MANGROVE FOREST STRUCTURE UNDER VARYING ENVIRONMENTAL CONDITIONS

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ABSTRACT

Vegetation assessments were carried out in three mangrove forests undergoing different levels of anthropogenic stress and varying environmental factors. These forests were in Hunts Bay, Fort Rocky Lagoon (part of the Port Royal mangroves on the south shore of Kingston Harbour), and Wreck Bay (Hellshire). The vegetation assessments included the determination of species composition, floristics, and leaf litter production of the mangrove trees. Selected environmental and biological conditions were also investigated at each site. The hypothesized gradient of environmental factors, eutrophication and disturbance was Hunts Bay > Fort Rocky Lagoon > Wreck Bay. With the exception of light on the forest floor, the soil and water column parameters were all significantly different among sites, but the values did not always follow the expected environmental gradient. For example, nitrate/nitrite values were maximum at Wreck Bay (34.4 μM), followed by Hunts Bay (12.41 μM) and Fort Rocky Lagoon (10.0 μM), and phosphates ranked with maximum at Fort Rocky Lagoon (9.69 μM), then Hunts Bay (4.41 μM) and Wreck Bay (1.24 μM). Of the vegetation characteristics, only average leaf litter production and percentage cover were significantly different among sites, with a ranking similar to the hypothesis (i.e., Hunts Bay > Fort Rocky Lagoon > Wreck Bay). The most important factors influencing the distribution of productivity and percentage cover among forests were soil salinity, soil NO₃, especially the nitrate to phosphate ratio, soil moisture content and soil temperature with R² values of 0.77 for litter production and 0.64 for percentage cover. Other factors such as diameter at breast height and tree height were not significantly different among forests and showed a weak relationship with edaphic factors. Overall results indicated that the forests were very different with respect to physico-chemical and edaphic factors, and there was a clear gradient of eutrophication. However, the effect of anthropogenic stress and varying environmental conditions is most reliably demonstrated in the productivity and percentage cover of the forests.

The influence of man on mangrove forest structure is intensive, non-selective, and non-specific. Worldwide it is estimated that as many as one million hectares of mangroves are lost every year (Bossi and Cintron, 1990). Although there are no figures for the Caribbean as a whole, there is need for concern. Mangrove areas in Jamaica tend to be smaller and easily cleared or converted to other uses. These losses are often irreversible (Bossi and Cintron, 1990). In cases involving reclamation for garbage disposal, there are problems not only with the loss of wetlands, but increased pollution potential as well. Such reclamations can result in the fringe zone being destroyed; the pollution load in the waterway increased; the tidal ventilation reduced; and velocity of runoff increased, resulting in increased siltation and less incoming ocean water to reduce the pollutants present in the estuary (Mangroves, 1998a). Shoreline development has replaced mangroves with marinas, dredged channels, airports, filled lots, sea walls, and other commercial and residential constructions. Of shallow water open mangroves in the upper Florida Keys, 60% were lost between 1965–1985 and 40% of that was due to dredging and filling of mangroves (Mangroves, 1999). While extensive documentation exists on the effect of these obvious activities on mangrove systems, there is a paucity of studies on the more subtle
effect of nutrient enrichment and eutrophication on mangrove forests. Organic effluents
can substantially alter a mangrove ecosystem by causing depletion of dissolved oxygen,
DO, and increases in nutrient levels in the water (Mangroves, 1998b). There is need to
examine the effects on Jamaican mangrove forests as well as to determine the forest
parameters and variables, which are useful indicators of eutrophication effects on man-
grove forests. To achieve this objective, assessments were conducted in three different
mangrove forests between January and August 1999.

Two mangrove areas were selected in Kingston Harbour, one in Hunts Bay and the
other on the south shore of the Harbor in an area of Port Royal Mangroves (Fort Rocky
Lagoon). A third station was sited in Wreck Bay, a pristine bay along the Hellshire coast.
This was regarded as a ‘control’ station, being far removed from the influence of Kingston
Harbour and other major sources of eutrophication (Webber, 1990).

