Sea Lettuce and Nutrient Monitoring in Tauranga Harbour 1991-2010

Bay of Plenty Regional Council
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NEW ZEALAND

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Cover Photo: Sun bleached sea lettuce at Ongare in northern end of Tauranga Harbour in September 2010

Acknowledgements

The assistance of laboratory staff with chemistry sample analysis and other equipment support has been invaluable in supporting this monitoring programme and the production of this report.

Thank you also to Dr Chris Battershill, Bay of Plenty Chair in Coastal Science, for reviewing and providing valuable comments on the draft report.

Executive summary

This report provides an updated analysis of sea lettuce abundance and environmental variables in Tauranga Harbour using data collected since 1991. Specifically the objectives of the report are to:

- Update the information – by using the latest data to provide a detailed analysis of sea lettuce tissue nutrient dynamics in terms of seasonality and inter-year variation.

- Investigate the factors that trigger sea lettuce blooms – by exploring the relationships between sea lettuce tissue nutrient content, growth and environmental factors.

- Assess nitrogen stable isotopes as a research tool – to provide guidance on the use of these to understand the role that different nutrient sources play in promoting sea lettuce blooms in the harbour.

The results of the investigations now provide more reliable data on the nature of the seasonal trends in sea lettuce abundance, sea water and sea lettuce tissue nutrient content. There are clear seasonal and geographical trends in the extent to which freshwater nutrient inflows affect nutrient content both in the estuarine water column and in sea lettuce tissue. Analysis of de-seasonalised data also showed significant correlations between the year to year variations in nutrient inflow and sea lettuce tissue nitrogen content but not with sea lettuce abundance. This indicates that nutrient derived from terrestrial sources (e.g. from land or point source discharges) is not a key factor (or ‘trigger’) driving the large year to year variability seen in the Tauranga harbour sea lettuce blooms.

Investigation of links between the Wairoa River nutrient inflows, which contributes 43% of the total catchment nitrogen load to Tauranga Harbour, and climate show strong correlations with around15% less nitrogen load in El Nino years. It is the periods of El Nino weather pattern that correlate most strongly with sea lettuce abundance and provides further support that terrestrial nutrients are not responsible for year to year variation.

Increased up-welling of cold deep-ocean water during El Nino years and its influence on Tauranga Harbour was another environmental variable that strongly correlates with sea lettuce abundance. Lower peak summer water temperatures allowing continued sea lettuce growth may be the controlling factor although other associated mechanisms could also be responsible. One associated factor is an increase in nutrient load usually present in the deep ocean water, but analysis of nutrients in tissue and water fails to show any clear influence of a climate associated deep ocean nutrient influx to the harbour. However, the lack of sea lettuce tissue samples in periods of low abundance reduces the ability to detect correlations and causes a bias in the data.

Geographical variation in nutrient levels in the environment and sea lettuce tissue are very clearly shown with Town Reach having consistently higher nutrient than Ongare Bay which reflects freshwater nutrient inflows from land. Although all sites show consistent seasonal and year to year patterns, variations in average abundance is strongly influenced by local deposition and wash out dynamics, not just in-situ growth. Hence variation in abundance at larger scales can not be accurately derived from the data. However, aerial observations of intertidal sea lettuce abundance over a number of years suggest similar magnitude of blooms in both the northern and southern harbour despite large differences in terrestrial nutrient inflow. Past research has shown intertidal sea lettuce is much less abundant than the subtidal populations for which there is little information to show year to year variations or clear links to the intertidal abundance.

During the period of sea lettuce monitoring (1991-2010) there has been significant reduction in point source discharges into the harbour. For example, the cessation of treated sewage discharge to the Otumoetai Channel from Tauranga City in 1995 reduced the daily terrestrial/anthropogenic nutrient load to the southern harbour by around 27% for dissolved inorganic nitrogen and 76% for dissolved phosphorus. Despite these reductions no clearly associated reduction in sea lettuce abundance has been observed.

The results presented in this report suggest that the power of tissue $\delta^{15}N$ to identify the relative sources of nutrients in sea lettuce may be limited in Tauranga Harbour. However, the technique has shown that freshwater inflows have low $\delta^{15}N$ values and that these influence harbour water and sea lettuce tissue isotope values. Sites with organic/nutrient enrichment and hence higher nutrient recycling display higher $\delta^{15}N$ values in sea lettuce tissue. This is consistent with increased levels of microbial action which is expected to increase the $\delta^{15}N$ values. Comparison with data from a wider study of sea lettuce stable isotopes (Barr 2007) shows that sea lettuce from the Town Reach basin has similar $\delta^{15}N$ values to his “urban enriched” sites. This infers that sea lettuce at “enriched sites” gains a significant portion of its nitrogen from nutrient recycling and also tends to have higher tissue nitrogen content - growths rates could also be higher if all other factors are equal.

Overall this analysis has improved our understanding of the factors driving sea lettuce growth in Tauranga Harbour. However, there are gaps in our knowledge and the following recommendations are made to address these:

- Develop a fully integrated hydrodynamic based growth model of sea lettuce in Tauranga Harbour. This is needed because of the complexity of interacting variables that ultimately drive abundance. A quantitative model would allow predictions of abundance under a range of conditions and assist with developing mitigation or control options.
- Implement harbour-wide surveys of subtidal sea lettuce to more accurately map extent and biomass.
- Improve spatial assessments of intertidal sea lettuce abundance across the whole harbour. This will help identify production areas and rates, accumulation/loss and nutrient recycling zones and ultimately more accurately identify growth drivers including climatic influences.
- Improve the frequency of nutrient measurements within the harbour. Ideally a nutrient logger with associated sensors (e.g. chlorophyll, turbidity, temperature) should be set up in the southern basin.
- Update the bathymetry of the subtidal areas throughout Tauranga Harbour. This is needed to improve the accuracy of hydrodynamic models and habitat mapping.
- Map and identify the dynamics of sediment nutrient recycling in the harbour. This is required to quantify contributions to algal production, particularly sea lettuce blooms.

Finally, while not the subject of this report, it is recommended that research also be initiated to help understand the effects that sea lettuce blooms have on the ecology of the harbour. These effects can be positive (e.g. providing a food source for fish) and negative (e.g. smothering of benthic communities).

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Part 1: Introduction

1.1 Scope

This report presents the results of research on sea lettuce tissue nutrient dynamics conducted by the Bay of Plenty Regional Council in Tauranga Harbour. It includes data that has been gained from baseline monitoring since 1991, as part of the regional monitoring programme, and additional studies that provide a spatial component to explore the environmental factors influencing nutrient inputs into the harbour.

Specifically the objectives of the report are to:

- Update the information – by using the latest data to provide a detailed analysis of sea lettuce tissue nutrient dynamics in terms of seasonality and inter-year variation.
- Investigate the factors that trigger sea lettuce blooms – by exploring the relationships between sea lettuce tissue nutrient content, growth and environmental factors.
- Assess nitrogen stable isotopes as a research tool – to provide guidance on the use of these to understand the role that different nutrient sources play in promoting sea lettuce blooms in the harbour.

1.2 Background

Tauranga Harbour periodically experiences extensive blooms of sea lettuce that cause a range of ecological, aesthetic, recreational, community, health and shipping related impacts. At times these impacts can be reasonably severe and cause either localised or widespread nuisance. In the late 1980's through to 1991 a series of extensive sea lettuce blooms prompted numerous complaints with many people thinking that the harbour was deteriorating rapidly and dying. It was at this point that Bay of Plenty Regional Council formed a technical committee which included a range of local government and research organisations and initiated research projects into the causes of the blooms.

In terms of bloom history there is little documentation prior to the 1980's to indicate sea lettuce abundance in Tauranga Harbour. However, anecdotal evidence from a number of long term residents confirmed that blooms had occurred in both the southern and northern Tauranga Harbour back as far the 1940's and probably earlier. Even though blooms may have occurred prior to the 1980's, there is no evidence to show whether bloom frequency or intensity has increased over longer time scales (>30 years?).

In a global context sea lettuce (*Ulva spp*.) is recognised as a common, naturally occurring seaweed of the low to mid-shore littoral zones (e.g. Round 1981). Many of the problem blooms of sea lettuce (and other green seaweed) are in response to nutrient pollution, particularly from sewage discharges (e.g. Cotton 1910; Sawyer 1965; Knox and Kilner 1973; Harlin and Thorne-Miller 1981; Reise 1983; Soulsby *et al*. 1985; Sfriso *et al*. 1987). The Tauranga Harbour blooms are likely to be supported by nutrient enrichment from land runoff and point source discharges but differ in terms of the marked periodicity with pronounced periods of virtual absence in between extensive blooms. This makes it very unclear to what extent land derived pollution versus other environmental factors trigger the blooms in Tauranga Harbour.

A number of research projects were commissioned by the Bay of Plenty Regional Council in the early 1990's to better understand the sea lettuce problem. These included studies of subtidal sea lettuce abundance (Hawes1992; de Winton & Clayton 1995; de Winton *et al*. 1996) and an assessment of the dynamics and eco-physiology of sea lettuce in Tauranga Harbour (de Winton *et al*. 1998). In addition two M.Sc students studied aspects of the intertidal ecology of sea lettuce (Gregor 1995; Snowe 1995).

In general sea lettuce grows in both the intertidal and subtidal areas of Tauranga Harbour. Biomass is generally much higher in the shallow subtidal habitat being most abundant in the main lower channels near the entrance (de Winton *et al*. 1996). Very little sea lettuce originates from the upper reaches of the harbour.

Nutrient physiology research showed sea lettuce can potentially grow at rates of up to 28% per day in Tauranga Harbour although this is not always achieved and is still below the theoretical rate of 48% (de Winton *et al*. 1998). Ambient nutrient levels within the harbour are one of the main limiting/controlling factors. This has also been shown by previous analysis of tissue concentrations in the baseline monitoring conducted by the Bay of Plenty Regional Council (Park 2007). Other key factors that limit growth in Tauranga Harbour are light levels below 8 metres (although these water depths are limited in the harbour) and water temperatures above 20 ^{o}C in summer. A detailed review of sea lettuce biology and additional findings of tissue nutrient dynamics in Tauranga Harbour can be found in Park (2007).

Single species of sea lettuce show a wide range of morphological variation (different shapes and form) in response to temperature, light, salinity and other factors. This has resulted in considerable confusion in identifying species without the use of genetic techniques. Previously it was thought that three similar species (*Ulva laetevirens, U. lactuca* and *U. rigida*) were present in Tauranga Harbour. A comprehensive genetic study (Heesch *et al.* 2007) prepared for Biosecurity New Zealand found 19 species of *Ulva* in New Zealand of which 13 were identified as previously named species. Two species were found in Tauranga Harbour, *Ulva pertusa* and "*Ulva* species 1". Both of these species are widely distributed in areas with low human influence and hence are likely to be native to New Zealand.

Part 2: Location and methods

2.1 Location

2.1.1 Description of study area - Tauranga Harbour

Tauranga Harbour is located on New Zealand's northeast coast in the northern Bay of Plenty. It is a large estuarine inlet with two entrances and covers a total area of 201 km^2. The harbour catchment covers an area of approximately 1,300 km^2 and is well developed with extensive horticultural and agricultural use (approximately 46% of the land catchment in 2008). At the southern end of the harbour, the city of Tauranga and surrounding area supports a large residential population (around 120,000). Near the southern entrance, the Mount Maunganui/Sulphur Point area has been progressively developed for port facilities.

In geological terms, the harbour is a moderately tidal estuarine lagoon impounded by a barrier island (Matakana Island) and two barrier tombolo's, Mount Maunganui at the southern entrance and Bowentown to the north (Healy and Kirk 1981). The harbour is predominantly shallow with 66% of its total area being intertidal.

There are three main harbour basins with the largest north and south basins separated by intertidal flats in the central region (at Matahui Point). The southern most basin (Town reach to Welcome Bay) is much smaller but still includes several sub-estuaries and large bays. There are many small sub-estuaries around the harbour. At mean high water, the northern basin has a volume of approximately 177,702,000 m^3 and the southern basins a volume of 277,518,000 m^3.

The northern harbour catchment is the smallest with a total area of 270 km^2 and a mean freshwater inflow of 4.1 m^3/s. The southern catchment has a total area of 1,030 km^2 and a mean freshwater inflow of 30.5 m^3/s. The Wairoa River catchment at 460 km^2 and mean freshwater inflow of 17.6 m^3/s is the largest feeding into Tauranga Harbour. In the northern harbour the freshwater inflow represents only 0.1% of the harbour volume per tidal cycle while the southern input represents 0.48%.

2.1.2 Site locations

(a) Sea lettuce samples

Samples of sea lettuce from eighteen sites were collected in 2010 for analysis of tissue nutrient and nitrogen stable isotope content. Most sites were soft shores with sediment ranging from reasonably clean sand (Ongare Bay, Ongare Pt, Ōmokoroa Pt, Ōmokoroa south, Te Puna Beach, Tilbey Point, Otumoetai and Waikareao) through to silty sand (Tuapiro, Town Reach, Waimapu and Welcome Bay) and muddy sand (Katikati and Te Puna sites). The Kauri Point and Kauri south sites had papa sandstone outcrops or rocks from which attached plant samples were taken. At Kauri Point in February extensive thick sea lettuce accumulations on the sand were rotting with black discolouration of the water. The Rangataua Bay sample site was the rock rip-rap on the eastern side of the bridge. The Mount site was rocky with attached plants collected. The location of the sites is shown in Figure 1 with the baseline monitoring sites (sampled every two months) shown in green.

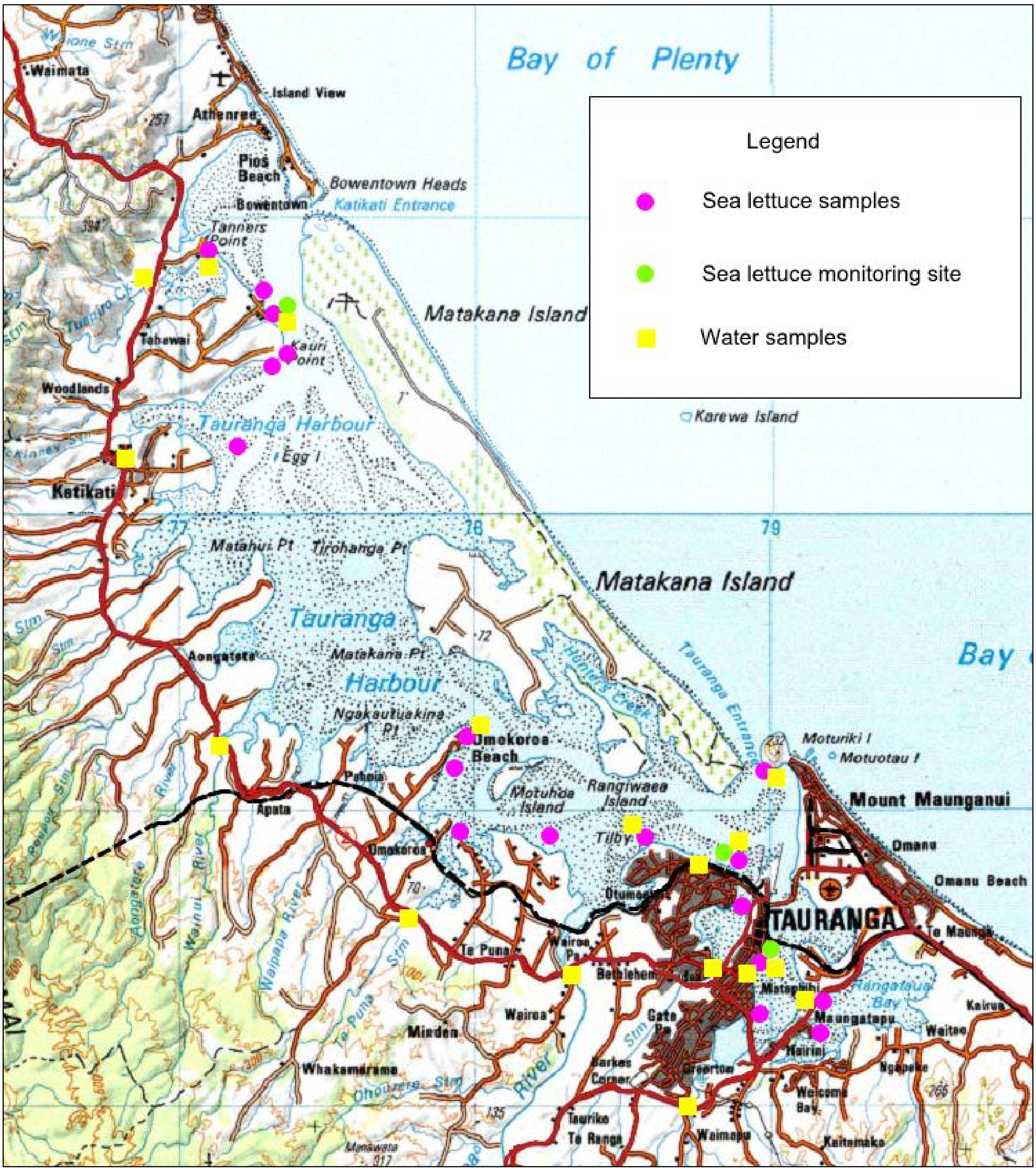

Figure 1 *Location of sites used for sampling sea lettuce, and water samples in 2010 (from the harbour, streams/rivers and stormwater), plus the baseline sea lettuce monitoring sites.*

(b) **Water samples**

Nine water samples were taken from eight sites in the harbour at low tide for measurement of nitrogen stable isotopes ($\delta^{15}N$). The sites were chosen to provide samples from areas exposed to a range of different catchment influences. The Mount Maunganui site was sampled at low and high tide. In addition seven of the streams and rivers flowing into the harbour were sampled along with two stormwater outlets (at Otumoetai and Town Reach). A sample of raw sewage from the Chapel Street wastewater treatment plant and a treated sample taken prior to discharge at Te Maunga were obtained from Tauranga City Council. A sample of surface and deep ocean water (200 m depth) from 30 km offshore of Whakatane was also obtained for analysis.

During periods of up-welling the deep ocean water can enrich the coastal shelf and possibly Tauranga Harbour with nitrate nitrogen, hence it was important to identify $\delta^{15}N$ from this source.

At the long-term baseline monitoring sites low tide water samples are collected every second month at the same time as sea lettuce sample collection and abundance measurements. These samples are analysed for nutrients. Sampling is limited to low tide and another monitoring programme provides data on high tide nutrients.

All of the sample location grid references are provided in Appendix 1.

2.2 Methods

2.2.1 Sea lettuce abundance (% cover)

Sea lettuce abundance is measured every second month (since 1991) at the three sea lettuce monitoring sites in Tauranga Harbour at the same time as collection of tissue and water samples. At each site there are two permanent plots within the mid to low tide zones. Within each of these plots 12 random sample measurements are taken of the percentage cover using a $0.25m^2$ quadrat. Results from each plot are used to generate mean values and these are combined to give an overall harbour mean value for sea lettuce cover.

