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EXECUTIVE SUMMARY

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The abundance of the agar seaweed *Pterocladia lucida* was estimated over a two-year period at Waihau Bay, eastern Bay of Plenty. Rectified aerial photographs were used as the basis of a Geographic Information System (GIS) database in which the area of reef was estimated. Abundance was estimated in replicate 0.25 m^2 quadrats in three strata. Biomass was estimated using both a stratified random sampling design and by kriging. Both methods produced estimates of biomass in summer-autumn of between 146 and 200 t in the 436 556 m^2 area sampled. Mean estimates of the winter biomass, in August 2000, were 119 and 121 t for the two methods respectively.

The recovery of plants harvested in summer and winter by plucking and cutting was quantified in an experiment. In the summer treatments, both cut and plucked plants recovered to their initial biomass levels in 12 months. When harvested in winter, both cut and plucked plants remained at significantly lower biomass than the controls and were significantly smaller than they were at the beginning of the experiment.

There was no significant effect of removing *P. lucida* on the abundance of large brown algae or large mobile invertebrates.

There is a large resource of *P. lucida* at Waihau Bay. Our small-scale experiments suggest that live plants may be harvested sustainably if harvested in summer. Whether this conclusion applies to larger scales and other years and places will need to be tested.

1. INTRODUCTION

Agar fisheries in New Zealand are based primarily on two species of *Pterocladia*: *P. lucida*, which makes up 95% of this harvest and *P. capillacea*, which accounts for the remainder. *P. lucida* occurs around the Three Kings Islands and the North Island and in the northern South Island as far south as Kaikoura and northwest Nelson and the Chatham Islands (Chapman 1970, Adams 1994). The main areas of commercial harvest are on the Wairarapa coast, the Bay of Plenty, Hawke Bay, Poverty Bay, and Northland, particularly at Brampton Shoals (Figure 1).

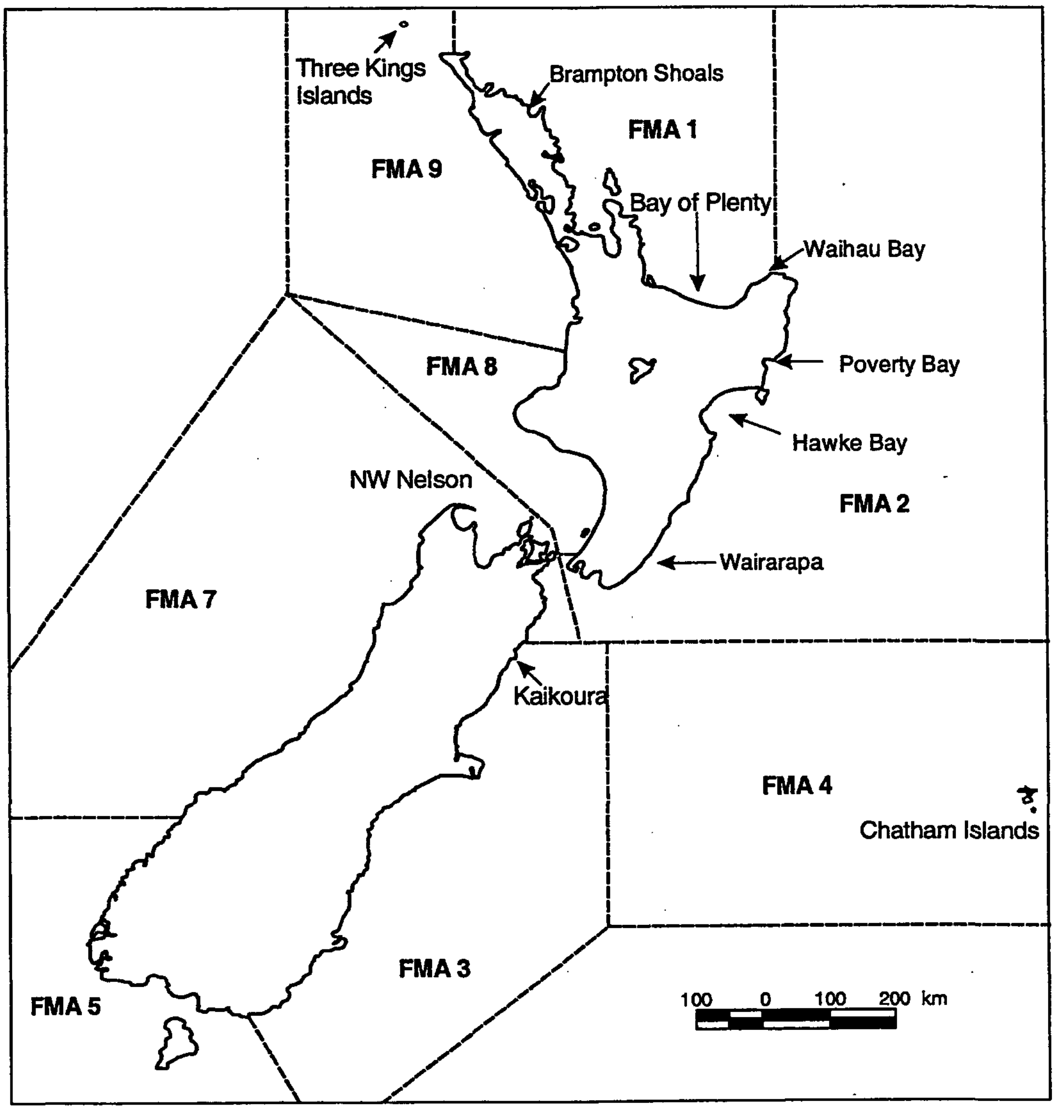

Figure 1: New Zealand Fisheries Management Areas and main *Pterocladia* harvesting zones.

Pterocladia lucida follows a typical rhodophycean biology in having a complex life cycle (with three generations and both vegetative regeneration and sexual reproduction) and a growth form that makes identification of individuals extremely difficult. Further, unlike other commercially exploited species, the ecology and population biology is poorly described. Where studied, related species such as *Chondrus crispus* (Chopin 1986, Chopin et al. 1992) and *Gelidium sesquipedale* (Santos 1993a, 1993b, 1994) show large fluctuations in biomass both within and among years as a result of storms, seasonal growth, and reproduction. Anecdotal information suggests that the drift component of the *P. lucida* resource is extremely variable, partially because it is storm-generated.

These sources of variability make quantifying population characteristics complicated (e.g., Bhattacharya 1985, Chopin 1986, Santelices 1988, Santos 1994) and estimating sustainable yields using steady-state modelling techniques difficult. The dynamics of fronds has been used as a proxy for entire plants in some studies (Santos 1993a, 1993b).

