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RESEARCH ARTICLE

Planktonic communities as indicators of water quality in mangrove lagoons; a Jamaican case study

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Abstract

1 - In mangrove lagoons, where natural conditions of high turbidity, detritus and microbiological activity combined with low light render traditional water quality indices unreliable, the planktonic community is proposed as a more appropriate and accurate index of eutrophication status.

2 - Over a 12 month period, monthly sampling was conducted at 9 stations representing different degrees of eutrophication.

3 - Phytoplankton size fractionated biomass, species composition and abundance as well as zooplankton total abundance, species composition and abundances of selected groups were examined along with depth, temperature, salinity, dissolved oxygen, pH, particulate organic matter, and reduction / oxidation potential (redox).

4 - Phytoplankton were collected using a horizontal niskin whole water sampler, zooplankton hauls (vertical/oblique) were taken using a modified Wildco net (158 µm mesh aperture 0.2 m hoop diameter) and a Hydrolab Surveyor IV Water Quality Data System was used to collect physic-chemical data *in situ*.

5 - While dissolved oxygen, salinity and pH demonstrated potential for use as water quality indicators, particulate organic matter, redox and temperature demonstrated inconclusive variations or insignificant differences between lagoons of known water quality.

6 - Phytoplankton biomass (Chlorophyll *a*) was among the most reliable planktonic indices distinguishing four groups of stations with different water qualities: oligotrophic (0.21-0.55 mg m^{-3}) mesotrophic (0.57 – 2.55 mg m^{-3}) eutrophic (3.00 to 6.55 mg m^{-3}) and extremely eutrophic (>31.17 mg m^{-3}).

7 - This was attributed to diatom and dinoflagellate cells of differing sizes being able to characterise eutrophication even after the source of eutrophication had dissipated and while physico-chemical parameters remained unchanged.

8 - Mean zooplankton abundances were also reliable, distinguishing pristine stations (789 - 3,111 animals m^{-3}) and highly eutrophic stations (114,970 – 563,339 animals m^{-3}).

9 - The group 'Larvae' and the copepod *Dioithona occulata* were major contributors to mean abundances, since as small herbivores they are able to take advantage of high phytoplankton concentrations.

10 - Other taxa like *Acartia tonsa* and harpacticoid copepods were ubiquitous and although never numerically dominant showed high numbers at the more eutrophic sites.

11 - This makes relative abundances of cosmopolitan species as reliable an index as presence absence of key species in mangrove lagoons.

Keywords: Phytoplankton, Zooplankton, communities, eutrophication, Jamaica, mangrove, lagoons.

Introduction

Mangrove lagoons are highly valuable and productive ecosystems which are vital to coastal stability (Wolanski and Boto, 1990). They occur in 112 countries and territories (Kathiresan and Bingham, 2001) with global coverage estimated between 10 and 24 million hectares. Mangroves form a range of estuarine, coastal fringe, basin and scrub communities; frequently associated with salt marshes and salinas. They develop best in low lying areas of the coast where there is river discharge and shelter provided by sand banks or offshore reefs. Mangroves are found on protected shallow shores where there is often an association with estuarine conditions (Chapman, 1976). They provide a buffer between the adjacent land and marine areas by reducing the quantities of sediment, nutrients and fresh water in land runoff. It is hypothesised that mangrove lagoons all have similar background physicochemical conditions and therefore eutrophication status will not be evident using traditional water quality monitoring techniques. These traditional water quality indices include: nutrients, water clarity (light penetration), biochemical oxygen demand, chemical contaminants, and bacterial content (Webber and Webber, 1998). The failure of these indices to accurately represent the mangal ecosystem water quality may be due to opaque tannin coloured waters, low light conditions from tree self-shading, high detrital, microbial and algal productivity and high suspended material, among other natural properties.

Eutrophication of coastal systems seems to be increasing due to various anthropogenic influences (Holdgate, 1980; Lindo, 1991; Hessen, 1999). While mangrove forest communities in Jamaica have been extensively studied (Chow, 1997; Alleng, 1997; Bacon and Alleng, 1992; Morgan, 1995; McDonald *et al*., 2003) and mangrove root communities are well known (Bingham, 1990; Goodbody, 1993; Hoilett and Webber, 2001), the water column conditions and planktonic communities are poorly understood. There is a paucity of studies, for example, comparing conditions in mangrove lagoon waters with other pelagic areas of these systems. Furthermore, while extensive work has been done on water quality monitoring in Jamaican bays, the monitoring tends to concentrate on the open, deeper waters of the bay or in areas not immediately affected by mangroves (Grahame, 1976; Youngbluth, 1980; Dunbar and Webber, 2003; Webber *et al*., 2005). The findings are usually extrapolated to include the mangrove lagoons or mangrove dominated areas of the bay. However, there is the danger of not confirming eutrophic conditions in mangrove waters because they may be masked or modified by the natural conditions.

Both phytoplankton and zooplankton communities have been successfully used in coastal water quality monitoring and as bioindicators of pollution (Clutter, 1972; Youngbluth, 1980; Elnabarawy and Welter, 1984; Turner, 1994; Wang *et al*., 1999; Brooks *et al*., 1999; Dunbar and Webber, 2003; Webber *et al*., 2005) but most studies have been focused in bays and not enough is known about the potential of planktonic communities as descriptors in mangrove lagoons. Although high phytoplankton biomass can be a reliable indicator of eutrophic mangals, low phytoplankton biomass due to inhibitory effects of phenolic materials (tannins) in the water may mask the condition (Herrera-Silvera and Ramirez-Ramirez, 1996). Moreover, zooplankton grazing not only reduces phytoplankton biomass, but removes other suspended particles from the water by concentration into much denser faecal pellets which then fall to the benthos. Consequently, the estuarine waters appear clearer and bottom sediments richer in nutrients (Ward and Montague, 1996). Because of the importance of mangals and the potential impact on other ecosystems, there is need to develop reliable indices and appropriate standards of monitoring water quality in these areas. This study will examine the use of the phytoplankton and zooplankton communities as reliable indices of water quality in mangrove lagoons experiencing varying levels of eutrophication.

Materials And Methods

Study area

Nine stations were selected for the examination of water quality indices in mangrove dominated coastal lagoons on the South Coast of Jamaica (Figure 1). These were expected to demonstrate a range of water qualities and so were organized in the following order from most eutrophic to least eutrophic status: The Great Salt Pond (GSP), Hunts Bay (HB), Buccaneer Swamp (Yacht Club) (YC), Fort Rocky Lagoon (FRL), Bowden Bridge (BB), Bowden West (BW), Galleon Harbour East (GHE), Galleon Harbour West (GHW), and Wreck Bay (WB). The stations were selected because they are exposed to different environmental conditions such that they ranged from eutrophic, sewage outfall point at the Great Salt Pond and disturbed lagoons in Kingston Harbour/Hunts Bay to pristine mangrove areas with clear subterranean springs in Wreck Bay (McDonald *et al.*, 2003; Webber