Plot locations were chosen on the basis that sea lettuce was relatively abundant at those points and representative of the wider area as determined from pilot surveys. Initial measurements also determined that at each plot the variability of the 95% confidence interval about the mean was within a range of 20% which was considered adequate for the purposes of detecting seasonal and inter-annual variation. Constraints on time with the need to do all sample collection and measurements at the three locations on the same low tide precluded adding additional plots.

2.2.2 Sea lettuce tissue sample collection and preparation

For the investigation of geographical influence in Tauranga Harbour, sea lettuce tissue samples were collected from the lower shore at each site at the end of February (26 February and the 2 March) and June 2010 (23 to 25 June) while baseline monitoring samples were collected every two months.

Sampling protocol required a minimum of ten plants or substantial fragments to be collected from the low tide zone and combined to form a sample. Healthy looking non-sporulating plants were selected for the samples and the whole plant used with the exception of the attachment point which was removed. Plants were washed on site to remove epiphytes and any other adhering matter and placed into labelled plastic bags in chilled bins for transportation. Once back at the lab plants were rinsed in fresh water to remove salt and once again checked for any contaminants. Cleaned samples were dried at 55 ^{0}C for 48 hours, then ground into a powder and stored in air-tight containers.

The health of sea lettuce plants did not appear to vary between sites and was generally high. Those plants in poor condition had most likely been subject to burial. The proportion of sporulating plants can vary slightly between sites (Snow 1995) and show a seasonal pattern with higher levels (up to 40%) through summer early autumn. Studying the nutrient status of healthy non-sporulating plants represents the bulk of the intertidal population and reduces variability and confounding variables that would otherwise have to be accounted for.

Samples analysed for nitrogen stable isotopes ($\delta^{15}N$) were finely ground with a mortar and pestle then screened through a 100 micron mesh sieve to ensure consistent particle size.

2.2.3 Tissue nutrient and stable isotope analysis

Sea lettuce tissue samples were analysed for the percentage of nitrogen, phosphorus, carbon content and nitrogen stable isotope ($\delta^{15}N$). Prior to chemical analysis samples are dried for 48 hours at 62 ^{0}C (residual moisture typically 5%). The percentage of total nitrogen content was analysed by Dumas combustion (default detection limit 0.1%). Total phosphorus content was analysed by nitric acid/hydrogen peroxide digestion followed by Inductively Coupled Plasma - Optical Emission Spectroscopy (default detection limit 0.02%). Total carbon content of the tissue samples was analysed using Dumas combustion (default detection limit 0.2%).

Nitrogen stable isotope ($\delta^{15}N$) analysis was undertaken by the University of Waikato's stable isotope unit using a Dumas elemental analyser interfaced to a stable isotope mass spectrometer. Weighed samples are combusted and analysed against a laboratory certified reference standard (urea) which has a delta value of $\pm$0.45. Instrument error is $\pm$0.5.

2.2.4 Water sample collection and analysis

Water samples have been collected every second month since 1991 around low tide at each of the three sea lettuce baseline monitoring sites. Harbour wide and stream/river water samples were collected on the same days as the sea lettuce tissue samples (summer and winter) and for the sea lettuce sampling sites, the same time and location. Samples were taken around mid water column in 0.5 m water depth using acid washed sample bottles. Samples were stored in chilled bins for transport back to laboratory. Most samples were analysed by Bay of Plenty Regional Council's IANZ accredited laboratory using the following methods;

- DRP – Molybdenum blue colorimetry, FIA, APHA 4500-P G, detection limit - 0.001 g/m^3
- TP – acid persulphate digestion, molybdate colorimetry, FIA APHA 4500-P H, detection limit - 0.001
- NH4-N – Phenyl/hypochlorite colorimetry. FIA, APHA 4500-NH3 G, detection limit - 0.001
- TOx-N – flow injection analyser, APHA 4500 NO3-I, detection limit - 0.001
- TN – persulphate digestion, auto cadmium reduction. FIA, detection limit - 0.01

Samples analysed for nitrogen stable isotope ($\delta^{15}N$ – dissolved organic and inorganic) were Millipore filtered then frozen before being sent to the GNS Science Stable Isotope Laboratory. These samples were then freeze dried and the residue analysed using a mass spectrometer.

Samples analysed for $\delta^{15}N$ (nitrate/nitrite-N) using the McIlvin method had a pellet of sodium hydroxide added to the sample to prevent any further biological activity before being frozen and sent for analysis. The McIlvin method (McIlvin & Altabet 2005) involves reduction of nitrate to nitrite using spongy cadmium with further reduction to nitrous oxide using sodium azide in an acetic acid buffer. Nitrous oxide is purged from the water sample and trapped cryogenically using an automated system and then analysed on a continuous flow GV Instruments IsoPrime mass spectrometer.

2.2.5 Terrestrial nitrogen contributions to the harbour

The relationships between sea lettuce and terrestrial nitrogen inputs to Tauranga Harbour were investigated primarily by looking at the river and stream inputs. The Bay of Plenty Regional Council has a number of water quality monitoring sites around Tauranga Harbour. A review of these sites was made to select those which had the longest record of nutrient and water flow records. Consideration was also given to selection of sites which are significant contributors to the harbour. The two sites chosen, Wairoa River (below the Ruahihi powerhouse) and Kopurereroa Stream (at State Highway 29) were then used to quantify nitrogen contributions to the harbour. This involved the use of statistical packages to find seasonal and flow relationships and checking for significant temporal trends in the data sets. Variations in the nitrogen loads where then used to check for relationships with sea lettuce abundance and tissue nitrogen.

Part 3: Results

3.1 Sea lettuce abundance

Abundance (% cover) measured at each of the three monitoring locations (Ongare Bay, Otumoetai and Town Reach) in Tauranga Harbour is shown in Figure 2 below as the mean of both the mid and low tide plots. The periodic and variable nature of abundance is shown with the highest abundance over the 1991 to 2010 monitoring period occurring in 1991/92.

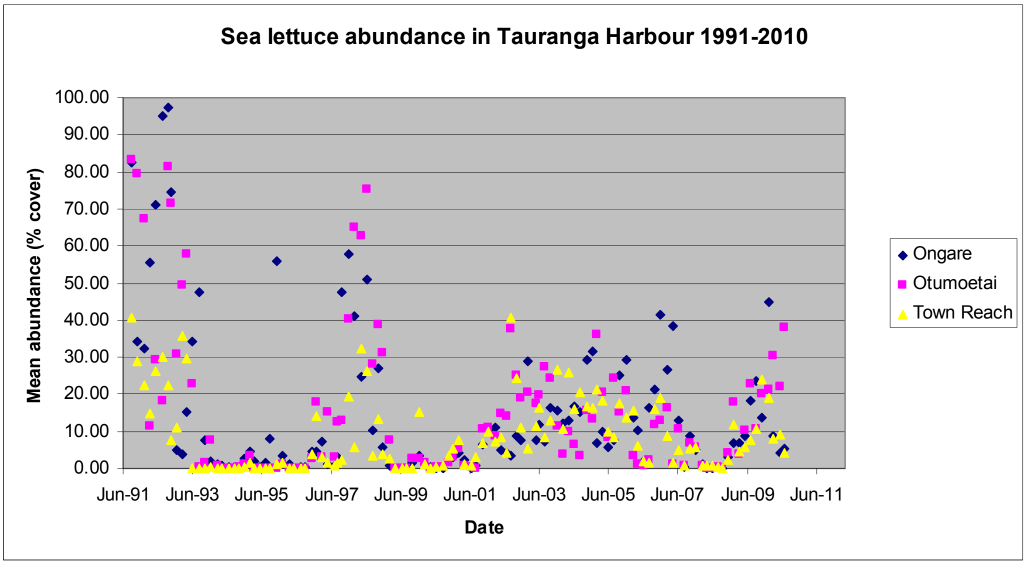

Figure 2 Abundance of sea lettuce (Ulva spp.) cover (mean % of mid and low tide plots) at monitoring sites in Tauranga Harbour from 1991 – 2010.

A seasonal pattern of abundance occurs at all the sites monitored as shown in Figure 3. Statistically the seasonal trends are not strong due to the high variability of abundance. The highest abundance of sea lettuce generally occurs in spring/early summer with a decline over the late summer. In late May/June all sites show another increase followed by a decline over the remaining period of winter. The median of sea lettuce cover for all sites combined provides the most reliable indication of the seasonal trend (Figure 3).

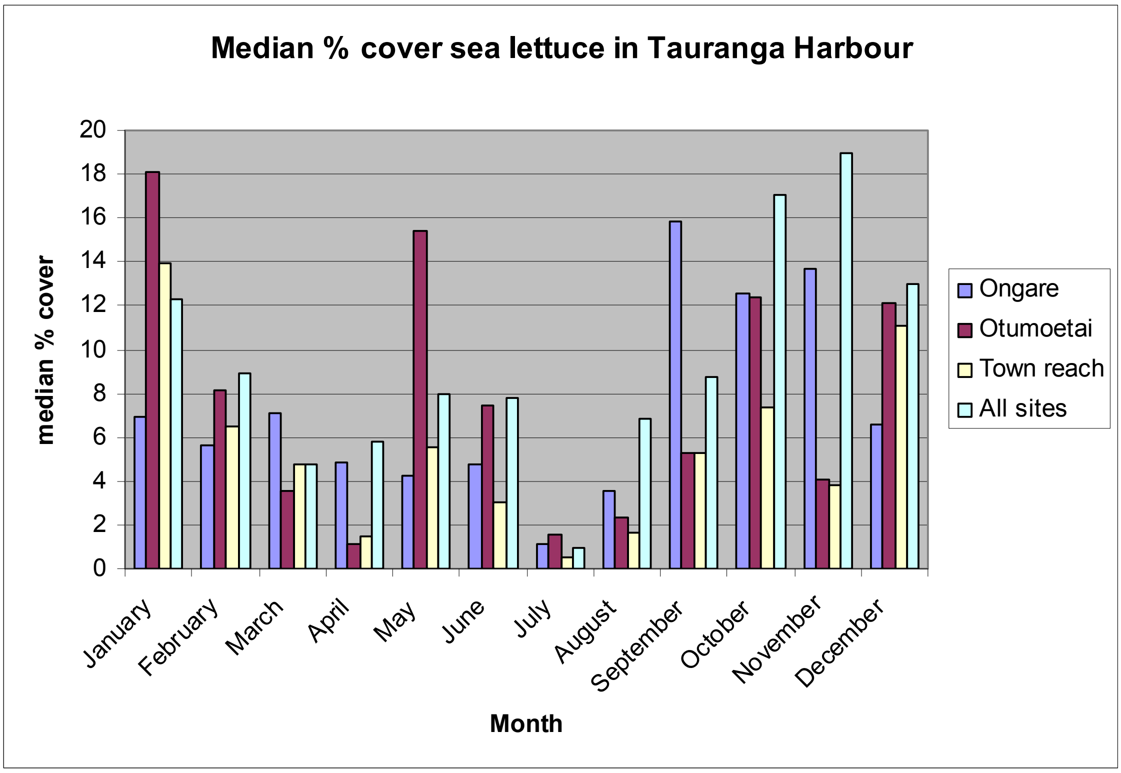

Figure 3 *Monthly median % cover of sea lettuce (Ulva spp.) at each of the monitoring sites and for all sites combined in Tauranga Harbour based on data from 1991 to 2010.*

Sea lettuce abundance (de-seasonalised % cover) at individual and all sites combined in Tauranga Harbour was correlated with a number of environmental variables including climatic indices, sea temperature, nutrient measurements at high and low tide, nitrogen inflows (Wairoa River and Kopurereroa Stream) and tissue concentrations of nitrogen and phosphorus. Table 1 provides statistics for parameters which had a significant result with at least one of the sites.

Table 1 *Correlations between sea lettuce (Ulva spp.) abundance in Tauranga Harbour between 1991 and 2010 and the Southern Ocean Oscillation Index (5 month moving average), Oceanic Nino Index, sun hours, sea temperature, dissolved inorganic nitrogen, and Otumoetai sea lettuce tissue nitrogen and phosphorus content. Negative sign on r^2 values indicates nature of original correlation.*

	All sites		Ongare Bay		Otumoetai		Town Reach	
	r^2	Prob.	r^2	Prob.	r^2	Prob.	r^2	Prob.
SOI (5mma)	-0.291	0.000	-0.207	0.000	-0.174	0.000	-0.156	0.000
ONI	0.173	0.000	0.125	0.000	0.111	0.000	0.124	0.000
Sun hours (5mma)*	-0.145	0.000	-0.091	0.001	-0.163	0.000	-0.099	0.001
Sea temperature*	-0.080	0.005	-0.087	0.003	0.044	0.040	-0.051	0.027
DIN (low tide)*	-0.036	n.s.	-0.009	n.s.	-0.036	n.s.	-0.048	0.027
Otumoetai tissue N*	0.058	0.028	0.102	0.000	0.002	n.s.	0.022	n.s.
Otumoetai tissue P*	0.033	n.s.	0.086	0.007	0.000	n.s.	0.000	n.s.

* de-seasonalised residuals

The most significant correlation between abundance (de-seasonalised % cover) and all the tested variables is the 5 month moving average of the Southern Ocean Oscillation Index with the average abundance of all sites combined. The related Oceanic Nino Index also had a very strong correlation with abundance as did sunlight hours and sea temperature to a lesser extent.

Abundance at Ongare Bay and for all sites combined showed a correlation with the Otumoetai sea lettuce tissue nitrogen content (de-seasonalised). Ongare Bay abundance also showed a significant correlation with the Otumoetai sea lettuce tissue phosphorus content while Town Reach sea lettuce abundance had a marginally significant negative correlation with the low tide sea water nitrogen concentrations (de-seasonalised).

A plot of the Southern Oscillation Index (five month moving average) and de-seasonalised sea lettuce abundance (inversed) from 1991 through to 2010 is shown in Figure 4 as a time series plot. Figure 5 is a simple plot showing the relationship between the two. The periods of higher sea lettuce abundance (or blooms) generally correspond with the negative ('El Nino') phase of the SOI.

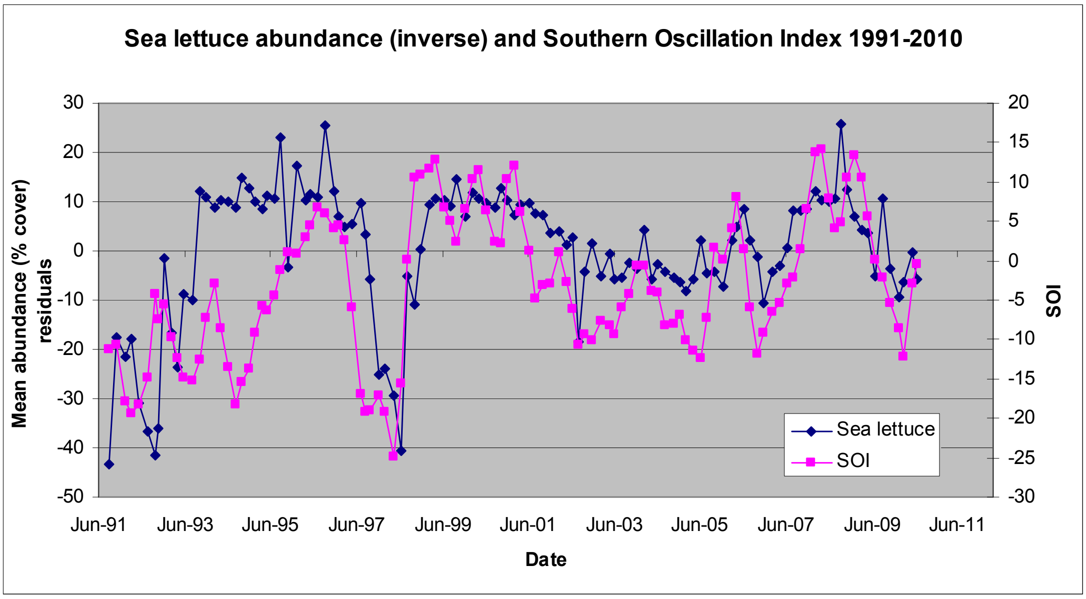

Figure 4 *De-seasonalised sea lettuce (Ulva spp.) abundance residuals as the mean of all monitoring plots/sites in Tauranga Harbour (inversed) and the Southern Ocean Oscillation Index as a five month moving average.*

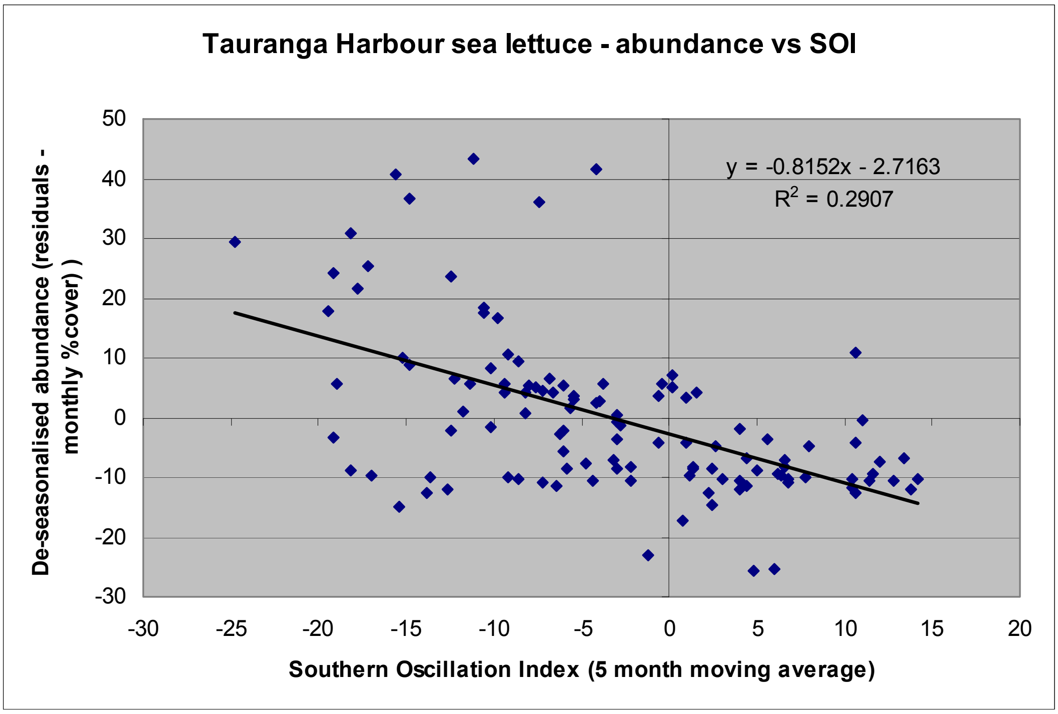

Figure 5 *Plot of de-seasonalised sea lettuce abundance for all the Tauranga Harbour sites combined using data collected from 1991 to 2010.*

3.2 Sea lettuce tissue nutrient

Sea lettuce tissue samples covering the period 1991 to 2010 from the three monitoring sites (Ongare Bay, Otumoetai and Town Reach) have been analysed for total nitrogen, phosphorus and carbon content. The nitrogen and phosphorus results from each site were checked for both seasonality and trends over time. Seasonality was tested using a Kruskal-Wallis test (non-parametric ANOVA) and trends over time were detected using a Seasonal-Kendall trend test which takes into account seasonal trends.

