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A Logistic Regression Model of Hurricane Impacts in a Mangrove Forest of the Mexican Pacific[1]

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ABSTRACT

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Hurricane Rosa inflicted considerable damage to the mangrove forests of the Teacapán-Agua Brava Lagoon System of Mexico. Data collected from five transects indicate an overall reduction in stem density and basal area of approximately 31 and 51 percent respectively. Of the 1390 trees examined, only 44% remained well vegetated and 28% were found with their main stem broken or uprooted. *Rhizophora mangle* was the species least affected by the event with 65% of these trees found in a well vegetated condition in contrast to 34% for *Laguncularia racemosa* and 42% for *Avicennia germinans*. A polytomous logistic regression model was developed to further examine the predicted outcome, vegetation condition, by species, main stem condition and diameter at breast height (DBH). *Rhizophora* was excluded from the model and DBH was reserved as a continuous variable. The results from this multivariate approach indicate that the probability of a mangrove being found in a dead condition as compared to a well vegetated one is significantly influenced by the diameter and main stem condition but not by the species. As diameter increases, the odds that an intact tree will be classified as dead rather than in a well vegetated condition also increases. A broken or uprooted main stem also augments this probability but diameter and the uprooted condition interact to attenuate the odds. By comparing a poorly vegetated to a well vegetated outcome, the model again indicates that, separately, increased diameter, the condition of a broken or uprooted main stem all increase the odds of a less favorable outcome. More significant interactions were also recorded, including the interaction of species by both diameter and the uprooted condition. Although seedling counts suggest considerable recovery following the hurricane, *Avicennia* and *Rhizophora* dominated the numbers. Changes in light conditions, local topography and substrate conditions following this rare storm event may not currently favour the growth of *Laguncularia* seedlings.

ADDITIONAL INDEX WORDS: *Coastal forested wetland, multinomial logit model, Pacific coast, Mexico.*

INTRODUCTION

Recent investigations are suggesting possible relationships between particular characteristics of mangrove forests and the extent of damage incurred from hurricanes. For example, in their study of Hurricane Gilbert's impact on mangrove forests in Jamaica, WUNDERLE *et al.* (1992) indicated that the most severe structural damage occurred amongst the larger diameter trees. This relationship has since been supported by others (ROTH, 1992; SMITH *et al.*, 1994; IMBERT *et al.*, 1996; MCCOY *et al.*, 1996) who have also suggested that the degree of impact may also be linked to the species. In their investigations, ROTH (1992) and IMBERT *et al.* (1996) both reported *Rhizophora mangle* as more readily damaged than *Avicennia germinans*. Moreover, ROTH (1992) indicated that *Rhizophora mangle* was also more susceptible than *Laguncularia racemosa*. In contrast, SMITH *et al.* (1994) and MCCOY *et al.* (1996) noted *Laguncularia racemosa* as equally if not more prone to hurricane impacts than *Rhizophora mangle.*

Each study has provided valuable insight into how hurricanes affect these forested wetlands but attempts at comparisons between the results of these investigations are difficult. Reasons for these limitations include unique criteria for measuring damage, numerous classification methods and multitudes of statistical tests. For example, although tree diameter measurements represent a continuous data set, researchers tend to transform this variable into discrete diameter classes that vary from one study to another. More notable are the individual methods of assessing tree damage. SMITH *et al.* (1994) and IMBERT *et al.* (1996) both employ a single measure of damage assessment (scale) that combines both the main stem and vegetation condition. However, the number of categories and their descriptors vary considerably from one another. MCCOY *et al.* (1996) adopt a criterion of assessment, similar to ROTH (1992), that considers separate evaluations for vegetation and stem condition. Although not assessed in

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a complete multivariate context, their study indicates various associations between diameter, species, main stem and vegetation condition, suggesting a potential dependency of vegetation condition on all three other variables.

