RELATING GUST SPEED TO TREE DAMAGE IN HURRICANE HUGO, 1989

by John K. Francis and Andrew J.R. Gillespie

Abstract. From 17 through 19 September 1989 Hurricane Hugo passed through the Antilles from Guadalupe to Puerto Rico, causing severe damage to ornamental and shade trees. Damage to 1226 trees of 81 species on 18 urban and rural sites was related to maximum wind gust speeds. Damage (defoliation, minor branch breakage, major branch breakage, trunk snap, and tipping) began at gust speeds of about 60 km/hr, increased rapidly with gust speeds to about 130 km/hr, and although highly variable, did not worsen at higher gust speeds. The most severe forms of damage are apparently avoided if the crown surface area is reduced quickly by loss of leaves and twigs. Palms were more wind resistant than broadleaved trees

From 17 through 19 September 1989 Hurricane Hugo passed through the Antilles from Guadalupe to Puerto Rico (Fig. 1). Hugo was classified as a category four hurricane, meaning it had sustained winds of at least 210 km/hr but less than 248 km/hr. Twenty-eight deaths and more than $2 billion in material damages were directly attributed to the hurricane in the Antilles (3). Damage to the environment by such natural and cyclical events is beyond inference. It has been estimated that the forests of eastern Puerto Rico are normally affected by hurricanes every 25-30 years and severely affected every 50-60 years (12).

One of the most striking evidences of a hurricane's passage is damage to trees. Although the damage is readily visible, surprisingly little is understood about how it relates to wind speed. The objective of this study was to relate damage sustained by exposed trees to measured and estimated gust speeds.

Data Collection

During the first 2 months following the storm, 18 sites were surveyed. Ideally, each site would have been a 1-km circle around a calibrated wind instrument. However, since so few good measurements of wind intensity were available, other sites with less reliable measurements or only estimates were used. The first five exposed trees of each species encountered were evaluated for degree of storm damage. From 11 to 24 species per site were observed, with a total of 81 species over all 18 sites. The 1226-tree sample consisted of planted ornamental and shade trees and naturally reproduced trees along fences and in undeveloped areas. Trees sheltered by buildings or groves of trees were not sampled. Thrown trees with artificially restricted root systems (such as one-sided root systems that had been cut during construction or that had grown up against a barrier) and trees toppled by the fall of other trees or structures were not sampled. Diameter at breast height (dbh) ranged from 3.5 to 216 cm, with most trees in the 10-50 cm range.

The sample trees were classified according to the most severe damage sustained by that tree. The system included six classes that progressed from no damage to windthrow.

The wind intensity variable used in this study was maximum gust speed. Not only are gust speeds higher than sustained wind speeds in storms, but gusts displace tree crowns more than constant wind and because of the inertia in swaying trees, repeated gusts can bend a tree crown three or more times as much as constant wind (8).

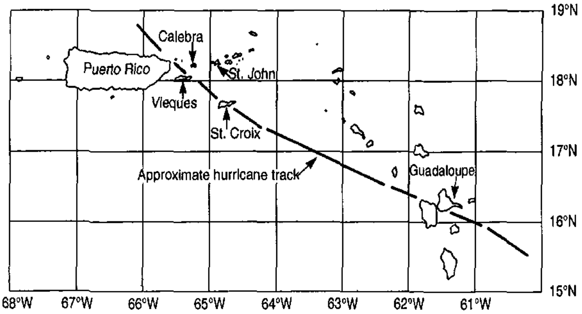

Figure 1. Map of study area indicating path of Hurricane Hugo in the Antilles.

The gust speeds used in this analysis were measured with a variety of instruments each with varying degrees of reliability. High-quality instruments were in place and recording at the airports at San Juan, Ponce, Borinquen Field, and the Arecibo Observatory. An instrument at Roosevelt Roads naval air field recorded gusts to 193 km/hr when it was destroyed by the storm. A number of other instruments in the path of the storm were destroyed or unattended. The gust speeds for four sites were given by privately owned instruments, types that are typically reliable up to 160 km/hr. Except for published information on the San Juan Airport gust speed, Roosevelt Roads, and open sea wind speeds near St. Croix (Natural Weather Service 1989), information was obtained by personal communication with airport managers, military officers, civil defense directors, and private citizens. Finally, gust speeds for other sites were estimated graphically (linearly) based on position and distance from measured wind speeds (Table 1).