The nitrogen and phosphorus content in tissue samples show a very similar seasonal pattern at all three sites as seen in Figures 6 and 7. Nitrogen content in the sea lettuce tissue reaches a maximum around June/July and minimum values occur around January/February each year. The monthly means at each site are set out in Table 2 for nitrogen and Table 3 for phosphorus. Figure 6 and Table 2 also show the difference in tissue nitrogen content at each of the three sites. Ongare Bay sea lettuce tissue samples have consistent year round lower nitrogen content than that of the other sites. The Town Reach site has the highest values which are 40-60% higher than the Ongare Bay values. De-seasonalised plots of tissue nitrogen and phosphorus are provided in Appendix V.

The amount of nitrogen in sea lettuce tissue from the three sites in Tauranga Harbour is relatively low even at the Town Reach site. In summer the minimum tissue nitrogen content is around or below 2.0% at which point nitrogen becomes limiting to growth (de Winton *et al*. 1998). In Figure 6 the subsistence level (0.8%) is the point at which nitrogen levels become so low that the plants would not be able to grow. The Ongare Bay sea lettuce tissue results for nitrogen get close to this limit.

There were no statistically significant trends showing increases or decreases over time (using the Seasonal-Kendall trend test) for either nitrogen or phosphorus tissue content at any of the three sites.

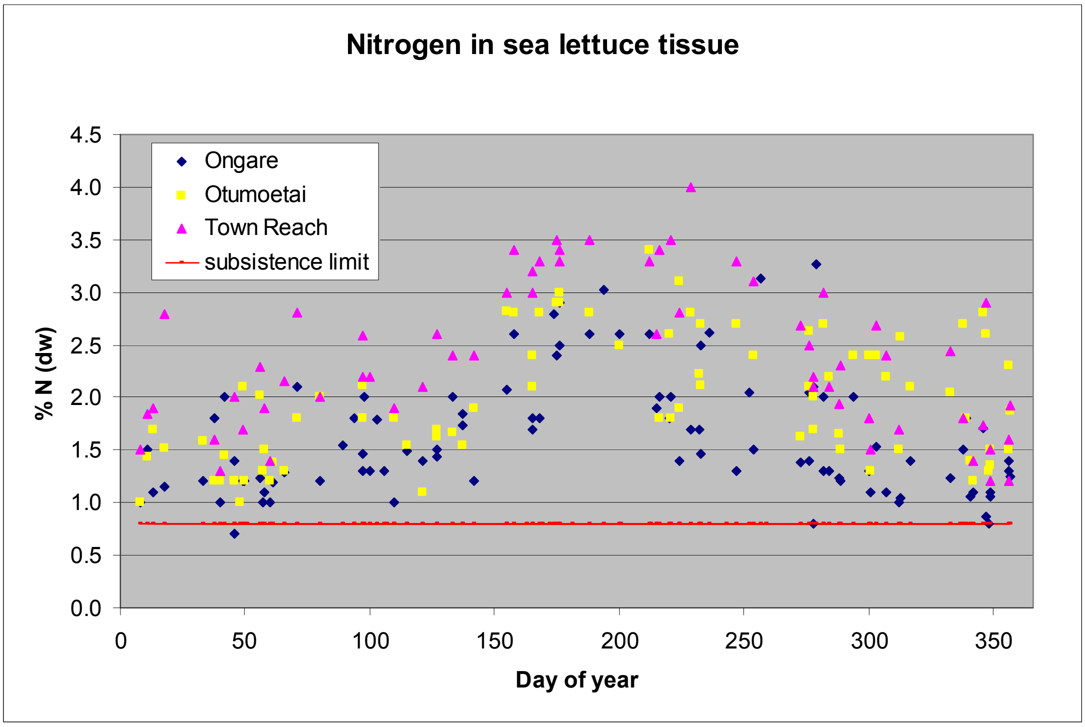

Figure 6 *Seasonal nitrogen content (% dw) in sea lettuce (Ulva spp.) tissue at the three monitoring sites in Tauranga Harbour from 1991 – 2010.*

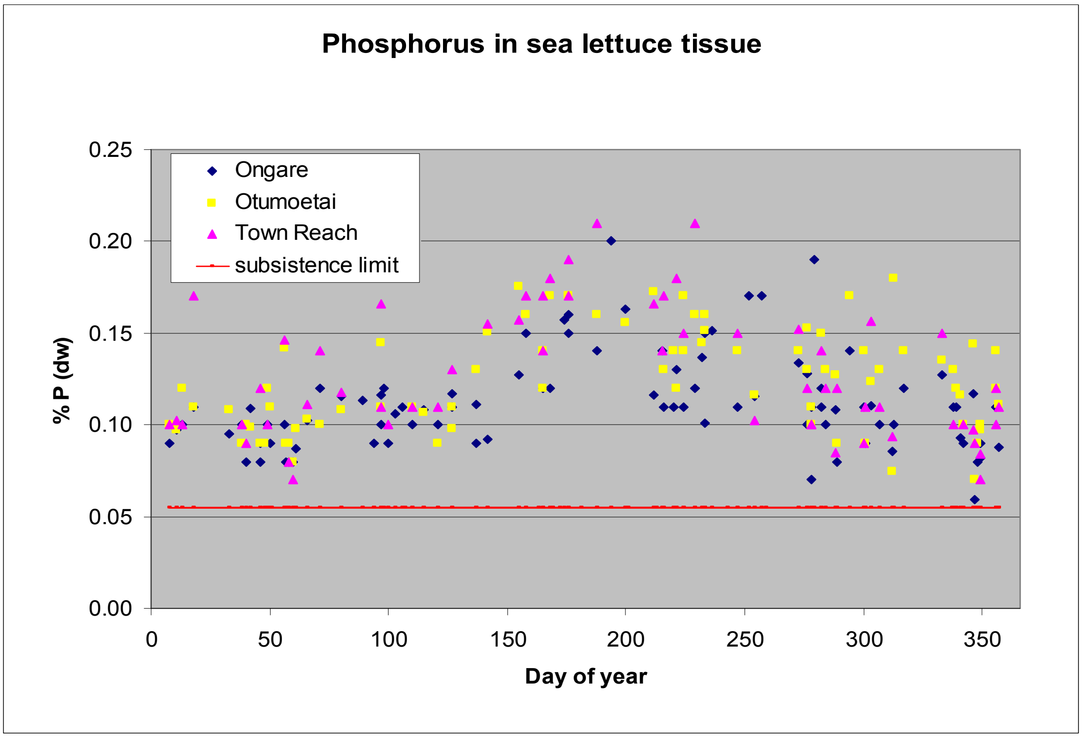

Figure 7 *Seasonal phosphorus content (% dw) in sea lettuce (Ulva spp.) tissue at the three monitoring sites in Tauranga Harbour from 1991 – 2010.*

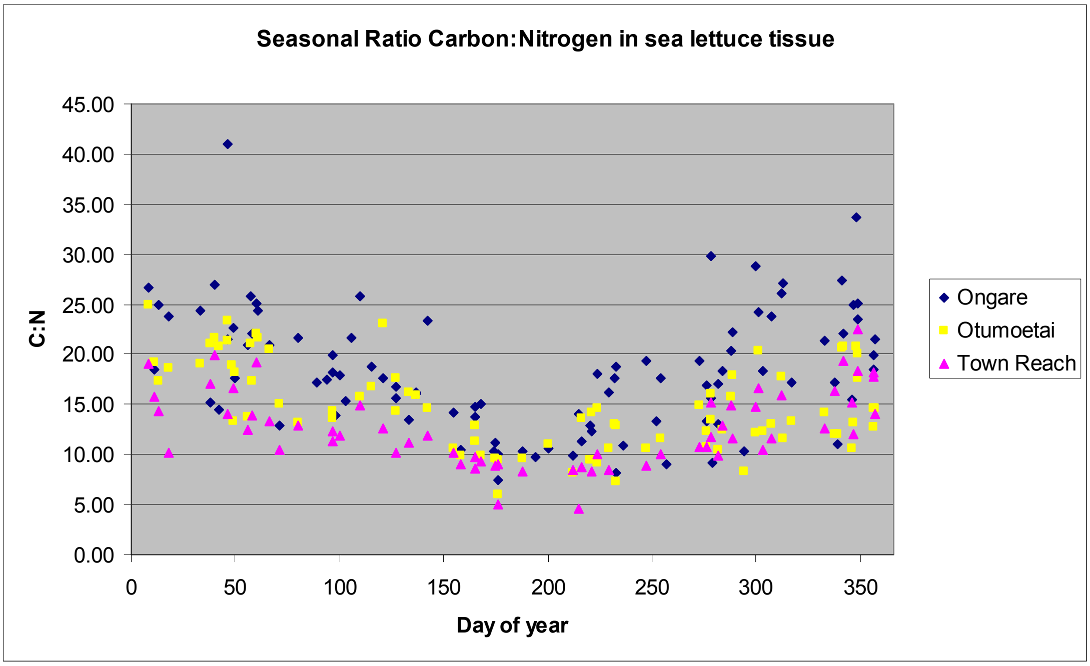

Figure 8 *Seasonal ratio of carbon to nitrogen in sea lettuce (Ulva spp.) tissue at three monitoring sites in Tauranga Harbour from 1991 -2010.*

Tissue phosphorus content shows similar patterns to that of nitrogen (Figure 6) with a seasonal peak in June/July (winter) and the lowest concentrations in summer (December to February). The mean sea lettuce tissue phosphorus content for each month of the year is set out in Table 3. As with nitrogen tissue concentrations, phosphorus values tend to be lowest at the Ongare Bay site and highest at the Town Reach site. This difference is most pronounced over the winter months (May to Aug) with 20-35% higher values. For the rest of the year differences in phosphorus tissue content between sites is low and during spring/early summer very similar at Ongare Bay and Town Reach sites.

Figure 7 shows that phosphorus concentrations in sea lettuce tissue at all sites in Tauranga Harbour generally fall below the optimum growth level of 0.12% (de Winton *et al*. 1998) over the summer period each year and in some years have been near the lower limit for growth (0.055%).

The ratio of carbon to nitrogen shown in Figure 8 shows a seasonal and site trend similar to that of nitrogen and phosphorus. This seasonal trend in the ratio essentially confirms that sea lettuce in Tauranga Harbour is able to take up more nitrogen in winter relative to the growth rate. The same pattern is shown in the ratio of nitrogen to phosphorus in sea lettuce tissue (Figure 9). The Town Reach site has the highest ratio of nitrogen to phosphorus while Ongare Bay has the lowest.

Pearson correlations were generated between the de-seasonalised nitrogen and phosphorus content at each of the monitoring sites with a range of environmental variables which included climate indices, sea temperature, flow of the Wairoa River, nitrogen (DIN) load of the Wairoa River and Kopurereroa Stream and nitrogen (DIN) and phosphorus (DRP) concentrations measured at low tide and high tide monitoring sites either at or near the sea lettuce sites. Correlation results for environmental parameters in which at least one of the sea lettuce tissue parameters showed a statistically significant result are provided in Table 4.

Table 2 *Mean monthly nitrogen content (% dw) in tissue of sea lettuce (Ulva spp.) at monitoring sites in Tauranga Harbour from 1991 – 2010.*

Month	Ongare Bay	Otumoetai	Town Reach
January	1.19	1.42	2.01
February	1.26	1.41	1.80
March	1.39	1.54	2.09
April	1.48	1.67	2.20
May	1.62	1.69	2.47
June	2.28	2.72	3.26
July	2.71	2.90	3.4
August	1.91	2.34	3.26
September	1.87	2.24	3.03
October	1.61	2.08	2.21
November	1.16	2.09	2.18
December	1.25	1.86	1.70

Table 3 *Mean monthly phosphorus content (% dw) in tissue of sea lettuce (Ulva spp.) at monitoring sites in Tauranga Harbour from 1991 – 2010.*

Month	Ongare Bay	Otumoetai	Town Reach
January	0.099	0.107	0.118
February	0.091	0.102	0.106
March	0.103	0.098	0.110
April	0.104	0.112	0.119
May	0.106	0.119	0.138
June	0.137	0.158	0.169
July	0.155	0.163	0.188
August	0.126	0.146	0.170
September	0.140	0.132	0.135
October	0.112	0.126	0.114
November	0.107	0.132	0.118
December	0.095	0.112	0.097

Correlations between sea lettuce tissue phosphorus content (de-seasonalised) and environmental variables produced only marginally significant results between the Ongare Bay and Otumoetai monitoring sites with the Wairoa River flow and Wairoa River DIN load.

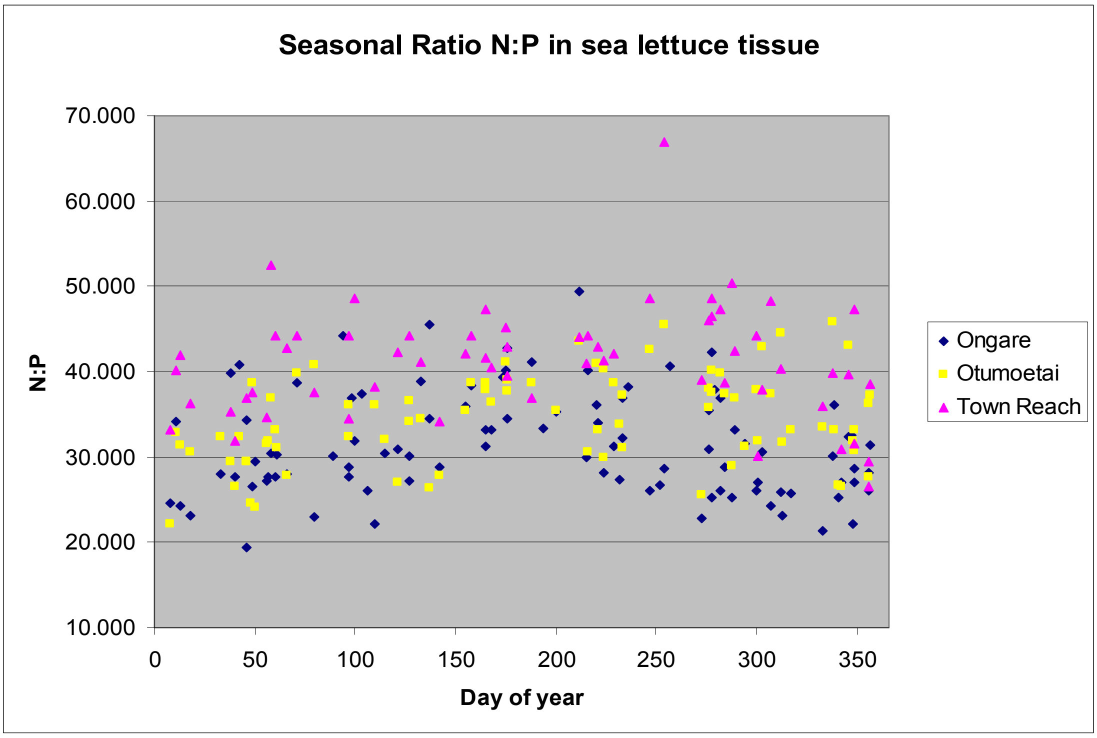

Figure 9 *Seasonal nitrogen to phosphorus (atomic ratio) in sea lettuce (Ulva spp.) tissue at three monitoring sites in Tauranga Harbour from 1991 -2010.*

Sea lettuce tissue nitrogen content (de-seasonalised) showed significant correlations between all sites and nitrogen inflow to the harbour from the Wairoa River and Kopurereroa Stream. The Otumoetai tissue nitrogen content and Wairoa River nitrogen (DIN) load displayed the strongest relationship with an r^2 value of 0.157. Marginally significant correlations were also found between Otumoetai tissue nitrogen and low tide sea water DRP concentrations, Ongare Bay tissue nitrogen content and low tide DIN. The Ongare site also had a significant correlation for tissue nitrogen with the Otumoetai low tide DIN concentrations.

Table 4 *Correlations (r^2 values and probabilities in brackets) of de-seasonalised sea lettuce tissue nitrogen and phosphorus content at each of the monitoring sites and environmental variables using data from 1991 to 2010.*

	Tissue nitrogen			**Tissue phosphorus**		
	Ongare	Otumoetai	Town Reach	Ongare	Otumoetai	Town Reach
Wairoa flow	0.127 (0.001)	0.154 (0.001)	0.099 (0.028)	0.051 (0.041)	0.059 (0.043)	0.057 (n.s.)
Wairoa–DIN load	0.129 (0.001)	0.157 (0.001)	0.085 (0.042)	0.057 (0.030)	0.056 (0.048)	0.046 (n.s.)
Kopurereroa-DIN	0.057 (0.022)	0.088 (0.008)	0.142 (0.003)	0.004 (n.s.)	0.000 (n.s.)	0.008 (n.s.)
DRP-All sites (lt)	0.027 (n.s.)	0.057 (0.032)	0.019 (n.s.)	0.007 (n.s.)	0.040 (n.s.)	0.003 (n.s.)
DIN-All sites (lt)	0.054 (0.035)	0.009 (n.s.)	0.000 (n.s.)	0.000 (n.s.)	0.002 (n.s.)	0.003 (n.s.)
DIN-Otumoetai (lt)	0.084 (0.009)	0.018 (n.s.)	0.001 (n.s.)	0.009 (n.s.)	0.002 (n.s.)	0.000 (n.s.)

3.3 Nutrient levels in Tauranga Harbour

Most nutrient monitoring sites in Tauranga Harbour have samples taken around the time of high tide while the three sea lettuce monitoring sites have samples collected at low tide. Data from all sites was first checked for seasonality using a Kruskal-Wallis test (non-parametric ANOVA). Dissolved reactive phosphorus (DRP) showed no statistically significant seasonal trends (based on 12 monthly intervals of the year) for either individual sites or all sites combined. Dissolved inorganic nitrogen (DIN) showed statistically significant seasonal trends at all sites except Bowen Town. Data was also checked for trends over time using a Seasonal-Kendall trend test. No sites show any de-seasonalised trends for nitrogen and phosphorus except for the Bowen Town site (adjusted P=0.011) with an annual increase of 0.002 g/m3 for DIN.