Building upon the success of these investigations, this study will employ a multiple logistic regression model to further examine the dependency of vegetation condition on the other independent variables and to explore potential interactions between the predictor variables. Using this approach, the diameter variable can be maintained as continuous. The use of the odds ratios, the output of this particular statistical model, may facilitate interpretability of hurricane impact data and, consequently, provide a platform that will allow for unconstrained comparison between future research.

STUDY AREA

Located on an alluvial plain that extends the Mexican Pacific coast (Figure 1), the Teacapán-Agua Brava Lagoon System is recognized as one of the largest mangrove systems on the western coast of the Americas (FLORES-VERDUGO *et al.*, 1990). With the vast majority of the forest located far inland, the basin mangrove forest type dominates the landscape (see LUGO and SNEDAKER (1974) for classification types). Large expanses of monospecific *Avicennia germinans* and *Laguncularia racemosa* are located in the northern and southern sections of this system, respectively (FLORES-VERDUGO *et al.*, 1992). *Rhizophora mangle* can be found along various inlets and channels as well as interspersed amongst the two more dominant species. *Conocarpus erectus* flourishes further inland in the drier reaches of the coastal plain. SNEDAKER (1982) has suggested that more research is needed to explain the unique dominance of *Laguncularia racemosa* in this region. Possible reasons for this anomaly include very high fresh water inputs (ROLLET, 1974; POOL *et al.*, 1977) and the regional development of the land-forms (SNEDAKER, 1982). However, a lack of detailed botanical maps, soil data and annual hydrologic data (*e.g.*, salinity, tides) limit any ecological explanation to this dominance.

In addition to the mangroves, the Teacapán-Agua Brava Lagoon System contains a complex of tidal channels, coastal lagoons, seasonal floodplains, three seasonal rivers and one perennial river. For an extensive review of the geomorphic history of the region, the reader is referred to CURRAY *et al.* (1969). The system is located in a tropical sub-humid climate zone with a mean annual temperature of 27° C. The majority of rainfall occurs in the summer months with a total annual precipitation ranging from 1000 to 1500 mm (INEGI, 1995).

On October 14 1994, Hurricane Rosa, with estimated maximum wind speeds of 167 km/hr and air pressure reaching approximately 975 mb, reached the Pacific Coast of Mexico (AOML, 1999). No previous accounts of the hurricane's strength or impacts on the mangroves have been reported for the Teacapán-Agua Brava Lagoon System. Indication of extensive hurricane damage to the mangroves came from the statements of elderly men from six of the local fishing villages. These fishermen possess an extensive knowledge of the system (KOVACS, 1999). Of the forty interviewed, whose average residence period was 41 years, no individual reported witnessing any other hurricane of this magnitude. Researchers have also noted the lack of recurrent hurricane activity for this region. For example, ROLLET (1974) reported that he could not identify any natural phenomena of destruction in the mangroves of the Teacapán-Agua Brava Lagoon System. POOL *et al.* (1977) stated that there was no visible evidence of the region ever being subject to a hurricane event. Moreover, they commented that, unlike other mangrove forests that are periodically influenced by strong winds and hurricanes, this region exhibited a taller canopy, a less dense stand and a larger number of trees with larger diameters. More recently, during their examination of productivity, FLORES-VERDUGO *et al.* (1992) suggested that, relative to other sites in Mexico, the low leaf fall for this area is indicative of an absence of major hurricanes.

METHODS

During the months of November and December 1997 five strip transects were conducted perpendicular to the water's edge. These transects were situated far inland from the coast, with three located in the northern section and two in the southern section of the Teacapán-Agua Brava Lagoon System. The northern and southern transects measured 0.1 ha (5 m × 200 m) and 0.05 ha (5 m × 100 m), respectively. Transportation by boat was supplied by the Tecuala branch of the Secretaria del Medio Ambiente, Recursos Naturales y Pesca of Nayarit and by the villages of Francisco Villa, El Pescadero and Pericos. The location of each transect was identified using maps and aerial photographs and confirmed using a Ground Positioning System. Within each transect, all trees measuring 2.5 cm in diameter or greater were recorded for their diameter at breast height (DBH), species, height, location, condition of main stem and vegetation condition. Similar to MCCOY *et al.* (1996), stem condition categories included "broken", "uprooted" and "intact" and vegetation condition categories included "well vegetated", "poorly vegetated" and "dead". Trees classified as "uprooted" were those whose main stem was found parallel to the ground. As with MCCOY *et al.* (1996), the dichotomy between the "well" and "poorly vegetated" cases was clearly visible in the field, with the 50% leaf loss as the criterion for separation. In addition to trees, seedlings were also recorded from quadrates (2 m × 2 m) selected at random from within each ten meter length of transect.