Agar seaweeds have been commercially harvested in New Zealand since 1941 when about 0.5 t dry weight (dw) of *Pterocladia* was collected from the Bay of Plenty. This was purchased by the DSIR for preliminary experiments on agar production (Moore 1944). Processing began in 1943 with the purchase of about 60 t dw of *Pterocladia.* In 1945, 105 t dw was collected and this rose to 110 t dw the following year. Between 1950 and 1968 collection fell to an average annual dry weight of 25.4 t (Chapman 1970). From 1968 to 1978 the annual harvest of *Pterocladia* averaged 109 t dw (Luxton & Courtney 1987). With the introduction of improved technology in 1979, a more valuable bacteriological grade product could be produced and the harvest increased to a peak of 239 t dw in 1983 (Luxton & Courtney 1987). Since that time the total harvest has declined to its present level of 65 t dw in 1997 (K. Coopey, pers. comm.). Currently, only one company (Coast Biologicals Ltd.) processes agar in New Zealand.

Pterocladia lucida is harvested as live plants by hand plucking and drift material is collected from intertidal reefs and beaches. Drift algae has historically accounted for the bulk of the harvest; about 15% of the harvest is currently taken by diving, compared with about 40% 15 years ago (Luxton & Courtney 1987). *P. lucida* harvested by divers is generally of both higher and more uniform quality than beach-cast material (Luxton & Courtney 1987). The agar in beach-cast material deteriorates if not harvested soon after deposition and requires time-intensive sorting to separate it from other species. The unpredictable nature of this beach-cast resource further diminishes its commercial viability.

The management of the fishery is based on limiting fishing effort. Although there are no regulations governing the taking of beach-cast red algae, since 1971 the harvest of attached algae has required a permit. There is presently a moratorium on the issue of such permits. There are currently no reporting requirements for the harvest of red algae.

In this report we provide estimates of the standing stocks of live and drift *P. lucida* at Waihau Bay and, by experimentally harvesting *P. lucida,* estimate regeneration rates of live plants. The objectives of this study are as follows.

1. To determine the distribution, abundance, and sustainable yield of *Pterocladia lucida* at Waihau Bay.

2. To assess the potential impacts of *P. lucida* harvesting on the associated aquatic ecosystem.

2. DISTRIBUTION, ABUNDANCE AND SUSTAINABLE YIELD

2.1 Site selection and area estimation

2.1.1 Methods

Site selection was based on relevant historical literature and discussions with industry and the Ministry of Fisheries. Three sites were identified as being important areas of current and historical harvest; Brampton Shoal in the Bay of Islands (FMA1), Waihau Bay in the eastern Bay of Plenty (FMA 1), and the southern Wairarapa (FMA2) (Figure 1). Of these three, Waihau Bay was selected because it offered the best mix of logistic efficiency and opportunity to conduct experimental harvesting without being confounded by commercial harvesting.

Accurate estimation of the area of the study site was critical for the expansion of density estimates to overall biomass estimates. Aerial photographs were used to estimate the area of reef at the site; these were taken within 2 hours of low tide on a day with low swell and relatively calm sea surface conditions. The photographs were taken using a Zeiss RMK 30/23 large-format camera with a 305 mm lens at an altitude of 8000 feet.

The positives were enlarged to 1:2500 which were then digitised using Auto-Cad and rectified using ground control points which were fixed using a Trimble Differential GPS. The resulting maps were imported into ArcView™ for area estimation and data recording. To this database was added the coast outline, roads, and rivers from the New Zealand 1:50 000 Topographic Dataset (LINZ, 2000). The resulting Geographic Information System (GIS) was used to analyse the data and to produce detailed maps of the study area. Preliminary maps created by this process were taken into the field and "ground-truthed" by divers. Adequate ground-truthing requires accurate positioning of features on the map, particularly underwater where interpretation of the photograph is likely to be problematic. The consequence of this error may be large compound variances associated with estimates of total biomass.

2.1.2 Results

The initial estimate of reef area as calculated from the aerial photographs was extensively ground-truthed in the surveys conducted since the programme began. In many cases, what appeared from the photographs to be contiguous reef areas were subsequently found to be a number of smaller discrete reefs and the GIS was continuously updated to reflect these changes. We acknowledge that there are more reefs in deeper water outside the study area and that we may have missed some smaller reefs within the area. The final estimates of reef area used in the data analysis assume no error and we are confident that there is no overestimate. The final map used in this study is shown in Figure 2.

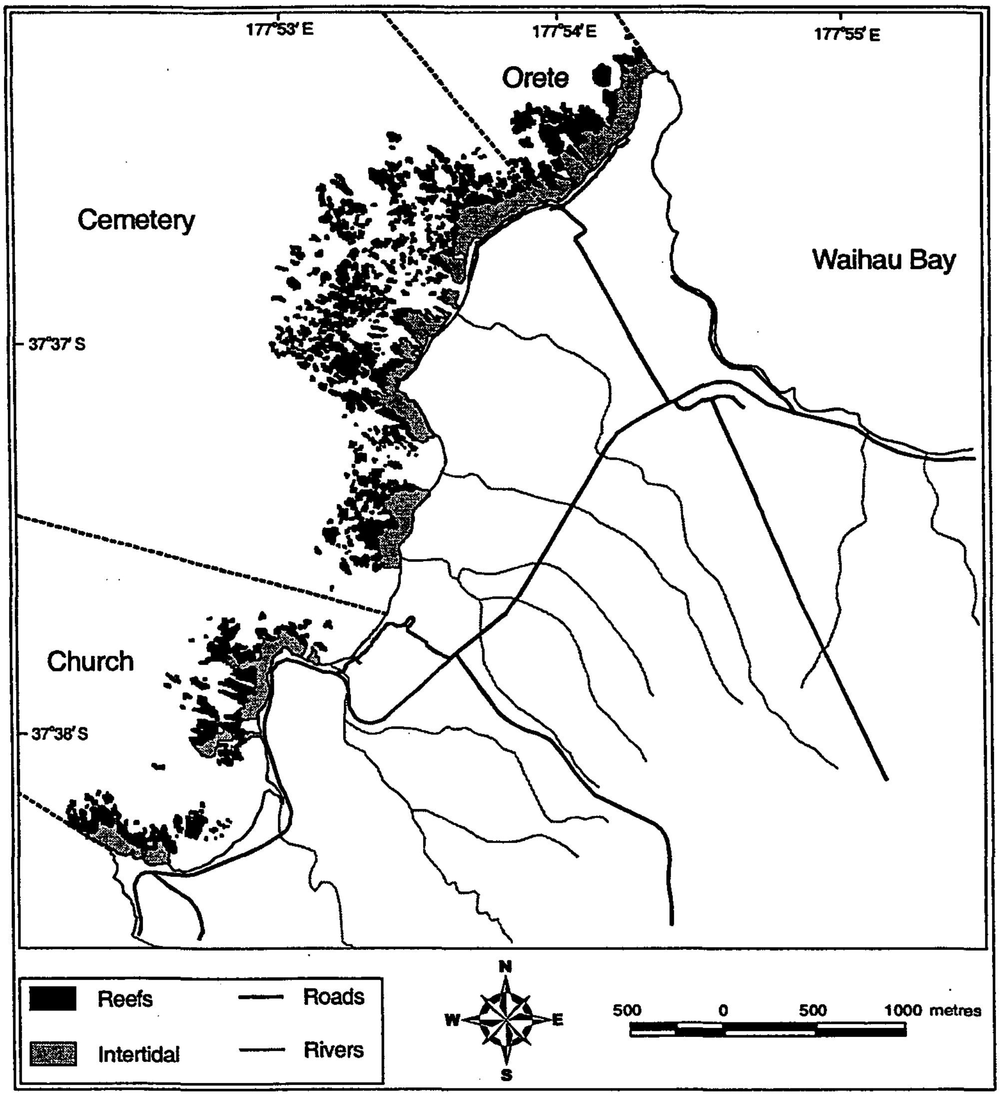

Figure 2: Map showing the study area at Waihau Bay and the three strata (Church, Cemetery, and Orete) used for biomass estimation.

