingrowth, and mortality; post disturbance rates of forest recovery; estimates of tree ages and productivity; response to silvicultural activities like thinning; and possibly information on nutrient dynamics within watersheds.
- **Climatic impacts** – impacts of persistent wind, heavy rains, drought, and hurricanes; immediate and delayed post-hurricane mortality; resistance to wind throw and uprooting by tree species and by site; and possibly, with excellent maintenance, long-term species responses to climatic change (i.e., global warming).

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LITERATURE CITED

- Beard, J. S. 1949. Natural vegetation of the Windward and Leeward islands. Oxford Forestry Memoirs 21:1-132.
- Bullen, R. 1962. Ceramic periods of St. Thomas and St. John Islands, Virgin Islands. Report 4. Maitland, FL: Central Florida Museum, William L. Bryant Foundation 1-49.
- Colón-Dieppa, E., H. Torres-Sierra, and J. Ortiz. 1991. U.S. Virgin Islands: floods and droughts. Water Supply Paper 2375. San Juan, PR: U.S. Department of the Interior, Geological Survey. P. 521-526.
- Crow, T. R. 1980. A rain forest chronicle: a thirty year record of change in structure and composition at El Verde, Puerto Rico. *Biotropica* 12:42-55.
- Crow, T. R., and P. L. Weaver. 1977. Tree growth in a moist tropical forest in Puerto Rico. Research Paper ITF-22. Río Piedras, PR: U.S. Department of Agriculture, Forest Service, Institute of Tropical Forestry. 17 p.
- Donnelly, T. W. 1966. Geology of St. Thomas and St. John, U.S. Virgin Islands. *In* Hess, H.H., editor. Caribbean geological investigations. Geological Society of America Memoir 98:85-176.

- Dookhan, I. 1974. A history of the Virgin Islands of the United States. St. Thomas, VI: Caribbean Universities Press and Bowker Publishing Company for the College of the Virgin Islands. 321 p.
- Ewel, J. J., and J. L. Whitmore. 1973. The ecological life zones of Puerto Rico and the U.S. Virgin Islands. Forest Research Paper ITF-18. Río Piedras, PR: U.S. Department of Agriculture, Forest Service, Institute of Tropical Forestry. 72 p.
- Grubb, P. J. 1977. Control of forest growth and distribution on wet tropical mountains with special reference to mineral nutrition. *Annual Review of Ecology and Systematics* 8:83-107.
- Forthun, G. 2005. Tropical systems affecting the U.S. Virgin Islands 1989-1999 as compared to Hurricane Hugo. SERCC Research Series Report. Columbia, SC: South Carolina Department of Natural Resources, Southeast Regional Climate Center. 29 p.
- Haas, W. H. 1940. The American empire: a study of the outlying territories of the United States. Chicago: University of Chicago Press. 408 p.
- Hatch, C. E., Jr. 1972. Virgin Islands National Park – St. John Island (“the quiet place”) with special reference to Annaberg Estate, Cinnamon Bay Estate. Washington, DC: Office of Archeology and Historic Preservation. 220 p.
- Knight, D. W. 1999. A brief history of the Cinnamon Bay Estate on St. John in the Danish West Indies 1718-1917. St. Thomas, VI: Little Norside Press. 85 p.
- Larsen, L. C. 1986. The Danish colonization of St. John 1718-1733. St. Thomas, VI: Virgin Islands Resources Management Cooperative. 72 p.
- Lawaetz, E. J. 1991. St. Croix: 500 years pre-Columbus to 1990. Herning, Denmark: Paul Kristensen. 494 p.
- Olwig, K. F. 1980. National parks, tourism and local development: a West Indian case. *Journal of the Society for Applied Anthropology* 39(1):22-31.
- Rivera, L. H., W. D. Frederick, and C. Farris, *et al.* 1970. Soil survey of the Virgin islands of the United States. Washington, DC: U.S. Department of Agriculture, Soil Conservation Service, Caribbean Area. 78 p. + maps.
- Rivera, L. H., W. E. McKenzie, and H. H. Williamson. 1966. Soils and their interpretation for various uses: St. Thomas and St. John, American Virgin Islands. San Juan, PR: U.S. Department of Agriculture, Soil Conservation Service, Caribbean Area. 52 p.
- Robinson, A., and F. Henle. 1978. Virgin Islands National Park: the story behind the scenery. Las Vegas, NV: KC Publications. 48 p.
- Rogers, C. S., and A. E. Reilly. 1998. Insights into forest dynamics from long-term monitoring on St. John, U.S. Virgin Islands. Pages 323-332 *in* F. Dallmeier, J. A. Comisky, editors. Forest biodiversity in North, Central and South America, and the Caribbean: research and monitoring. Washington, DC: Smithsonian Institution.
- Rogers, C. S., and R. Teytaud. 1988. Marine and terrestrial ecosystems of the Virgin Islands National Park and Biosphere Reserve. Biosphere Reserve Research Report 29. St. Thomas, VI: U.S. Department of the Interior, National Park Service; Virgin Islands Resource Management Cooperative; Island Resources Foundation. 112 p.
- Southeast Regional Climate Center. 2003. Catherinberg, Virgin Islands NCDC 1971-2000 monthly normals. sercc@dnr.state.sc.us (access date: November 11, 2003).
- Tyson, G. F., Jr. 1987. Historic land use in the Reef Bay, Fish Bay, and Hawksnest Bay watersheds St. John, U.S. Virgin Islands, 1718-1950. Biosphere Reserve Research Report No. 19. St. Thomas, VI: U.S. Department of the Interior, National Park Service; Virgin Islands Resource Management Cooperative; Island Resources Foundation. 54 p.
- Wadsworth, F. H. 1947. Growth in the lower montane forest of Puerto Rico. *Caribbean Forester* 8:27-35.
- Wadsworth, F. H. 1953. New observations of the growth in tabonuco forest. *Caribbean Forester* 14:106-111.
- Weaver, P. L. 1983. Tree growth and stand changes in the subtropical life zones of the Luquillo Mountains. Research Paper SO-190. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 24 p.
- Weaver, P. L. 1994. Effects of Hurricane Hugo on trees in the Cinnamon Bay watershed, St. John, U.S. Virgin Islands. *Caribbean Journal of Science* 30(3-4):255-261.

