PROBABILITY OF DAMAGE TO SIDEWALKS AND CURBS BY STREET TREES IN THE TROPICS

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Abstract. For 75 trees each of 12 species growing along streets in San Juan, Puerto Rico and Merida, Mexico, diameter at breast height and distance to sidewalk or curb was measured and damage (cracking or raising) was evaluated. Logistic analysis was used to construct a model to predict probability of damage to sidewalk or curb. Distance to the pavement, diameter of the tree, and species were all found to contribute significantly to the probability of damage. Predictive models are presented for each species and numerical trials are used to illustrate the relationship of the independent variables to probability of damage.

One of the major problems of managing trees in metropolitan areas is the damage caused by roots to sidewalks and curbs. Cracking, and subsequent lifting of the broken pieces, proceeds as roots growing under those concrete structures thicken. It is obvious to even casual observers that problems are more severe near large trees. Deserved or not, some species have gained a worse reputation for damage than others. Two quantitative studies, one in San Francisco, California (3) and the other in Manchester, United Kingdom (2), have verified that tree size, species, and proximity to sidewalk or curb are all factors in damage to sidewalks and curbs. However, tree size and rate of growth within a given species seemed to be more important than species, per se.

Street trees are at least as important to quality of life in the tropics as in temperate areas. Tropical trees cause damage to sidewalks and curbs just as their temperate counterparts do. Unfortunately, relatively little is known about the growth and development of urban trees in the tropics, except that they usually grow faster than trees in the temperate zones. This study was conducted to quantify the probability of damage caused by tropical street trees in relation to tree species, size, and distance to sidewalk or curb.

Materials and Methods

The 2 areas chosen for study were San Juan, Puerto Rico, and Merida, Yucatan, Mexico. San Juan, a city of about 750,000, is situated at 18.5" N latitude and varies in altitude from sea level to 50 m. Various parts of the city receive from 1500 to 1900 mm of rainfall, and mean annual temperature is about 26%. Merida has a population of about 400,000 and lies at 21° N latitude. The topography is flat, and the elevation is a few meters above sea level. Mean annual rainfall is about 950 mm, and mean annual temperature is about 25°C. The soils of San Juan are usually deep acid clay Ultisols, often capped with gravely clay fill. The soils of Merida are shallow clays over limestone.

In each area, 75 trees each of 12 of the most commonly planted species or genera (Table 1) were assessed. For each tree, diameter at breast height (dbh) was measured in centimeters with a diameter tape. The distance to sidewalk and/or curb from the center (midpoint) of the tree was measured in meters with a cloth tape. It was noted whether the sidewalk or curb was cracked or raised, or if it was undamaged. If there was any suspicion that damage had resulted from another cause—such as settling of the soil base, or reconstruction of the curb or sidewalk during the life of the tree—a new tree was selected.

The resulting data were analyzed using logistic analysis, specifically the categorical data modeling procedure published by the SAS Institute Inc. (1). Damage was entered as a binary dependent variable, tree species as an independent class variable, and dbh and distance to the structure as continuous variables. Data from San Juan and Merida were analyzed separately, as was

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Table 1. Species of trees sampled and their respective identification numbers used during analysis.

City	#	Scientific name	Common name
San Juan	1	*Swietenia* spp. (*S. macrophylla, S. mahagoni, S. macrophylla* x *mahagoni*)	Caoba
	2	*Ficus* spp. (*F. retusa, F. benjamina*)	Laurel
	3	*Calophyllum* spp. (*C. calaba, C. inophyllum*)	Maria
	4	*Bucida buceras*	Ucar
	5	*Tabebuia* spp. (*T. heterophylla, T. rosea*)	Roble
	6	*Dalonix regia*	Flamboyan
	7	*Melaleuca quinquenervia*	Melaleuca
	8	*Pterocarpus macrocarpus*	Terocarpus
	9	*Lagerstroemia speciosa*	Reina de flores
	10	*Bauhinia* spp. (*B. variegata, B. monandra, B. purpurea*)	Arbol orchidia
	11	*Cassia javonica*	Cassia rosada
	12	*Termanalia catappa*	Almendra
Merida	1	*Ficus* spp. (*F. retusa, F. benjamina*)	Laurel
	2	*Tabebuia rosea*	Maculis
	3	*Dalonix regia*	Flamboyan
	4	*Cassia fistula*	Lluvia de oro
	5	*Termanalia catappa*	Almendra
	6	*Tamarindus indica*	Tamarindo
	7	*Spathodea campanulata*	Tulipán
	a	*Samanea saman*	Samán
	9	*Erythrina variega ta*	Eritrin
	10	*Ehretia tinifolia*	Roble
	11	*Brosimum alecastrum*	Ramón
	12	*Albizia lebbeck*	Algarrobo ebano