Employing a SYSTAT 8.0 statistical package, variable selection for the polytomous multiple logistic regression model was computed using a stepwise approach. The procedure taken involved a forward selection of variables with a test for backward elimination. A p-value of 0.05 was chosen as the criterion for both entry and removal from the model. For a detailed account of this methodology, the reader is referred to HOSMER and LEMESHOW (1989). Based on previous literature, vegetation condition was selected as the outcome (or response) variable with the continuous covariate diameter and the categorical and design covariates stem condition and species as the predictors. *Rhizophora mangle* was excluded from the model because no uprooted cases were found and, if broken, were always recorded as dead.

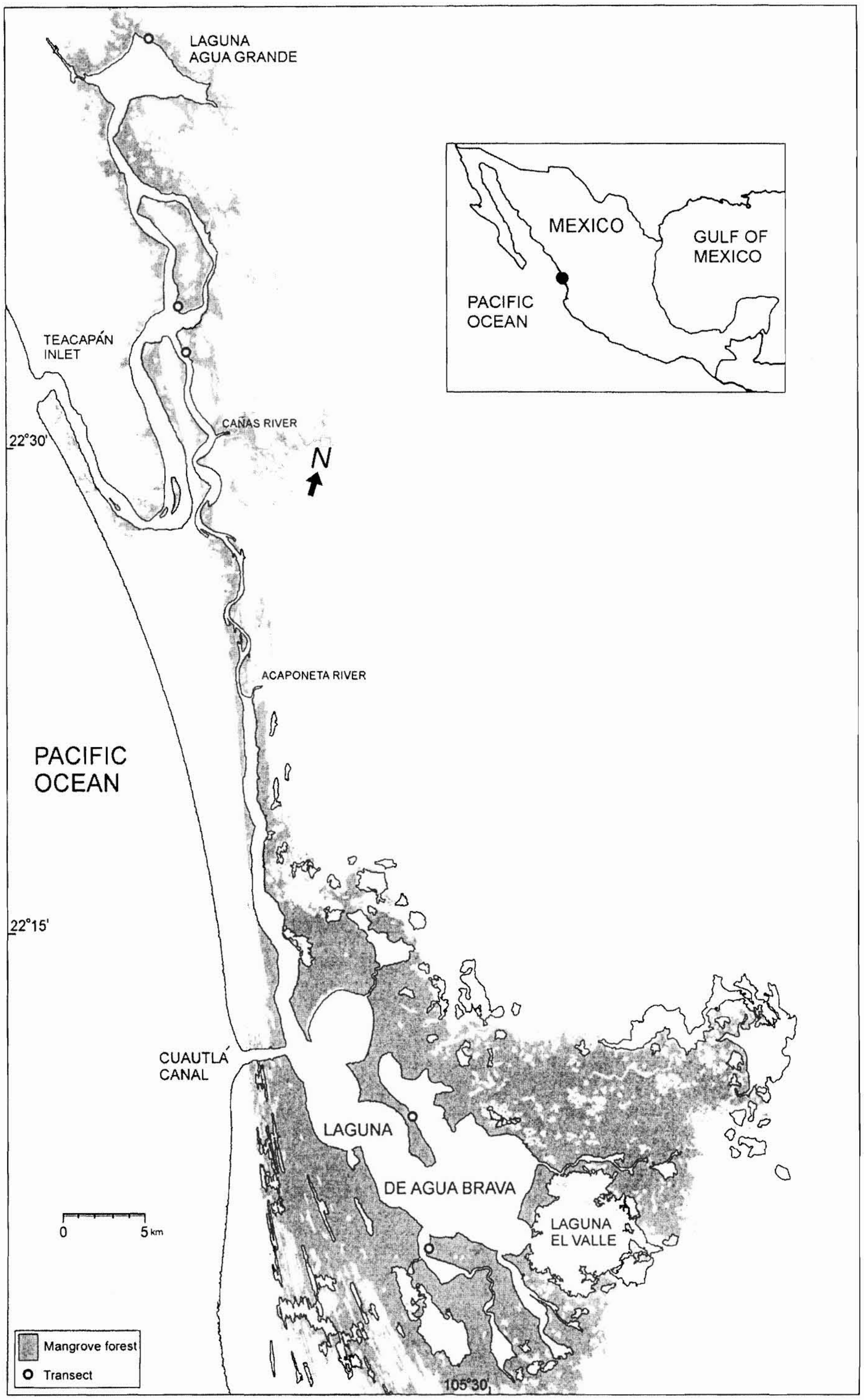

Figure 1. The Teacapán-Agua Brava Lagoon System.

RESULTS AND DISCUSSION

General Observations

The results from Table 1 indicate that Hurricane Rosa inflicted considerable damage to the mangrove forests of this region. It is important to note that the pre-disturbance values from this table were calculated by adding those trees believed to be killed by the hurricane to the remaining alive trees. In addition, eighteen trees found cut were added to both the pre and post values but not further considered. Given the number

Table 1. *Stem density and basal area before and after Hurricane Rosa by transect location (includes all trees >=2.5 cm DBH; L.r = Laguncularia racemosa; R.m = Rhizophora mangle; A.g = Avicennia germinans).*

Site			Agua Grande	Ilsa La Palma	Cañas	Chantilla	Punta Burro	Total
Latitude (N)			22°44′	22°35′	22°34′	22°05′	22°09′	