2.2 Estimation of distribution and abundance

We developed sampling methods that satisfy the specific objectives of estimating the distribution and abundance of *Pterocladia lucida* at one site and will be applicable to other sites. As well as standard statistical methods we used kriging to provide estimates of distribution and abundance of *P. lucida*. Recent advances in our capacity to fix the position of samples in the subtidal zone along with improved statistical methods of estimating abundance from point estimates allows greater flexibility in survey design. The dataset used to estimate abundance was analysed within the stratified random survey (SRS) framework proposed by McCormick (1990). The data obtained were also analysed by kriging to test the generality of the finding by Ecker & Heltche (1994) that abundance estimates derived from kriging are more precise than those from stratified random sampling. Kriging differs from the methods recommended by McCormick (1990) in that it allows better characterisation of the spatial distribution of the resource.

For the duration of the study, only negligible quantities of *P. lucida* were found in the intertidal zone. Therefore, the distribution and abundance of *P. lucida* in the subtidal zone was estimated within three strata as shown in Figure 2. Haphazard points were allocated to strata according to naturally occurring breaks in the reefs and the position of each point estimate was determined using differential GPS.

2.2.1 Stratified random survey methods

For the stratified random sampling design, we can estimate abundance and variance from standard theory (Raj 1968, Jolly & Hampton 1990, Barnett 1991).

For a sample quadrat, *j*, in stratum *I*, the wet weight biomass of seaweed is measured as b_{ij} kg. The mean weight of seaweed per unit area for the j^{th} sample is:

$$\hat{p}_{ij} = \frac{b_{ij}}{L_{ij}} \text{, where } \quad L_{ij} = \text{the quadrat size.}$$

The mean density for the stratum is then:

$$\hat{p}_i = \frac{1}{n_i}\sum_{j=1}^{n_i} w_{ij}\hat{p}_{ij}\text{, where } w_{ij} = \frac{L_{ij}}{\bar{L}_i} \text{ and where } \bar{L}_i = \frac{1}{n_i}\sum_{j=1}^{n_i} L_{ij}$$

The mean density of the population is calculated as:

$$\hat{p} = \frac{\sum_i A_i\hat{p}_i}{\sum_i A_i}\text{, where } A_i \text{ is the stratum area for strata } i = 1,..,L$$

The variance of $\hat{p}$ is then: $\mathrm{Var}\left(\hat{p}\right) = \dfrac{\sum_i A_i^2 Var\left(\hat{p}_i\right)}{\left(\sum_i A_i\right)^2}$

where $\mathrm{Var}\left(\hat{p}_i\right) = \dfrac{\sum_{j=1}^{n_i} w_{ij}^{\,2}\left(\hat{p}_{ij} - \hat{p}_i\right)^2}{n_i\left(n_i - 1\right)}$ for the j^{th} sample in stratum *i* (Cochran, 1977).

A minimum of 50 spot dives on haphazardly-selected reefs in the subtidal zone were made on each of three occasions (April 1999, February 2000 and August 2000). Biomass was estimated by removing (by careful plucking) all *P. lucida* from five 0.25 m^2 (0.5 x 0.5 m) quadrats at each position. The samples from the quadrats were placed in individual bags and taken back to the boat for weighing. The bags were shaken to remove excess water and weighed to the nearest 10 g on a hand-held spring balance.

In April 1999, the divers sampled *P. lucida* by sampling haphazardly placed quadrats across the reef. On the two subsequent surveys, each reef was sampled by a quadrat immediately beneath an anchored boat and a further four quadrats 2 m away north, south, east, and west from the central one.

To estimate seasonal patterns in harvestable biomass, we repeated the sampling in April 1999, February 2000, and August 2000. On each survey, all strata were surveyed and the wet weight of live and dead *P. lucida* estimated. Following Pringle (1984), Downing & Anderson (1985), and McCormick (1990), 0.25 m^2 quadrats were used provide the point estimates of biomass of live plants in the subtidal zone. The wet weight of *P. lucida* per quadrat has been shown to be an adequate predictor of dry weight McCormick (1990). Additional variables were followed in these quadrats and the associated sampling as part of Objective 2 (detailed below). All SRS weights and derived biomass values are given as drained wet weights.

To estimate the amount of beach-cast *Pterocladia*, the shore between Raukokore church and Orete Point was searched for drift *P. lucida* in April 1999, February 2000, and August 2000. Although we planned to sample *P. lucida* in the intertidal zone in the same way as in the subtidal, it soon became clear that only negligible amounts were present. Consequently, only the total weights from the searches are reported. The weights reported are from partially dried plants and cannot be considered as wet or dry weights.

2.2.2 Stratified random survey results

The pattern of reefs in the study area form three natural strata, shown in Figure 2. Estimates of biomass are given in Figure 3 and the coefficients of variation (c.v. s) for the three samples are given in Table 1. A total of 151 dives was made on reefs within the study area for biomass estimation with five replicate 0.25 m^2 quadrats sampled per site. A further 144 dives were made on sites without reefs to confirm that there was no *P. lucida* growing between the reefs.

Pterocladia was found to grow on the upper third of the reefs in association with the large brown algae *Carpophyllum maschalocarpum* and *Cystophora platylobium*. *Ecklonia radiata* was present lower on the reefs and scattered in between them on the cobbly substrate. Other red algae such as *Osmundaria colensoi* and *Rhodomenia* spp. were occasionally encountered. The intertidal zone was dominated by *Xiphophora* and *Zonaria turneriana* with no *P. lucida*, although small amounts of *P. capillacea* were found at some sites.