Since there is no seasonal trend in DRP concentrations, the results for both the high and low tide sites are presented as means (in Table 6) for the whole of the data record from 1990 to 2010. Mean DRP concentrations show a small amount of variation between sites with Town Reach having the highest overall value. This is likely to reflect the influence of catchment runoff as the Town Reach site is further from the harbour entrance. There is also variation between the low and high tide results from comparative sites. Low tide DRP concentrations tend to be around 15% higher than high tide values. The variation between sites is shown in Tables 5 and 6 and Figure 10.

The DIN concentrations analysed and reported are the total of nitrate/nitrite and ammonium nitrogen recorded from respective sites between 1993 and 2010. All sites show the same consistent seasonal trend with low concentrations in summer and a significantly higher winter peak. The monthly values for both high and low tide results are set out in Table 5 and shown as a bar graph in Figure 10. Winter DIN concentrations are much higher than summer for all sites. There is also a much larger increase in mean DIN concentrations at the Town Reach site compared to either the Otumoetai or Bowen Town sites close to the entrance. The difference between high and low tide DIN values is not as great as the seasonal or location influences.

Table 5 Seasonal (monthly) mean DIN (NOx + NH4-N g/m^3) at high and low tide monitoring sites in Tauranga Harbour based on the period 1993 - 2010.

		Month											
	Site	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
High Tide	Bowen	0.028	0.025	0.045	0.023	0.029	0.034	0.063	0.050	0.036	0.044	0.041	0.035
	Te Puna	0.027	0.027	0.052	0.037	0.074	0.063	0.142	0.077	0.049	0.061	0.028	0.041
	Otumoetai	0.043	0.041	0.074	0.041	0.080	0.056	0.149	0.095	0.067	0.079	0.039	0.042
	Town reach	0.056	0.045	0.097	0.052	0.129	0.233	0.271	0.189	0.127	0.087	0.044	0.081
Low tide	Ongare	0.028	0.030	0.039	0.025	0.060	0.081	0.158	0.087	0.069	0.034	0.038	0.025
	Otumoetai	0.022	0.031	0.062	0.041	0.038	0.066	0.122	0.121	0.220	0.050	0.045	0.043
	Town reach	0.077	0.060	0.087	0.081	0.108	0.230	0.353	0.154	0.294	0.144	0.083	0.044

Table 6 *Mean DRP (g/m³) at high and low tide monitoring sites in Tauranga Harbour based on the period 1990 - 2010.*

	High tide				Low tide		
Site	**Bowen Town**	**Te Puna**	**Otumoetai**	**Town Reach**	**Ongare**	**Otumoetai**	**Town Reach**
Mean	0.006	0.006	0.007	0.008	0.007	0.008	0.009
Median	0.005	0.006	0.007	0.007	0.006	0.007	0.008

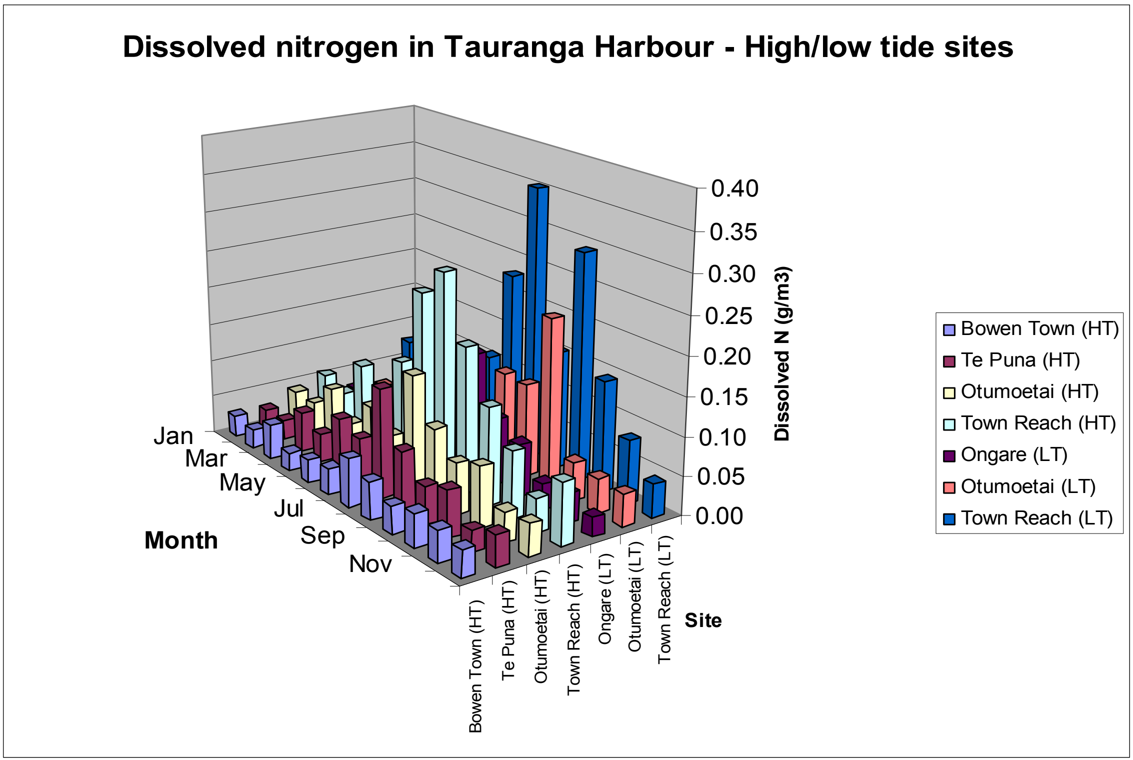

Figure 10 *Seasonal (monthly) mean concentration of DIN measured at high tide and low tide sites in Tauranga Harbour using data from 1993 to 2010.*

3.4 Terrestrial nitrogen contributions to the harbour

3.4.1 Wairoa River load

A data set of matching flow and nutrient records from a monitoring site below the power station on the Wairoa River were used to determine the variation of DIN (nitrate/nitrite and ammonium nitrogen) flowing into the harbour over time. The data spans the period from September 1993 to September 2008. River flow at this monitoring site is highly modified due to operational management of flow through the power station and average daily flow was used rather than an instantaneous value at the time of sampling. Four very high flow values were removed from the data set as outliers.

A seasonal Kendall trend test was used to investigate whether any trends occur in nitrate/nitrite (NO_x) concentration over time. The test used flow as the covariate factor and Lowess adjustment which explained 20.4% of the variation in NO_x concentrations. The trend for the flow adjusted model was P = 0.006 with a median annual slope of 0.005 (g/m3). The relationship of NO_x concentration with flow was then determined to be: $NO_x = 0.007 * flow + 0.240$ which is shown in Figure 11 below.

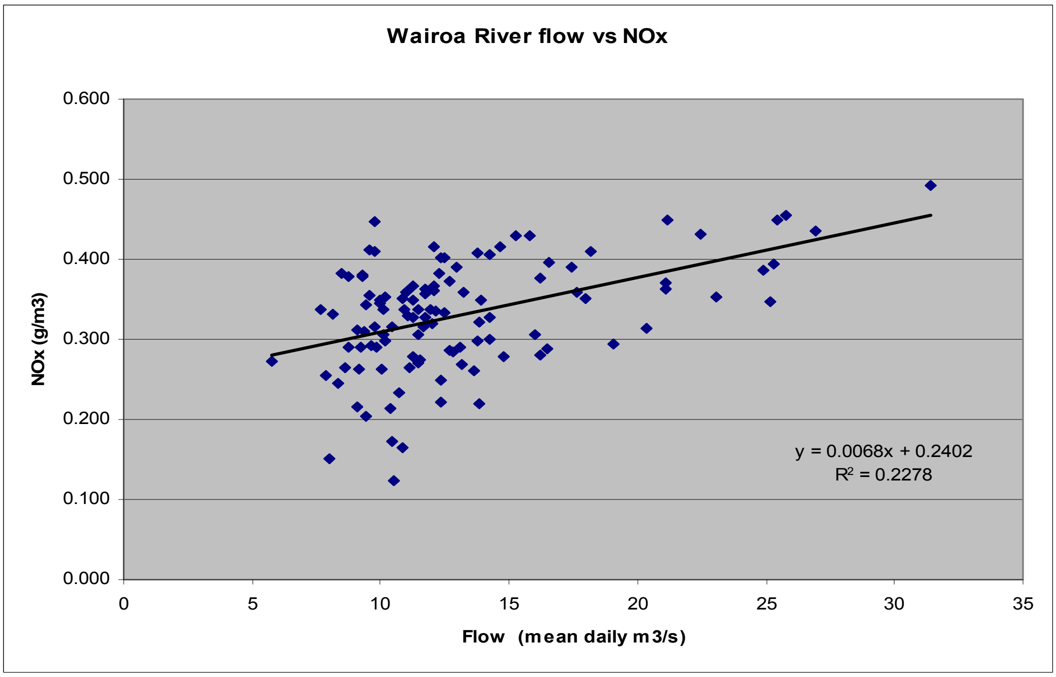

Figure 11 *Plot of oxidised nitrogen (NO_x) versus flow recorded on the Wairoa River below the power station between 1993 and 2008.*

Ammonium nitrogen concentrations in the Wairoa River (below the power station) were also analysed using a seasonal Kendall trend test with flow adjustment and showed no trend over time or significant relationship with flow or season (using monthly divisions of year).

Using the relationships between flow and nitrogen concentration, monthly nitrogen loads were calculated based on measured flow and the variation (residuals) from the expected mean monthly seasonal flow as given in Table 7 below. The residuals are shown in Figure 12 below.

River flow variation with climate

Analysis of the de-seasonalised Wairoa River mean monthly flow (m^3/s) against climatic indices showed significant correlations between the Oceanic Nino Index and five month moving average of Southern Oscillation Index (r^2 value of *0.035* and *probability 0.008)*. Four values were identified as statistical outliers and omitted from the final regression analysis. Graphs showing the mean monthly flow and the flow residuals plotted against the SOI are provided in Appendix 3.

The equation for the relationship being: *Wairoa flow variation (m^3/s) = 0.101 x SOI (5mma) – 0.297.*

During a period of strong El Nino (i.e. SOI value $\leq$ -20) this equates to a reduced monthly mean flow of around 2.5 m^3/s in the Wairoa River. In summer this represents a 20% reduction in flow reducing to 10% of the peak winter flow (see Table 7 below). The percentage change in river flow will have a corresponding change in the DIN load to the harbour.

3.4.2 Kopurereroa Stream load

Matching nitrogen results from water samples and instantaneous flow values collected from September 1993 to April 2010 in the Kopurereroa Stream were used to test for trends over time. A Seasonal Kendall trend test on NO_x with flow as the covariate factor and Lowess adjustment showed that flow explained 23.3% of the variance in NO_x. Flow adjusted results show a significant trend over time (P=0.000) with a median annual slope of 0.012. There was no statistically significant seasonal (monthly) trend or relationship with flow. Calculation of dissolved nitrogen load was modelled using the average value of NO_x and NH4 combined (0.844 g/m^3) and the seasonal monthly average flow from Table 7. The residual nitrogen load values were derived by subtracting those seasonal means from the recorded mean monthly flow/load

Table 7 Monthly mean flow values (m^3/s) for the Wairoa River (below the power station) and Kopurereroa Stream (SH29) based on data from July 1993 and July 1991 to April 2010. Included is the estimated % reduction in flow that occurs during a strong El Nino event for the Wairoa River.

Month	Wairoa River flow m^3/s	% reduction – El Nino	Kopurereroa flow
January	12.756	19.6	1.646
February	12.589	19.9	1.685
March	12.522	20.0	1.739
April	15.837	15.8	1.891
May	17.889	14.0	1.957
June	18.378	13.6	1.978
July	24.086	10.4	2.141
August	21.077	11.9	2.092
September	16.792	14.9	1.877
October	15.750	15.9	1.887
November	12.574	19.9	1.781
December	14.237	17.6	1.793

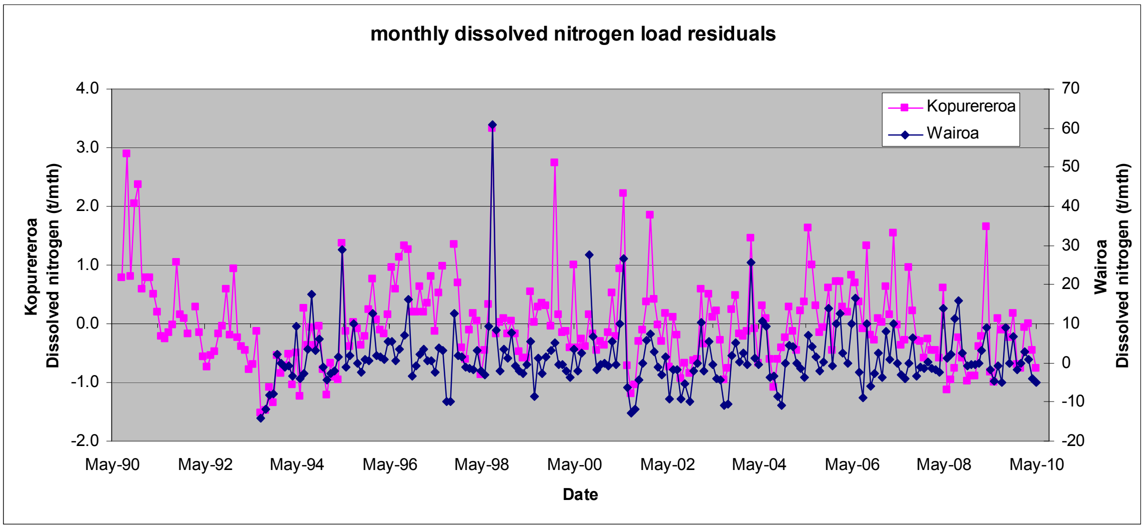

Figure 12 DIN (NO_x+NH4) load residuals (de-seasonalised) for the Wairoa River below the power station and Kopurereroa at SH29.

3.4.3 Correlations between terrestrial nitrogen and sea lettuce

Table 8 below provides some figures for the modelled DIN load in Wairoa River and Kopurereroa Stream. In combination with Figure 12 it provides context for the correlations between variations in the nitrogen load from these two catchments and sea lettuce. The Wairoa River catchment at the power station represents only 56% of the total Wairoa catchment flow and area (449 km^2). The Kopurereroa Stream at SH29 represents 81% of the total catchment (74 km^2). Together these catchments represent 61% of the total southern harbour catchment (854 km^2) and the Wairoa River inflow has been estimated to be 60% of the southern harbour total.

Table 8 Mean monthly DIN load (tonnes/month) by season for Wairoa River and Kopurereroa Stream sites with estimates for total catchment in brackets.

Period	Wairoa River	Kopurereroa Stream
Spring	10.1 (18.0)	4.4 (5.4)
Summer	12.8 (22.9)	4.9 (6.0)
Autumn	21.0 (37.5)	5.5 (6.8)
Winter	14.1 (25.2)	4.8 (5.9)
Annual	14.5 (25.9)	4.9 (6.0)

Results for statistically significant correlations between de-seasonalised DIN load of the Wairoa River and Kopurereroa Stream with sea lettuce, nutrient and climate parameters are set out in Table 9. Variations in the DIN load of the Wairoa River correlate reasonably well to the indicators of climate pattern. Both the climate indices (SOI &ONI) are indicators of El Nino/La Nina climatic variation. The correlations show that DIN load from the Wairoa River is lower during El Nino and higher during La Nina climate phases. Nitrogen load from the Kopurereroa Stream is far more variable and has a weak but similar correlation with climate.

Table 9 Correlations between the DIN load (nitrate+nitrite+ammonium-N) in the Wairoa River (below the power station) and Kopurereroa Stream (at SH29) and climate, sea lettuce abundance, tissue nutrients and harbour water.

			Wairoa - DIN load		Kopurereroa -DIN	
			r^2	Prob.	r^2	Prob.
Sea lettuce	Abundance mean % cover		-0.019	n.s.	-0.001	n.s.
	Tissue N%	Ongare	0.129	0.001	0.057	0.022
		Otumoetai	0.157	0.001	0.088	0.008
		Town Reach	0.085	0.042	0.142	0.003
	Tissue P%	Ongare	0.057	0.030	0.004	n.s.
		Otumoetai	0.056	0.048	-0.000	n.s.
		Town Reach	0.046	n.s.	0.008	n.s.
Sea water	Low tide DIN	Ongare	0.001	n.s.	0.009	n.s.
		Otumoetai	0.145	0.000	0.190	0.000
		Town Reach	0.049	0.027	0.104	0.001
	High tide DIN	Bowen Town	0.004	n.s.	0.000	n.s.
		Otumoetai	0.203	0.000	0.011	n.s.
		Town Reach	-0.000	n.s.	-0.000	n.s.
	DRP low tide	Mean of all	0.000	n.s.	0.003	n.s.
	DRP high tide	Mean of all	-0.001	n.s.	-0.018	n.s.
Climate	Oceanic Nino Index		-0.066	0.009	-0.035	0.050
	SOI (5mth moving ave)		0.069	0.008	0.053	0.015

Both the Wairoa River and Kopurereroa Stream DIN loads correlate strongly with DIN concentrations measured at low tide at the Otumoetai site which is close to both inflows. There is also a weaker but statistically significant correlation with the Town Reach low tide DIN concentrations. The Ongare Bay site in the northern end of Tauranga Harbour has no significant correlation between sea water DIN concentrations and the DIN load of these two inflows.

There is also a correlation between the DIN load of the Wairoa River and Otumoetai high tide sea water DIN concentrations but not with Bowen Town or Town Reach sites. There are no correlations between the Kopurereroa Stream DIN load and high tide sea water DIN concentrations.

DRP concentrations in sea water were only tested for correlations against inflow DIN loads as high and low tide means of all sites combined and there were no significant results.

The nitrogen content of sea lettuce tissue shows statistically significant correlations for all three monitoring sites and DIN inflow to Tauranga Harbour. The strongest of these correlations is between the Wairoa River and Otumoetai monitoring site which is close to the river inflow. Phosphorus content of sea lettuce tissue at the Ongare Bay and Otumoetai sites had a marginally significant correlation with Wairoa River flow/DIN load. There were no significant correlations with sea lettuce phosphorus content at the Town Reach site with the DIN inflows from the Wairoa River and Kopurereroa Stream.