Longitude (W)			105°42′	105°41′	105°42′	105°32′	105°33′	
Stem density, stems ha^{-1}	before		3470	3840	2550	3980	4460	3520
	after		2520	2410	1770	2880	3100	2423
	−%		27.38	37.24	30.59	27.64	30.49	31.16
Basal area, m^2 ha^{-1}	before		20.85	17.31	21.99	31.99	32.82	23.15
	after		9.5	7.4	6.4	21.8	21.4	11.23
	−%		54.44	57.25	70.90	31.85	34.80	51.49
Relative density	before	L.r	5.5	5.7	11	86.9	80.3	
		R.m	2	3.4	21.2	13.1	19.7	
		A.g	92.5	90.1	67.8	0.0	0.0	
	after	L.r	0	1	4.5	86.2	73	
		R.m	1	3	17.5	13.8	27	
		A.g	99	96	78	0.0	0.0	
Relative dominance	before	L.r.	24.4	34.1	44.4	91.3	89.6	
		R.m	4.3	2.9	12.7	8.7	10.4	
		A.g	71.3	63	42.9	0.0	0.0	
	after	L.r	0	12.2	10.9	93.5	86	
		R.m	5.2	2.7	20.3	6.5	14	
		A.g	94.8	85.2	68.8	0.0	0.0	

of dead trees recorded, it is estimated that the overall stem density and basal area were reduced by approximately 31 and 52 percent respectively. In particular, the three northern transects sustained the greatest reductions in basal areas relative to stem density. The loss of several large diameter *Laguncularia racemosa* trees contributed to these reductions. In general, the dominance of *Avicennia germinans* in the north and *Laguncularia racemosa* in the south remained unchanged.

Of the 1390 trees recorded (cut removed), 92 were uprooted and 300 had their main stem broken (Table 2). Although 44% were found well vegetated three years after the event, 24% were in poor condition and 32% were recorded as dead. Significant differences between stem and vegetation condition were observed ($\chi^2 = 486.8$, df = 4, $p<0.01$). Dead trees represented 16, 45 and 81 percent of all intact, uprooted and broken trees respectively.