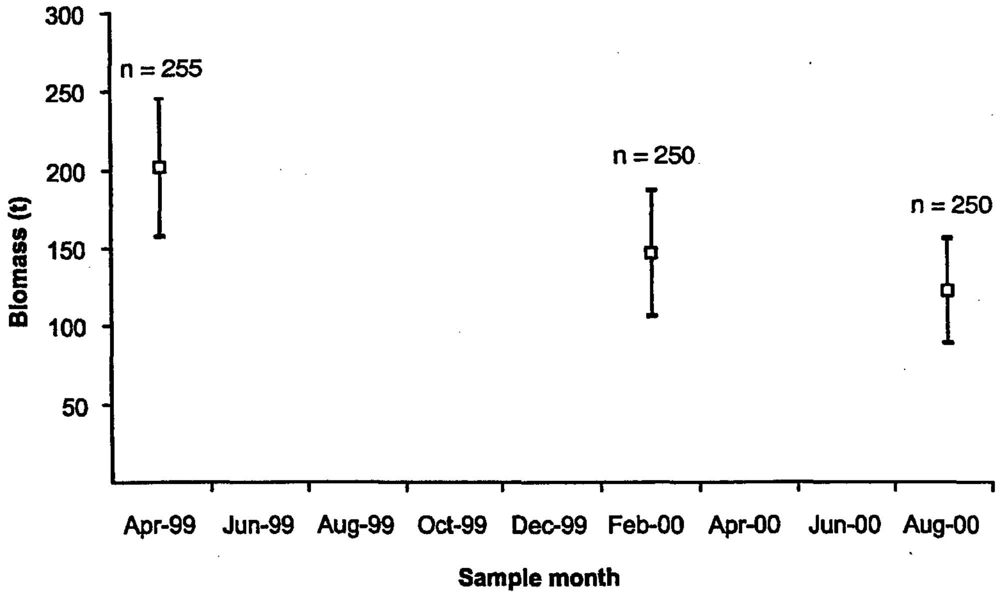

Figure 3: Biomass estimates (+/- 95% C.I.) of *Pterocladia* at Waihau Bay for the three sampling months, pooled across strata.

Estimates of mean wet weight biomass per unit area ranged from 0.46 ± 0.1 (± 95% C.I. kg.m^{-2}) in April 1999 to 0.28 ± 0.08 in August 2000. There was no apparent pattern to the density of *P. lucida* within the study area. Reefs with high densities were found adjacent to reefs with low densities.

The estimates of total biomass in the study area ranged from about 120 ± 33 t in August 2000 to just over 200 ± 44 t in April 1999 (Figure 3).

Table 1: Mean densities (kg.m^{-2}), number of samples, and c.v. s of *P. lucida* in the three strata for the three sampling months and for all samples.

	April 1999			February 2000			August 2000			All		
Stratum	Mean	N	c.v.	Mean	N	c.v.	Mean	N	c.v.	Mean	N	c.v.
Church	0.61	30	23.6	0.59	90	22.2	0.15	85	25.8	0.41	205	15.8
Cemetery	0.43	185	13.9	0.27	135	21.7	0.38	120	17.2	0.37	440	9.7
Orete	0.38	40	26.1	0.20	25	29.2	0.13	45	23.8	0.23	110	17.5
Total	0.46	255	11.3	0.33	250	14.2	0.28	250	14.0	0.35	755	7.6

The c.v. s for the total standing crop of *P. lucida* in the study area for each of the three sampling periods ranged from 11.3% in April 1999 to 14.2% in February 2000. The c.v. for all strata in all months was 7.6%.

Only negligible amounts of *P. lucida* were found along the shore where the study was carried out. In February 1999 1.5 kg was found between Orete Point and a point about 3 km towards Raukokore. None was found in August 1999 or February 2000. In August 2000 about 7 kg was found.

2.3 Kriging

2.3.1 Kriging methods

Kriging is a geostatistical procedure that investigates spatial relationships between random or non-random observations. Kriging methods are usually used to estimate surfaces from regularly or irregularly spaced spatially defined data by modelling both the variance and spatial covariance of spatial data. The procedure predicts values suggested by the model onto a regular grid by modelling the relationship between the location and values of the samples (Ripley 1981, Cressie 1985).

We define a state space process $Z(t)$: $t \in T$, defined over some region *A*, with mean defined as $m(t) = \mathrm{E}\left[Z(t)\right]$ and variance $C(u,v)=\mathrm{Cov}\left[Z(u),Z(v)\right]$. Further, we assume a covariance function $C(r) = c(d(r))$ that is some function of the Euclidean distance *r* (Ripley 1981, Cressie 1991). Covariance was investigated by visual inspection of the semi-variogram and correlogram assuming a surface model with constant trend. Estimates of the distance parameter were determined by assuming a Gaussian covariance function $C(r) = \sigma^2 \exp\left(-(r/d)^2\right)$ with distance parameter *d* (Ripley 1981, Cressie 1991), i.e., we assume that the covariance between points of distance *d* declines as a logistic function of the Euclidean distance between sample locations.

Weighted least squares (WLS) estimates of Gaussian covariance parameters from models with and without assumptions of a nugget effect (i.e., micro-scale spatial variation and measurement error) were investigated using the weighted least squares method of Cressie (1985), and implemented in S-Plus (MathSoft 1997) by Ribeiro & Diggle (2000). While other covariance functions are plausible for these data, exploratory analysis suggested that there was little difference between covariance models for the observed data. Hence we report only the results for the Gaussian model.

The estimation of kriged surfaces and covariance functions is confounded by the association of *Pterocladia* with reef structures. Implementation of co-kriging models is difficult, and hence this association was ignored in the development of kriging models. Kriged surfaces were passed through a filter defining reef boundaries for purposes of plotting surfaces and estimating *Pterocladia* biomass. This had the effect of determining estimates of density surfaces based on grid locations defined as being on a reef.

Estimates of biomass density were evaluated over a uniform 500 x 500 unit grid then filtered by reef locations. Estimates of density confidence intervals were determined by empirical bootstrap. For each estimated density surface, 500 simulated surfaces were generated from the point estimates and associated variance under assumptions of a Gaussian random field where grid points are independent. Bootstrap percentile confidence intervals were then calculated for the mean density and hence for the total biomass. Additional variance from non-independence between adjacent points, measurement error, and error in the estimates of covariance parameters was ignored.

2.3.2 Kriging results

Covariance functions and kriged estimates for the three survey periods, April 1999, February 2000, and August 2000 were determined separately, and WLS estimates of covariance parameters are shown in Table 2. Figure 4 shows the semi-variance plots for the empirical semi-variance, smoothed semi-variance, and estimated covariance functions for the April 1999 survey. Plots for the February 2000 and August 2000 surveys show similar, although less distinct, patterns and are not shown here.

Table 2: Covariance models, model parameter estimates (nugget, sill, and distance *d*) and model sum of squares (SSQ) for each of the three surveys (Gaussian model) with maximum distance set to 1 km.

Survey	Model	Nugget	Sill	d	SSQ
April 1999	Pure nugget	0.217	na	na	180.7
	Gaussian, without nugget	na	0.440	0.055	175.6
	Gaussian, with nugget	0.181	0.343	0.421	145.8
February 2000	Pure nugget	0.317	na	na	234.0
	Gaussian, without nugget	na	0.660	0.073	215.9
	Gaussian, with nugget	–	–	–	–
August 2000	Pure nugget	0.243	na	na	241.9
	Gaussian, without nugget	na	0.500	0.489	238.7
	Gaussian, with nugget	0.214	0.315	0.206	234.0

'na' indicates not applicable, and '–' indicates that the function could not be minimised.