3.5 Nitrogen stable isotope values around Tauranga Harbour

3.5.1 Spatial variability in sea lettuce tissue and water $\delta^{15}N$ values

Nitrogen and $\delta^{15}N$ values in water samples

Nitrogen isotope values were determined for a range of sea lettuce tissue and water samples from around Tauranga Harbour in summer and winter. Results for water samples are shown in Table 10. The $\delta^{15}N$ isotope results are given according to the two methods by which samples were analysed with $\delta^{15}N$ – DN results based on all the dissolved nitrogen (inorganic and organic) in the water sample. Salts present in many of the summer samples prevented any result being obtained and analysis methods were changed to avoid this problem with the winter samples. Winter $\delta^{15}N$-NO_x results assess $\delta^{15}N$ on the NO3 and NO2 present in the samples. The Waimapu River and Kopurereroa Stream samples were analysed by both methods in winter and show consistent $\delta^{15}N$ values from summer to winter on a dissolved nitrogen basis.

Analysis of only oxidised forms of nitrogen (NO_x) results in a lower $\delta^{15}N$ value compared to assessing all the dissolved nitrogen present as seen in the Kopurereroa Stream and Waimapu River results (Table 10) with $\delta^{15}N$ values around 6.5 for dissolved nitrogen and -11 for nitrate/nitrite. Tuapiro Stream water sample has the highest and only positive $\delta^{15}N$-NO_x value (5.2) for the winter freshwater samples.

The harbour and offshore sea water samples consistently show higher $\delta^{15}N$ values than all the freshwater inflows. The range of harbour $\delta^{15}N$-NO_x value is significantly correlated to salinity (p=0.007). Tilbey Point has the highest freshwater influence of the harbour samples and has the lowest $\delta^{15}N$-NO_x value.

Nitrogen and δ15N tissue values in sea lettuce

Summer and winter tissue nitrogen content for the sea lettuce samples from around Tauranga Harbour are shown in Figure 13 along with mean values from Barr (2007) for different environments around New Zealand. Summer values for most Tauranga Harbour sites are low and similar to the values obtained for sheltered rural sites (Barr 2007). Winter tissue nitrogen content varies more widely with all sites showing much higher values.

The lowest tissue nitrogen values in the sea lettuce samples from Tauranga Harbour were recorded from the Katikati site in both summer and winter (0.7%, 2.2%) while the highest (1.6%, 3.4%) were at Waimapu Estuary. In general the sites close to the Wairoa and Waimapu Rivers have the highest values while sites out in the open harbour away from stream inputs have the lowest values.

Nitrogen $\delta^{15}N$ values in sea lettuce tissue in summer and winter samples from Tauranga Harbour are shown in Figure 14 along with mean values from Barr (2007) for different environments around New Zealand. The highest summer $\delta^{15}N$ tissue value came from sea lettuce at Kauri Point ($\delta^{15}N$ 9.3‰). Other high summer $\delta^{15}N$ tissue values tended to be similar for northern and southern harbour sites. The lowest summer $\delta^{15}N$ tissue values occurred at Tilbey Point and Waikareao Estuary ($\delta^{15}N$ 7.6‰) and both are close to significant freshwater inflow.

Table 10 Nitrogen isotope values and concentration (g/m^3) and salinity for each of the water samples taken in summer (26th Feb) and winter (24th Jun).

	Saln (PSU)		NO_x-N		NH4-N		δ15N - DN		δ15N - NO_x	
Marine sites	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**
Tuapiro Estuary	28.9	26.5	0.005	0.069	0.014	0.027	-	-	-	8.1
Ongare Bay	30.8	31.9	0.005	0.033	0.035	0.039	-	-	-	10.0
Omokoroa	30.0	-	0.004	0.087	0.001	0.052	-	-	-	7.4
Tilbey Point	14.9	13.1	0.169	0.352	0.044	0.039	-	-	-	5.6
Otumoetai	29.9	30.1	0.004	0.019	0.001	0.013	-	-	-	9.3
Town Reach	28.3	17.7	0.022	0.383	0.005	0.043	-	-	-	7.0
Maungatapu	28.4	21.0	0.008	0.242	0.066	0.075	-	-	-	6.4
Mount – low tide	30.4	24.4	0.009	0.234	0.006	0.049	-	-	-	6.4
Mount – high tide	31.9	34.0	0.006	0.051	0.003	0.009	-	-	-	8.4
Offshore - surface	-	34.4	-	0.037	-	0.008	-	-	-	11.8
Offshore – 200m	30.1	34.4	0.194	0.184	0.004	0.011	-	-	-	7.6
River/Stream sites										
Tuapiro Stream	6.6	0.6	0.023	0.169	0.029	0.011	-	-	-	5.2
Uretara Stream	6.8	0.0	0.014	0.381	0.027	0.011	-	-	-	-11.9
Wainui Stream	2.8	0.1	0.093	0.491	0.034	0.011	-	-	-	-8.6
Te Puna Stream	6.0	0.1	0.225	0.971	0.05	0.010	-	-	-	-9.6
Wairoa River	1.6	0.0	0.365	0.490	0.009	0.027	-	-	-	-12.8
Kopurereroa Stream	0.4	0.1	0.917	0.994	0.015	0.260	6.6	6.1	-	-12.3
Waimapu River	0.0	0.0	0.740	1.010	0.022	0.032	6.5	6.7	-	-10.5
Otumoetai	4.1	0.6	1.12	1.53	0.204	0.083	-	-	5.8	-10.5
Grace Rd stormwater	1.9	0.2	1.17	1.35	0.025	0.016	-	-	-0.2	-11.2
Sewage raw	-	-	0.006	-	38.40	-	5.2	-	-	-
Sewage treated	-	-	0.977	-	19.50	-	7.0	-	-	-

Most of the summer and winter $\delta^{15}N$ values in sea lettuce tissue samples from around Tauranga Harbour were similar for each site. The exception to this was the high $\delta^{15}N$ summer value for sea lettuce at Kauri Point. Sites with the highest overall summer and winter $\delta^{15}N$ values were the Welcome and Rangataua Bays which are adjacent at the southern end of the harbour.

In winter, samples of two other macro algal species were collected from along side the sea lettuce plants at the Mount Maunganui site and analysed for $\delta^{15}N$ values. These were *Undaria pinnatifida*, a fast growing exotic brown seaweed and *Carpophyllum flexuosum*, a slower growing native brown seaweed. Respective tissue nitrogen content was 2.3 and 1.6 for growing tips of the plants and $\delta^{15}N$ values of 8.4‰ and 8.3‰. Although the tissue nitrogen values are lower than for sea lettuce, the $\delta^{15}N$ values are the same.

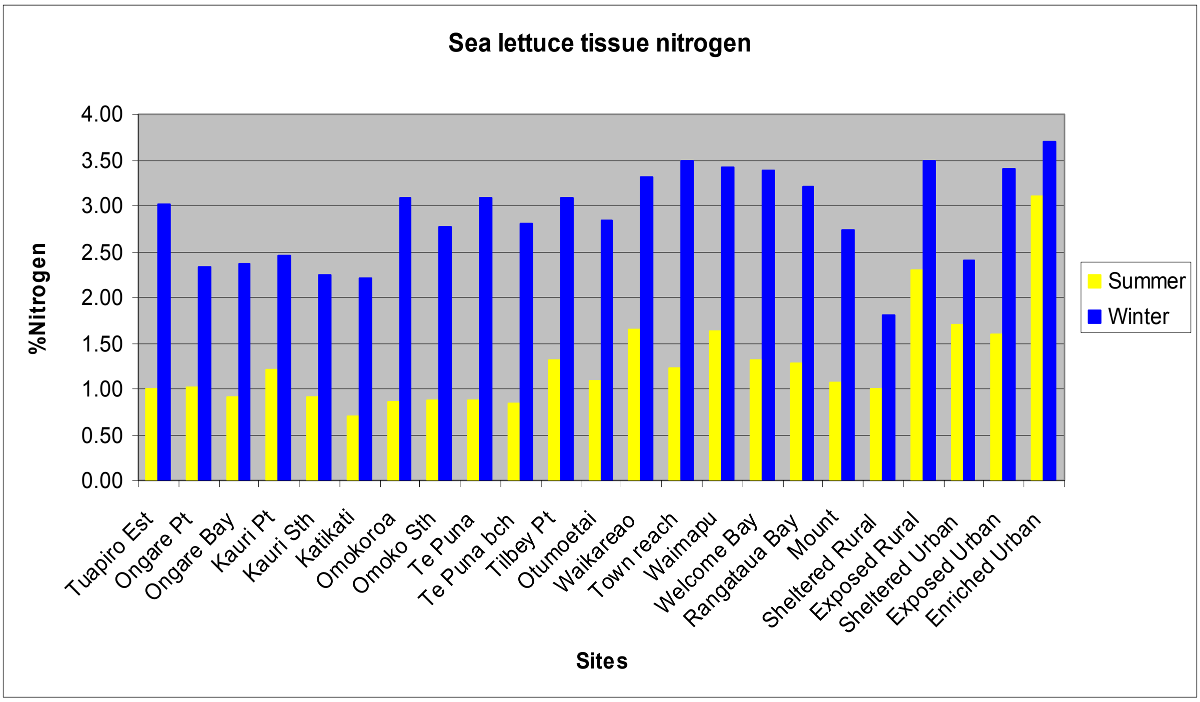

Figure 13 *Seasonal tissue N content in sea lettuce (Ulva spp.) samples from Tauranga Harbour with a comparison to means from Barr (2007) for different environments.*

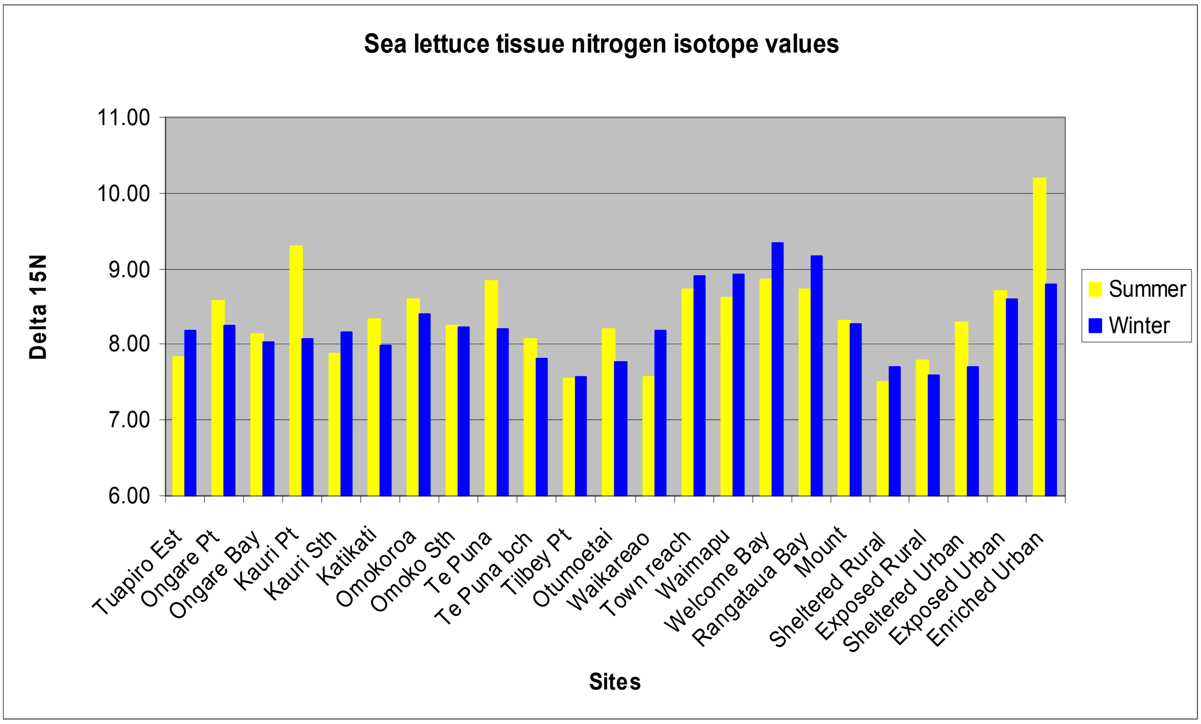

Figure 14 *Seasonal tissue δ15N values of sea lettuce (Ulva spp.) from Tauranga Harbour with a comparison to means from Barr (2007) for different environments.*

3.5.2 Temporal and environmental variation in tissue $\delta^{15}N$ values

Nitrogen $\delta^{15}N$ results from the time series of sea lettuce tissue samples from 1994 to 2010 from each of the Ongare Bay, Otumoetai and Town Reach monitoring sites were used to assess trends over time. Seasonality of the data from each site was tested using a non-parametric Kruskal-Wallis One-way Analysis of variance grouping the data into six two-month blocks for the year. There is no significant seasonal trend for Ongare Bay which has the least missing data. Otumoetai shows a marginally significant seasonal trend (prob. 0.015) while Town Reach site (prob. 0.007) shows a more statistically significant result but shows a different seasonal pattern. Box plots showing the seasonal trends for the $\delta^{15}N$ data are provided in Appendix 4. Figure 15 shows the seasonal spread of $\delta^{15}N$ values for the three sea lettuce monitoring sites.

A seasonal Kendall trend test was used to test for trends in $\delta^{15}N$ values over time at each of the sites. The Ongare Bay $\delta^{15}N$ data showed a marginally significant (prob. 0.02) median annual slope change of -0.025. Town Reach $\delta^{15}N$ data also showed a marginally significant (prob. 0.019) median annual slope change of -0.031.

Table 11 gives descriptive statistics for $\delta^{15}N$ values at each of the three monitoring sites. Ongare Bay has the highest mean $\delta^{15}N$ value (8.7‰) and Otumoetai the lowest (7.9‰). Figure 15 and 16 show the difference in $\delta^{15}N$ values between the sites. Figure 16 shows that the $\delta^{15}N$ values are not related to the tissue N content of sea lettuce.

Table 11 Descriptive statistics for sea lettuce tissue nitrogen stable isotope ratio at each of the monitoring sites for data collected from 1994 to 2010.

	Ongare $\delta^{15}N$	Otumoetai $\delta^{15}N$	Town Reach $\delta^{15}N$
Sample number	51	43	27
Minimum	7.14	6.86	7.71
Maximum	9.90	8.68	9.59
Median	8.67	7.86	8.57
Mean	8.685	7.901	8.590
95% CI	0.147	0.131	0.201
Std dev	0.523	0.425	0.508

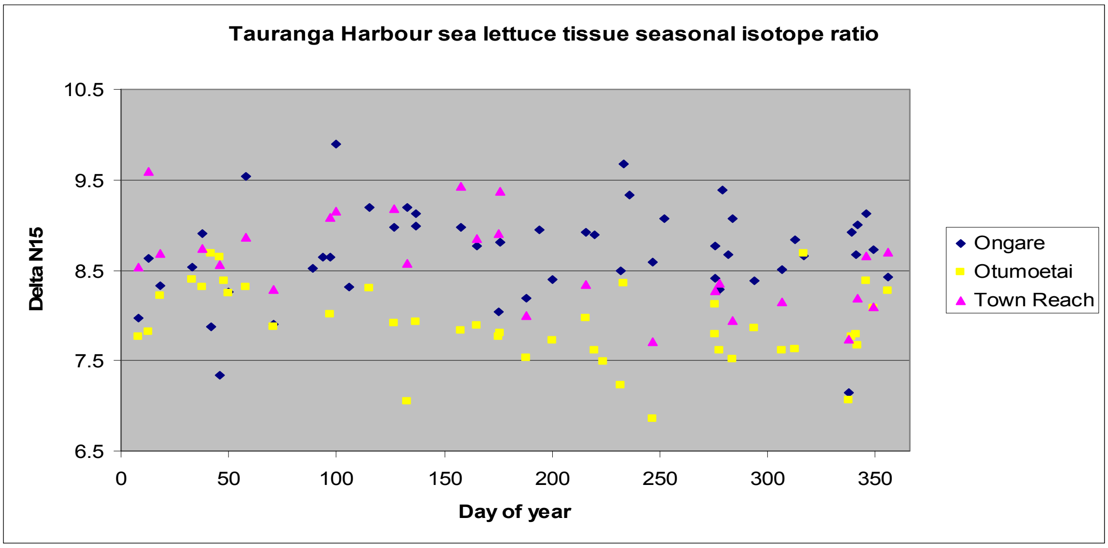

Figure 15 Sea lettuce (Ulva spp.) tissue nitrogen isotope ratio at sites in Tauranga Harbour plotted against the day of year using data from 1994 to 2010.

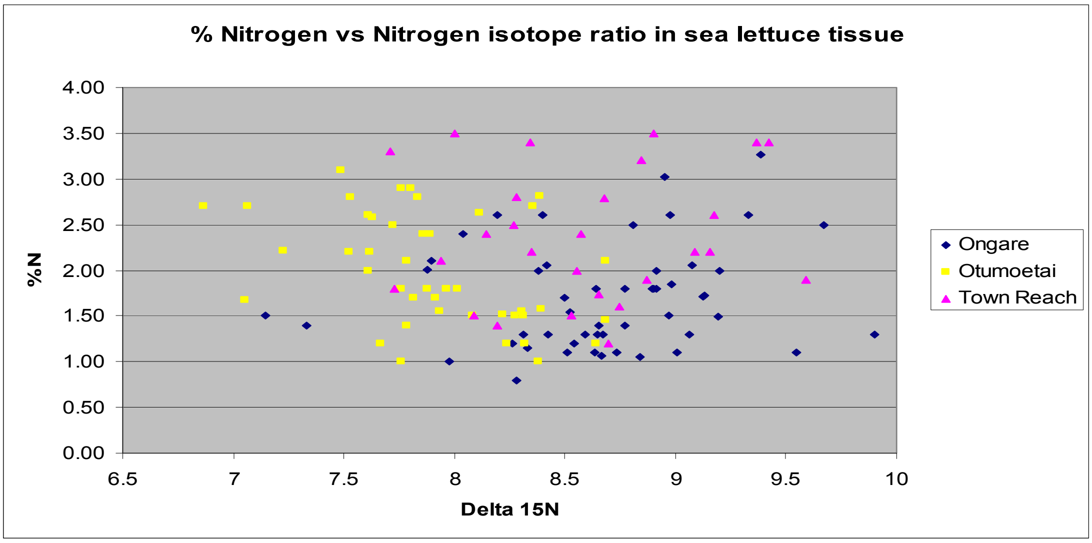

Figure 16 Sea lettuce (Ulva spp.) tissue nitrogen content versus $\delta^{15}N$ at sites in Tauranga Harbour based on samples from 1994 to 2010.

The results of Pearson correlation tests between the nitrogen isotope ratios of sea lettuce tissue and a range of de-seasonalised environmental and sea lettuce nutrient parameters are provided in Table 12 (for parameters that showed a significant result against at least one of the sites). Environmental parameters included climate indices, sea temperature, river inflow and nitrogen load, sea water nutrient concentrations, sea lettuce abundance and tissue nutrient concentrations. Overall there were no strong correlations in the data sets tested and the Town Reach site showed no significant correlations with any of the variables.