Table 2. *Vegetation condition of intact (I), broken (B) and uprooted (U) trees by species following Hurricane Rosa.*

		Good	Poor	Dead
Laguncularia racemosa	I	116	47	35
	B	8	11	108
	U	14	34	31
	total	138	92	174
Rhizophora mangle	I	94	8	29
	B	0	0	13
	U	0	0	0
	total	94	8	42
Avicennia germinans	I	366	210	93
	B	17	22	121
	U	2	1	10
	total	385	233	224

With regards to species differences, *Laguncularia* appears the most and *Rhizophora* the least affected by the hurricane. Only 34% of *Laguncularia* remained in a well vegetated condition whereas 42% of *Avicennia* and 65% of *Rhizophora* were similarly classified. Differences between species are also apparent in the condition of the main stem. Approximately 31% of *Laguncularia,* 19% of *Avicennia* and 9% of *Rhizophora* trees were found broken. Twenty percent of *Laguncularia* and only two percent of *Avicennia* were uprooted, with no cases of *Rhizophora* recorded.

By simple observation of the results in context of species, by stem condition, and by vegetation condition, several patterns become apparent. For example, when the main stem is broken, all *Rhizophora* are found dead. When uprooted, *Laguncularia* fares much better than *Avicennia,* with only 39% of *Laguncularia* classified as dead in contrast to 77% for *Avicennia.*

If diameter values are arbitrarily grouped into classes with a range of 2.5 cm, there are indications that larger diameter trees are more prone to damage than smaller ones (Figure 2). For example, approximately 80% of trees with DBH greater than 20 cm were classified as dead whereas only 16% of the smallest diameter class (2.5–5 cm) were similarly classified. When considering stem condition, these two groups exhibit similar contrast (Figure 3). Sixty and six percent of the larger and smaller diameter classes were recorded as broken respectively. Overall, very few small diameter trees were found uprooted.

Logistic Regression Model

The final regression model developed is significant in comparison to the constant only model (*G* = *531.366, df* = *18,* $p<0.01$) and to the previous eight variable model (Table 3).

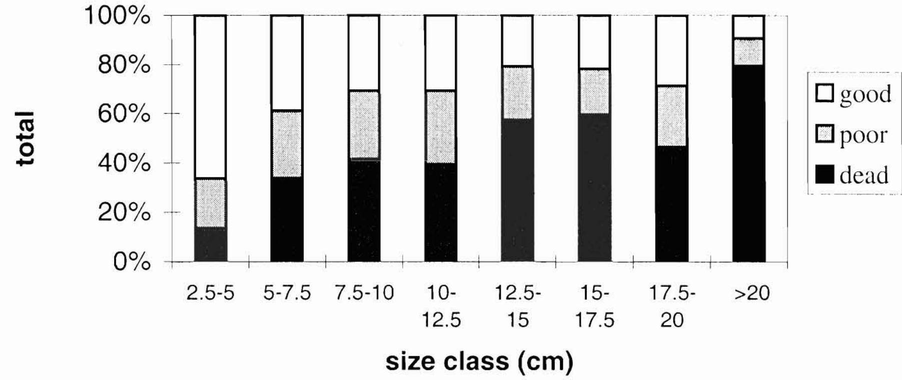

Figure 2. Vegetation condition of mangrove trees by their diameter following Hurricane Rosa.

Because of the polytomous case for the outcome variable vegetation condition, two logit functions were computed, one for the dead and the other for the poorly vegetated condition (Table 4). The values of the parameters for both logits are referenced to the well vegetated condition outcome value. Comparison between the dead and poor conditions can be examined by subtracting the estimated coefficients from one another and transforming them by their exponential to reveal the odds ratios. Within each logit, the variable *Avicennia* (species) is referenced to *Laguncularia* and both uprooted and broken coefficients are referenced to the intact main stem condition.