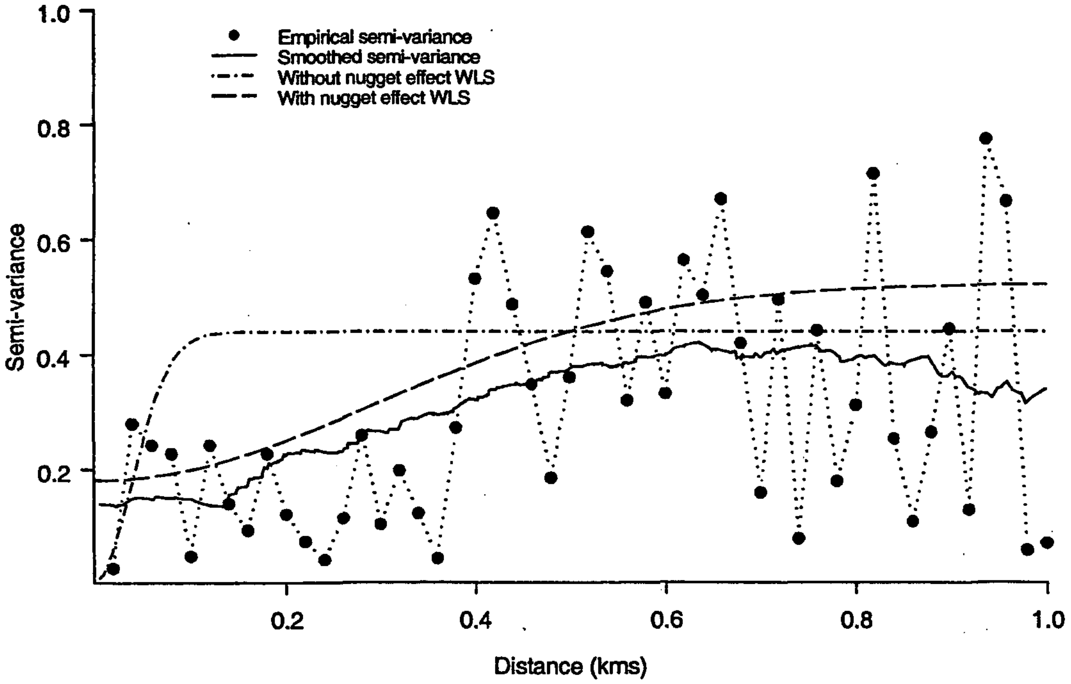

Figure 4: Plots of the empirical (binned) semi-variogram, smoothed semi-variogram, and fitted (WLS) estimates for the with- and without-nugget effect covariance parameters for the April 1999 survey, with maximum distance set at 1 km.

Estimates of the covariance parameters of the WLS parameters of the model with a nugget effect for the February 2000 survey could not be minimised and no estimates for this model were obtained.

Estimates of the distance parameter *d* suggest that the covariance operates over a distance of between about 0.01 and 0.60 km (see Figure 4).

Models all improved with the estimation of covariance over a simple pure nugget effect model (i.e., a random noise model), although for the February and August 2000 data this improvement was small. This is consistent with the visual inspection of the semi-variance diagnostics for these data, and suggests little evidence for rejecting the pure nugget (random noise) model.

We employ the results of the WLS estimates for the with nugget Gaussian covariance model for the April 1999 and August 2000 surveys to estimate the kriged biomass estimates. In the case of the February 2000 survey where this model was not available, we use the Gaussian model without nugget effect instead.

Estimates of mean density and hence total biomass (assuming a total reef area of 436 556 m^2) are given in Table 3, along with approximate 95% bootstrap percentile confidence intervals.

Table 3: Estimated density (95% percentile confidence intervals) and total biomass (95% percentile confidence intervals) for kriged models with Gaussian covariance.

Survey	Model	Density (kg.m^{-2})	Total biomass (t)
April 1999	Gaussian, with nugget	0.43 (0.42–0.45)	189.3 (184.4–196.0)
February 2000	Gaussian, without nugget	0.41 (0.39–0.43)	178.3 (170.4–186.2)
August 2000	Gaussian, with nugget	0.27 (0.26–0.29)	119.0 (113.1–126.2)

3. ESTIMATION OF SUSTAINABLE YIELD

3.1 Introduction

The complicated life history of *P. lucida* and its spatial and temporal variability makes quantifying population characteristics complicated (see Bhattacharya 1985, Santos 1994, and Chopin 1986, Santelices 1988 for reviews of similar species) and estimating sustainable yields using modelling techniques difficult. Although modelling the dynamics of fronds has been used as a proxy for entire plants in some studies (e.g., Santos 1993a, Santos 1993b), the dynamics of populations are not sufficiently well understood to adequately parameterise an assessment model within the present programme. We have not, therefore, provided estimates of sustainable yield based on surplus production theory as defined by the Fisheries Act (1996) and interpreted by Annala & Sullivan (1997). In preference to these methods we have approached the problem experimentally.

We provide preliminary assessments of sustainable harvest for one site by (i) providing reliable and precise estimates of the standing stocks of live and drift *P. lucida* and (ii) by experimentally harvesting *P. lucida* to estimate regeneration rates of live plants and quantify the effects of such harvesting on drift biomass. The surveys and experiment provide the basis for determining, in future years, whether a predictive relationship can be developed between the biomass of living plants on subtidal reefs and drift algae collected from adjacent intertidal areas.

The experimental assessment of sustainable yield concentrated on the response of patches of *P. lucida* to harvesting under various scenarios. The experiment focussed on the response of live plants rather than dead material washed ashore because, inevitably, the issue of sustainability will revolve around the capacity of populations to replenish themselves. We assumed that beach-cast material no longer contributes spores and therefore is essentially lost from the system in a demographic sense. The hypotheses tested by this experiment were framed as three questions (brief rationales for inclusion in the experiment are provided).

1) *Will patches in which all the* P. lucida *has been removed be recolonised by* P. lucida *and, if so, over what time frame*? This was the core question asked in the experiment and was answered by comparing biomass in unmanipulated control plots with all other plots in which *P. lucida* had been removed.

2) *Does the season of removal influence whether such recolonisation occurs or the rate of recolonisation*? The capacity and rate at which *P. lucida* recolonises or regrows following harvesting is likely to be strongly influenced by season. The experimental harvesting was repeated in summer and winter to assess the yield and sustainability consequences of harvesting in these seasons. Autumn and spring were not included in this preliminary study to keep costs down.

3) *Does the method of removal – either hand-plucking or cutting — make a difference to recolonisation*? In *P. lucida* and related species, the harvested fronds rise from prostrate holdfasts. The method of removal of the fronds may influence the extent of damage to these holdfasts to a greater or lesser extent. Such damage diminishes the capacity of plants to vegetatively regenerate following harvesting (Santos 1993b). Cutting the fronds above the holdfast may increase the rate of regeneration of individual plants.

3.2 Methods

Reefs dominated by *P. lucida* were haphazardly selected and within these 20 plots, each about 10 m^2 in area, the density of algae was estimated by clearing five replicate 0.25 m^2 quadrats by plucking. Plots were then randomly allocated to treatments and the *P. lucida* was either plucked, cut or left untouched.