Table 2. Means and other statistics for dbh's and distances to sidewalks and curbs for sample trees of various species in San Juan and Mérida.

City/species	#	Dbh Mean±SD	Min.	Max.	Dissw*	Discb**
San Juan						
Caoba	70	40.9±1 6.4	10	97	0.60±0.37	0.61±0.32
Laurel	50	102.2±69.9	13	278	1.84±1.96	2.03±1.80
Maria	75	37.3f11.5	13	66	0.62f0.12	0.69f0.29
Ucar	75	26.8± 9.7	9	54	0.58±0.12	0.63±0.19
Roble	69	23.8f12.3	8	72	0.64±0.36	0.61±0.19
Flamboyan	64	31.1f19.7	7	105	0.92f0.77	0.96±0.51
Melaleuca	70	16.4±11.9	6	80	0.58±0.24	0.59M.32
Terocarpus	64	48.4±24.7	1 2	126	1.34±0.98	1.29±1.31
Reina de flores	49	40.3f16.8	14	66	0.99M.64	0.75fl.23
Arbol orchida	68	23.7f13.1	10	77	0.72M.60	0.86±0.60
Cassia rosada	71	27.8f10.5	11	76	0.58f0.16	0.69f0.77
Almendra	50	30.6±17.3	9	90	1.57fl.59	1.67fl.47
Merida						
Laurel	57	59.6k43.9	16	296	0.90±0.71	1.21f0.69
Maculis	71	41.9±13.3	1 1	71	0.60±0.34	0.74±0.58
Flamboyan	67	37.0±14.3	1 3	76	0.61M.31	0.67±0.35
Lluvia de oro	73	31.4f10.8	14	63	0.52M.29	0.73±0.58
Almendra	65	26.6f14.0	14	79	0.58±0.42	0.89M.71
Tamarindo	3 5	49.3±30.6	1 3	146	0.61f0.22	0.87±0.64
Tulipán	5 %	26.7f12.6	IO	55	1.11±0.99	1.00±0.81
Samán	66	64.3±29.2	1 5	147	1.00±0.74	0.91±0.50
Eritrina	69	27.1f12.3	IO	72	0.42f0.20	0.51±0.40
Roble	47	53.6f13.4	26	104	0.70±0.47	0.76±0.78
Ramón	60	36.8±11.2	1 4	68	1.14±0.46	0.87±0.52
Algarrobo ebano	56	29.0f14.7	11	95	0.71±0.42	0.67M.63

*Distance to sidewalk
**Distance to curb
Note: Dbh data are given for trees used in relation to curb damage. Because a portion of the trees did not have both sidewalk and curb nearby, means for sidewalk trees may differ slightly.

damage to sidewalks and curbs, making 4 separate analyses in all (Table 2). Initial analyses were conducted using all possible interaction terms. If an interaction proved nonsignificant (a > 0.05), it was dropped from the analyses to produce a simpler model.