Given a 95% confidence level, only four variables, one an interaction term, are significant to the dead condition logit. Increased diameter results in increased probability that a tree will be more likely classified as dead than in a well vegetated condition. Every 5 cm increase in diameter increases by two-fold the odds of an intact tree being classified as dead rather than in good condition. Thus, an intact tree of 10 cm will be approximately four times more likely to be classified as dead, a 15 cm tree eight times (7.92)[1], a 20 cm tree sixteen times (15.8) and a 25 cm intact tree thirty times (31.5). Species type does not contribute to the probability of the condition outcome for this logit. The status of a broken main stem greatly increases the odds that a tree will be found as dead over a healthy condition, approximately 65 times greater. The condition of an uprooted stem also considerably alters the probability but there is a strong interaction with diameter thus altering the probability of the outcome response. An uprooted 5 cm tree has a 34 times[2] and a 10 cm tree a 28 times greater likelihood of being classified as dead rather than in a healthy vegetated condition. Thus, in the case of uprooted trees, larger diameters attenuate the probability of being classified as dead.

With regards to the poor condition logit model, six variables, three interactive terms, contribute significantly to the response variable. Increased diameter again increases the odds that a tree will be categorized as in poor condition versus a well vegetated condition. Species alone does not contribute to the outcome but does interact with the diameter variable. An intact *Avicennia* of 5 cm diameter and one of 10 cm will have respectively a 2.5[3] and 6 times greater chance of being classified as in poor condition than in a healthy con-

[1] $D = e^{0.138(15)} = e^{2.07} = 7.92$

[2] $D + S\_U + S\_U{*}D = e^{0.138(5)+3.693-0.174(5)} = e^{3.513} = 33.5$

[3] $D + A{*}D = e^{0.074(5)+0.105(5)} = e^{0.895} = 2.45$

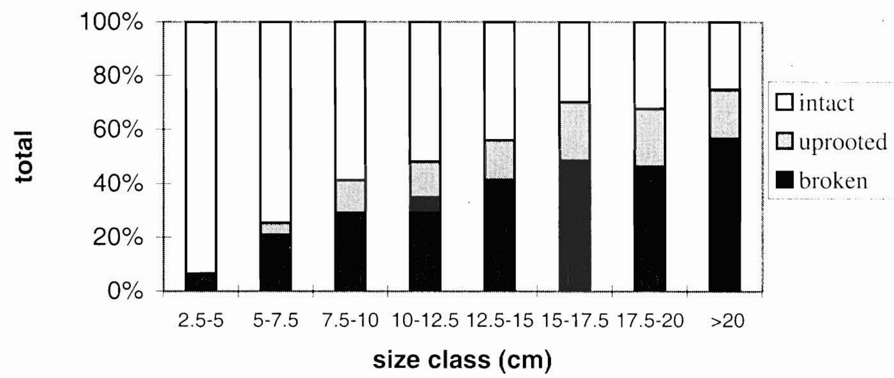

Figure 3. Stem condition of mangrove trees by their diameter following Hurricane Rosa.

Table 3. *Log likelihood and log likelihood ratios for a stepwise multiple logistic regression model (C = constant, D = diameter, A = Avicennia, S_U = uprooted, S_B = broken).*

Model	Log likelihood (D)	G-test against pervious model
C	−1344.994	
C + D	−1254.880	180.228
C + D + A	−1252.667	4.426
C + D + A + S_U + S_B	−1095.427	314.480
C + D + A + S_U + S_B + S_U*D + S_B*D	−1089.510	11.834
C + D + A + S_U + S_B + S_U*D + S_B*D + A*D	−1087.379	4.262
C + D + A + S_U + S_B + S_U*D + S_B*D + A*D + S_U*A + S_B*A	−1079.331	16.096

dition in comparison to an intact *Laguncularia* of the same diameter. Broken trees are 6 times more likely to be in poor condition than in a healthy state. The uprooted condition significantly contributes to the outcome variable but also interacts with both species and diameter. In particular, the odds ratio of the interaction term S_U*A indicates that uprooted *Avicennia* are less likely to be found in poor condition than healthy condition in comparison to a *Laguncularia* counterpart. However with interaction present, an uprooted *Avicennia* of 7.6 cm (average) will have a 2.24[4] times greater odds ratio in contrast to an uprooted *Laguncularia* of similar diameter. Comparing the dead versus poor condition logit, it is quite apparent that broken trees are 11 times more likely to be in dead condition versus poor condition.