Hunts Bay, according to Ranston (1998), supports generally ‘unhealthy’ ruinate man-
grove swamps along its shores. The Soapberry swamp lies along the north shore of the
bay and the mangrove swamps on the north and northeastern shores taper gradually into
nearby residential and industrial sectors (Ranston, 1998). From initial general observa-
tions, this site was deemed representative of an area of mangroves influenced by a high
volume of fresh water and a high level of eutrophication as well as disturbance from
direct human activity. The site is situated between the Duhaney River and the Sandy
Gully, thus should receive large quantities of fresh water and sediments especially dur-
ing periods of high rainfall. The observed species composition is depauperate with
Laguncularia racemosa and Avicennia germinans accounting for the majority of the
vegetation, and Rhizophora mangle occurring in very small patches and being in very
poor health where they occurred. This site may be classified on the basis of Lugo and
Snedaker (1974) as a riverine forest. Hunts Bay mangroves can also be classified ac-
cording to Asprey and Robbins (1953) as silt/mud mangroves. The soil here is predomi-
nantly anaerobic so that pneumatophores, or breathing roots are critical to survival; there-
fore, Hunts Bay is dominated by A. germinans and L. racemosa along with the occasion-
sal R. mangle tree.

Fort Rocky Lagoon represents an area of moderate disturbance, which is indirectly
influenced by the polluted waters of Kingston Harbour. It is part of the Port Royal man-
grove swamp, which is an area of mangrove lagoons and channels between large islands
of mangrove forests. The most obvious sign of impact on the mangrove forests on the
south shore of Kingston Harbour is the build up of solid waste deposited on the forest
floor in areas adjacent to the open waters (Green and Webber, 1996), on the windward
side of the mangrove islands. The mangrove areas adjacent to the lagoon (the leeward
side of the mangrove islands) are not influenced by any major fluvial inputs, but due to
the indirect influence of Kingston Harbour, the site is ranked next to Hunts Bay with
respect to pollution. The site can be classified as a fringe forest and the area sampled can
best be described as typical of an associes of mature R. mangle and L. racemosa with R.
mangle dominant. Alleng (1990) found that most of the trees were tall and light penetra-
tion was minimal. The 27 km coastline of Hellshire consists of a variety of bays that are
under different influences (Lindo, 1991). Wreck Bay is situated within the northeastern
sector of the Hellshire coastline, and is a shallow (1–5 m) bay protected by reefs and sand
banks to varying degrees. There is significant fresh water input from an underground
source that has been observed percolating through fissures in the porous limestone rocks
on the shallow bay floor (Webber, 1990). Due to the distance of Wreck Bay from the
 mouth of the Kingston Harbour, and that it is relatively exposed to the open ocean, it was deemed a pristine site. The mangals in this area have a sand substrate and the mangrove species, notably an abundance of *R. mangle*, are interspersed with other coastal plant species in the zone nearest to land, but the *R. mangle* plants were observed to be in their typical zone along the fringe (seaward edge) of the forest. The area can thus be classified according to Asprey and Robbins (1953) as a sand mangrove and according to Lugo and Snedaker (1974) as a fringe forest. This area was chosen to be the site least influenced by anthropogenic stress whether industrial, domestic, or otherwise.

**MATERIALS AND METHODS**

**VEGETATIVE SURVEY**

The mangrove vegetation and associations at each site were described according to the methods of Lugo and Snedaker (1974) and Snedaker and Snedaker (1984). The classification of five major forest types: fringe, overwash, riverine, basin and dwarf forests, was used to describe the different mangrove communities under investigation at the four locations.

*Vegetation Profiles.*—A representative portion of the forest vegetation at each site was chosen and sampled using a belt transect. The transects all started from the lagoon end (Datum point), but the exact area sampled varied in each of the forests as follows: Hunts Bay: 40 m in length × 4 m in width, Fort Rocky Lagoon: 50 m in length × 2 m in width and Hellshire: 25 m in length × 2 m in width.