Results

First, we developed a general model for the 2 dependent variables (damage to curb and sidewalk) by country. We specified separate intercepts for each species and separate slopes for dbh (Dbh) and distance to sidewalk (Dissw) or distance to curb (Discb), plus an interaction term between the 2 quantitative independent variables. This resulted in a 48-parameter model (by country). The results of the first iteration showed that this model was overparameterized and, in general, the interactions were redundant. Therefore, we simplified the model, without interaction terms (but keeping separate intercepts and slopes). This yielded a 36-parameter model with species, dbh, and distance to the pavement being significant in the maximum-likelihood analysis of variance test. The model worked well with the San Juan data, on both damage to sidewalk and damage to curb. However, in Merida, a simpler model was just as efficient. The results seemed to indicate that the effect of distance to sidewalk (or curb) was independent of species. Also, for the dependent variable damage to sidewalk (Damsw), separate intercepts did not seem necessary. Therefore, we modified the model further for Damsw, using a common intercept for each species, separate Dbh slopes, and a common Dissw slope, for a 14-parameter model. For damage to curb (Damcb), we had separate intercepts for each species and separate Dbh slopes, but a common Discb slope, for a 25-parameter model.

The final models follow a similar generalized form. For example, the logistic model for damage to sidewalks in San Juan appears as follows:

$$\text{logit}_i = (\mu + \alpha_i) + (\kappa + \beta_i)\text{Dbh} + (\tau + \gamma_i)\text{Dissw} + \varepsilon$$

where

- logit_i is the logisticly transformed (see later) value for the ith species
- ε is residual error
- μ is a general intercept
- α_i is the effect of the ith species
- κ is a general Dbh slope
- β_i is the effect of the ith species on the Dbh slope
- τ is a general Dissw slope
- γ_i is the effect of the ith species on the Dissw slope
- i is from 1 to 11 (Table 3)

Table 3. Listing of the parameters and estimates for the 4 final models for probability of damage to sidewalks and curbs by street trees.

Effect	Parameter	Estimate San Juan sidewalk	San Juan curb	Mérida sidewalk	Mérida curb
Intercept	μ	-1.6360	-1.6664	0.5835	0.0736
Species	α_1	-1.8022	-0.6923	- -	0.8909
	α_2	2.0275	1.9054	- -	-2.3440
	α_3	-3.4049	-0.2606	- -	0.5564
	α_4	0.0649	0.4896	- -	-1.1223
	α_5	-1.6406	-0.4792	- -	2.7646
	α_6	0.0836	0.5012	- -	-0.1745
	α_7	3.4326	1.6149	—	-1.6436
	α_8	2.7517	0.8643	- -	1.1730
	α_9	1.8439	-2.1100	- -	1.1786
	α_{10}	-0.6447	-0.4915	- -	-2.4619
	α_{11}	-2.0429	-1.0380	- -	0.6212
Dbh	κ	0.1200	0.0634	0.0579	0.0614
	β_1	0.1243	0.00242	-0.0179	-0.00875
	β_2	-0.1128	-0.0573	0.0269	0.0934
	β_3	0.0173	0.0561	0.0142	-0.0207
	β_4	0.0731	0.00655	0.0369	0.0664
	β_5	-0.00185	0.0138	0.00275	-0.0731
	β_6	-0.0479	-0.0299	-0.0329	-0.0144
	β_7	-0.00627	-0.0205	-0.0167	0.0220
	β_8	-0.0616	-0.0238	0.00346	-0.0195
	β_9	-0.0694	0.0399	0.0630	-0.0191
	β_{10}	0.0645	0.0289	-0.0365	0.0404
	β_{11}	0.0309	-0.0197	-0.0337	-0.0513
Distance	τ	-2.3839	-1.4120	-1.6246	-1.5544
	γ_1	-2.5750	1.1964	- -	- -
	γ_2	1.9972	1.2072	—	—
	γ_3	4.6061	-3.1230	—	—
	γ_4	-2.2974	-0.7724	—	—
	γ_5	3.0914	-0.0369	—	—
	γ_6	1.5733	1.2070	—	—
	γ_7	-6.2708	-2.6060	—	—
	γ_8	1.5834	1.0715	—	—
	γ_9	0.4232	0.6530	—	—
	γ_{10}	-4.4372	-1.6771	—	—
	γ_{11}	1.3082	1.5841		—