Seedling Densities and Potential for Uprooted *Laguncularia*

All transects located in the northern section exhibited high seedling densities with Agua Grande achieving 103,875 seedlings/ha (Table 5). These transects also yielded values that corresponded to their relative tree species densities for after hurricane values (Table 1), with *Avicennia germinans* dominating. In contrast, *Rhizophora mangle* seedlings dominate regeneration in the remaining transects even though *Laguncularia* constitutes the majority according to both the pre-hurricane and post-hurricane relative tree densities and dominance values.

The poor recovery of *Laguncularia racemosa* seedlings relative to other mangrove species has been reported by others (BALL, 1980; ROTH, 1992; MCCOY *et al.*, 1996). The unique dominance of *Laguncularia* in the Teacapán-Agua Brava Lagoon System cannot currently be explained (SNEDAKER, 1982) but it would appear that environmental conditions prior to the hurricane did favour the regeneration of these particular seedlings. Modifications in light conditions, local topography and substrate conditions following this rare storm event may now favour the growth of *Rhizophora* propagules in the southern section of the system. For example, we encountered numerous gaps in the forest canopy and observed highly irregular local topography resulting from uprooted trees. The irregular topography not only contributes to stagnant ponds and supratidal patches but also exposes the substrate to erosion and allows for continued re-profiling of the canopy floor (SMITH *et al.*, 1994; TILMANT *et al.*, 1994; SWIADEK, 1997). The breaking up and washing away of the peat and the large volumes of decaying organic material from the fallen trunks, leaves and rotting roots should also create significant changes in the condition of the substrate. Together, the changes in light conditions, local topography and substrate conditions following the hurricane may currently preclude recolonization of *Laguncularia* propagules in some areas and favour the growth of *Rhizophora* seedlings in others.

Although *Laguncularia racemosa* did not achieve high seedling concentrations, we believe that several of the uprooted but healthy ones may contribute to numerous offspring. *Laguncularia* can vigorously resprout (coppice) following a natural break or cut of the main stem (WALDSWORTH, 1959; TOMLINSON, 1986). In our investigation, we observed what appears to have been a similar activity from several old and decaying uprooted *Laguncularia*. In the field we recorded 55 *Laguncularia* (all in the southern section) that could be linked to 17 originally uprooted, now decaying, main stems. It appears that many of these new trees were once connected via a parental main stem but have been separated. Where this has occurred, a straight row of trees of similar diameter

[4] D + S_U + S_U*D = $e^{0.074(7.6)+3.412-0.158(7.6)} = e^{0.8056} = 2.24$

Table 4. *Estimated coefficients and odds ratios for the multiple logistic regression model (D = diameter, A =* Avicennia*, S_U = uprooted, S_B = broken).*