During sampling several characteristics (floristic features) were recorded for all the plants encountered within the belt transect. Diameter at breast height (dbh) was determined with the use of the Haglof caliper. Tree height, which was taken as the linear vertical distance between the ground
and the tip of the tree crown (Cintron and Schaeffer-Novelli in Snedaker and Snedaker, 1984), was measured directly where possible. Where direct measurement was impossible, an inclinometer was used to obtain this value of height. Visual estimates of percentage cover were made for the individual plants sampled. Generally, plant species composition was determined with the aid of the Vegetative Key to Mangroves referred to by Tomlinson (1994).

**Leaf Litter Production.**—The levels of leaf litter were determined as an indication of primary productivity at the three sampling sites. To measure productivity, leaf litter traps were deployed at the beginning of the transect (datum point) and at successive 5 m intervals. The traps were constructed of 0.5 × 0.5 m (0.25 m²) wooden frames with 0.25 m² of nylon netting (mesh aperture size 2.0 mm) attached to one side. The litter from these traps was collected after a two-week period. The collected material was allowed to dry to a constant weight at 55°C before weighing. Productivity was determined using the following formula:

$$\text{Productivity (g m}^{-2} \text{d}^{-1}) = \frac{\text{Dry weight (g m}^{-2}) \text{ of litter over a 1 m}^2 \text{ area}}{\text{Time (d)}}$$

**Environmental, Edaphic and Physicochemical Variables**

Environmental variables were measured in the lagoon immediately adjacent to the forest and in any standing water on the forest floor. These included: salinity, temperature (°C), dissolved oxygen (mg L⁻¹), Redox potential (mV) and pH. These measurements were taken at mid-depth in the lagoon immediately adjacent to the study sites, and where the entire forest floor was permanently inundated by sea water or had fresh water present, measurements were taken at the beginning of the transect and at every successive 5 m interval. The instrument used to measure these variables was the Hydrolab H₂₀ Water Quality Multiprobe. Nutrients were also measured (NO₃ and PO₄) via water samples, which were collected at mid-depth from the lagoon adjacent to each site as well as at the beginning and each successive 5 m interval along the transect in instances where the forest floor was covered with fresh/sea water. These water samples were preserved using chloroform (to produce a 10% chloroform solution) within a maximum time of three hrs after collection to maintain the quality and status of the samples.

**Field Measurements.**—Light available under the forest canopy (Lux) was measured at breast height at datum point and every successive 5 m intervals along the transect at each sampling area, using a Davis® Light Meter (Model 0198).

Soil cores were collected at the same intervals, stored in Ziploc™ bags and placed in coolers until taken to the laboratory later that day. The samples were analyzed for soil salinity and pH, as well as interstitial water, nitrate and phosphate levels. Soil temperature was determined in situ using a Reotemp soil temperature probe.

**Laboratory Procedures.**—Soil moisture content was determined gravimetrically using the conventional drying temperature of 60°C to a constant weight and calculated as the difference between fresh and dry weight as a percentage of the original (fresh weight).

Soil organic matter was also determined gravimetrically with the oven dried soil being ashed in a muffle furnace for three hrs at 550°C. The total organic matter in the soil samples was obtained by difference between dry weight and ash weight and reported as a % of the original (dry weight).

Soil nutrient analyses first involved extraction of soil pore water from soil cores collected along each transect. 80 ml of deionized water was added to a volume of approximately 160–180 mL of soil to form a 2:1 soil to water solution. This mixture was stirred vigorously until the soil lumps had completely disintegrated, at which time chloroform was added. The solution was allowed to settle for a few minutes after which it was vacuum filtered using cellulose filter paper with a pore size of 0.7 μm. and the filtrate frozen for further analysis (i.e., determination of nitrates and phosphates) using an autoanalyzer. Seawater, fresh water and soil water samples preserved in the field were filtered and stored as above. Soil water salinity (± 0.5) was determined using the American Optical
The pH (± 0.5) of the samples was determined using an Orion pH Tester. The Cadmium Reduction method was used to determine nitrate-N concentrations. This was measured colorimetrically at a wavelength of 550 nm using a TechniconTM autoanalyser (Technicon Instruments Corporation, 1972b). Concentrations of ortho-phosphate were determined using a molybdenum complex. This was measured colorimetrically at a wavelength of 880 nm also using a TechniconTM autoanalyser (Technicon Instruments Corporation, 1972a).