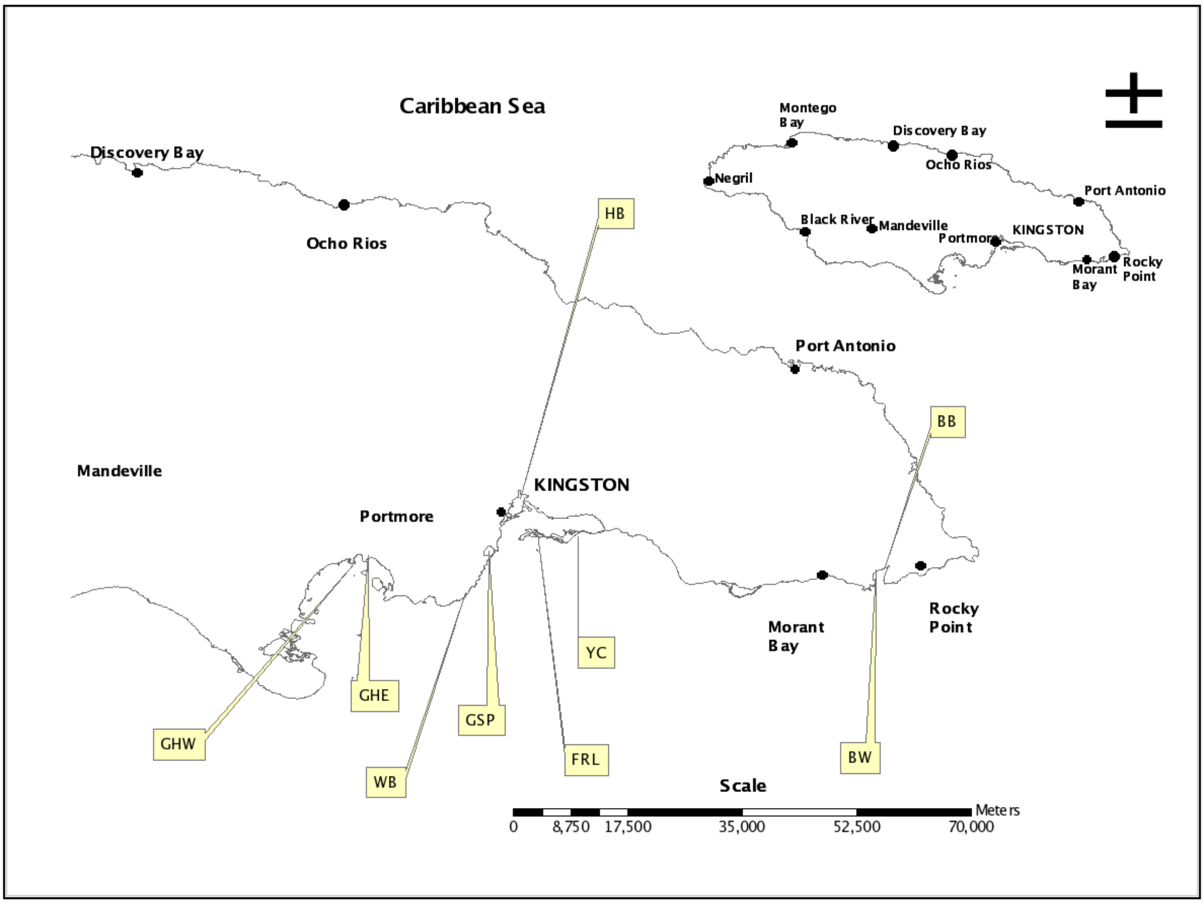


Figure 1. Map of Jamaica with details of eastern half showing the south coast bays where mangrove lagoons stations were located. GSP – Great Salt Pond, HB- Hunts Bay, YC- Yacht Club, FRL- Fort Rocky Lagoon, BB- Bowden Bridge, BW- Bowden West, GHE- Galleon Harbour East, GHW Galleon Harbour West and WB- Wreck Bay.

and Wilson-Kelly, 2003). All these lagoons, however, share the characteristics of low light penetration because of tannin coloured waters, high productivity, high turbidity and high detritus and microbial activity.

Sampling

Sampling was conducted routinely at approximately four week intervals for one year over the wet and dry seasons. Physical and chemical data were collected using a Hydrolab® Surveyor IV® Water Quality Data System. Parameters included depth (± 0.08 m); temperature (± 0.10 °C); dissolved oxygen (± 0.2 mgL^{-1}); salinity (± 0.2 ‰); pH (± 0.2 units); and reduction/oxidation potential- redox (± 20 mV). Readings were taken at mid-depth, however, at stations with riverine inputs surface salinities were also recorded. Particulate organic matter (POM) was determined gravimetrically on water samples collected in 1 L nalgene bottles from mid-depth. In order to explore seasonality within the various mangrove lagoons, monthly rainfall averages associated with each area were obtained from the National Meteorological Service.

Phytoplankton collection

Water samples were collected in replicate at all stations using a horizontal Niskin sampler (3.5 L). One 250 ml aliquot was fixed in the field using 2 – 5 ml Lugol's iodine solution for identification and enumeration of phytoplankton species. A second aliquot ranging from 0.5 L to 2.0 L was used in the determination of chlorophyll a biomass. Samples were filtered within four to six hours of collection (Parsons *et al*., 1984) through a fractionating tower of nitex screening 20µm, Whatman GFD glass fibre filters 2.7µm and Whatman GFF glass fibre filters 0.7µm at approximately 15 mmHg pressure (Li and Dickie, 1985). Chlorophyll a extraction, was conducted at room temperature in the dark for twenty-four hours using 6 ml of 90 % acetone (Lorenzen and Jeffrey, 1978) and was determined using a Turner Designs TD700 version 1.8 laboratory fluorometer (of sensitivity < 20 picograms ml-1 at standard wavelength 300 - 650 nm and optional red sensitive wavelength 185 - 870nm).

Identification and enumeration of phytoplankton samples were conducted on four occasions to encompass the wet and dry seasons of the annual cycle (December 1999, March 2000, June 2000 and October 2000). For each occasion the contents of the 250 ml preserved sample were gently homogenized by hand and poured into settling chambers of 10, 50 and 100 ml volumes. The chambers were allowed to stand for between 3 and 48 hours before examination (Edler 1979). A Leitz Labovert inverted transmitted light microscope model # 090-122.012 was used to carry out examinations (Mag. X 320) (Utermohl, 1958). Individual cells were identified to species level with the aid of the following keys and plates: Kofoid and Swezy, 1921; Lebour, 1930; Schiller, 1933; Schiller, 1937; Davis, 1955; Brunel, 1962; Lebour, 1962; Cupp, 1967; Saunders and Glenn, 1969; Steidinger and Williams, 1970; Newell and Newell, 1977; Bellinger, 1992; UNESCO, 1995.

Zooplankton collection

Zooplankton samples were collected using a 153 µm Wildco net with a 0.2 m hoop diameter. Replicate (n=2) oblique or vertical hauls (depending on station depth) were done at each station as close to the mangrove roots as was possible. A seven meter depth of water column was hauled through each time yielding a filtered volume of 0.2198 m^3. This volume was therefore employed in the calculation of numbers m^{-3} at most stations and on most occasions. On a few occasions, when water depth was less than the 7 m required for the haul or, when the water column was filled with debris, water samples were collected in 2 L Nalgene bottles at mid-depth. The bottle sample was then poured through a 153 µm mesh to condense the animals, which provided values which were not significantly different (p=0.073) from net hauls. Animals were preserved immediately in the field after collection using 10 % formalin. Samples were enumerated and identified for all taxa present using a Wolfe Binocular Microscope (mag. x40) and with the aid of zooplankton guides (Wickstead, 1965; Davis, 1955; Gonzalez and Bowman, 1965; Owre and Foyo, 1967; Yeatman, 1976; Newell and Newell, 1977; Todd *et al*., 1996; Gerber, 2000).

Community coefficients and statistical manipulations

Community analysis tests were employed which used species composition to investigate station affinities and identify possible associations. These included Jaccard Community Coefficient (JCC), Percentage Similarity Coefficient (PSC) and Principal Components Analysis (PCA).

The JCC values used to compare species composition across stations were computed using the equation:

$JCC = [C/(A+B-C)] \times 100$

Where, A=total number of species in stand A

B= total number of species in stand B

C= total number of species in both stand A and stand B.

Percent Similarity Coefficient was similarly calculated for each month, using the equation:

$PSC=100 – (0.5 \times \Sigma [a'-b'])$

Where a' and b' are for each species the respective percentages of animals at each pair of stations. The relative abundance of species at each successive pair of stations was thus used to determine station linkages. This coefficient neglects single and rare occurrences. When used with the Jaccard community coefficient this weakness may be compensated (Lindo, 1991).

Cluster analysis diagrams/dendrograms were then used for to display station linkages using the PSC and JCC values.

All data collected were transformed when necessary to fit a normal distribution. Analysis of Covariance (ANCOVA) tests and Principal Component Analyses were then conducted. PCA involves finding the eigenvalues of the sample covariance matrix (Manly, 1989) while MANCOVA tested whether there were significant differences between samples at stations and on occasions at the 95% confidence level ($P<0.05$). The accompanying multiple range test (Turkey's Least Significant Difference - LSD) grouped most similar stations based on the 95% confidence limit.

Results

Physico-chemical parameters

All parameters tested over the sample period varied significantly between stations with the exception of particulate organic carbon (POM) (Table 1). There were significant differences in average depth across the nine stations with Bowden Bridge (BB), Fort Rocky Lagoon (FRL) and Yacht Club (YC) being the deepest stations (0.5 m - 1.0 m). Variability in water column depth at specific stations also demonstrated significant differences over the sampling period with BB and FRL again showing the highest variability. Variability in "depth" or water level would be indicative of tidal or riverine influence on the water level, the extent of which is shown by the standard error bars (Figure 2A).

The average water temperature ranged from 26.7 ºC to 29.3 ºC at Bowden West (BW) and Galleon Harbour West (GHW), respectively, however while significant differences were found no station distribution patterns associated with eutophication status were identified. Temperature variability about the mean was low at all stations over the sample period (Figure 2B). The average salinity ranged from 10 to 35 ‰ (Figure 2C) and showed low variability at Yacht Club (YC), Fort Rocky Lagoon (FRL), Bowden West