The proper parameters for the 12th species are given differently:

$$\text{logit}_{12} = \left(\mu - \sum_{i=11}^{11} \alpha_i\right) + \left(\kappa - \sum_{i=11}^{11} \beta_i\right)\text{Dbh} + \left(\tau - \sum_{i=11}^{11} \gamma_i\right)\text{Dissw} + \varepsilon$$

To predict the logit for species 1 (caoba) in San Juan, for example, use:

$$E(\text{logit}_1) = (\mu + \alpha_1) + (\kappa + \beta_1)\text{Dbh} + (\tau + \gamma_1)\text{Dissw}$$

$$E(\text{logit}_1) = (-1.6380 - 1.8022) + (0.1200 + 0.1243)\text{Dbh} + (-2.3839 - 2.5750)\text{Dissw}$$

Assuming Dbh = 50 cm and Dissw = 0.5 m, we have:

$$E(\text{logit}_1) = -3.4402 + 0.2443(50) - 4.9589(0.5) = 6.2954$$

Since the probability of damage to sidewalk can be calculated, we obtain:

$$\text{logit} = \text{natural log } [\hat{P} / (1 - \hat{P})]$$

Then:

$$\hat{P}_{\text{damage.1}} = e^{6.2954} / (1 + e^{6.2954}) = 0.9982$$

As another example, consider species 12 (almendra) in San Juan. For Dbh = 36.6 and Dissw = 1.65 we have:

$$E(\text{logit}_{12}) = -2.2071 + 0.1297(36.6) - 1.3863(1.65) = 0.2525$$

$$\hat{P}_{\text{damage.12}} = e^{0.2525} / (1 + e^{0.2525}) = 0.5628$$

These particular results support the intuitive conclusion that the smaller the tree and the farther away it is situated from sidewalk or curb, the lower the probability of damage.

Each species displayed different probability trends that overlap one another in the range of diameters and distances from sidewalks or curbs. Therefore, we ran simulations to compare the various species in their potential to cause damage to sidewalk and curb, selecting a 75% probability (an arbitrary level) of damage and a distance of 0.5 m as test parameters (Table 4). In San Juan the least

Table 4. Dbh at which probability of damage reaches 75% for trees planted 0.5 m from sidewalks and curbs.

	San Juan		Mérida	
Species#*	sidewalk(cm)	curb(cm)	sidewalk(cm)	curb(cm)
1	28.7	54.2	33.2	17.3
2	125.3	157.7	15.7	26.8
3	36.6	44.3	18.4	30.6
4	26.0	48.1	14.0	22.9
5	35.7	51.4	21.9	81.4
6	42.4	70.6	53.1	42.1
7	31.9	69.0	32.2	41.3
8	10.0	52.3	21.6	15.0
9	37.0	50.9	11.0	14.7
10	36.3	52.0	62.0	41.9
11	35.2	85.1	54.8	116.9
12	30.8	49.7	27.4	26.7

*Number is the species identification used during analysis. See Table 1 for scientific and common names. Species differ between San Juan and Merida.

damaging species or genus is clearly laurel (*Ficus* spp.) followed by flamboyan *(Dalonix regia)*. The species with the greatest potential for causing damage is terocarpus *(Pterocarpus macrocarpus)*. The other species fall between these extremes. Possibly, curbs are less likely to be damaged because the adjacent streets (usually cement paved) have more compacted beds and are more poorly aerated and thus are a more effective barrier to root penetration than are sidewalks. The critical dbh's for curb damage are much larger than for sidewalk damage.

In Merida, the trends are not as clear cut. The species least likely to cause damage are ramón (*Brosimum alecastrum)*, roble (*Ehretia tinifolia)*, and tamarindo (*Tamarindus indica)*. Five species in Merida seem to cause damage at small to moderate sizes: eritrin (*Erythrina variegata)*, samán *(Samanea saman)*, lluvia de oro *(Cassia fistula)*, maculis *(Tabebuia rosea)*, and flamboyan (*Dalonix regia)*. For 5 species, it appears that curb damage would occur before sidewalk damage. This is a marked contrast from the San Juan results, for which critical diameters were always substantially larger for curb damage than for sidewalk damage. Underlying soil or local construction methods probably account for these differences between San Juan and Merida.