**Statistical Analyses.**—Tests for significant differences in environmental characteristics among the forests were using analysis of variance (ANOVA) with sites as the main effect. The grouping and ranking of sites was done using the multiple range/ post hoc test, Tukey’s Honest Significant Difference (HSD) test. Stepwise variable selection multiple regression was used to determine the relationship between the physico-chemical variables and the vegetation parameters of the combined results for the three sites. The stepwise variable selection multiple regression model was used to determine the parameters that were most important in explaining the variations in vegetation parameters between sites.

**RESULTS AND DISCUSSION**

**LAGOON ENVIRONMENTAL PARAMETERS**

The variation in temperature, salinity and pH of the lagoons adjacent to the three mangrove forests sampled showed a similar pattern (Fig. 2). Mean temperatures of 29.59º C were recorded in Fort Rocky Lagoon, 28.79º C in Wreck Bay and 26.11º C in Hunts Bay. Fort Rocky lagoon had an average salinity of 34.2, Wreck Bay 33.6 and Hunts Bay lagoon 5.5. The lowered salinity and temperature of the Hunts Bay lagoon was due to fresh water influence in the lagoon from the rivers and gullies, which drain into Hunts Bay. The lagoon adjacent to the Wreck Bay mangroves was slightly less saline than Fort Rocky due to the direct influence of a small fresh water spring. Fort Rocky lagoon has no such direct sources of fresh water. The pattern in temperature is probably due to degree of shading as well as inputs of cold fresh water. The pH seemed to be affected by relative amounts of fresh water and seawater as pH of the lagoons followed a similar pattern to temperature and salinity: pH values of 9.5 for Fort Rocky Lagoon, 9.32 for Wreck Bay and 9.01 for Hunts Bay.

Dissolved oxygen values in the adjacent lagoons were highest for Wreck Bay with a value of 10.43 mg L$^{-1}$ followed by Fort Rocky Lagoon with 5.62 mg L$^{-1}$ and then Hunts Bay which had the lowest value of 4.57 mg L$^{-1}$ (Fig. 2D). This trend suggests that as the level of eutrophication decreases, the dissolved oxygen increases.

Redox potential increased with decreasing eutrophic conditions, being the highest (257 mV) at Wreck Bay, 223 mV at Fort Rocky Lagoon and extremely low (9 mV) at Hunts Bay (Fig. 2E). Redox potential and dissolved oxygen are useful indicators of water quality and these two variables show similar trends with high values for Redox potential relating to good dissolved oxygen conditions at Wreck Bay, and the converse at Hunts Bay.

The nitrate content of the lagoons adjacent to the mangrove forests did not show the expected eutrophication gradient (Fig. 2F). Hunts Bay lagoon had a mean value of 22 μM, Fort Rocky Lagoon had a value of 9.5 μM and Wreck Bay had a value of 31 μM. The expected gradient may have been observed, but for an exceptionally high value at Wreck Bay. This high value was probably due to the influence of a fresh water stream in the
Figure 2. Physicochemical parameters and variables determined for the lagoon adjacent to each forest (A- Temperature, B- Salinity, C- pH, D- Dissolved Oxygen, E- Redox potential, F- Nitrates, G- Phosphates as well as, H- Average annual rainfall influencing the three areas sampled).