Table 12 Statistically significant Pearson correlations (r^2 and prob.) for sea lettuce tissue $\delta^{15}N$ against environmental and tissue nutrient content variables (all de-seasonalised) using data collected from 1994 to 2010.

	$\delta^{15}N$ – Sea lettuce		
	Ongare	Otumoetai	Town Reach
Wairoa River flow	0.113 (0.018)	0.025 (n.s.)	0.008 (n.s.)
Wairoa River DIN load	0.128 (0.012)	0.027 (n.s.)	0.017 (n.s.)
Ongare Bay tissue -%N	0.014 (n.s.)	0.112 (0.033)	0.020 (n.s.)
Ongare Bay tissue - C:N ratio	-0.005 (n.s.)	-0.125 (0.024)	0.014 (n.s.)
Town Reach tissue -%P	-0.161 (0.038)	-0.000 (n.s.)	-0.027 (n.s.)

The most statistically significant correlation result was between the Ongare site $\delta^{15}N$ values and the Wairoa River DIN load. The Ongare site is not influenced by input from the Wairoa River and the Otumoetai and Town Reach sites do not show the same correlation. It is a similar case with the other significant results with no consistent pattern in correlations between any of the variables and all the sites.

Figure 17 shows $\delta^{15}N$ recorded in sea lettuce tissue plotted against time for each of the monitoring sites along with the Oceanic Nino Index. There was no significant correlation between the climate indices and $\delta^{15}N$ values. As with the tissue nitrogen content results, data for the periods of low sea lettuce abundance (i.e. during La Nina) are consistently missing and reduces the ability to detect correlations with climate or other factors.

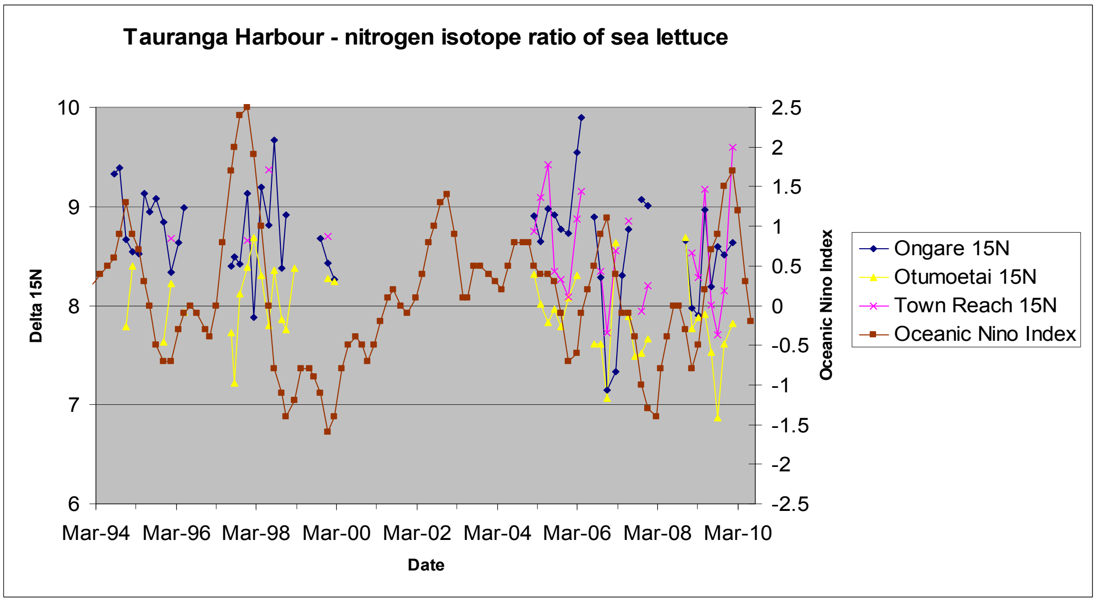

Figure 17 $\delta^{15}N$ isotope ratios in sea lettuce (Ulva spp.) at monitoring sites in Tauranga Harbour from 1994 to 2010.

Part 4: Discussion and summary

4.1 Discussion

4.1.1 Key factors influencing growth/loss (abundance)

The abundance of sea lettuce in Tauranga Harbour is determined by the interaction of complex growth and loss processes and the balance between them. Key determinants of growth rates include nutrients, light and temperature. Loss processes are influenced by physical characteristics with grazing pressure being much lower on sandy shores compared to rocky shorelines. Wave energy and current speeds are also important factors influencing loss rates, particularly through burial or washout from the harbour. The drift and burial components of sea lettuce in Tauranga Harbour have been investigated to some extent (Snow 1995, de Winton et al. 1996, 1998).

(a) Light and sea lettuce abundance

Tauranga Harbour is shallow with 112.5 km^2 of intertidal and 88.5 km^2 of subtidal area of which less than 1.5 km^2 (excluding the port dredged area) exceeds 10 m depth. The average depth of all subtidal area is likely to be around 3 m or less. It has been calculated that for the mid harbour area the depth at which 10% of surface light occurs, which is the point that photosynthesis and growth could start reducing, was around 4-8 m depth (de Winton *et al*. 1996, 1998). Water clarity and light penetration is lower in the upper harbour reaches and higher near the entrances. For a large part of the harbour's subtidal area, light limitation of growth may be low and added to this Tauranga has some of the highest sunshine hours in New Zealand with an annual average of 2260 hours (NIWA 2010) making it an ideal growing environment.

In the analyses of results presented in this report, de-seasonalised sea lettuce abundance showed a significant correlation with de-seasonalised sun hours (prob. = 0.000, r^2 = 0.145) but the relationship is one of declining abundance with increasing sunlight hours. The result although statistically significant is counter to the relationship between light and growth and other correlations in the data sets. For example variation in sunlight hours using a data set from 1971 to 2010 has a small but significant Statistical relationship with the Oceanic Nino Index (prob. 0.002, r^2 0.021). Strong El Nino/La Nina events have around a 3-5% change in average sunshine hours. El Nino events result in more sunshine hours. So although it is clear that light is important in influencing growth, the analysis and results of the abundance data obtained to date do not show this in the extensive year to year variations seen in Tauranga Harbour.

(b) Temperature

Water temperature significantly influences the rate of sea lettuce growth. It is tolerant of low temperature (Vermaat and Sand-Jensen 1987) and a temperature-growth relationship determined for sea lettuce from Christchurch, New Zealand showed increasing growth rate up to a maximum of 16-20 ^{o}C which then fell to zero at 25 ^{o}C (Steffensen 1976). The same result was found for plants taken from Tauranga Harbour (de Winton 1998). Seasonally, water temperature in the main Tauranga channels varies from 12-22 ^{o}C while the shallow upper zones experience a wider range (10-28 ^{o}C).This shows that temperature in the subtidal zones will be near optimum for sea lettuce growth over spring and autumn. In summer the shallow areas of the harbour will exceed optimum or maximum temperature points and result in reduced growth. Results from both subtidal surveys (de Winton 1996, 1998) and this monitoring programme of intertidal sea lettuce show a summer reduction in abundance.

Correlation of de-seasonalised sea lettuce abundance and sea water temperature records from Tauranga Harbour showed a significant result (prob. = 0.005, r^2 = 0.080) with less sea lettuce in years with higher sea temperature. Warmer water temperatures will increase growth only up to the maximum of 20 ^{o}C and summers with higher water temperatures over a longer period will result in greater reductions in growth. Hence it is possible that the results are showing the effect of cooler/warmer summer temperatures on abundance.

(c) **Nutrients**

One of the key factors influencing growth and hence abundance is availability of the two key nutrients, phosphorus and nitrogen with sea lettuce able to use either form of nitrogen (NH_4 or NO_3) and store surplus (Fujita 1985). Either phosphorus or nitrogen can become a limiting nutrient to growth if concentrations fall below critical levels and there is an ideal ratio of both required for growth depending on structural requirements (Atkinson and Smith 1983) and climatic zone (Lapointe *et al.* 1992). These studies and other such as Sfrisco *et al.* (1995) show an N:P ratio of 30:1 to be a relevant standard for assessing nutrient limitation. This would suggest the Town Reach site nearly always has sufficient nitrogen available for growth with Ongare site showing some possible limitation in summer. This is also supported by estimates from De Winton *et al*. (1998) for minimum tissue concentration of 0.8 or more required to support growth. On average neither nitrogen or phosphorus are clearly a "limiting nutrient" (see graph Appendix V) as the N:P ratios and tissue concentrations tend to be favourable.

In terms of growth rates, studies show that high nutrient concentrations are important to maximise growth (Waite & Mitchell 1972, Taylor 1996). Specific growth rates of sea lettuce are high under favourable conditions with recorded rates from 20-30% per day (Parker 1981, Floreto *et al*. 1994, Taylor 1996, Dudley *et al*. 2010). A study of sea lettuce in Tauranga Harbour (de Winton 1998) provides a maximum growth rate estimate, using realistic assumptions, of 28% per day. A growth model developed by Solidoro *et al*. (1997) gives a maximum of 45% per day.

Analysis of variations in de-seasonalised sea lettuce abundance against water nutrient content at each of the monitoring sites shows only one weak result (r^2 0.048 p = 0.027) for the Town Reach site. The relationship is decreasing sea lettuce abundance with increasing DIN. Although this is contrary to expectation it is only a marginally significant result and may show that other growth/loss processes are dominating. Also the high variability in both sea lettuce abundance and water chemistry spot samples would require a large amount of data to clearly identify weaker growth effects.

The cellular nutrient status of sea lettuce reflects the availability of nutrient delivered to the plants over time and generally provides a more reliable indication of nutrient concentrations in the environment. Analysis of relationships between variations in sea lettuce tissue nutrient status and abundance (de-seasonalised) could potentially show links between sea water nutrient concentrations and sea lettuce growth. A marginal correlation (prob. = 0.028, R^2 = 0.058) was found between the nitrogen tissue concentration of

Otumoetai plants and the mean abundance of all sites but not directly with the Otumoetai site. An even stronger correlation (prob. = 0.000, $R2 = 0.102$) exists with Ongare sea lettuce abundance but there is no direct physical connection between these two sites. So at best the result may reflect the existence of a nutrient-abundance relationship or as mentioned above other growth/loss processes dominate.

Although sea lettuce abundance measurements do not show strong correlations with either water chemistry or tissue nutrients, correlations were found between the Otumoetai tissue nitrogen concentration and Wairoa River flow and DIN load. This shows that the variations in catchment derived DIN over time can be detected in sea lettuce nearby and potentially affect growth rates. In a similar way the Town Reach site consistently shows the highest tissue concentrations of nitrogen and phosphorus and N:P ratios and water nutrients. Despite the potential for high sea lettuce growth at this site, no correlations with abundance were found which is consistent with the other results. Abundance is site specific and strongly influenced by hydrodynamic gain/loss processes rather than just in situ growth per se. Abundance at larger scales may be a more reliable indicator of growth in the harbour but flights over the harbour during the more severe blooms of the early 1990's indicated quantitative differences between the north and southern blooms are not great.

Another important factor limiting the ability to find correlations between sea lettuce tissue nutrients and abundance or water chemistry variations over time is that during La Nina weather patterns it is often not possible to collect tissue samples from the routine monitoring sites as no sea lettuce is present. This means that if nutrient is an important factor in determining sea lettuce abundance then we have little data and hence statistical power for those periods of low abundance. It also means that seasonal tissue means using the full length of record are biased towards El Nino conditions.

(d) Terrestrial nutrient inputs

Variations in DIN input of the Wairoa River not only correlated with the tissue concentrations of plants at Otumoetai but also with the sea water concentrations. An interesting aspect of analysing the terrestrial DIN inputs is the climate correlation. It is estimated that during El Nino the DIN load would be reduced by 10% in summer and more in winter. This is in line with climatic variation in rainfall found by Griffiths *et al.* (2003) for the Bay of Plenty using much longer datasets and similar to results found by McKerchar *et al.* (2010) for stream flow on the east coast of the South Island. A consequence of this is that DIN inputs to the harbour are greatest in La Nina years when sea lettuce abundance tends to be lower. Hence, although sea lettuce tissue may reflect variations in terrestrial DIN inputs, sea lettuce abundance in Tauranga Harbour appears to be driven by factors other than variation in terrestrial DIN.

Another key question for the blooms in Tauranga Harbour is whether the terrestrial/anthropogenic nutrient sources are increasing over time and causing increased sea lettuce growth. This can only be checked for the period since the start of the Bay of Plenty Regional Council's water quality monitoring programme in 1990 and the sites that it covers. For estuarine water quality sites a report by Scholes (2005) shows that total phosphorus concentrations (for the period 1991 – 2005) in the northern harbour show no change and declined in the southern harbour. The decline in total phosphorus is most pronounced in the Town Reach. For nitrate/nitrite nitrogen the only change is a weak decline for a shorter time period (98-05) in the Otumoetai Channel. The northern harbour shows the only change in ammonium nitrogen with an increase from 1991 – 2005. Overall the harbour does not show any strong or consistent trends of nutrient increase over this period but this does not exclude probable past increases.

Changes in the concentrations of nutrients in rivers and streams discharging to Tauranga Harbour have been analysed and presented by Scholes and McIntosh (2009) and these are summarised in Table 13.

Table 13 Changes in the concentrations of nutrients in rivers and streams discharging to Tauranga Harbour (data from 1990-2008, Scholes and McIntosh 2009).

River/stream	Harbour	NOx-N	NH4-N	TN	DRP	TP
Waitao	south	decrease	decrease	decrease	decrease	decrease
Kopurererua	south	increase	no change	increase	no change	decrease
Ngamuwahine	south	no change	increase	no change	no change	no change
Omanawa	south	increase	no change	increase	no change	no change
Wairoa	south	increase	no change	increase	no change	increase
Waipapa	south	decrease	decrease	decrease	decrease	decrease
Te Mania	north	no change	no change	no change	no change	no change

Overall the changes to the harbour for this period can be summed up by stating that the most significant nutrient increases have been for nitrogen inputs to the Omanawa, Kopurererua and Wairoa catchments. The Wairoa River nitrogen inputs were shown to be correlated with climate and this may account for some if not all of the increase over this period due to the strong and prolonged El Nino in the early 1990's. Since nitrogen increases are only detectable for some of the southern harbour inputs the overall impact on sea lettuce growth (if any) is likely to be low and localised.

Although catchment nutrient input pressures will be increasing with rapid growth and development over time, there have been a number of policy and regulatory changes to reduce nutrient inputs to Tauranga Harbour since 1991 when monitoring of sea lettuce started. In 1989 the fertiliser plant (now owned by Ballance Agri-nutrients Ltd) was discharging around 50 kg/day of dissolved phosphorus to the Town Reach compared to the catchment load of 7 kg/day measured in 1990/91 or 33 kg/day for the whole southern harbour (McIntosh 1994). By 1992 this had dropped dramatically to less than 2 kg/day and is now even lower.

Another major point source discharge to the southern harbour that ceased in 1995 was the Tauranga City Council treated sewage discharge from the Chapel Street plant into the Otumoetai Channel. Prior to ceasing discharge it contributed around 130 kg/day of phosphorus and 500 kg/day of nitrogen in the form of ammonium nitrogen. In comparison the estimated 1990/91 input of total dissolved inorganic nitrogen from the Wairoa River is 611 kg/day (43% of total harbour catchment inputs). These two changes alone represent a large reduction in catchment/anthropogenic nutrient input to the southern harbour but there have not been any clearly discernable reductions in sea lettuce abundance.

The northern harbour catchment is significantly smaller than the southern harbour with much less nutrient inflow. Dissolved phosphorus inflows in 1990/91 were estimated to be less than 4 kg/day and dissolved inorganic nitrogen 48 kg/day (McIntosh 1994). Despite this low nutrient input the sea lettuce blooms have usually been just as extensive if not worse than in the southern harbour. The extensive Tauranga Harbour water quality survey in 1990/91 (McIntosh 1994) noted that at some sites dissolved nutrient loads of the incoming tide are higher than the water in the harbour and that there is little difference in water chemistry between similar sites in the northern and southern ends. The weight of evidence suggests that while terrestrial/anthropogenic nutrient inputs to Tauranga Harbour are an important factor to consider in sea lettuce growth, they are not the main drivers of the harbour wide blooms.

4.1.2 The use of nitrogen stable isotopes

Stable isotopes have been frequently used to trace nutrient contributions from specific sources such as land runoff or other anthropogenic inputs (Udy & Dennison 1997, McClelland & Valiela 1998, Gartner *et al*. 2002). The technique has also been used in New Zealand to examine the impact of sewage discharges on the $\delta^{15}N$ values of sea lettuce (Rogers 1999, 2003, Dudley & Shima 2010). In general microbial processes and transfer of nitrogen between trophic levels in food webs are strongly discriminatory processes selectively utilizing ^{14}N to produce $\delta^{15}N$ enriched values. Hence values in raw sewage tend to be much lower than tertiary treated sewage and ground water influenced only by atmospheric deposition typically bears NO_3^--$\delta^{15}N$ values ranging from +2 to +8‰ while nitrate from synthetic fertilizer is depleted in 15N (-3 to +3‰). In the marine environment $\delta^{15}N$ values vary with environment, depth and the form in which nitrogen is measured. A review by Liu & Kaplan (1989) suggest typical coastal values for POM-N range around 6.3-10‰ while NO3-N of deep oceanic water is typically low around 5.7‰ but ranges up to 19‰ in tropical denitrifying zones.

The $\delta^{15}N$ values for marine water samples around Tauranga Harbour displayed a wide range due to freshwater influence which complicates comparison with other studies. The offshore surface and deep water samples are similar to other reported studies (Liu & Kaplan 1989) but the freshwater inflow nitrate $\delta^{15}N$ values are lower than typical from overseas studies. All the measured inflows do have reasonably consistent values with the exception of Tuapiro Stream in the northern end of the harbour.

As nitrate nitrogen is the main form of nitrogen found in terrestrial nitrogen inputs to Tauranga Harbour the implication is that if the nitrate $\delta^{15}N$ values are correct, terrestrial inflows will tend to lower the $\delta^{15}N$ values in algae or animals utilizing this source of nitrogen. This is supported by the observed correlation between the marine results and salinity. The Kopurereua Stream and Waimapu River typically have 75-80% of the nitrogen present as nitrate and have $\delta^{15}N$ results with low values while results based on all dissolved nitrogen shows the organic and ammonium nitrogen fraction must have a high $\delta^{15}N$ value, presumably as a result of biological processes.

The effect of nitrogen inflows potentially reducing $\delta^{15}N$ values in sea lettuce tissue from around Tauranga Harbour is also seen in the results for the Tilbey Point site with the lowest summer and winter values of 7.6‰ compared to all other sites. Tilbey Point also recorded the lowest salinity with a strong influence from the Wairoa River. In contrast the highest $\delta^{15}N$ value of 9.3‰ occurred in summer at Kauri Point in an area of low land runoff influence but with very large quantities of rotting sea lettuce suggesting the in-situ effect of microbial processes fractionating out ^{15}N.