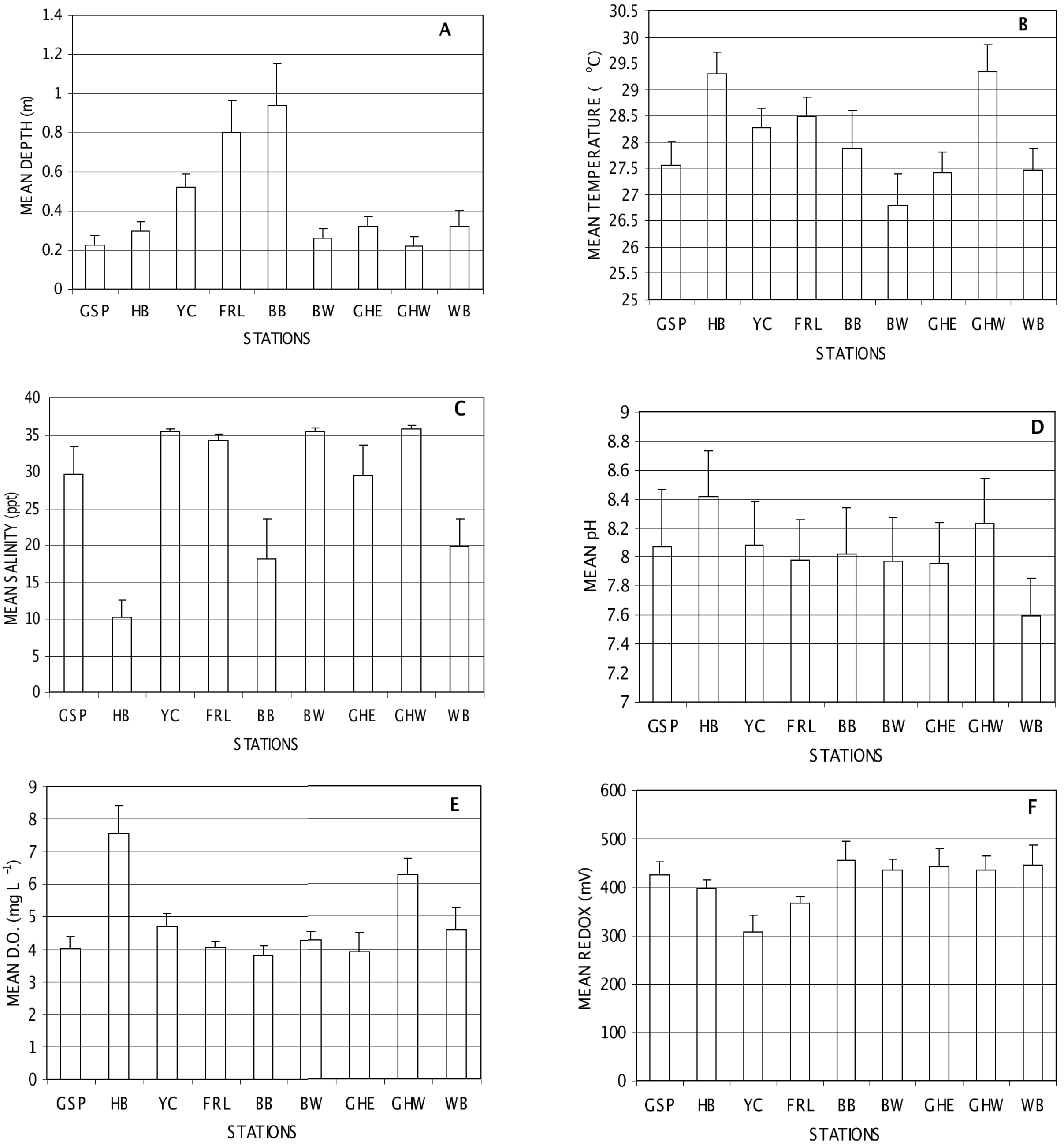


Figure 2. Distribution of physicochemical variables (mean with S.E. bars) over the range of stations. GSP – Great Salt Pond, HB- Hunts Bay, YC- Yacht Club, FRL- Fort Rocky Lagoon, BB- Bowden Bridge, BW- Bowden West, GHE- Galleon Harbour East, GHW Galleon Harbour West and WB- Wreck Bay.

(BW) and Galleon Harbour West (GHW), while, Great Salt Pond (GSP), Hunts Bay (HB), Bowden Bridge (BB), Galleon Harbour East (GHE), and Wreck Bay (WB) all had high variability (all with fresh water influences). However presence of these freshwater influences and salinity variability did not result in the ranking of the mangrove lagoons by eutrophic status. These salinity data only showed normal distribution when they were split in terms of high and low salinities. Too few data points, however, were obtained for the high salinities and did not allow for statistical analysis. Low salinity values were shown to be significantly different with a significance level of 0.0023 (Table 1).

Table 1.MANCOVA summary for each physico-chemical parameter. Significant difference calculated between stations using the months (and log rainfall, in the case of low salinity) as covariates.

PARAMETER	Degrees of Freedom (d.f.)	Significance Value (p)	HOMOGENOUS GROUPING (mean values increase from left to right)
Depth	8	**<0.0001**	GHW GSP BW HB WB GHE YC FRL BB
Temperature	8	**0.0005**	BW GHE WB GSP BB YC FRL HB GHW
Log Salinity	8	**0.0023**	GHE HB BB WB GSP FRL BW GHW YC
Log pH	8	**<0.0001**	WB GHE FRL BW BB YC GSP GHW HB
Log Dissolved Oxygen	8	**<0.0001**	GHE BB GSP WB FRL BW YC GHW HB
Log Redox	8	**0.0011**	YC FRL HB GSP GHW WB GHE BW BB
Log POM	8	0.1030	N/A

***Significant values are written in bold face and red.

Average pH values ranged between 7.6 and 8.4 units with Wreck Bay samples showing the lowest values over all stations (Figure 2D). Four homogenous groups were generated by the LSD multiple range test with WB being the only member of one group but again not eutrophic status pattern was demonstrated. Average Dissolved Oxygen (D.O.) for the sample period ranged between 3.8 mg L^{-1} at Bowden Bridge (BB) and 7.5 mg L^{-1} at Hunts Bay (HB) (Figure 2E). Water samples at HB also showed the greatest fluctuation about the mean. The MANCOVA test (Table 1) indicated that D.O. values were significant different between stations and homogenous groups generated by the LSD post hoc test placed GHW and HB in one group. These stations had the highest D.O. values and also high variability about the mean. However, the other stations were ranked in an order not associated with eutrophic status. Average redox values ranged from approximately 300 mV to 450 mV (Figure 2F). Wreck Bay (WB), Galleon Harbour East (GHE) and West (GHW), Bowden West (BW) and Bowden Bridge (BB) all had comparable high mean values while Yacht Club (YC) had the lowest. Overall redox values were significantly different between stations (p=

0.0011), but only two homogenous groups were generated by the LSD multiple range test. YC was the sole member of one group while all other stations formed the second group.

Biological variables

Biological data included planktonic species composition, frequency of occurrence and zooplankton community coefficient at the different locations, chlorophyll a biomass and total phytoplankton cell density and number of zooplankton individuals m^{-3}. MANCOVA tests (Table 2) were carried out on each biological parameter after normalising. All biological variables tested varied significantly between stations (Table 2).

Table 2.MANCOVA summary for each biological parameter. Significant difference calculated between stations using months (and log rainfall, in the case of low salinity) as covariates.

PARAMETER	Degrees of Freedom (d.f.)	Significance Value (p)	HOMOGENOUS GROUPING (mean values increase from left to right)
Log Total Chl. *a* (Phytoplankton) biomass	9	<0.0001	WB BB GHE BW GHW YC FRL GSP HB
No. of Zooplankton species	8	<0.0001	BW BB WB HB GHW YC GHE FRL GSP
Log Total zooplankton	8	<0.0001	BW WB GHE GHW FRL YC BB GSP HB
Log Larvae	8	<0.0001	BW WB GHW GHE YC FRL HB GSP BB
Log Calanoida.	8	<0.0001	WB BW HB GHE BB GHW YC FRL GSP
Log Cyclopoida	8	<0.0001	WB BW GHE GHW FRL BB YC HB GSP
Log Harpacticoida	8	<0.0001	YC BB BW HB GHW FRL GHE WB GSP

Phytoplankton Species

Two Hundred and forty-nine (249) species of phytoplankton were recorded over the one year programme across all sampling locations. While *Cylindrotheca closterium* was the only species present at all nine locations, nineteen species (Table 3) were deemed cosmopolitan (i.e. occurring at five or more locations) such that only variations in their abundance could used as an indicator of difference in water quality. Three stations were dominated by dinoflagellates and six stations by diatoms (Table 4). Dinoflagellate dominated stations were Hunts Bay (HB), Fort Rocky Lagoon (FRL) and Yacht Club (YC) all of which may be considered to be part of the eutrophic Kingston Harbour. All other stations sampled were dominated by diatoms.

Comparison of species richness between stations (Table 4) facilitated the division of sample stations into four discrete groups. At the two extremes, YC had the lowest number of species (34) and WB the greatest (83). Both GHE and GHW may be grouped and the entire Galleon Harbour considered as one homogenous group (62 & 64 species). The final group consists of those sites which were found to have between 45 and 53 species or an approximate mean of 49 ± 4 species per site.

Phytoplankton abundance - Chlorophyll a analysis

Mean chlorophyll a for the sampling period ranged from 0.535 ± 0.624 mg m-3(observed at Wreck Bay, WB) to 31.172 ± 25.701 mg m^{-3}(observed at Hunts Bay, HB) (Figure 3). Results indicated that generally coefficients of variation (CV) were high (Table 5), suggesting that there were significant changes in total biomass during the sampling period, however no seasonal pattern was demonstrated. The lowest percentage CV was 44% at FRL. Phytoplankton chlorophyll a biomass at stations BB, GHE, GSP, GHW and BW all had CV values in the 61 - 71% range while HB and YC had greater than 80% CV. WB biomass was most variable with the highest CV at 116.67% even though that site had the lowest biomass values. ANOVA performed on log transformed data indicated that there were significant spatial differences ($p < 0.001$) between all stations. Tukey's Least Significant Difference (LSD) post hoc test showed that there were five homogenous groups with WB and HB forming

Table 3. Phytoplankton species % occurrence over the annual cycle at all stations and % occurrence at the nine Stations.