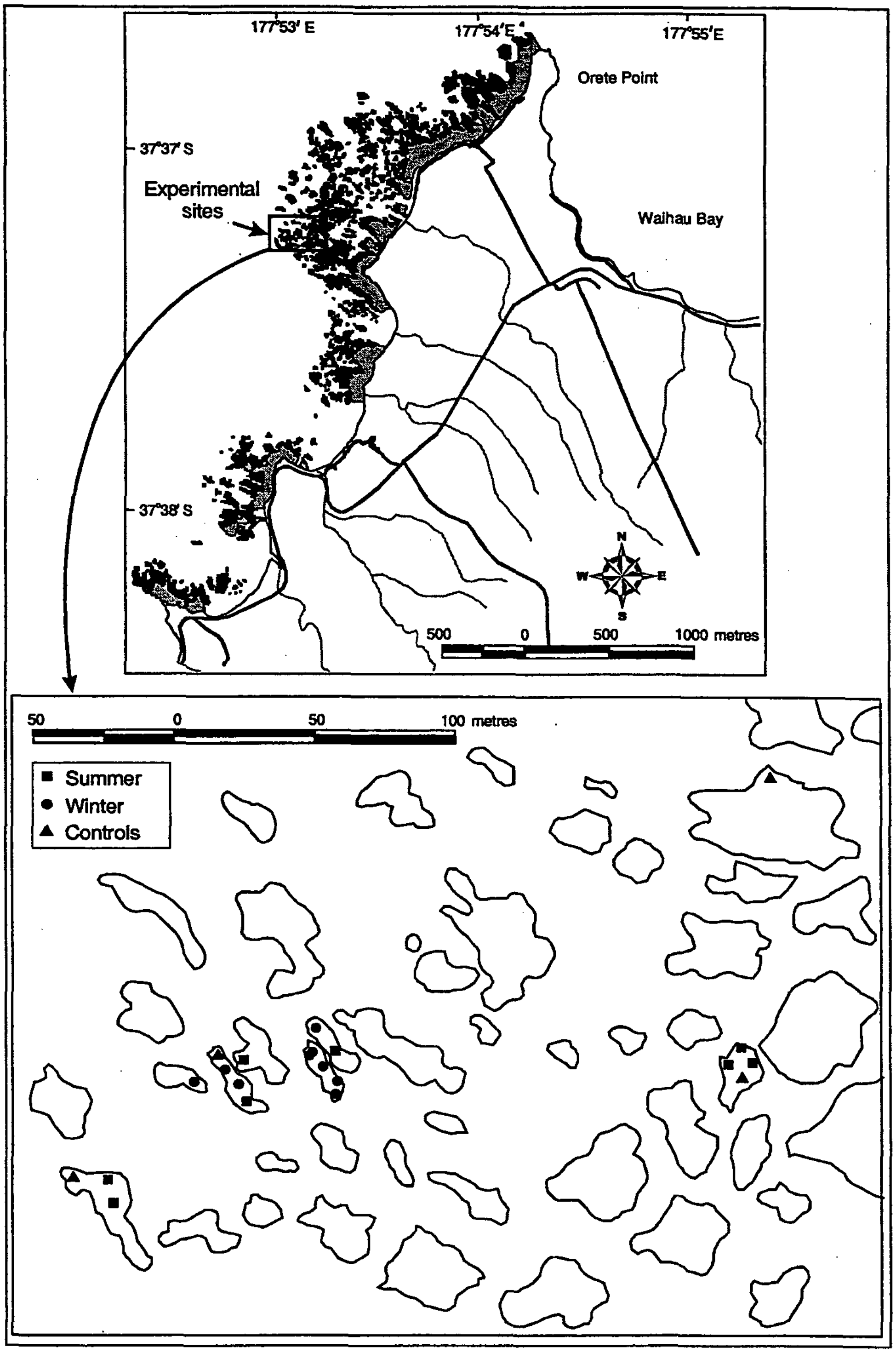

Figure 5: Sites chosen for the manipulation experiments.

The experiment was set up and sampled in summer and winter 1999, and further sampled in summer and winter 2000. The experiment was designed to allow a formal test of difference between summer and winter harvesting, but the large seasonal trends in the data meant that the time elapsed since the manipulation was confounded by seasonal differences in biomass irrespective of the experiment (Figure 6). Differences among treatments and plots at the end of the experiment were therefore analysed separately in the summer and winter treatments using univariate analyses of variance with the factor Plot nested within Treatment (cut, plucked, and control). Differences among treatments were compared using Tukey's HSD. All analyses were done in S-Plus.

An estimate of the relative amounts of algae removed by cutting and plucking was investigated by first cutting the *P. lucida* from ten replicate quadrats and weighing the algae removed. The quadrats were then cleared of the remaining algae by plucking and the algae was weighed.

3.3 Results

Cutting removed an average of 70.3 ± 3.6 % of the total biomass of algae removed by plucking. Plucking did not completely remove all the *P. lucida*; the prostrate holdfasts together with small fronds were left after the treatment.

3.3.1 Summer manipulations

There was a clear seasonality in the amount of *P. lucida* present on the reefs. In the control plots in February 1999, there was 1286 ± 231 g/0.25 m^2 which dropped to 723 ± 83 g/0.25 m^2 in winter and then recovered again in February 2000. Responses of *P. lucida* to the two methods of harvesting for the experiments begun in summer are shown in Figure 6.

The initial density of *P. lucida* in the 'Cut' treatments was 1242 ± 205 g/0.25 m^2. In August 1999, density had dropped to 336 ± 127 g/0.25 m^2. In February 2000 the density had returned to slightly higher than pre-treatment levels at 1518 ± 275 g/0.25 m^2 (Figure 6, Table 5).

For the 'Pluck' treatment, the initial density was 993 ± 246 g/0.25 m^2 which had decreased to 292 ± 50 g/0.25 m^2 when resampled in August 1999. By February 2000 it had recovered again to 951 ± 185 g/0.25 m^2.

The plants in the Pluck treatment were significantly smaller at the end of the experiment than those in either the cut or control treatments (Table 5; Tukey's HSD $p < 0.05$). There was no significant difference between the Cut and Control treatments at the end of the experiment (Tukey's HSD, $p < 0.05$). There were significant differences between patches within each treatment (Table 4).