Analysis and Results

Our first interest was to examine the effect of maximum gust speed on the distribution of damage. We plotted percentage of occurrence of all forms of damage combined (classes 2-5) *vs.* maximum gust speed at each site and by logistic regression analysis, found a significant response. No trees were damaged at the site with the lowest maximum gust speed (56 km/hr). The proportion of undamaged trees dropped to approximately 20 percent at a gust speed of 125 km/hr, and varied from 0-10 percent for gust speeds greater than 200 km/hr (Fig. 2). There were too few samples to compare the many species with one another, but we did compare palms as a groups with broadleaves and found palms significantly more resistant to damage than broadleaves.

Because a given damaged tree may be classified into only one damage category, potential trends within the individual damage categories tend to obscure one another. The only significant trends found were in small and large branch damage (categories 3 and 4). The rates of small branch loss (class 2) and large branch loss (class 3) increased slightly (but with substantial variation) as gust speed increased from 100 km/hr to 325 km/hr. At lower gust speeds (100-150 km/hr), small-branch loss exceeded large-branch loss; at higher gust speeds, large branch loss exceeded small-branch loss. The proportion of trees with defoliation (class 1) as the worst form of damage

Table 1. Measured and estimated maximum gust speeds by location and the reliability of each.

Location	Maximum gust speeds as reported	Reliability*
	Km/hr	
Aguadilla, PR, Borinquen Field	105	A
Arecibo, PR	121	E
Arecibo Observatory, PR	97	A
Culebra, PR	322	C
Guadalupe, WI. Grande Terre, north	322	E
Guadalupe, WI, airport area	306(300+)	B
Guavate, PR, Tropic Ventures	121	C
Humacao, PR, WALO Radio	174	C
Isla Grande, PR	148	B
Manatí, PR, Tortuguero	129	E
Ponce, PR, airport area	56	A
Río Piedras, PR, Botanic Garden	137	E
Roosevelt Roads Naval Base, PR	217(192+)	B
San Juan, PR, airport area	148	A
St. Croix, USVI	306	E
St. Thomas, USVI, airport area	296	C
St. Thomas, USVI, Coral World	296	E
Vieques, PR	274	E

*A = calibrated instrument, B = extrapolated from A-class measurement, C = uncalibrated and possibly unreliable instrument, E = estimate based on distance from instrument-measured gust speed.

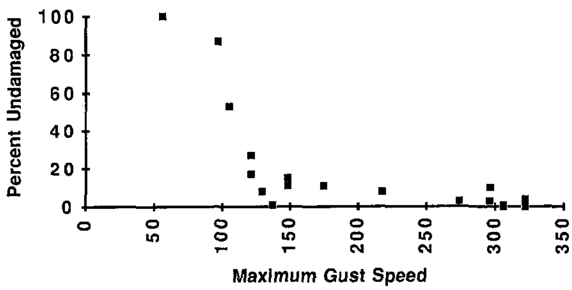

Figure 2. Percentage of all trees surveyed receiving no damage plotted against maximum gust speed.

varied between 5 percent and 40 percent at gust speeds greater than 100 km/hr. There was no trunk snap below 121 km/hr and it occurred in sites with higher gust speeds at 5-10 percent independent of gust speed. Windthrow was near 0 below gust speeds of 121 km/hr, and thereafter accounted for generally 10 to 20 percent of the trees.

We attempted to relate tree damage to maximum gust speed and tree size (dbh) by using a variety of logistical regression models. We began with a series of binary response models, one model per damage class, of the form (1)

$$\log (p / (1-p) = b'X$$

where

p = the condition probability that the tree is in the damage class, given the vector X;

X = a vector of independent (predictor) variables;

b = a vector of parameters

We used a stepwise procedure, testing the predictor variables gust speed (G), gust speed squared (G^2), dbh, and dbh^2. We used the maximum-likelihood procedure PROC LOGISTIC under SAS/PC 6.04 (SAS Institute 1990) to fit the models. The statistic g (gamma) is an index of the concordance association between modeled and observed responses and is used as an index of fit (1). Like r, g varies from -1 (complete discordance) to 1 (complete concordance).

In the following discussion, the probabilities being estimated are those of a tree finishing the storm in a given damage class, not the probability of a tree sustaining a certain type of damage (in addition to other types of damage). For example, a tree that finished the storm with large-branch loss and was included in that class also certainly suffered small-branch loss and defoliation.

The results of logistic regression indicate the following: The probability of a tree suffering some form of damage increases with both increasing gust speed and increasing tree dbh. The relationship is fairly strong ($g = 0.78$).

The probability of a tree suffering defoliation and no other form of damage decreases with increasing dbh. The effect of gust speed is curvilinear: the probability of defoliation alone increases with gust speed up to a point (approximately 200 km/hr under the model) and thereafter decreases. The relationship is fairly weak ($g = 0.25$), which indicates that other factors (*e.g.* species) may be more relevant.