Phytoplankton Species	% occurrence over time	% Occurrence at Stations
Cylindrotheca closterium	69.4	100
Melosira sp.	59.4	89
Navicula directa	65.6	89
Nitzschia reversa	46.4	78
Protoperidinium sp.	53.6	78
Scrippsiella trochoidea	42.8	78
Paralia sulcata	41.6	67
Thalassiothrix frauenfeldii	35.1	67
Alexandrium tamarense	35.0	56
Ceratium lineatum	50.0	56
Coscinodiscus radiates	35.0	56
Grammatophora marina	45.0	56
Navicula sp.	40.0	56
Navicula transitrans	45.0	56
Pleurosigma angulatum	55.0	56
Pleurosigma formosum	50.0	56
Prorocentrum gracile	60.0	56
Pseudonitzschia sp.	40.0	56
Streptotheca thamensis	30.0	56

separate "homogeneous groups" at the lowest and highest mean values respectively (Table 2). All other stations were displayed by the Tukey'LSD in an order similar to that expected in a range in eutrophic status.

The smallest phytoplankton size class examined (the picoplankton; ≤0.7μ) was least represented at all locations (Figure 3). Largest percentage (30%) of picoplankton was observed at BB. In general, there was a higher percentage of both net and nanoplankton over picoplankton with high variability between locations. GHE and HB had the highest nanoplankton (2.7-0.7μ) percentage, (approximately 60 - 70% biomass) while highest netplankton percentage was at BW (approximately 70%). Other sites of high netplankton biomass were GHW, YC, WB, GSP, and FRL with stations having approximately 50% percentage dominance of netplankton.

Phytoplankton abundance - Cell density

Cell counts were done for the indicated four month period spanning the annual cycle and representing the wet and dry seasons. Results indicated that GHE on all occasions had the highest cell density and mean density of 38,580 ± 8,394 cells L^{-1} and WB the lowest density at 840 ± 187 cells L^{-1}. GSP, FRL, YC, and GHW had similar densities and appeared to constitute one group. BB and BW also had similar densities and seemingly constituted another group. Coefficients of variation (CV) indicated

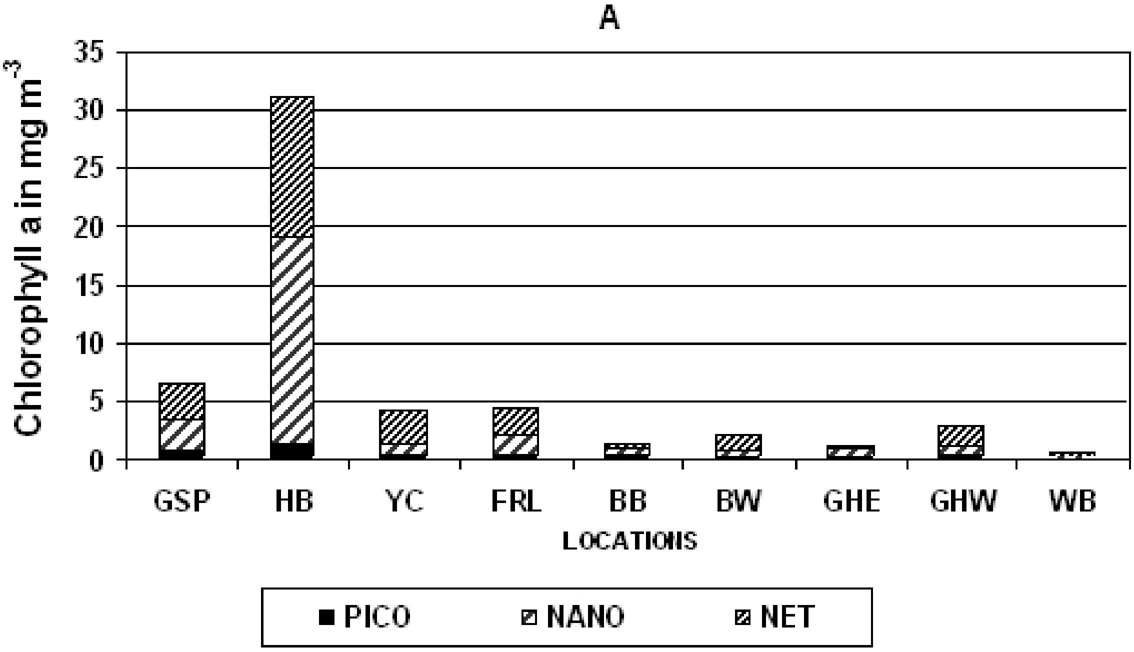
Table 4. Species Richness (increasing values) and dominant phytoplankton group across nine locations for four months during the sampling period.

Location	No of species	Dominant Phytoplankton Group
YC	34	Dinoflagellate
FRL	45	Dinoflagellate
BB	47	Diatom
GSP	51	Diatom
HB	52	Dinoflagellate
BW	53	Diatom
GHW	62	Diatom
GHE	64	Diatom
WB	83	Diatom

Table 5. Mean Annual size fractionated and total chlorophyll *a* biomass (mg m-3) with standard error and percentage coefficient of variation across all locations.

	Net	Nano	Pico	Total	SE	CV
GSP	3.12	2.62	0.78	6.53	± 1.35	65.61
HB	12.04	17.74	1.39	31.17	± 7.13	82.45
YC	2.75	1.17	0.31	4.23	±1.09	88.66
FRL	2.11	1.79	0.4	4.3	± 0.56	44.00
BB	0.48	0.52	0.32	1.32	± 0.25	61.85
BW	1.63	0.52	0.15	2.3	± 0.48	69.34
GHE	0.47	0.64	0.18	1.29	± 0.27	65.39
GHW	1.9	0.87	0.28	3.05	± 0.62	70.21
WB	0.27	0.23	0.03	0.54	± 0.18	116.67

that there was significant variability in cell density for BB, WB and BW all having %CV >100 (Table 6). Highest percentage CV was at BB (147.40%) and lowest CV at YC (21.34%). Cell density was best reviewed in association with mean chlorophyll *a* at stations for the four months analysed. Results indicated that YC and HB had highest phytoplankton biomass while GHE had the highest cell density but a very low biomass. In general these results reveal that at some locations high cell density corresponded to low chlorophyll *a* biomass (BB and GHE) and at others while cell density was low, chlorophyll *a* was high (GSP, FRL and YC).



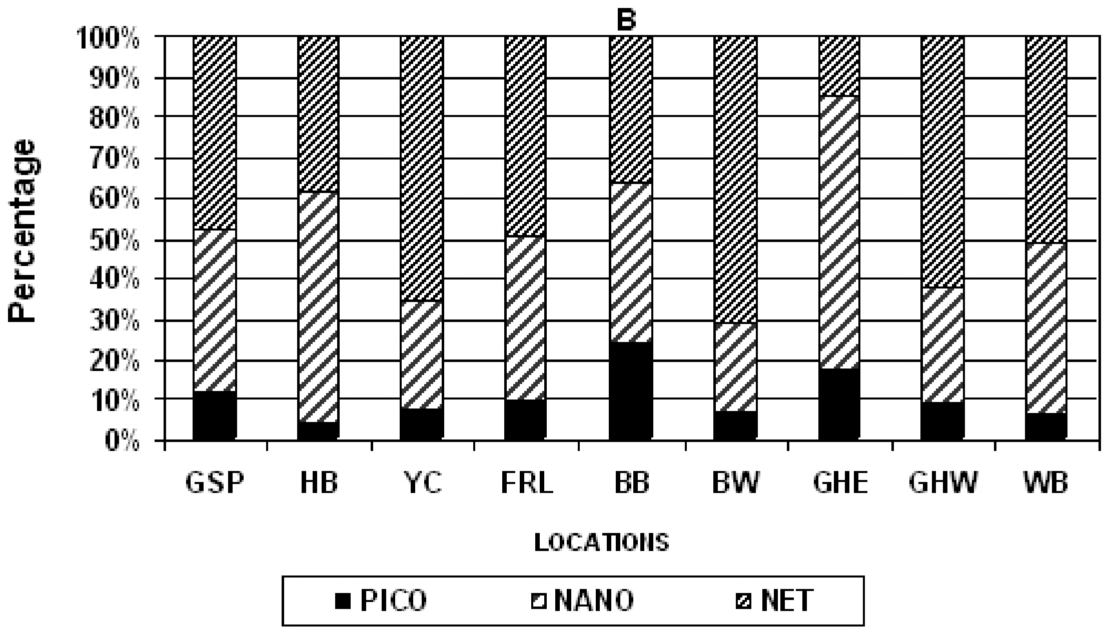


Figure 3. Mean size fractionated biomass as chlorophyll a in mg m-3 over the range of stations.

Table 6. Phytoplankton Cell Density with mean, standard error and percentage coefficient of variation across all locations.