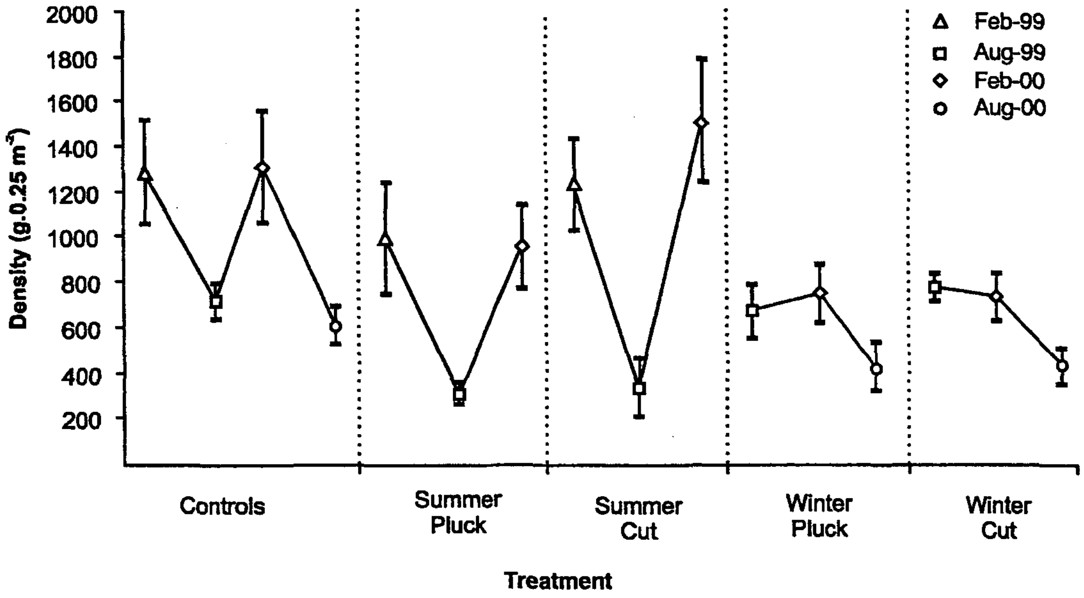

Figure 6: Responses of *P. lucida* to cutting and plucking in winter and summer (mean ± 95% C.I.).

Table 4: Results of ANOVA tests for the response of *P. lucida* to plucking and cutting in summer and winter (* = significant at p = 0.05).

		Summer		Winter	
	df	MS	F-ratio	MS	F-ratio
Treatment	2	1 646 531	10.66 *	252 073	7.64 *
Patch (treatment)	9	1 061 552	6.87 *	78 451	2.38 *
Residual	48	154 422		33 016	

3.3.2 Winter manipulations

Responses of *P. lucida* to the two methods of harvesting for the experiments started in winter are shown in Figure 6. The marked seasonal effect is again evident in the control plots with a peak density of 1315 ± 248 g/0.25 m^2 in February 2000 as compared to 723 ± 83 and 614 ± 80 g/0.25 m^2 for the August 1999 and August 2000 samples respectively. In contrast to the summer harvesting, patches manipulated in winter did not increase in biomass during the following summer (Figure 6).

Both plucking and cutting significantly reduced the amount of *P. lucida* present at the end of the experiment compared to the control plots (Table 5, Tukey's HSD $p < 0.05$). In the cut patches the mean biomass was 416 ± 79 g/0.25 m^2 and in the Pluck treatment the mean biomass was 423 ± 102 g/0.25 m^2. (Table 5). There was no significant difference between the Cut and Pluck treatments as the end of the experiment (Tukey's HSD, $p < 0.05$). There were significant differences between patches within each treatment (Table 4).

4. ASSESSMENT OF THE EFFECT OF *P. LUCIDA* HARVESTING

4.1 Introduction

In satisfying this objective we concentrated on harvest of live plants because, although harvesting beach-cast material may have ecosystem impacts, they are likely to be indirect and difficult to quantify (Fraser et al. 1987). Examples of such effects include:

(i) changes to beach morphology as large drifts become covered by sand
(ii) recycling of nutrients
(iii) provision of resources for food (birds) and habitat (amphipods and isopods) and
(iv) on rocky intertidal shores, smothering effects on algae and sessile invertebrates.

The unpredictable and ephemeral nature of this resource meant that determining more than patterns in the availability of beach-cast *P. lucida* was impossible in the present study.

The effect of harvesting *P. lucida* was assessed in the same experiment as described in Objective 1. The questions asked may be re-cast as three questions (brief rationales for inclusion in the experiment are provided).

1) *Did plots from which all* P. lucida *was removed develop different assemblages of algae and associated species from unmanipulated plots?* It is possible that the removal of *P. lucida* from areas of reef provides space for the settlement and recruitment of large brown algae and sessile invertebrates. If this occurs then there is likely to be consequent changes in the abundance of mobile invertebrates.

2) *Did the season of removal influence the nature of the species assemblage found in manipulated plots?* The above effects are likely to depend on season because of the limited reproductive seasons of most large brown algae. For example, the dominant kelp *Ecklonia radiata* recruits in

late winter–early spring. A large scale recruitment of sporophytes of this kelp could lead to the development of a canopy-forming forest and large scale changes in community structure.

3) *Did the method of harvest influence the identity and rate of colonisation by associated species*? The capacity of *P. lucida* to maintain itself in the face of competition from large brown algae, and the pre-emptive effects described above, will depend, in part, on the degree to which the holdfasts are damaged and therefore the potential for rapid vegetative regeneration.

4.2 Methods

The densities of algae, sea urchins, and small gastropods were estimated in five replicate 0.25 m^2 quadrats per plot. The experimental design, analysis and sampling timetable were as described for the experiment in Section 3 (Objective 1).

4.3 Results

Of the species of algae other than *P. lucida* found in the experimental plots, only *Carpophyllum maschalocarpum* was found in sufficient quantities to analyse.

There was no evidence from the experiments to suggest that either plucking or cutting the *P. lucida* altered the subsequent amount of *P. lucida* relative to *C. maschalocarpum* found within the plots. Nor was there a difference in the relative amount of *P. lucida* according to whether the treatment was applied in summer or winter (Figure 6).

The seasonal trend previously noted for *P. lucida* was also evident for *C. maschalocarpum*, which had a mean density in the control plots of 177 ± 134 g/0.25 m^2 in summer which decreased to 42 ± 47 g/0.25 m^2 in winter, then increased to 184 ± 141 g/0.25 m^2 by the following summer (Figure 7).

There were no significant differences in the densities of *C. maschalocarpum* between any of the treatments one year after the experiment began (Figure 7, Table 5)