forest, which had a very high NO$_3^-$ content. Hunts Bay lagoon also had a high NO$_3^-$ content and this is due to the heavy nutrient loads deposited in the lagoon by the rivers that enter the lagoon as well as the storm water gully. Additionally, all the outputs from land (sewage and otherwise), which enter the harbor, would influence the nutrient content of the Hunts Bay lagoon.
The mean phosphate content of Hunts Bay was 10.7 μM, Fort Rocky Lagoon had a value of 3 μM and Wreck Bay had a value of 1.8 μM (Fig. 16). The distribution of PO₄ in the lagoons manifested the hypothesized eutrophication gradient, (i.e., Hunts Bay > Fort Rocky Lagoon > Wreck Bay). When examined in relation to the nitrate values at all sites it is clear that phosphate values are extremely high and indicate enrichment and eutrophication. However, only at Wreck Bay was the ratio of nitrate to phosphate (17:1) close to that required (15:1) for optimal algal growth (Redfield, 1934) and greater than ratios considered optimal (8:1) for higher plant growth (Clarkson, 1985). While values were high at Hunts Bay and Fort Rocky Lagoon, nitrate to phosphate ratios were never in excess of 3:1 suggesting nitrogen limitation.

Forest Environmental/Physicochemical Parameters

Average soil temperature decreased from 27.24º C at Wreck Bay to 26.27º C at Fort Rocky Lagoon forest, and Hunts Bay accounted for the lowest soil temperature on average with a value of 24.44º C (Fig. 3A). Average soil temperature was significantly different among sites (Table 1). This trend in soil temperature could be due to an increase in level of exposure to oceanic water renewal, with Wreck Bay being the most exposed site and Hunts Bay being the least. It could also be due to canopy cover as average soil temperatures for the forests showed an inverse trend to average percentage cover (Fig. 5).

Soil salinity was highest for Fort Rocky with a mean value of 22.36, Hunts Bay had a value of 15 and Wreck Bay had the lowest soil salinity of 6.4 (Fig. 3B). Average soil salinity varied significantly among the sites (Table 1). Soil salinity decreased with increasing direct freshwater influence at these sites so that the site with the lowest freshwater influence (Fort Rocky) had the highest salinity and Wreck Bay, where the stream flowed through the forest, had greatest direct freshwater influence and the lowest soil salinity. Despite the fact that the lagoon adjacent to the Wreck Bay mangrove forest had a high salinity, which should influence the soil pore water salinity in the forest, the stream saturated the soil with freshwater, resulting in very low values for soil water salinity.

The average soil pH was highest for Wreck Bay with a value of 7.74, then Hunts Bay with a value of 6.83, and Fort Rocky Lagoon forest with a value of 6.18 (Fig. 3C). Average soil pH values varied significantly among the three sites (Table 1). Soil pH increased with decreasing eutrophication for the respective sites. This may be due to eutrophic conditions increasing microbial activity, which result in a decrease in pH. Alternatively, pH on the forest floor may be affected by the degree of saline intrusion. The forest with the greatest saline intrusion would be expected to have the highest pH due to the slightly alkaline nature of sea water and its buffering capacity. However, the importance of this is negated by the fact that Fort Rocky lagoon, which has the highest soil salinity, is the forest with the lowest pH and Wreck Bay, with the lowest soil salinity, has the highest pH.

Average soil moisture content for the Fort Rocky forest was 80.47%, Wreck Bay had a value of 72.83% and Hunts Bay had a value of 52.23% (Fig. 3D). Average soil moisture content values varied significantly among the sites (Table 1). Soil moisture content was highest at Fort Rocky Lagoon because of the high amount of roots of R. mangle in the substratum, which created a mat into which soil was admixed; thus, conferring a spongy nature to the substrate and high water holding capacity. The same situation existed for Wreck Bay except the soil comprising that portion of the substrate was sandy so that this sandy soil combined with the intertwining roots of R. mangle did not confer as high a
water holding capacity. Hunts Bay was lowest because the soil there was quite coarse and there were very few *R. mangle* trees, hence a loss of the intertwining roots of this species.