	DEC"99	MAR"00	JUNE"00	OCT"00	Mean	SE	CV
GSP	10,080	1,310	1,660	3,250	4075	± 2,045	100.4
HB	26,230	13,480	26,610	15,910	20,557	± 3,421	33.29
YC	3,380	4,520	3,040	4,740	3,920	± 418	21.34
FRL	3,780	1,280	3,600	4,600	3,315	± 712	42.98
BB	1,660	2,720	23,240	1,360	8,340	± 5,339	147.4
BW	3,160	1,320	4,480	24,520	8,370	± 5,422	129.6
GHE	47,840	56,560	19,240	30,680	38,580	± 8,393	43.51
GHW	5,000	6,560	2,640	1,960	4,040	± 1,062	52.62
WB	1,100	325	1,130	793	839.5	± 186	44.66

Zooplankton Species & community coefficients

A total of 81 taxa were identified from the nine stations. Of these, the group 'Copepoda' dominated with 49 members. This was followed by the group 'Larvae' with 28 members. Most major taxa were identified to species or genera except for the group 'Larvae'. Major group names were used during statistical manipulation of the data. 'Minor' groups were combined to form the general group 'Others' (cf. Figure 6). The average number of zooplankton species found for the sample period ranged between twelve (12) at BW and twenty-three (23) at GSP (Figure 4A). Fort Rocky lagoon (FRL) also had high taxonomic richness. The number of zooplankton species showed relatively little fluctuations about the mean (low temporal variability).

The Jaccard Community Coefficient (JCC) comparing species composition between stations showed values ranging from 51.5 % similarity (between BB and GHW) and 72.1 % (between FRL and YC) (Table 7A). The dendrogram indicated 3 main groups of stations with similar species composition. The smallest group had only Wreck Bay (WB) and Bowden Bridge (BB) (Figure 5A). Percent Similarity Coefficient (PSC) showed values ranging between 29.8 % (for BB and WB) and 92.2 % (for BB and YC) (Table 7B). The dendrogram plot for PSC generated four groups with Wreck Bay (WB) being the sole member of one group (Figure 5B). Principal Components Analysis (PCA) showed BW and GHW with the greatest number of major principal components (8) while BB had the least (3). The group Cyclopoida and the animal *Dioithona oculata* were major components for all stations except BB while the group, 'Larvae' was important for all stations except WB. The group Calanoida was important for FRL, YC, WB, BW, and GHW (Figure 6). Based on these results stations could be grouped with WB and BB in discrete but individual groups, GHE, GSP, and HB forming one group; FRL and YC forming another and BW and GHW forming the fifth group. WB and BB were the stations with least similarity to the other stations with respect to the principal components (Table 8).

Zooplankton Abundances

The mean values for the total numbers of zooplankton found for the sampling period varied significantly between stations (Table 2). Average values ranged from 789 animals m^{-3} at Wreck Bay (WB) to 114,970 animals m^{-3} at Hunts Bay (HB) (Figure 6A). HB also had maximum fluctuations about the mean (Figure 6). The group Larvae followed a similar pattern of distribution to the total numbers, perhaps because it was the major contributor, between 30 and 60% to this

Table **7.** The (A) Jaccard Community Coefficient matrix and (B) Percentage Similarity Coefficient matrix (percentages) calculated for zooplankton species at each selected station on the South Coast of Jamaica for the sample period October, 1999 to September, 2000.

A. JCC

STATIONS	GSP	HB	YC	FRL	BB	BW	GHE	GHW	WB
GSP	100								
HB	62.5	100							
YC	60.9	64.1	100						
FRL	71.0	64.7	72.1	100					
BB	55.6	62.1	59.4	61.2	100				
BW	55.6	62.1	53.0	58.2	53.0	100			
GHE	64.5	63.2	53.9	59.2	60.8	55.4	100		
GHW	56.9	62.7	62.3	61.9	51.5	51.7	59.5	100	
WB	51.9	57.7	53.7	58.8	66.7	52.5	62.7	57.6	100

B. PSC

STATIONS	GSP	HB	YC	FRL	BB	BW	GHE	GHW	WB
GSP	100								
HB	37.5	100							
YC	62.3	66.9	100						
FRL	46.1	64.2	69.3	100					
BB	65.1	61.7	92.2	68.2	100				
BW	87.2	42.5	67.4	47	74.5	100			
GHE	49.3	65.3	78.3	74.7	77.2	54.6	100		
GHW	51.8	64	83.3	71.6	83.4	60.2	88.2	100	
WB	36	34.4	34.4	31.5	29.8	31.4	37.6	36.1	100

Table 8.Principal Components (major contributors) generated by PCA for each station for the sampling period October, 1999 to September, 2000.

	STATIONS								
ZOOPLANKTON VARIABLES	GSP	HB	GHE	FRL	YC	WB	BW	GHW	BB
Calanoida				*	*	*	*	*	
Cyclopoida	*	*	*	*	*	*	*	*	
Harpacticoida		*	*	*			*	*	*
Harpac. B		*					*	*	*
Dioithona oculata	*	*	*	*	*	*	*	*	
Larvae	*	*	*	*	*		*	*	*
Paracalanus sp.				*	*			*	
Parvocalanus crassirostris						*			
Cladocerans					*				
Nematoda	*	*					*		
'Others'								*	
Number of Principal Groups	4	4	6	6	6	4	8	8	3

** Principal components of each station are marked with an asterix(*)

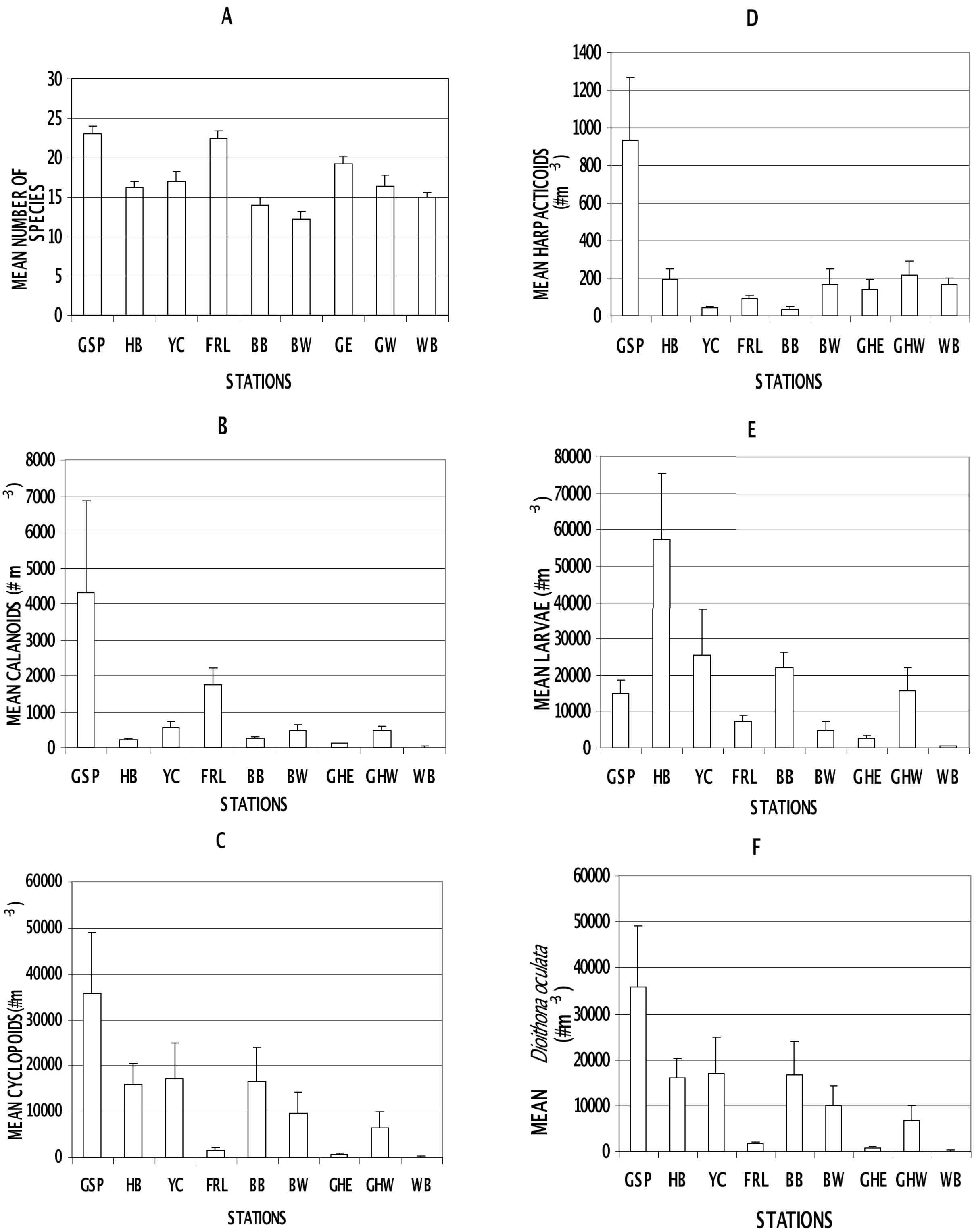
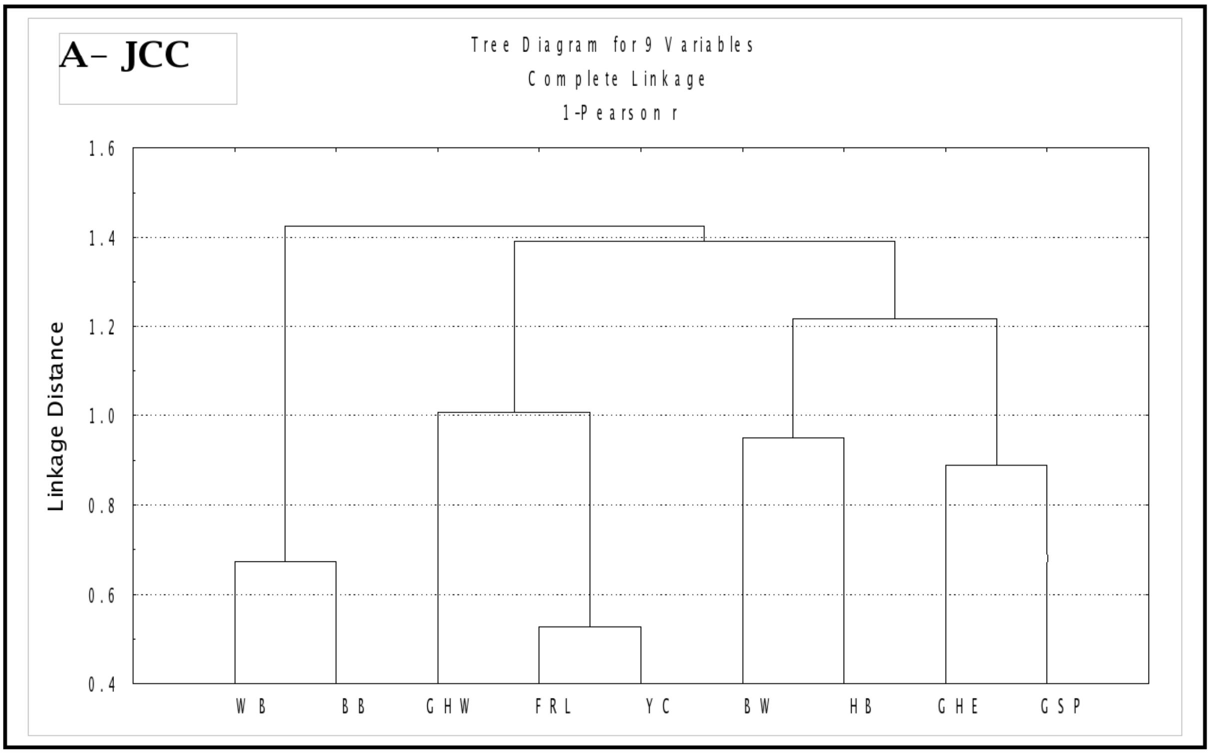