The probability of a tree sustaining small branch loss is independent of tree dbh and is also curvilinear with respect to gust speed, peaking at approximately 250 km/hr. This relationship, however, is very weak ($g = 0.15$), implying that other factors may be more relevant.

The probability of a tree sustaining large-branch loss is dependent upon both gust speed and dbh. Both effect are curvilinear, with the effect of gust speed peaking at approximately 260 km/hr, and the effect of dbh peaking at approximately 150 cm. The association is intermediate ($g = 0.47$).

The probability of a tree sustaining a snapped trunk is independent of gust speed and decreases with increasing diameter. The association is relatively weak ($g = 0.32$).

The probability of a tree being windthrown is independent of both dbh size and gust speed. Factors of soil and rooting depth (not measured) are probably important.

The first relationship is the most meaningful. Large trees are at greater risk than small trees. This finding confirms the results reported by Reilly (10). Damage, once it begins to occur, is divided among all the damage categories. It is clear that there is substantial variation in the probabilities of damage classes that is not explained by tree size or gust speed. Leaf retention strength, and to a lesser extent, wood strength are probable important, and both are associated with species. Topographical position and location of neighbors and structures relative to the direction of the winds also probably affected results, although an attempt was made to exclude this effect by sampling only open-grown trees.

Figure 3 summarizes the effect of gust speed on the tree population by plotting the mean damage class across all broadleafs and palms at each site *vs.* the maximum gust speed at each site. While the scatter diagram is instuctive, the data cannot be used to calculate regression models because mean damage class is not a linear variable. The damage classes are ranked according to their

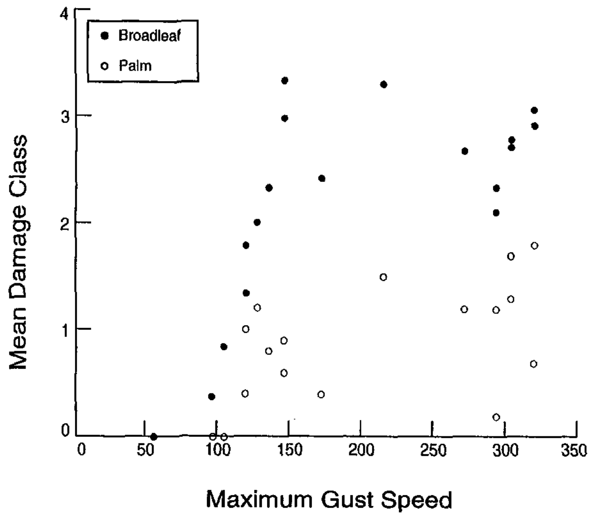

Figure 3. Mean damage class index for each site plotted against maximum gust speed.

physiological impact on the tree, but the index is not really quantative. This figure suggests that 1) damage was nil below gust speeds of about 60 km/hr, 2) damage increases rapidly as gust speed increases from 60 to 130 km/hr, 3) beyond about 130 km/hr, variability increases greatly (the effect of increasing gust speed on tree damage beyond this point may depend on the interplay of species characteristics, individual tree morphology, soil factors, and how long it takes a storm to build to its maximum, and 4) regardless of gust speed, palms are substantially less susceptible to damage than are broadleafed trees.

Discussion

Leaves and branches are normally resistant to winds that occur from time to time through the year. Breakage that would occur at or below those common gust speeds has already occured. As wind speeds increase beyond those in common events, defoliation becomes more and more general, twigs and minor branches are stripped away, and even major branches break. Eventually, a point is reached at which any tree than has not shed its crown must be toppled or snapped. But even very high gust speeds have little additional effect on denuded boles and a few remaining branches. The process is analogous to a sailing ship striking its sail to survive a storm. Hence, from the standpoint of tree damage, a storm with gust speeds just above the point at which trees have lost most of their crowns may be as damaging as one with gusts of 300 km/hr or more. Probable a storm with a slow buildup to maximum, allowing defoliation, will cause less snap and throw than one with a quick buildup to maximum.

Not all trees are created equal with respect to hurricane resistance. Strength of the wood in the branches and bole makes a relatively minor contribution to resistance to breakage at high wind speeds. There is roughly a ten-fold difference in wood breaking strength (molulus of rupture) between the strongest and weakest tropical woods (5,12). Because the fluid pressure of wind increases with the square of the wind velocity (13) and wind damage in like manner (6), the differences in limb and trunk breaking strength are overcome by relatively small increases in wind speed. The key to survival in hurricanes is quick reduction of drag (wind resistance) through defoliation. Cases in point: balsa (*Ochroma lagopus*) and yagrumo (*Cecropia peltata*) have light, relatively weak wood but lost all their few, large leaves and suffered minor structural damage; cupey (*Clusia rosea*) and casuarina (*Casuarina equisetifolia*) have strong, heavy wood but did not defoliate and suffered heavy trunk snap and major branch breakage in Hurricane Hugo.