Other aspects of the results are comparable to the extensive sea lettuce tissue $\delta^{15}N$ values obtained by Barr (2007) from a range of sites and environments around New Zealand. As found by Barr (2007) there is a trend for enriched urban sites to have higher $\delta^{15}N$ values as seen in the Town Reach, Waimapu, Welcome Bay and Rangataua Bay sites. Waikareao Estuary also has an urban catchment and stands out from this trend as it has similar $\delta^{15}N$ values to all other rural harbour locations.

Overall results suggest that at relatively small scales, sediment enrichment and the extent of microbial activity and subsequent nutrient recycling may play an important role in producing the variability in $\delta^{15}N$ values with the trend to higher values as the local environment is more enriched. There is a need to understand the variability of microbial processes and nutrient recycling around the harbour, their input to productivity and sea lettuce blooms.

The results presented in this report suggest that the power of tissue $\delta^{15}N$ to identify the relative sources of nutrients in sea lettuce may be limited in Tauranga Harbour. In particular there is a need to better understand the local dynamics of nutrient recycling. The relationship between $\delta^{15}N$ and %N in sea lettuce tissue (Figure 16) highlights this as the Ongare Bay site has little land runoff influence but the same $\delta^{15}N$ value as Town Reach which has higher catchment influence and higher tissue nitrogen content.

Due to missing samples in the time series of sea lettuce tissue $\delta^{15}N$ values it remains unclear how and to what extent values at a given site vary over time. The key factors are likely to be variations in land runoff influence with that from deep ocean water and perturbations in local nutrient recycling as seen at Kauri Point with the decomposing sea lettuce.

4.2 Summary

This re-analysis of spatial and temporal environmental data has provided increased confidence and understanding of the dynamics between environmental factors and sea lettuce abundance in Tauranga Harbour. The key points can be summarised as follows:

- The strongest correlation between sea lettuce abundance and environmental factors is that of climate with high abundance tending to occur in El Nino periods and low abundance during La Nina. The influence of climate on water temperature in the harbour is at least part of the reason climate drives variations in abundance. Analysis of nutrients in tissue and water fails to show any clear influence of a climate associated deep ocean nutrient influx to the harbour.
- Analysis of climate and terrestrial nutrient inputs against sea lettuce tissue and water nutrient content shows that terrestrial nutrient variations can be detected in the sea water and in tissue. These variations are also shown in a geographical context with Town Reach showing higher water and tissue nutrient content. However the variations in terrestrial nutrient inputs do not correlate with overall sea lettuce abundance in the harbour. Terrestrial inputs of nitrogen vary with reductions of around 15% in El Nino years, the period in which sea lettuce has been most abundant in the harbour. This does not mean that nutrient is not increasing growth to some extent but more a case of other growth/loss processes dominating sea lettuce abundance.
- Previous analysis of harbour water concentrations over time (Scholes 2005) and freshwater inflows (Scholes & McIntosh 2009) show only minor changes in nutrients at a few sites. Overall the minor change in the nutrient status of the harbour since 1990 is not likely to be linked to any significant increase in sea lettuce abundance. During the same period the marked reduction of phosphorus discharged from the fertiliser plant to Town Reach in the early 1990's and removal of the Tauranga City Council sewage discharge from the harbour have made a significant reduction to the terrestrial nutrient inputs.

- Strong seasonal patterns are shown in a number of important factors influencing sea lettuce growth including nutrient concentrations and water temperature which is now well defined. These environmental trends are shown in sea lettuce abundance and tissue nutrient status.

- Nitrogen stable isotope values ($\delta^{15}N$) in harbour inflows are low and these are influencing the values in harbour water. As a result sea lettuce tissue $\delta^{15}N$ values are lower at sites that are influenced by freshwater inflows and highest in areas of sediment nutrient/organic enrichment where nutrient recycling is likely to be higher. Comparison with data from Barr (2007) shows values in the southern most area of the harbour match sites classified as "urban enriched".

Overall the analysis of sea lettuce abundance against a range of environmental variables has highlighted the complexity of the dynamic interactions that drive growth and loss processes and the limitations of data analysis without complex models. In that respect it shows the need to create a full hydrodynamic and physiological growth model for sea lettuce in Tauranga Harbour. Development of a growth model will capitalise on the extensive environmental and physiological research already undertaken on sea lettuce in Tauranga Harbour. This will allow quantitative assessments to be made of the influence of factors affecting growth such as terrestrial nutrient inputs.

4.3 Recommendations

This analysis has improved our understanding of the factors driving sea lettuce growth in Tauranga Harbour. However, there are gaps in our knowledge and the following recommendations are made to address these:

- Develop a fully integrated hydrodynamic based growth model of sea lettuce in Tauranga Harbour. This is needed because of the complexity of interacting variables that ultimately drive abundance. A quantitative model would allow predictions of abundance under a range of conditions and assist with developing mitigation or control options.
- Implement harbour-wide surveys of subtidal sea lettuce to more accurately map extent and biomass.
- Improve spatial assessments of intertidal sea lettuce abundance across the whole harbour. This will help identify production areas and rates, accumulation/loss and nutrient recycling zones and ultimately more accurately identify growth drivers including climatic influences.
- Improve the frequency of nutrient measurements within the harbour. Ideally a nutrient logger with associated sensors (e.g. chlorophyll, turbidity, temperature) should be set up in the southern basin.
- Update the bathymetry of the subtidal areas throughout Tauranga Harbour. This is needed to improve the accuracy of hydrodynamic models and habitat mapping.
- Map and identify the dynamics of sediment nutrient recycling in the harbour. This is required to quantify contributions to algal production, particularly sea lettuce blooms.

Finally, while not the subject of this report, it is recommended that research also be initiated to help understand the effects that sea lettuce blooms have on the ecology of the harbour. These effects can be positive (e.g. providing a food source for fish) and negative (e.g. smothering of benthic communities).

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Appendices

Appendix 1 – Site information

Site sample number information for sea lettuce (and *Undaria*, *Carpophyllum*) tissue samples collected on the 26 February and 24 June.

Site	BOPRC site number	east	north	Sample-Feb	sample-Jun
Tuapiro Estuary	160295	2770848	6409043	101499	103446
Ongare Point	160297	2772675	6407526	101501	103461
Ongare Bay	720025	2772900	6406800	101500	103443
Kauri Point	160298	2773429	6405348	101502	103447
Kauri Point South	160210	2772964	6405053	101503	103448
Katikati – Beach Rd	150009	2771500	6401800	101504	103449
Ōmokoroa Wharf	800068	2779700	6392100	101505	103456
Omokoroa South	160300	2779133	6391392	101506	103457
Te Puna Estuary	160293	2779190	6389130	101507	103458
Te Puna beach	720048	2782300	6389100	101508	103459
Tilbey Pt	150008	2785700	6388900	101509	103454
Otumoetai	720004	2788800	6388700	101510	103444
Waikareao Estuary	900025	2789000	6387300	101511	103450
Town Reach	720001	2789500	6383900	101512	103445
Waimapu Estuary	160302	2789261	6382586	101513	103451
Welcome Bay	980061	2791600	6382540	101514	103455
Rangataua Bay	160049	2791400	6383600	101515	103452
Mount Maunganui	160301	2789906	6391305	101516	103453
Mt - Undaria	160301	2789906	6391305	-	103559
Mt - Carpophyllum	160301	2789906	6391305	-	103560

Site and sample number information for water samples collected on the 26 February and 24 June.

Site	Sample-Feb	Sample-Jun	BOPRC site number	East	North
Tuapiro Estuary -ramp	101334	103401	160295	2770848	6409043
Tuapiro Stream	101335	103402	110038	2769100	6407800
Ongare Bay	101336	103423	720025	2772900	6406800
Uretara Stream	101337	103402	160123	2768100	6401600
Wainui Stream	101338	103404	710027	2771300	6392200
Ōmokoroa - wharf	101377	103439	800068	2779700	6392100
Te Puna Stream	101376	103405	160294	2777880	6386403
Wairoa River – SH2	101375	103406	160122	2783100	6384500
Tilbey Point	101378	103442	150008	2785700	6388900
Otumoetai	101380	103424	720004	2788800	6388700
Otumoetai – storm water	101379	103426	720094	2788420	6388070

Site	Sample-Feb	Sample-Jun	BOPRC site number	East	North
Kopurererua	101422	103407	210290	2788110	6384640
Grace Road	101381	103425	720001	2789500	6383900
Grace Road - storm water	101382	103427	720100	2789410	6383870
Waimapu River	101374	103408	110032	2787200	6380000
Maungatapu Bridge	101423	103430	160049	2791400	6383600
Harbour entrance - low tide	101425	103428	160301	2789906	6391305
Harbour entrance - high tide	101424	103429	160301	2789906	6391305
Sewage raw – Chapel St	101683	-	400004	2789285	6387329
Sewage treated – outfall point	101684	-	900097	2796535	6387555
Whakatane 200 m surface	-	103393	730042	2877580	6380890
Whakatane 200 m depth contour	101892	103394	730042	2877580	6380890

Appendix 2 – Pearson correlation matrix of sea lettuce and environmental parameters

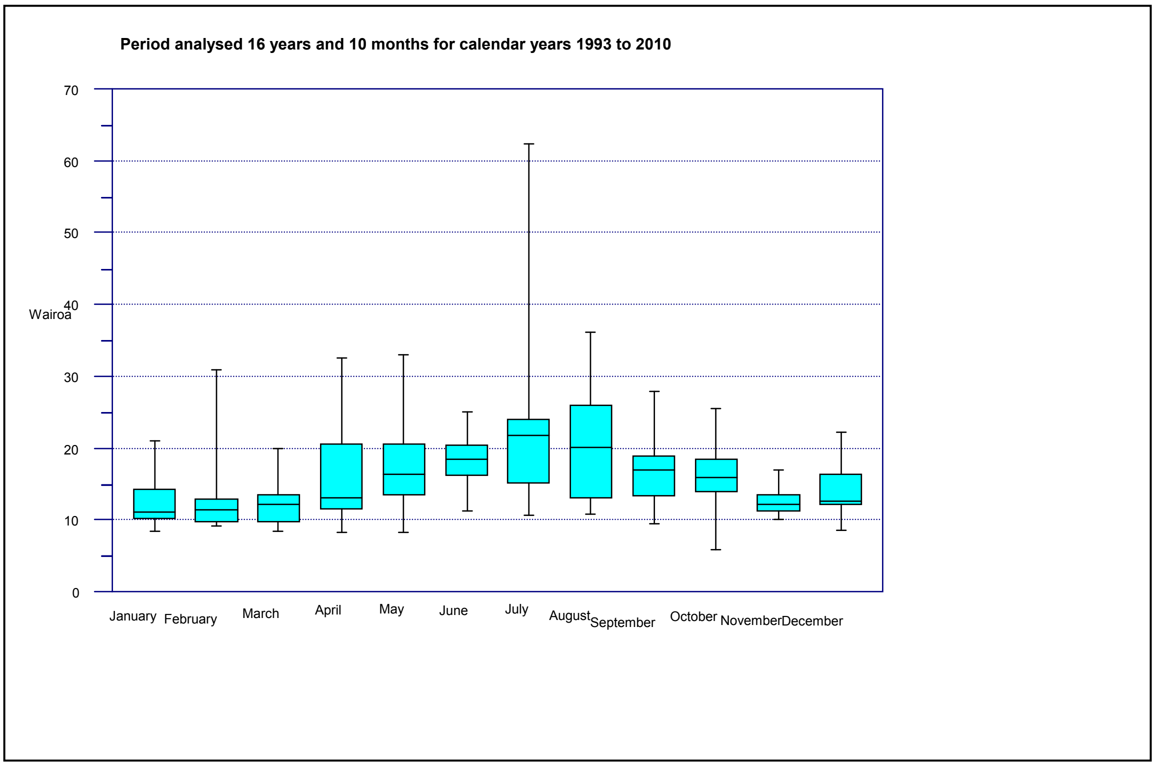
	Abundance	Ong-abd	Otu-abd	Town-abd	SOI	SOI5mma	ONI	SeaTemp	Wai-F	Wai-N
Ong-abd	0.847									
Otu-abd	0.843	0.556								
Town-abd	0.743	0.472	0.675							
SOI	-0.406	-0.278	-0.337	-0.320						
SOI5mma	-0.539	-0.455	-0.417	-0.395	0.773					
ONI	0.416	0.354	0.333	0.352	-0.700	-0.823				
SeaTemp	-0.283	-0.295	-0.210	-0.225	0.395	0.374	-0.400			
Wai-flow	-0.155	-0.078	-0.114	-0.143	0.259	0.275	-0.266	0.030		
Wai-DN	-0.139	-0.064	-0.094	-0.124	0.243	0.262	-0.257	0.004	0.978	
Kopu-DN	-0.030	0.027	0.003	-0.105	0.131	0.230	-0.186	0.059	0.617	0.591
Ong-N	-0.155	-0.201	-0.020	-0.172	0.021	0.004	0.019	-0.046	0.356	0.360
Otu-N	0.241	0.319	0.042	0.149	-0.120	-0.169	0.209	-0.228	0.392	0.397
Town-N	0.065	0.004	0.045	0.086	-0.096	-0.004	0.027	-0.004	0.315	0.292
Ong-CN	0.044	0.141	-0.077	0.064	-0.113	-0.121	0.126	-0.037	-0.354	-0.339
Otu-CN	-0.253	-0.259	-0.109	-0.202	-0.007	0.030	-0.019	0.223	-0.433	-0.436
Town-CN	-0.125	-0.107	-0.067	-0.058	0.068	0.053	0.002	-0.004	-0.226	-0.210
Ong-P	-0.161	-0.197	-0.049	-0.178	0.004	-0.063	0.018	-0.150	0.225	0.239
Otu-P	0.181	0.293	-0.020	0.017	0.064	-0.055	0.017	-0.189	0.242	0.238
Town-P	0.091	0.036	0.097	0.014	0.065	0.039	-0.125	-0.135	0.239	0.215
HT-DRP	-0.053	-0.044	-0.077	-0.048	-0.137	-0.086	0.060	-0.069	-0.016	-0.026
LT-DRP	-0.107	-0.113	-0.131	-0.055	-0.087	-0.029	0.003	0.023	0.034	0.004
HT-N	-0.003	-0.083	0.032	0.067	-0.095	0.017	-0.027	0.159	0.131	0.135
LT-N	-0.190	-0.093	-0.190	-0.220	0.004	0.147	-0.161	0.026	0.328	0.330
Ong lt-N	-0.130	-0.112	-0.095	-0.146	0.094	0.118	-0.137	0.051	0.040	0.037
Otu lt-N	-0.158	-0.033	-0.198	-0.182	0.009	0.138	-0.082	0.053	0.363	0.381
Town lt-N	-0.091	-0.030	-0.067	-0.172	0.118	0.138	-0.174	0.101	0.234	0.222
Bowen ht-N	0.101	-0.034	0.127	0.218	-0.061	0.107	-0.072	0.091	0.079	0.068
Out ht-N	-0.093	-0.127	-0.073	-0.001	0.133	0.168	-0.161	0.113	0.435	0.451
Mau ht-N	-0.074	-0.066	-0.052	-0.064	0.023	0.037	-0.019	0.097	-0.007	-0.001

	Kopu-N	Ong-N	Otu-N	Town-N	Ong-CN	Out-CN	Town-CN	Ong-P	Out-P	Town-P
Ong-N	0.239									
Out-N	0.297	0.324								
Town-N	0.377	0.273	0.570							
Ong-CN	-0.246	-0.801	-0.292	-0.341						
Out-CN	-0.304	-0.390	-0.858	-0.548	0.466					
Town-CN	-0.348	-0.246	-0.550	-0.765	0.372	0.640				
Ong-P	0.066	0.777	0.312	0.120	-0.616	-0.435	-0.247			
Out-P	-0.010	0.308	0.665	0.213	-0.277	-0.668	-0.259	0.487		
Town-P	0.091	0.257	0.336	0.642	-0.299	-0.377	-0.496	0.400	0.474	
HT-DRP	-0.133	-0.051	0.010	-0.120	0.082	0.040	0.080	0.018	-0.043	-0.200
LT-DRP	0.018	0.163	0.240	0.138	-0.122	-0.114	-0.014	0.085	0.201	0.059
HT-N	0.003	0.128	0.038	0.096	-0.155	-0.020	-0.010	0.098	-0.071	-0.028
LT-N	0.236	0.233	0.095	-0.012	-0.167	-0.055	0.022	-0.011	-0.047	0.050
Ong lt-N	0.095	0.207	0.215	0.046	-0.114	-0.110	0.021	0.013	0.133	0.062
Otu lt-N	0.436	0.290	0.133	-0.024	-0.180	-0.120	0.035	0.095	0.042	-0.012
Town lt-N	0.323	0.110	-0.087	-0.011	-0.094	0.081	0.022	-0.070	-0.220	0.077
Bowen ht-N	0.007	0.031	0.015	0.118	-0.034	-0.079	-0.026	-0.018	-0.081	0.104
Out ht-N	0.104	0.085	0.071	0.080	-0.118	-0.061	0.007	0.106	0.062	0.050
Mau ht-N	-0.001	0.056	0.090	0.190	-0.022	-0.042	-0.025	0.085	-0.095	-0.087

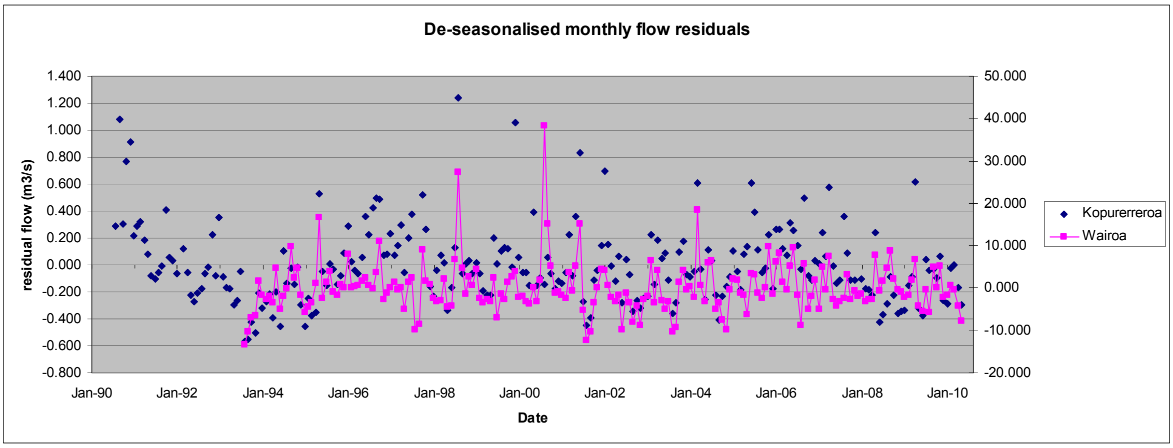
	HT-DRP	LT-DRP	HT-N	LT-N	Ong lt-N	Otu lt-N	Town lt-N	Bowenht-N	Out ht-N
LT-DRP	0.101								
HT-N	0.206	0.078							
LT-N	0.080	0.092	0.037						
Ong lt-N	0.067	0.238	-0.115	0.433					
Otu lt-N	-0.081	0.041	0.067	0.734	0.186				
Town lt-N	-0.101	0.023	0.035	0.712	0.154	0.551			
Bowen ht-N	0.304	-0.137	0.513	0.131	0.003	0.058	0.006		
Out ht-N	0.253	0.038	0.686	0.171	-0.004	0.110	0.064	0.476	
Mau ht-N	0.158	-0.012	0.813	-0.048	-0.161	0.009	0.023	0.252	0.370

Parameters in matrix are all de-seasonalised residuals except SOI, ONI, HT-DRP and LT-DRP. Abbreviated parameters are: **Abundance** is mean % cover of all sites, **Ong/Out/Town-abd** is mean % cover of each site, **SOI5mma** is the 5 month moving average of Southern Oscilation Index, **ONI** is the Oceanic Nino Index, **Wai-flow** is mean monthly flow of Wairoa River, **Wai-DN** is monthly dissolved nitrogen for Wairoa River, **Kopu-DN** is monthly dissolved nitrogen for Kopurererua Stream, **SeaTemp** is monthly sea temperature from Tauranga Harbour, **Ong/Otu/Town-N** is tissue nitrogen, **Ong/Out/Town-CN** is carbon to nitrogen ratio, **Ong/Out/Town-P** is tissue phosphorus, **HT-DRP** is high tide dissolved reactive phosphorus of water, **LT-DRP** is low tide dissolved reactive phosphorus of water, **HT-N** is high tide dissolved inorganic nitrogen water concentrations, **LT-N** is low tide dissolved inorganic nitrogen water concentrations, **Ong lt-N** is low tide concentrations of dissolved inorganic nitrogen water concentrations at Ongare Bay, **Otu lt-N** is low tide concentrations of dissolved inorganic nitrogen water concentrations at Otumoetai, **Town lt-N** is low tide concentrations of dissolved inorganic nitrogen water concentrations at Town Reach, **Bowen ht-N** is high tide concentrations of dissolved inorganic nitrogen water concentrations at Bowen Town, **Otu ht-N** is high tide concentrations of dissolved inorganic nitrogen water concentrations at Otumoetai, **Mau ht-N** is high tide concentrations of dissolved inorganic nitrogen water concentrations at Maunganui Bridge.