Figure 4. Mean total number of zooplankton species (taxonomic richness) (A) and mean abundances of selected taxonomic groups across stations. (B) Calanoids, (C) Cyclopoid, (D) Harpacticoid (E) Larvae and (F) *Diothona oculata.*



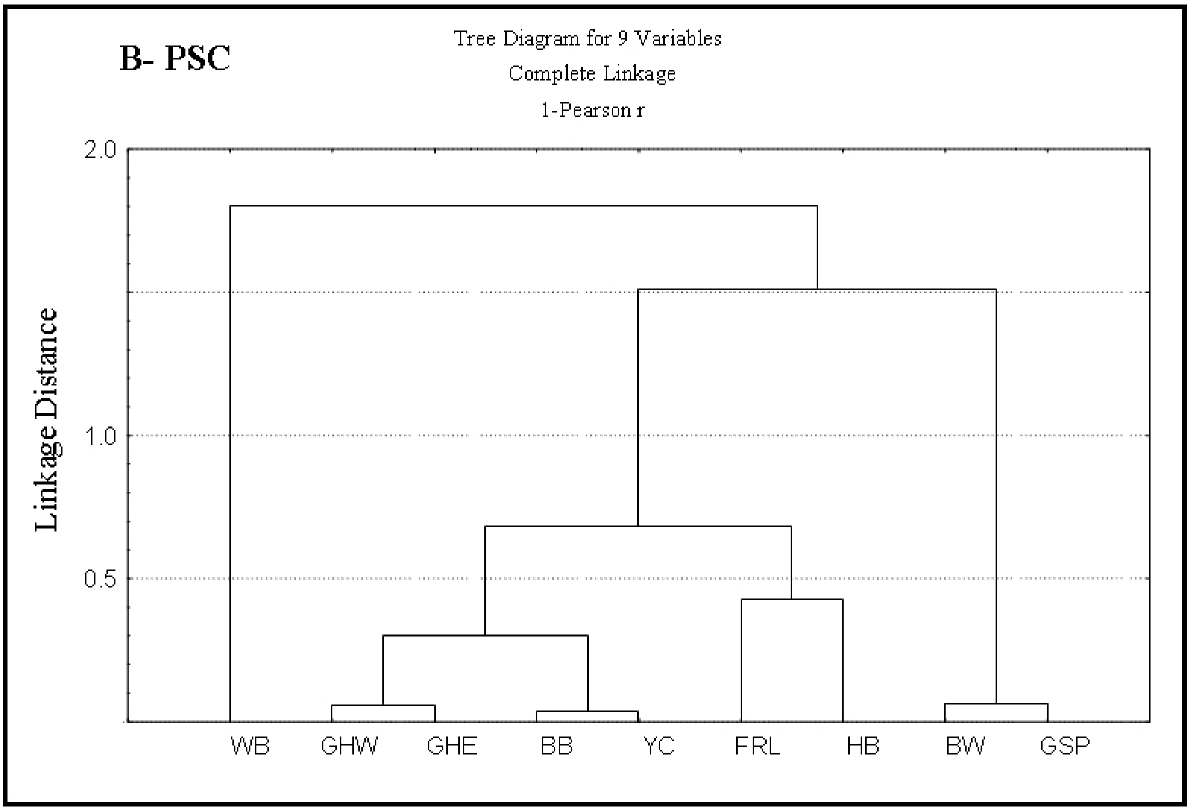


Figure 5.Dendrograms showing (A) clustering according to the Jaccard Community Coefficient results and (B) according to the Percent Similarity Coefficient.

number at all stations (Figure 6B). Calanoid, cyclopoid and harpacticoid mean numbers and fluctuations around these means were greatest at the Great Salt Pond (GSP) and these groups demonstrated significant reductions in numbers from the hypothesized

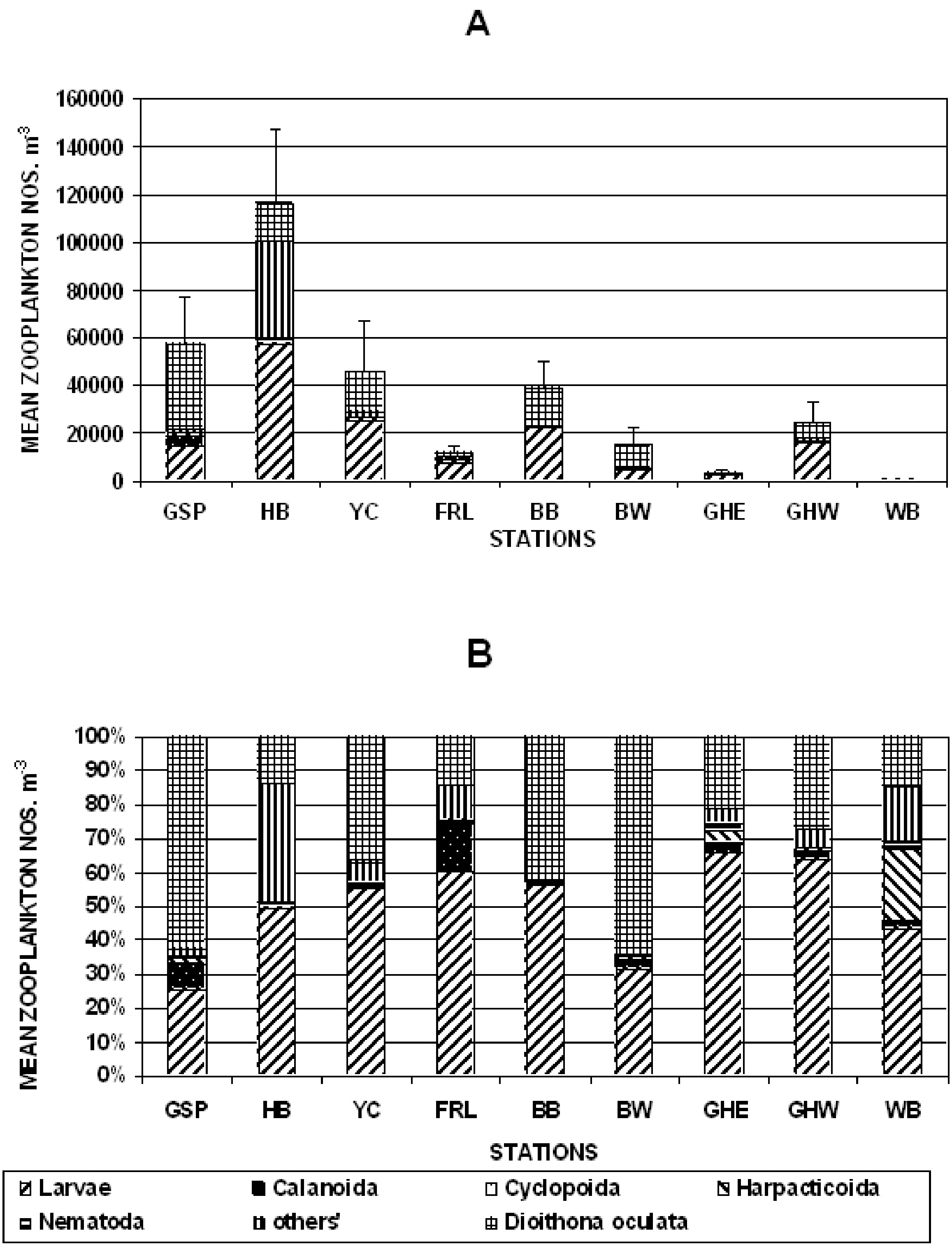


Figure 6. Zooplankton abundance at each station (A) actual values and (B) % abundances.