Palms, however, appear to behave differently in storms than conifers and broadleafs. They have relatively low leaf areas relative to trunk diameters and no limbs to break. Their leaves also tend to trail in the wind rather than resisting it rigidly. Defoliation of palms began at fairly high gust speeds and proceeded gradually through the highest wind speeds. Indeed, on the plots with higher gust speeds, most of the few undamaged trees were palms. All the local palms, native and exotic, appear to be highly resistant to storm damage.

The experience in the Caribbean from Hurricane Hugo may relate to storms in other areas in only a general way. Hurricanes are extremely variable events and differences in tree species, soils, and topography greatly complicate the issue.

What can be done to lessen the impact of hurricanes and other strong winds on ornamental and shade trees? The most obvious preventative is to plant wind-resistant species. For some trees, the degree of resistance to wind damage is known from experience in past storms (2,7,15,16); the resistance of other species can only be estimated. In the absence of a better index, ease of defoliation under wind stress might be inferred from ease with which leaves can be plucked from twigs. Shallow or artificially restricted rooting is an invitation to disaster. If soils do not permit deep rooting and alteration of the rooting profile before planting is impractical, only shrubs and low-statured trees should be chosen. Locating moderate-sized trees in the shelter of taller building can also prevent both throw and breakage. Weather service bulletins usually allow many hours to prepare for the arrival of hurricanes. The key to reducing damage is a small crown surface area exposed to the wind. Surface area can be reduced by pruning away as much of the foliage as possible.

Summary

From 17 through 19 September 1989 Hurricane Hugo passed through the Antilles from Guadalupe to Puerto Rico, causing severe damage to ornamental and shade trees. This event provided an opportunity to asses the damage to 1226 trees of 81 species on 18 urban and rural sites. Damage was related to maximum gust speeds measured or estimated in 18 sites in Puerto Rico and the Lesser Antilles. Damage (defoliation, minor branch breakage, major branch breakage, trunk snap, and tipping) began at gust speeds of about 60 km/hr, increased rapidly with gust speeds to about 130 km/hr, and although highly variable, did not worsen at higher gust speeds. The most severe forms of damage did not occur if the crown surface area was reduced by the early loss of leaves and twigs. Palms were more wind resistant than broadleafed trees.

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Research Forester
International Institute of Tropical Forestry
USDA Forest Service, Call Box 25000
Río Piedras, Puerto Rico 00928-2500
and
Group Leader
Forestry Inventory and Analysis
USDA Forest Service
Northeastern Forest Experiment Station
100 Matsonford Road
Radnor, Pennsylvania 19087-4585

Résumé. Du 17 au septembre 1989, l'ouragan Hugo passa au travers des Antilles depuis la Guadeloupe jusqu' à Porto Rico, causant de sévères dommages aux arbres ornementaux. Les dommage sur 1226 arbres de 81 espèces différentes dans 18 villes et campagnes furent attribuables aux vents qui soufflèrent à une vitesse maximale. Les dommages (defoliation, bris mineurs de branches, bris majeurs de branches, cassures de troncs, renversements) commençaient lorsque les rafales soufflaient à 60 km/h, augmentant rapidement avec des rafales s'élevant jusqu' à 130 km/h, et même si elles étaient d'intensité très variable, elles ne soufflèrent pas à vitesse plus élevée. Les formes les plus sévères de dommages sont évitées si la surface de contact de la cime est réduite rapidement par la perte des feuilles et des ramilles. Les palmiers furent plus résistants aux vents que les arbres à feuilles caduques.

Zusammenfassung. Vom 17. bis 19. September 1989 fegte der Wirbelsturm Hugo über die Antilien von Gaudalupe bis Puerto Rico und verursachte schwere Schäden an Zier- und Schattenbäumen. Der Schaden an 1226 Bäumen aus 81 Arten and 18 städtischen und ländlichen Standorten wurde in Beziehung gestzt zu maximalen Windgeschwindigkeiten. Der Schaden (Entlaubung, geringer Astbruch, schwerer Astbruch, Stammbruch und Herausbrechen der Spitze) begann bei einer Böengeschwindigkeit von 60 km/h, nahm rapide zu bei einer Geschwindigkeit von bis zu 130 km/h und obwohl immer noch variabel verschlimmerte sich nicht bei höheren Geschwindigkeiten. Die schlimmste Form des Schadens kann verhindert werden, wenn die Kronenoberfläche schnell reduziert ist durch den Verlust von Laub und Zweigen. Palmen zeigten sich mehr windresistent als Laubbäume.