Logit	Variable	Odds ratio	Estimated coefficient	Standard error	*t*-ratio	p-value
Dead	Constant		−2.434	0.365	−6.663	0.001
	D	1.148	0.138	0.033	4.227	0.001
	A	1.060	0.058	0.412	0.140	0.888
	S_U	40.184	3.693	0.860	4.297	0.001
	S_B	65.162	4.177	0.723	5.780	0.001
	S_U*D	0.841	−0.174	0.062	−2.802	0.005
	S_B*D	0.940	−0.062	0.058	−1.066	0.287
	A*D	1.046	0.045	0.045	0.988	0.323
	S_U*A	1.227	0.205	0.914	0.224	0.823
	S;lB*A	0.421	−0.865	0.543	−1.592	0.111
Poor	Constant		−1.483	0.319	−4.651	0.001
	D	1.077	0.074	0.033	2.229	0.026
	A	0.947	−0.055	0.367	−0.149	0.881
	S_U	30.321	3.412	0.857	3.983	0.001
	S_B	6.084	1.806	0.824	2.193	0.028
	S_U*D	0.854	−0.158	0.066	−2.406	0.016
	S_B*D	0.928	−0.074	0.066	−1.122	0.262
	A*D	1.111	0.105	0.045	2.332	0.020
	S_U*A	0.063	−2.766	1.306	−2.117	0.034
	S_B*A	0.414	−0.882	0.628	−1.406	0.160

Table 5. *Seedling densities by transect (L.r = Laguncularia racemosa; R.m = Rhizophora mangle; A.g = Avicennia germinans).*

	Size	Actual number			Density (seedlings ha⁻¹)	Relative density		
		L.r	R.m	A.g		L.r	R.m	A.g
Agua Grande	$2m^2$ (n = 20)	2	9	820	103875	0.2	1.1	98.7
Isla Palma	$2m^2$ (n = 20)	0	10	194	25500	0.0	4.9	95.1
Cañas	$2m^2$ (n = 20)	16	50	271	42125	4.7	14.8	80.4
Chantilla	$2m^2$ (n = 10)	30	65	0	23750	31.6	68.4	0.0
Punta Burro	$2m^2$ (n = 10)	5	17	0	5500	22.7	77.3	0.0

can be found. We have noted that several of the more recently uprooted *Laguncularia* are exhibiting what seems to be precursors to this activity, hence suggesting an increase in contribution to stem density for the next generation.

CONCLUSION

From the results of this investigation it is apparent that simple comparison between the various characteristics for each tree may not be sufficient for describing the relationships between mangrove forests and hurricanes. In this study, the logistic regression model provided an ideal tool for identifying the significant predictor variables, for assessing interactions amongst the variables and as a means of maintaining the nature of a continuous variable all within the multi-variate context. As noted by HOSMER and LEMESHOW (1989), this statistical approach does not ignore the probability that a collection of variables, each weakly associated to the outcome, may be important predictors when taken together. For example, our results indicated that although species by itself was not a significant predictor of vegetation condition, it does interact with both diameter and the uprooted condition in altering the odds of a poor rather than well vegetated outcome. The simplicity of the odds ratio for describing the various relationships may entice other researchers to employ this statistical modeling technique, possibly leading to a more comprehensive means for comparative studies. However, it must be noted that certain species, such as *Rhizophora mangle,* may have to be precluded from this statistical modeling procedure.

Within the context of the methodological approach taken in this investigation, it is recommended that other variables be tested for inclusion in the model. By integrating other variables, the predictive ability of the model may be enhanced. For example, LUGO *et al.* (1983) have suggested that the examination of wind velocity, direction of hurricane travel and time exposed to such an event may assist in predicting the impacts on forests. IMBERT *et al.* (1996) have suggested that overall forest structure and canopy roughness may also provide important clues to understanding the relationship between hurricanes and mangrove forests. The interactions between biomechanical properties of stems and hurricane winds have been investigated for upland tropical forests (ASNER and GOLDSTEIN, 1997) and could also be considered in the modeling of mangrove forest impacts.

With regards to seedling growth, *Avicennia* appears to be regenerating as the dominant species in the northern section of the system. However, in the southern transects, the observed small number of *Laguncularia* propagules relative to *Rhizophora* indicates a different situation. Changes in light conditions, local topography and substrate conditions following the storm may, at present, favour the growth of propagules of the less dominant species. The ability of *Laguncularia* to regenerate (coppice) following damage from a hurricane may provide an inter-species competitive advantage to the otherwise skewed seedling recovery rate. Fierce hurricanes may severely limit the reproductive capability of *Laguncularia racemosa* in this system.

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