most eutrophic GSP and Hunts Bay (HB) to oligotrophic Wreck Bay (Figures 5B, 5C and 5D). These groups were also the major contributors to the average total numbers m-3 for all stations except in Hunts Bay where the group Larvae alone (55,000 animals m^{-3}) accounted for more that these three groups combined (Figure 5E). Of significance is the fact that the group cyclopoids, normally less abundant than calanoids, were more abundant than any other group except larvae and one species *Dioithona oculata* was responsible for most of the 35,000 animals m^{-3} cyclopoids reported (Figure 5F). Stations were ranked in order of decreasing total abundances as follows: Hunts Bay (HB), Great Salt Pond (GSP), Yacht Club (YC), Bowden Bridge (BB), Galleon Harbour West (GHW), Bowden West (BW), Fort Rocky Lagoon (FRL), Galleon Harbour East (GHE) and Wreck Bay (WB).

Discussion

Water bodies can be fully characterised by three major components: hydrology, physico-chemistry and biology. A complete assessment of water quality is based on appropriate monitoring of these components (Chapman and Kimstach, 1996). Water quality can be described through a range of quantitative and qualitative measurements such as physicochemical and biological tests, species inventories and biotic indices (Chapman and Kimstach, 1996). The intent therefore is to indicate whether the planktonic communities can be reliably used to determine water quality in mangrove lagoons, especially where physico-chemical parameters may be inadequate.

Physico-chemical data evaluation

It was expected that physicochemical conditions would be significantly different between mangrove lagoons due to extreme differences in background conditions and levels of anthropogenic stress in each area. This relationship should then be manifested in a predictable range of physicochemical, water quality parameters from eutrophic to oligotrophic lagoon stations. Hunts Bay (in Kingston Harbour), the Great Salt Pond and Galleon Harbour East (in Galleon Harbour) are known eutrophic sites while Wreck Bay is pristine (McDonald *et al.*, 2003).

Most physico-chemical parameters used in this study showed significant differences between stations, however their distribution did not show the expected pattern. Furthermore, the lack of significant difference in particulate organic matter (POM) values between stations was not expected since this parameter is often an important indicator in water quality analyses (Phillips, 1972; Chapman and Kimstach, 1996; Thomas and Mevbeck, 1996). Usually the mixing of fresh water with sea water involves a marked change in pH and increases the level of dissolved salts, which promote the coagulation of fine particulate matter (Phillips, 1972). The type and concentration of suspended matter controls the turbidity and transparency of the water. Suspended matter consists of silt clay, fine particles of organic and inorganic matter, soluble organic compounds, plankton, and other microscopic organisms (Chapman and Kimstach, 1996). Despite the diverse sources and the nature of mangrove lagoons, high POM may be a constant feature – irrespective of the eutrophication levels being experienced in the lagoons. Thus, POM may not be an adequate descriptor of eutrophic status.

Variability in depth was examined because of the expected influence of this variable on several physico-chemical parameters (e.g. Dissolved Oxygen (D.O.), temperature, salinity. There was the expectation therefore, that shallow and more exposed stations (e.g. Galleon Harbour West- GHW, Bowden West-BW, and Hunts Bay- HB) would consistently have extreme values for variables like temperature and salinity. However, these variables are often affected by other features of mangrove lagoons. For example, Bowden West (BW) which was also a shallow area did not have high temperatures because this station was almost always shaded by mangrove trees, hence, lower mean water temperatures (< 26.7°C). Therefore, temperature and vadiability in temperature are not adequate descriptors of eutrophication status.

The Dissolved Oxygen (D.O.) content was another variable that could be affected by the peculiarities of each site. The D.O. content of natural waters varies with temperature, salinity, turbulence, the photosynthetic activity of algae and plants, and atmospheric pressure. The solubility of oxygen decreases as temperature and salinity increase. Significant variations in D.O. can occur seasonally or even over 24 hour periods, in relation to temperature and biological activity (i.e. photosynthesis and respiration). Biological respiration, including that related to decomposition processes, reduces D.O. concentrations. Waste discharges high in organic matter and nutrients can lead to decreases in D.O. concentrations as a result of the increased microbial activity (respiration) occurring during degradation of organic matter (Chapman and Kimstach, 1996). Increases in D.O. relate to phytoplankton concentrations as algal blooms in eutrophic waters can cause D.O. concentrations to rise dramatically. This makes Dissolved Oxygen (D.O.) values in coastal systems difficult to explain as both extremes in D.O. (very high or very low values) may be indicative of deteriorating water quality. The diurnal fluctuation in this parameter has been suggested to be a better index than the absolute value. According to Gordina *et al*., (2001), oxygen super-saturation is indicative of a degree of eutrophication and decaying organic matter will also decrease the D.O. concentration in coastal waters especially at night (or at depth) in the absence of high phytoplankton photosynthetic activity. Borsuk *et al*. (2001) also suggested that oxygen depletion in estuarine bottom waters resulted from chemical and biological oxygen consumption associated with the decomposition of organic matter in the sediments and water column. The dissolved oxygen concentration at Great Salt Pond- GSP was consistently low (averaging < 4 mg L^{-1}). This site is a semi-enclosed, shallow lagoon which receives "treated" sewage water discharge from the Greater Portmore sewage treatment plant. These factors could contribute to the low oxygen concentration at this station. The eutrophic Hunts Bay (HB) had a high oxygen concentration (averaging > 7 mg L^{-1}) but also with the greatest fluctuation about the mean. Poor water quality was expected at this station (Webber and Webber, 1998; Ranston and Webber, 2003); with constant blooms of sometimes toxic phytoplankton species. Ranston and Webber (2003) further reported a rapid decline in DO from supersaturation at the surface to almost anoxic conditions at depth. Thus D.O. as an index may identify poor water quality and high eutrophic status (particularly at the surface) but the index seems less reliable at moderate and good water quality.

The reduction / oxidation potential (redox) is related to the oxygen concentration as it characterises the oxidation state of natural waters. Oxygen, iron, and sulphur, as well as some organic processes can affect redox. Anaerobic respiration and the resultant presence of hydrogen sulphide are usually associated with a sharp decrease in redox and is evidence of reducing water quality conditions. REDOX values would therefore also increase when D.O. concentrations increase (Chapman and Kimstach, 1996). This means that the higher the redox value the better the water quality should be. The average redox ranged between 300 and 450 mV for the stations sampled and the variation between stations was significantly different. However, the overall similarity of these relatively low redox values suggests that high reducing conditions are a constant feature of all these mangrove lagoons rendering redox as a weak tool in mangrove lagoon water quality assessment.

The pH is an important variable in water quality assessment as it influences many biological and chemical processes within a water body. In unpolluted waters, pH is principally controlled by the balance between the carbon dioxide, carbonate and bicarbonate ions as well as other natural compounds such as humic and fulvic acids. The natural acid-base balance of a water body can be affected by industrial effluents and atmospheric deposition of acid-forming substances. Deil variations in pH can be caused by the photosynthesis and respiration cycles of algae in eutrophic waters (Chapman and Kimstach, 1996). A combination of several factors (for example, rainfall, eutrophication, decaying detritus) would influence the pH of the mangrove lagoon water system. The pH of seawater is usually relatively stable for tropical systems ranging between7.4 – 8.5. Any significant deviations above or below this normal range suggests some form of disturbance. High concentrations of dissolved polyphenolic compounds leached from mangrove detritus can cause decreases in the pH as they are oxidized, this would also lower the oxygen concentration of the water (Boto and Bunt, 1981).

Rainfall data obtained from the National Metrological Agency was another parameter used in the station evaluation. The average monthly rainfall ranged between 40 mm and 210 mm for the sampling period with the highest being recorded at Bowden. The values were extremely high in October and November, 1999; and September, 2000 being 796.7, 530.7, and 447.7 mm of rainfall respectively. These values were way in excess of the average found at all other stations and were expected to result in a marked decrease in salinity at the Bowden stations. This however, was not seen and is thought to be evidence of the ability of mangrove forests to remove excess fresh water from land runoff. It must be concluded that few physicochemical parameters could be reliably used to determine the eutrophication status of mangrove lagoons.

Biological data evaluation

Phytoplankton

Plankton are sensitive to many environmental influences such as salinity, rainfall, temperature, dissolved oxygen levels, turbidity, and other factors (Grahame, 1976, Satsmadjis, 1985, Herrera-Silvera *et al*., 1996, Webber and Webber, 1998). As was the case with physicochemical parameters, some biological parameters were not reliable indicators of water quality because of their lack of predictability. Species richness was one such parameter. As was expected, water samples from the pristine Wreck Bay (WB) had the highest mean number of species; however, the eutrophic Hunts Bay (HB) did not have the lowest number of species, which would have completed the expected species richness pattern. Sites having lower species numbers than HB were Great Salt Pond (GSP), Bowden Bridge (BB), Fort Rocky Lagoon (FRL) and Yacht Club (YC), with YC having the lowest number of species. Therefore high species richness may indicate pristine conditions in mangrove lagoons, but low richness does necessarily indicate eutrophication.