Soil organic content showed similar trends to soil moisture content for Hunts Bay, Fort Rocky Lagoon and Wreck Bay (Fig. 3E). This is because water-holding capacity is conferred onto the soil by an increase in soil organic content. An increase in soil organic content leads to the creation of more small soil particles, which then increases the capacity of the soil to hold water. Soil organic content values were highest for Fort Rocky

**Figure 3. Edaphic features measured for each forest.**
Lagoon forest (63.5%), followed by Wreck Bay (40.79%) and then Hunts Bay with a value of 15.07%. Average soil organic content was significantly different between each site (Table 1). Soil organic content was expected to be highest for the sites with greater numbers of individuals of the species *R. mangle* (i.e., Wreck Bay and Fort Rocky Lagoon). This is because *R. mangle* species have much higher rates of leaf fall than other species. Hunts Bay had few individuals of the species *R. mangle* and had the lowest value for soil organic content. The leaves of *R. mangle* falling to the forest floor greatly increases surface organic matter content of the soil as does the matted root system of this same species (Tomlinson, 1994).

Wreck Bay had an average soil NO$_3$ content of 34.4 $\mu$M, Hunts Bay 12.41 $\mu$M, and Fort Rocky lagoon 10 $\mu$M (Fig. 3F). Average soil NO$_3$ at Wreck Bay was significantly higher than the other two sites (Table 1). The observed pattern was not what was expected. Hunts Bay, deemed the most eutrophic, was expected to have the highest value for soil NO$_3$ content and Wreck Bay was expected to have the least. The high values seen at Wreck Bay are probably due to the presence of the fresh water stream, which transports these nutrients from land and this serves as a nutrient rich land runoff source. This high NO$_3$ value reflects the complex vegetation structure. This result is similar to findings made by Pool et al. (1977) in that areas which receive large amounts of fresh water and nutrients will have taller trees and overall a complex, well developed forest.

Soil PO$_4$ content at Hunts Bay had an average value of 4.1 $\mu$M, Fort Rocky 9.69 $\mu$M, and Wreck Bay 1.24 $\mu$M (Fig. 3G). There were significant differences in average soil PO$_4$ content among sites. Again, the pattern observed was not what was expected, as Hunts Bay was expected to have the highest concentration of soil PO$_4$. Instead, the Fort Rocky Lagoon forest had the highest value for soil PO$_4$ content, although the Hunts Bay mean value was higher than that for Wreck Bay. These PO$_4$ values must be interpreted with care since low oxygen concentrations in mangrove soils can lead to phosphate release particularly at pH less than 7 (Patrick and Mahapatra, 1968).

Light available to the forest floor was not significantly different among forests, although the average at Fort Rocky was more than twice that at the other stations (Fig. 3H). There was very high within forest variation and this may have reduced the significance of the between forest variation.

### Table 1. Results of ANOVA tests for significance between sites using physicochemical parameters/variables and floristics. Ranking was done using Tukey HSD post hoc test.

<table>
<thead>
<tr>
<th>Independent variable</th>
<th>Dependent variable</th>
<th>P value</th>
<th>df</th>
<th>Ranking</th>
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<td>1-3-2</td>
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<td>1-2-3</td>
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FOREST STRUCTURE

Leaf Litter Production.—Average leaf litter production was highest for the Wreck Bay forest, which had a value of 5.24 g m$^{-2}$d$^{-1}$. The Fort Rocky Lagoon site had an average value of 2.46 g m$^{-2}$d$^{-1}$, and Hunts Bay had the lowest value for average productivity with a value of 0.71 g m$^{-2}$d$^{-1}$ (Fig. 4A). There was a significant difference in productivity at all the sites (Table 1): productivity decreased with increasing pollution/eutrophication.

Litter production in these mangrove forests of different structures (Hunts Bay-riverine mangrove forest, Fort Rocky Lagoon-fringe mangrove forest and Wreck Bay-fringed mangrove forest) is similar to that produced by forests of similar structure within the tropics (Snedaker, 1982).

The maximum leaf litter production at the Wreck Bay site may be explained by the presence of fresh water and high nitrate to phosphate ratios, which optimizes growth conditions so that more leaves are produced, which would imply a higher rate of leaf fall. The trend seen in the other sites (i.e., a decrease from Fort Rocky Lagoon to Hunts Bay) is likely due to increasing eutrophic conditions, especially phosphate availability, but nitrate limitation at each site. This trend could also be due to a reduction in the density of the species *R. mangle*, which produces leaf litter in copious amounts.