- Weaver, P. L. 1996. Forest productivity in the Cinnamon Bay watershed, St. John, U.S. Virgin Islands. *Caribbean Journal of Science* 32(1):89-98.
- Weaver, P. L. 1998. The effects of environmental gradients on hurricane impact in Cinnamon Bay watershed, St. John, U.S. Virgin Islands. Pages 333-348 *in* F. Dallmeier, J. A. Comiskey, editors. *Forest biodiversity in North, Central and South America, and the Caribbean*. Paris, France: The Parthenon Publishing Group.
- Weaver, P. L. 2006a. A summary of 20 years of forest monitoring in Cinnamon Bay watershed, St. John, U.S. Virgin Islands. General Technical Report GTR-IITF-34. Río Piedras, PR: U.S. Department of Agriculture, Forest Service, International Institute of Tropical Forestry. 35 p.
- Weaver, P. L. 2006b. Estate Thomas Experimental Forest, St. Croix, U.S. Virgin Islands: research history and potential. General Technical Report GTR-IITF-30. Río Piedras, PR: U.S. Department of Agriculture, Forest Service, International Institute of Tropical Forestry. 62 p.
- Weaver, P. L. 2009. Conservation strategies: long-term monitoring of permanent plots in Caribbean forest reserves. Pages 82-101 *in* P. L. Weaver, G. P. Bauer, editors. *Proceedings of the Fourteenth Meeting of Caribbean Foresters in Dominica, April 28 –May 2, 2008*. Río Piedras, PR: U.S. Department of Agriculture, Forest Service, International Institute of Tropical Forestry.
- Weaver, P. L., and J. D. Chinea-Rivera. 1987. A phytosociological study of Cinnamon Bay watershed, St. John, U.S. Virgin Islands. *Caribbean Journal of Science* 23(2):318-336.
- Woodbury, R. O., and P. L. Weaver. 1987. The vegetation of St. John and Hassel Island, U.S. Virgin Islands. Research/Resources Management Report SER-83. Atlanta, GA: U.S. Department of the Interior, National Park Service. 101 p. + map.