Cell density is also another parameter which may be confounding. Higher phytoplankton cell density is expected in an area with greater eutrophication (Ranston 1998, Clarke 2000). Both Hunts Bay and Salt Pond have been confirmed as receiving sewage effluent and classified as eutrophic (Ranston 1998, Clarke 2000). From observation, it is suspected that GHE receives some effluent but in much smaller volumes when compared with HB and GSP; but it was at GHE that the highest mean cell density was recorded.

Cell densities become more reliable when an evaluation is done in concert with chlorophyll a biomass. Phytoplankton type (i.e. diatoms or dinoflagellates) may also assist with the evaluation as dinoflagellates have been associated with more eutrophic conditions (Matsuaka, 1999; Dale, 2001; Matsuoka *et al*., 2003). However, the presence of a diatom dominated community does not necessarily indicate oligotrophic conditions. The consideration of cell density and type with biomass gives a more accurate picture of variations in water quality. For example, GHE, a diatom dominated location, with the highest cell density, had a consistently low biomass, (<2.0 mg m^{-3}), while HB, which is dinoflagellate dominated, had the second highest cell density but greatest biomass (>30.0 mg m^{-3}). High cell density, which is often associated with eutrophic conditions, must therefore be qualified by chlorophyll a biomass as well as high variability in both indices over time. Ranston (1998) indicated that HB was an extremely eutrophic site characterised by mean chlorophyll a biomass values of > 10 mg m^{-3}. Of the phytoplankton parameters sampled, the most reliable for use in grouping similar stations and therefore indicative varying water quality types is chlorophyll a or phytoplankton biomass. Green and Webber (2003) gave biomass values indicative of different water quality types as follows; oligotrophic 0.21 ± 0.01 mg m^{-3}, mesotrophic 0.57 ± 0.03 mg m^{-3} and eutrophic > 2.0 ± 0.09 mg m^{-3}. Using the Chlorophyll *a* values, the sites in this study would be categorised as follows: Oligotrophic (Wreck Bay-W), Mesotrophic (Bowden West- BW; Galleon Harbour East-GHE; Bowden Bridge- BB), Eutrophic (Yacht Club-YC; Galleon Harbour West- GHW; Fort Rocky Lagoon- FRL; Great Salt Pond- GSP and extremely Eutrophic (Hunts Bay- HB).

Zooplankton

Copepod nauplii, polychaete larvae, *Acartia tonsa*, *Paracalanus* sp., *Pseudocyclops* sp., *Dioithona oculata*, an unidentified harpacticoid species called Harpac. B, and nematodes were the most frequently occurring taxa at all stations. Surgeon (1994) working in the Port Royal mangroves, Jamaica found *Acartia* sp., *Paracalanus* sp., *Oithona* sp., *Euterpinna acutifrons*, amphipods, copepod nauplii, and mysids at all or most of the mangrove stations. *Temora turbinata*, *Saphirella* sp., ostracods, miscellaneous harpacticoids and *Lucifer* protozoae were among the other zooplankton observed. Rios-Jara (1998) also found that seven (7) taxa accounted for 96 % of the annual mean abundance in mangrove dominated lagoons. These included *Oithona* spp., *Acartia tonsa*, copepod nauplii, *Paracalanus* sp., gastropod veligers, larvaceans, and *Pseudodiaptomus cokeri*. It was also observed that copepods were numerically dominant throughout the year and comprised 94.3 % of the total zooplankton found. The similarities in taxonomic composition between studies suggest that mangrove lagoons have a basal group of zooplankton species. These may only be used as indicators if they vary in relative abundance according to the levels of eutrophication of each lagoon.

Acartia tonsa was the most consistent calanoid copepod species found in the mangrove lagoons. Tester and Turner (1991) found that the salinity tolerance of the naupliar stages of A. tonsa was a major factor accounting for the success of the copepod in estuarine and near-shore waters. There was a significantly greater nauplii survival at salinities less than full strength sea water. Salinity – temperature interaction experiments indicated < 25 ‰ and > 15 °C as optimal conditions for *Acartia tonsa* nauplii. The adult was also found to be a good osmoregulator and consequently, was able to tolerate a wide range of salinities. Dunbar and Webber (2003) reported A. *tonsa* to be one of the ‘hardier’ euryhaline species which dominated the eutrophic Hunts Bay.

Armstrong (1978) working in Laguna Joyuda in Puerto Rico also found *Acartia tonsa* to be a dominant holoplankton species. The cyclopoid, *Dioithona oculata*, which was another dominant zooplankter in this study, was also found to form swarms in water < 30 cm deep among the prop roots of red mangroves (*Rhizophora mangle*) which fringe protected areas of lagoonal cays in Twin Cays, Belize during the day (Ambler et al., 1991). *Dioithona oculata* swarms are mainly composed of adults and later copepodid stages as the younger stages could not swim as rapidly as other stages to stay in swarms (Ambler, 2002). The occurrence of these and other small herbivorous copepods has been used as a sign of highly productive or eutrophic waters (Teixeira et al., 1964; Bacon, 1971; Lindo, 1991)

The entire group Harpacticoida, though small in total numbers, occurred with great frequency throughout the sampling period. These organisms are said to be epibenthic and often resided as epizoites on sea grass blades. All stations sampled possessed sea grass beds which were suitable for these harpacticoids. However, some stations (for example, Galleon Harbour West GHW, and Bowden West -BW) had extremely low tides and the sea grass blades became exposed for lengthy periods during the study. Also, for some months GHW had very strong wave action that uprooted the sea grasses close to the trees. Strong wave action would probably increase the number of harpacticoids found in the water column.

When the PSC and JCC results were compared both gave a different list of similar stations and groups. However, both community indices have identified significant differences in species composition between Wreck Bay (WB) and most stations. This was probably due to that station experiencing less eutrophication than all the others and also being directly influenced by offshore waters. The low percentage values obtained for comparison of stations using the JCC indicated that all stations consisted of a relatively similar species assemblage. This was probably due to all stations being tropical mangrove lagoon systems within a similar locale (south coast of Jamaica). The PSC, on the other hand, showed wider ranging values with extreme differences being between Bowden Bridge (BB) and Wreck Bay (WB). Thus the PSC test seemed to be somewhat more sensitive to changes in the water quality within these systems and would be a better index when compared to the JCC for application in the mangrove lagoon systems. Wreck Bay (WB) as the most dissimilar station when compared to all the others, using both indices.

The Principal Component Analysis (PCA) also showed that Wreck Bay (WB) and Bowden Bridge (BB) were the least similar stations. Both of these stations were influenced by fresh water but WB was actually influenced by an underground stream and also pristine sea water (due to its relative exposure to oceanic influences). BB, on the other hand, was influenced mainly by a river which was enriched by fertilizers and other farming effluents. The grouping of GHE, GSP and HB; FRL and YC; BW and GHW using the PCA was expected and more similar to the PSC results.

Abundances of zooplankton in mangrove lagoons can be extremely high reaching 10 5 individuals $^{m-3}$ (Kathiresan and Bingham, 2001). This was comparable to values found at Hunts Bay (HB) during this study. The total abundance of zooplankton present at HB was consistently relatively high with very large fluctuations about the mean. Dunbar and Webber 2003, reported an average total of 3,662 animals m^{-3} from Hunts Bay (with the number of animals ranging between 128 and 16,499 animals m^{-3}). Hoilett and Webber (2001) reported an average in excess of 1,000,000 animals m^{-3} found in the immediate area of the *Rhizophora mangle roots*, while 15 m from this point an average of < 400,000 animals m^{-3} was found. Hunts Bay is known to be a highly eutrophic area as HB receives nutrient rich water as well as high levels of pollution from several gullies (Ranston and Webber, 2003). Areas of the mangroves have also been disturbed by "dredge and fill" activities occurring in the Bay. This disturbance of the sediments will also lead to significant enrichment of the water column. The pristine mangrove areas of Wreck Bay (WB) by contrast showed consistently low numbers (an average of 789 animals m^{-3}). Stations could therefore be ranked from highest to lowest based on the average total abundance of the zooplankton found. The ranking was: Hunts Bay (HB), Great Salt Pond (GSP), Yacht Club (YC), Bowden Bridge (BB), Galleon Harbour West (GHW), Bowden West (BW), Fort Rocky Lagoon (FRL), Galleon Harbour East (GHE), and Wreck Bay (WB). This is in keeping with expectations as eutrophic conditions generally decreased in the same order across the stations confirming the value of zooplankton abundance and community structure as predictable indices in mangrove lagoons.

Kathiresan and Bingham (2001) states that mangroves are tightly bound to the coastal environments in which they occur. They are influenced by physical and chemical conditions and can, also help to create them. As a result, changes to the system can have cascading long term effects. Monitoring of these changes must be efficiently and accurately done and the phytoplankton and zooplankton communities are here shown to be reliable indices for such monitoring exercises.

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