There is greater than a 95% probability that 77% of the variation in leaf litter production in the different forests is due to the location of the forest, variations in soil temperature, variations in soil NO$_3$ content and light availability to the forest floor (Table 2). All these parameters exhibit a strong positive correlation with litter production with the exception of soil temperature, which shows a strong negative correlation.

Percentage Cover.—Average percentage cover for the Fort Rocky Lagoon site was 20.57% m$^{-2}$. Percent cover increased with increasing eutrophication/disturbance: Wreck Bay
Bay had a value of 15.5% m\(^{-2}\) while Hunts Bay had the highest value of 27.29% m\(^{-2}\) (Fig. 4B).

There were significant differences in average percentage cover between sites (Table 1). Percentage cover is a function of forest structure and complexity. Hunts Bay had the highest value for average percentage cover because it is highly disturbed and composed of a large number of small trees, creating multiple layers in the canopy. Fort Rocky Lagoon was next in disturbance level, followed by Wreck Bay.

There is greater than a 95% probability that 64% of the variation in percentage cover in the different forests is due to the location of the forests, variations in soil salinity, soil moisture content and light availability to the forest floor (Table 2).

**Tree Height.**—The trees at the Wreck Bay were the tallest, with an average height of 8.15 m, while those at the Fort Rocky Lagoon had an average height of 5.53 m, and those at Hunts Bay had the lowest height of 4.63 m (Fig. 4C). Tree height is usually greatest in areas receiving large amounts of fresh water and nutrients (Smith, III, 1992). The forest at Wreck Bay had the lowest soil salinity and highest soil nitrates; yielding the tallest trees and with greatest productivity. Hunts Bay had low salinity in the lagoon but not necessarily in the forest. Nitrates were also low in the forest soil and this coupled with large amounts of organic and other pollutants being introduced (evidenced by very low Redox potential) in the runoff from Kingston, which had negative effects on the forest. Generally, Hunts Bay had stunted trees with multiple layers from frequent and indiscriminate cutting, and low productivity due to the high disturbance and eutrophication/pollution levels. The trend in tree height, although consistent with that predicted, was not significantly different among sites (Table 1).

According to Snedaker (RSMAS, Univ. Miami, pers. comm.) the maximum height for the three species of mangrove trees depends wholly on local growing conditions particularly with regard to limiting factors such as physical composition of the substrate (e.g., rock versus silt or clay), fertility, water availability and other such factors. Within the Caribbean region, hurricanes also play a major role in altering tree height (McCoy et al., 1996). Along the Pacific coasts of Costa Rica and Panama, areas outside the Hurricane belt support *R. mangle* trees, which can reach heights in excess of 30 m (Pool et al., 1977). Furthermore, the species under study (i.e., *L. racemosa, A. germinans* and *R. mangle*) can exist in a dwarf form, which is defined by a decurrent architecture. In the dwarf form, the species seldom reach a height above 1.2–1.5 m, which can be assumed to be the
The occurrence of the tallest trees at Wreck Bay may be explained by the small, but constant inputs of fresh water, optimal nitrate to phosphate ratios and the lack of disturbance in the area. The decrease in height from Fort Rocky Lagoon to Hunts Bay is more likely explained by the high phosphate dominated eutrophication and anthropogenic disturbance at Hunts Bay. This suggests that the positive contribution of riverine inputs to the lagoon is being negated by disturbance and pollution, and since the more eutrophic areas tend to be those with significant riverine inputs, tree height is probably not a reliable indicator of stress in mangrove forests.

**Diameter at Breast Height (DBH).**—Maximum DBH was recorded at the Wreck Bay site and was 19.36 cm. This was followed by DBH at the Fort Rocky lagoon site (12.62 cm) while the Hunts Bay site had a value of 11.58 cm (Fig. 4D). However, although there was no significant difference among sites (Table 1), average DBH showed a similar trend to average tree height and that could be accounted for in the same manner as was done for average tree height. Based on findings by Smith III (1992), an increase in basal area (or DBH) is consistent with forests, which are influenced by large amounts of fresh water.