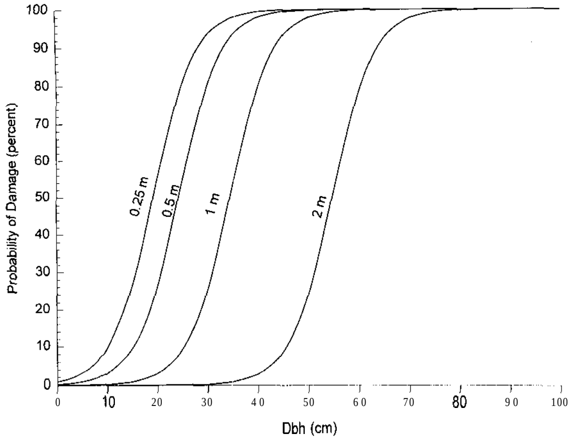

Figure 1. Probability of damage to sidewalks by San Juan species 1 (*Swietenia* spp.) at various dbh's and distances from the structure.

Discussion

For *Swietenia* in San Juan, the probability of damage to sidewalk is projected under various diameters and distances (Figure 1). At small diameters, probability of damage is 0 or nearly so until some threshold dbh is reached. Probability of damage increases slowly at small diameters, then very rapidly as diameters increase, and again more slowly as 100% probability is approached. The slow approach to 100% probably results from a fortuitous lack of large roots under certain sections of sidewalk or from soil conditions, such as extraordinary compaction, that inhibit roots from growing under particular sidewalk sections. In positions close to the structure, only trees with small dbh's result in little probability of damage, but with increasing distance from the sidewalk, larger and larger dbh's are possible without a high probability of damage.

A price must be paid in terms of tolerated dbh or minimum distance to curb in order to assume a lower degree of certainty of damage. Although greater precision at the lower probabilities of damage could be obtained if it were possible to completely eliminate Type II experimental error (attributing damage to sources other than tree roots), it is not practical to reduce predicted probability of damage to very low levels.

The most obvious way to avoid damage to sidewalks and curbs is to plant far enough away from them that damage will not occur. For some species that grow large, such as terocarpus and samán, this can be 5 m or more away-practical in parks and large estates, but hardly useful in the space between the sidewalk and curb along city streets. Even those large-growing species are sometimes planted in constricted spaces with the intention of removing them in 10 to 15 years, before they have cracked or raised the nearby pavement.

The alternate approach is to plant trees that do not become large enough to be a threat to structures or that, because of their growth patterns, do little or no damage. A number of ornamentals, such as the *Bauhinia* group included in this study, usually do not exceed 15 to 20 cm in diameter and consequently cause few problems for sidewalks or curbs. Another group that very rarely causes problems in even constricted rooting space, presumably because their roots do not thicken beyond a few mm, are the palms. A maintenance treatment used occasionally in San Juan is to periodically cut narrow trenches 30 cm deep along sidewalks and curbs to sever young roots beginning to extend under them. This treatment may have dangerous consequences in the long run. A large tree with a constricted root system is very prone to tipping in high winds.

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Résumé. Douze espèces (75 arbres par espèce) poussant le long des rues de San Juan, Puerto Rico et Merida au Mexique ont été évaluées en mesurant leur diamètre à hauteur de poitrine, leur distance par rapport au trottoir ou la bordure de rue et les dommages (fissures ou soulèvements) causés dans le voisinage sur ces structures. Une analyse logistique a été utilisée afin de construire un modèle pour prédire la probabilité de dommages au troltoir ou à la bordure de rue. La distance de l'infrastructure, le diamètre de l'arbre et l'espèce ont tous été jugés comme des facteurs significatifs en regard de la probabilité de dommages. Des modèles de prédiction sont présentés pour chaque espèce et des essais numériques sont employ& pour illustrer la relation des variables indépendantes face à la probabilité de dommages.