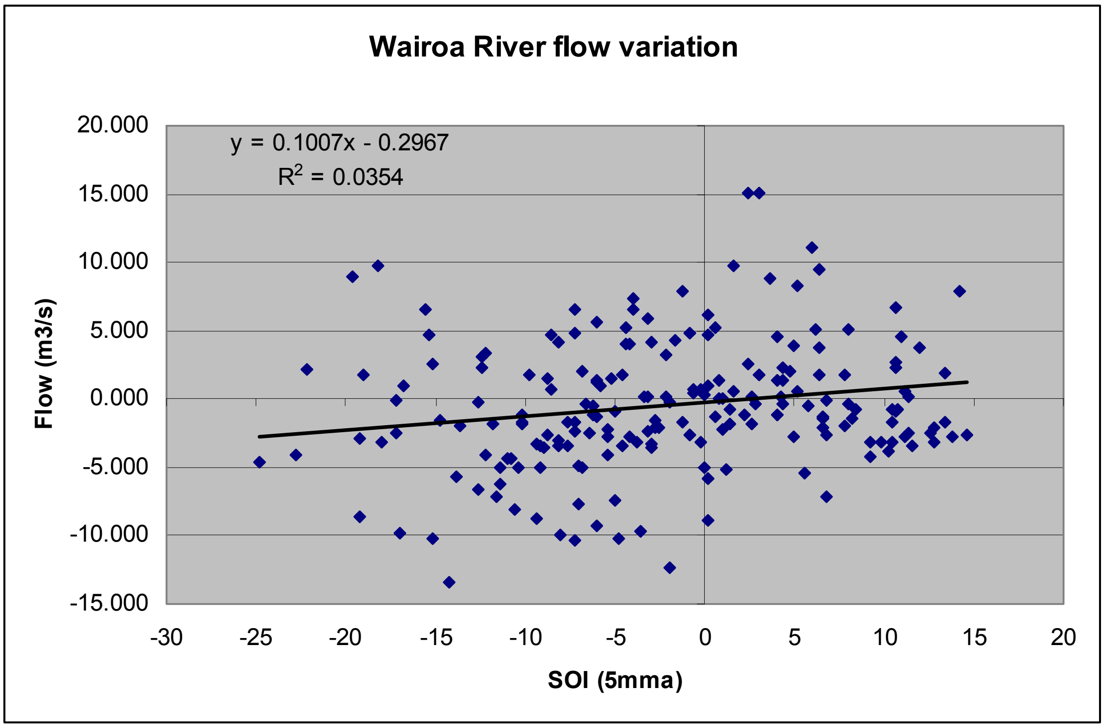
Appendix 3 – Wairoa River flow plots



Box plot of seasonal monthly mean flow (m^3/s) for the Wairoa River below the power station based on flow records from 1993 to 2010.

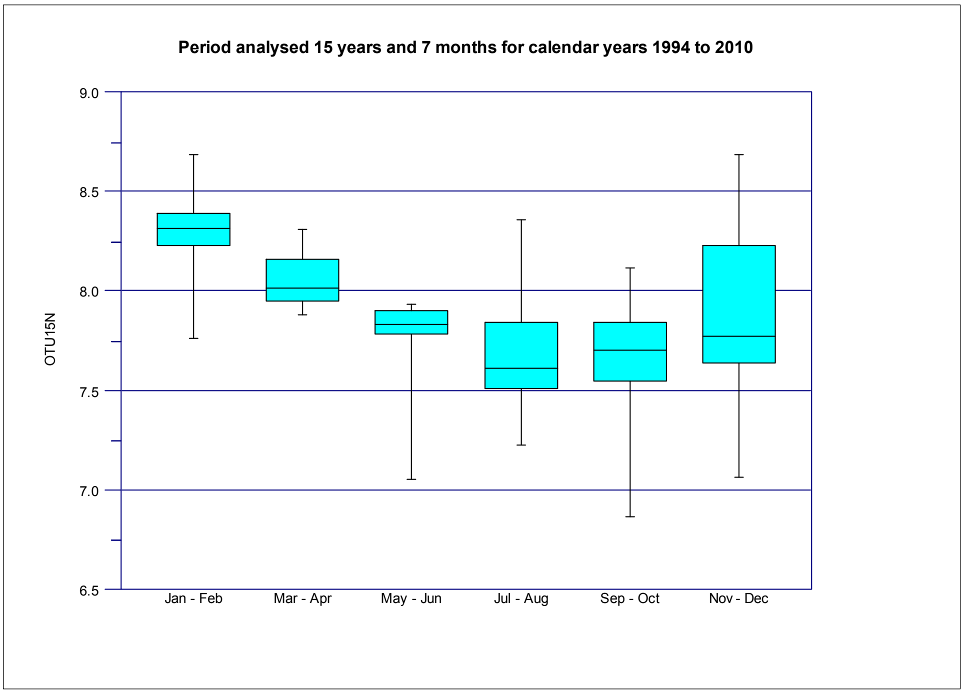


De-seasonalised flow residuals (monthly mean m^3/s) for the Wairoa River (below the power station) and Kopurereroa Stream (SH29).

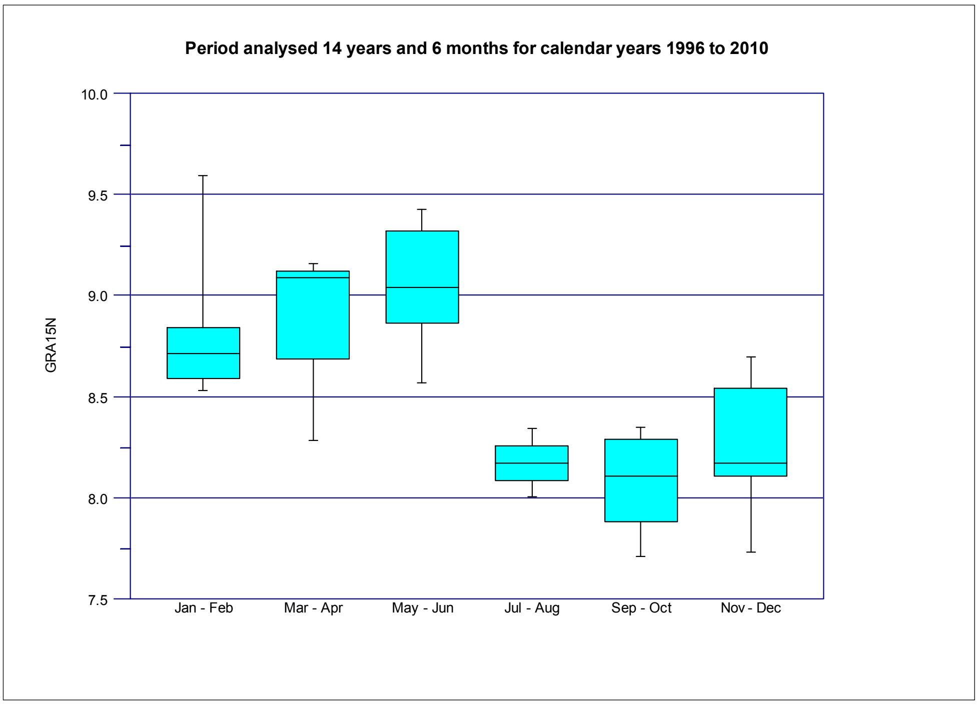


Plot of the de-seasonalised flow (monthly mean m^3/s) residuals for Wairoa River below the power station versus the five month moving average of the Southern Oscillation Index.

Appendix 4 – Plots of seasonal δ15N values in sea lettuce

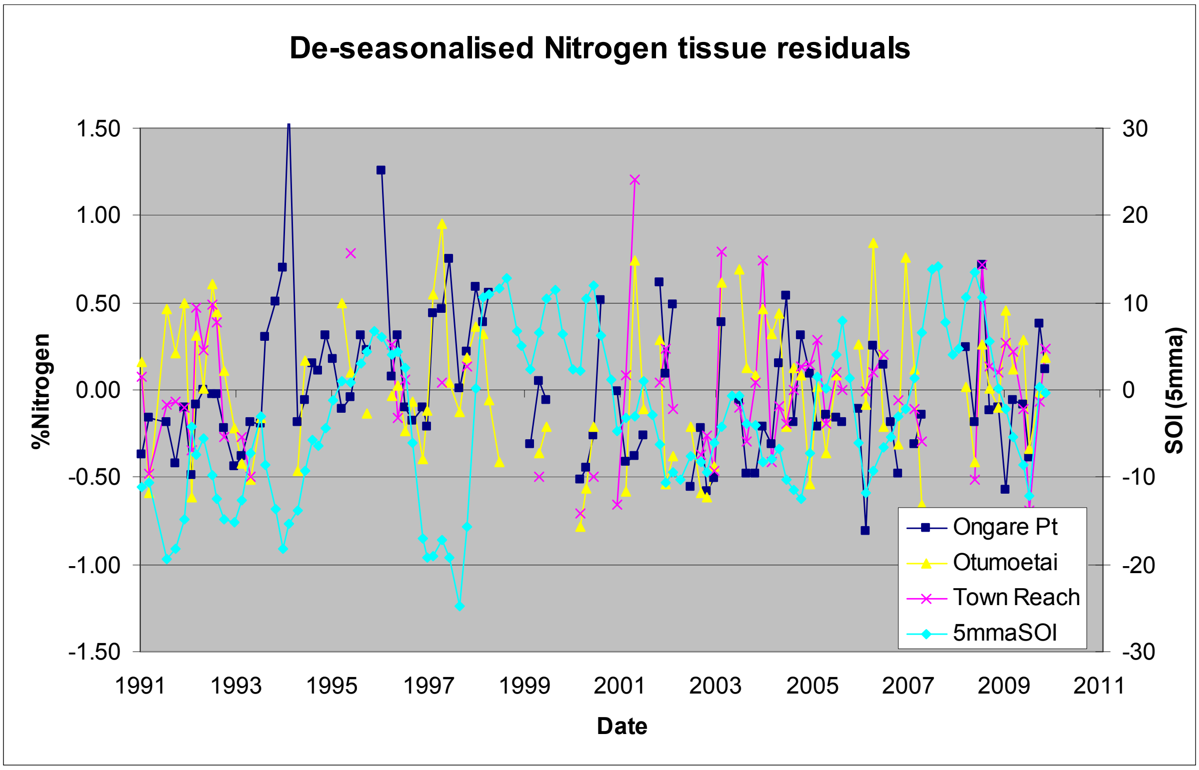


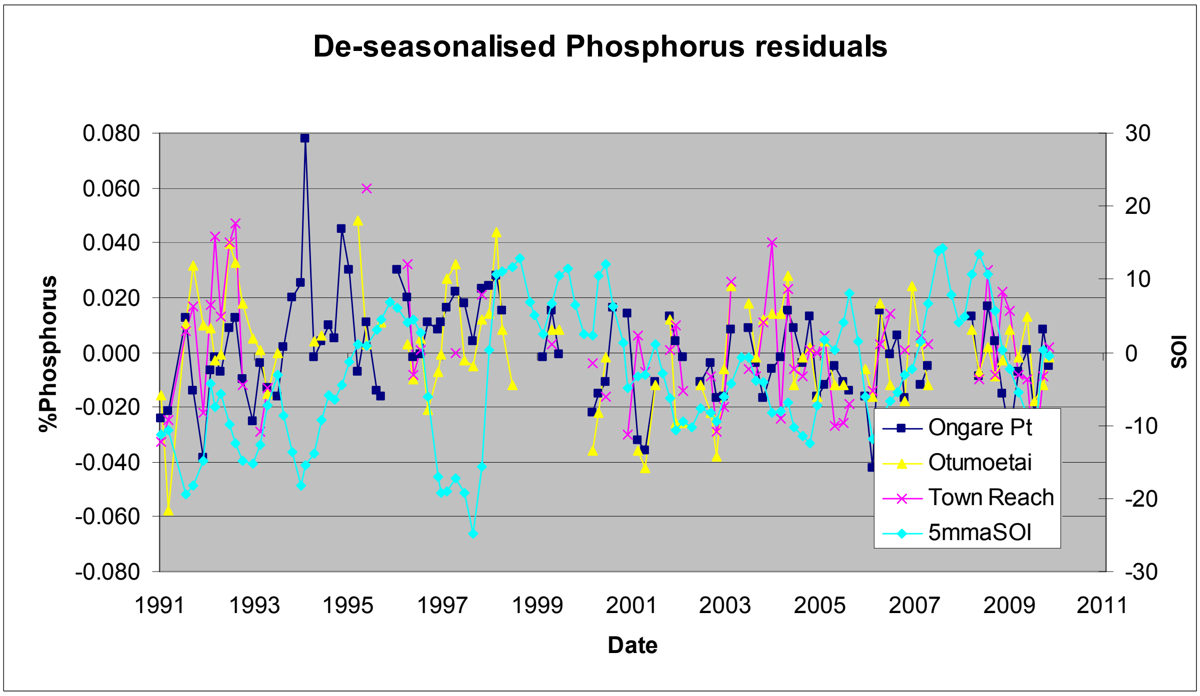
Seasonal box plot of sea lettuce tissue $\delta^{15}N$ values from the Otumoetai site.

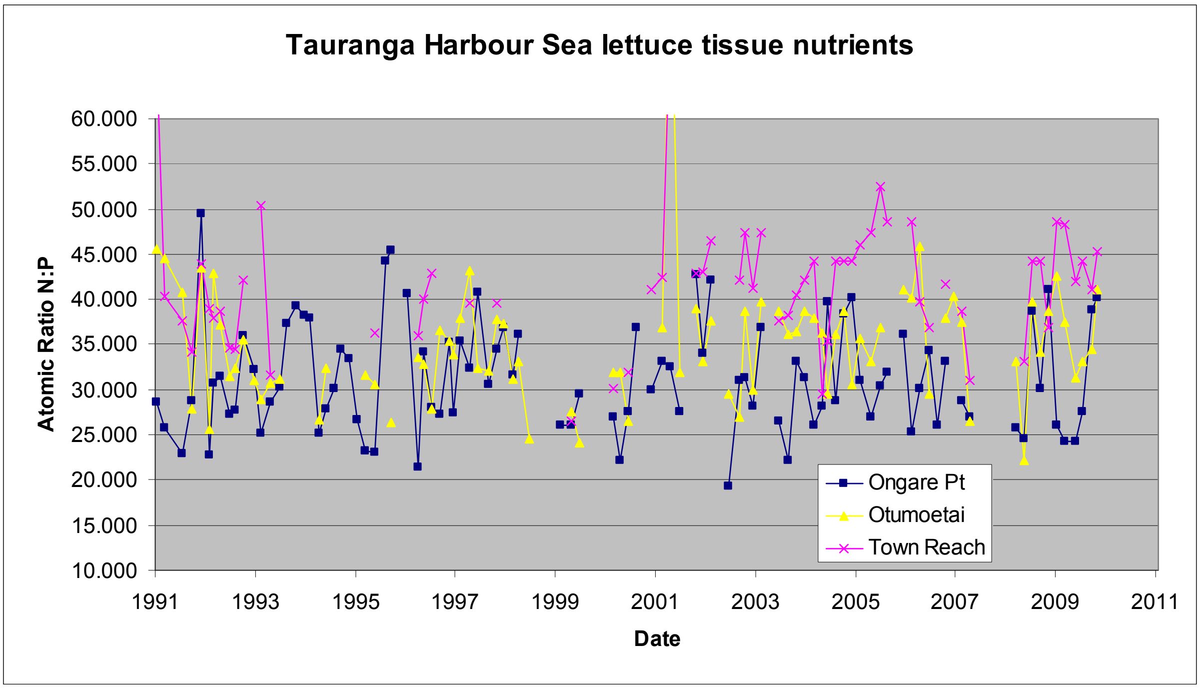


Seasonal box plot of sea lettuce tissue $\delta^{15}N$ values from the Town Reach site (based on data from 1994 to 2010).

Appendix 5 – Plots of tissue nutrient values in sea lettuce






Tauranga Harbour Sea lettuce tissue nutrients
60.000
55.000
50.000
45.000
40.000
35.000
30.000
25.000
20.000
15.000
10.000
Atomic Ratio N:P
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
Date
Ongare Pt
Otumoetai
Town Reach