According to Snedaker (RSMAS, Univ. Miami, pers. comm.), *R. mangle* can reach DBH’s in excess of 1 m under the most ideal growing conditions. Hunts Bay had low values for DBH since it is very disturbed by removal of trees for charcoal burning and has a high density of small diameter trees.

**EVALUATION OF THE LEVEL OF EUTROPHICATION/ENVIRONMENTAL STRESS AT EACH SITE**

**Hunts Bay.**—Of the three forests studied, the Hunts Bay mangrove forest has undergone the highest levels of human disturbance mainly through the harvesting of mature trees for the purpose of charcoal burning. This forest is also impacted by human influence via encroachment on the forest for residential as well as industrial purposes. Industrial and domestic waste enters Hunts Bay via five major gullies, which originate and run through the city of Kingston.

Terrigenous sources, which drain into the lagoon adjacent to the forest, are a major source of organic and inorganic pollution. These sources supply pollutants in the form of...
solid wastes, sewage, dead plants and animals as well as vast amounts of sediments. These contributing factors result in the highly eutrophic status and subsequently high levels of stress experienced by this mangrove forest. The level of stress is also mirrored in the vegetation, for example in the form of species composition and species density as well as other vegetation characteristics of the forest, such as DBH, percentage cover of the canopy and height of lowest living limb. The trends in these parameters are obviously due to high levels of stress. Some environmental factors measured for the lagoon (for example DO levels, Redox potential and salinity) are also indicators of the status of the Hunts Bay mangroves. The bay is characterized as having eutrophic nutrient levels, but low nitrate to phosphate ratios and low salinity.

Fort Rocky Lagoon.—The Fort Rocky Lagoon mangrove forest ranks next after Hunts Bay with respect to anthropogenic disturbance and eutrophication. It is used by a few people for relatively nondestructive purposes, which is obvious from the footpaths observed through the vegetation. Major damage in this regard is reflected in the trampling of seedlings and the damaging of prop roots.

The Port Royal mangrove forest is greatly influenced by the polluted waters of the Kingston Harbour in which this forest is situated. The level of stress, due to eutrophication, experienced at this site is second highest of the three forests studied. This site is characterized as having high salinity, moderate nitrate levels, but high phosphate availability due to the low pH and dissolved oxygen concentrations.

Wreck Bay.—The Wreck Bay mangrove forest is the least influenced by anthropogenic disturbances of the three sites. There is a footpath through the vegetation as well as a quantifiable amount of solid wastes at the most landward edge of the forest. However, this mangrove forest is relatively pristine and is not influenced by pollution of an industrial or domestic nature due to its location, far from areas of high population density. This directly implies a reduction in pollution by human and other terrigenous sources. Wreck Bay is also deemed to be pristine due to its distance from the negative influences of Kingston Harbour.

The vegetation comprising this forest is very successful in terms of growth and development and exhibits the characteristics and complexity of a mangrove forest existing under the most ideal conditions for mangrove growth. It is owing to this fact that the Wreck Bay mangrove forest can be described as the site characterized by ideal conditions for the successful development of mangrove forests: low salinity and moderate to high nutrient levels in near optimal ratios.

It can be concluded that the vegetation type and floristics of the three forests are different and that differences between forests are driven by various environmental/edaphic factors. The environmental factors most responsible for variations in forest structure are soil and lagoon salinity, soil and lagoon NO₃ absolute concentration and ratio with PO₄ concentration, soil moisture, and soil temperature. From this study, the most useful vegetation parameters for differentiating between mangrove forests are litter production and percentage cover. Diameter at breast height and tree height can be positively or negatively affected by different aspects of anthropogenic stress and so can be confounding.

It is difficult to interpret with confidence the relative importance of each factor to productivity, percentage cover and growth owing to the complexity of interactions between all factors and the influence of anthropogenic stress. However, the quantification of environmental factors of importance and identifying the most demonstrable forest attribute to ob-
serve and record environmental influences provides a significant tool towards conceptualizing and interpreting functional relationships within mangrove systems.

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