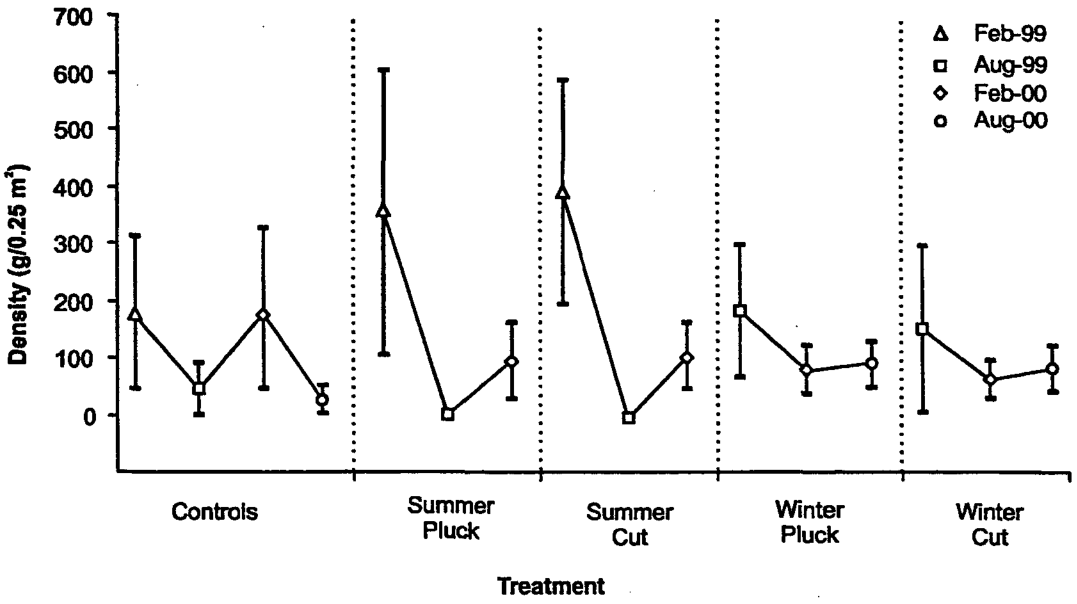

Figure 7: Responses of *Carpophyllum maschalocarpum* to cutting and plucking in winter and summer (mean ± 95% C.I.).

Table 5: Results of ANOVA tests for the response of *C. maschalocarpum* to plucking and cutting in summer and winter (ns, not significant at p = 0.05).

		Summer		Winter	
	df	MS	F-ratio	MS	F-ratio
Treatment	2	54 922	1.09 ns	21 293	2.75 ns
Patch(treatment)	9	35 881	0.71 ns	3 463	0.45 ns
Residual	48	50 285		7 733	

In the winter control plots, *C. maschalocarpum* reached a maximum mean density of 184 ± 141 g/0.25 m^2 in summer and a minimum of 42 ± 47 g/0.25 m^2 in August 1999 and 24 ± 25 g/0.25 m^2 in August 2000 (Figure 7).

For the 'Cut' and 'Pluck' treatments, the density of *C. maschalocarpum* was found not to differ significantly from the 'Control' plots after one year (Figure 7, Table 7).

Of the invertebrates in the plots, only *Evechinus chloroticus* (kina) and *Cookia sulcata* were found in sufficient numbers to analyse.

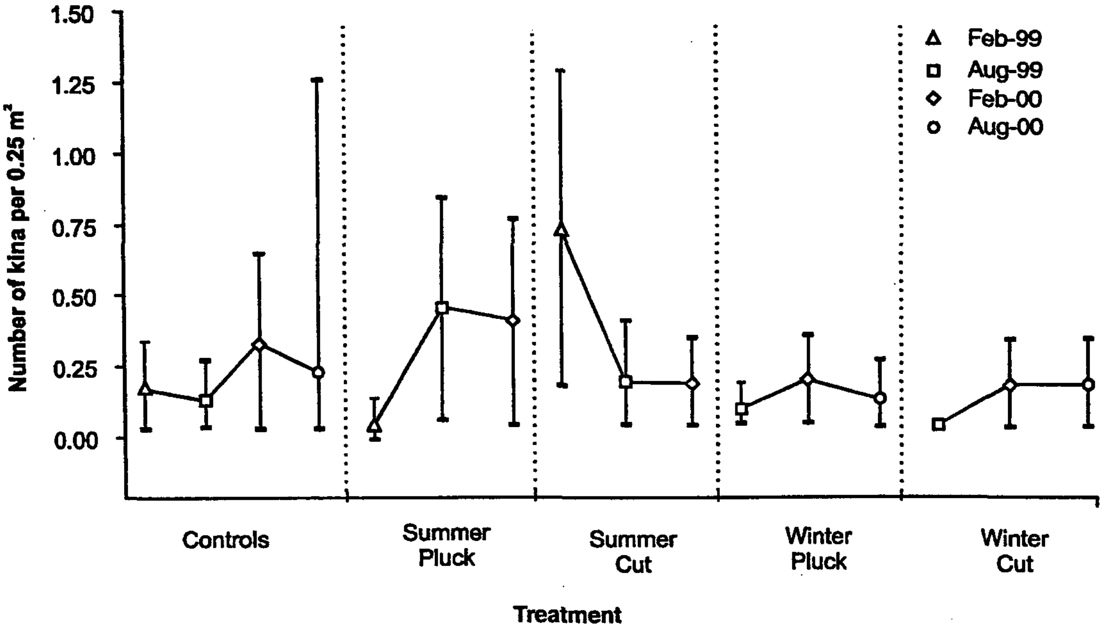

Figure 8: Responses of *Evechinus chloroticus* to harvesting *P. lucida* (mean ± 95% C.I.).

The mean number of kina per 0.25 m^2 quadrat ranged from 0 to 0.7 ± 0.6 (Figure 8) and of *Cookia sulcata* from 0 to 0.6 ± 0.3 per 0.25 m^2 quadrat (Figure 9). The variance on these estimates was too high to be considered for further analysis, although there was no evidence that harvesting had any effect on the densities of these invertebrates.

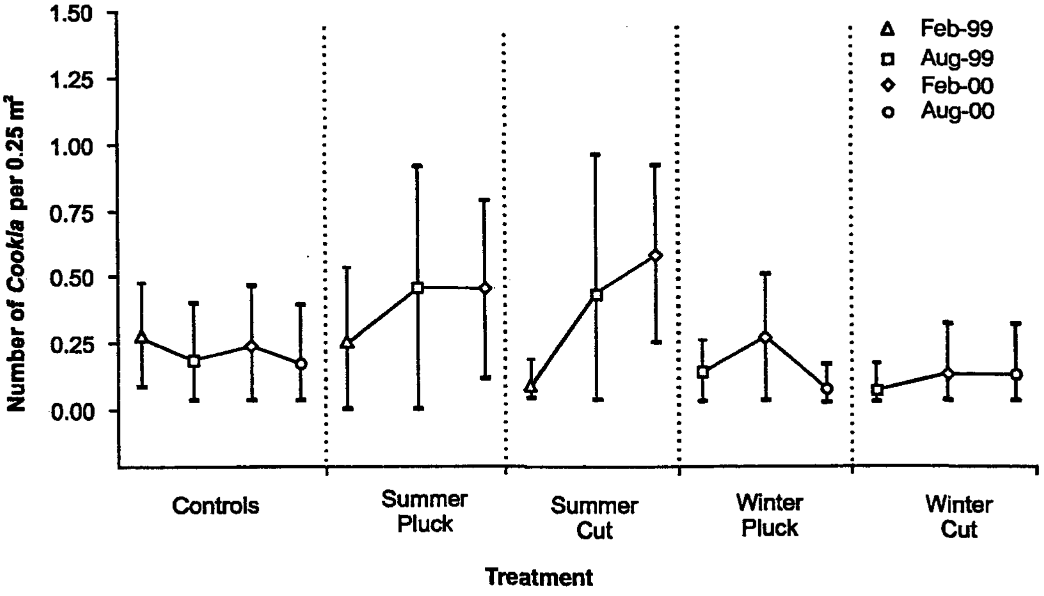

Figure 9: Responses of *Cookia sulcata* to harvesting *P. lucida* (mean ± 95% C.I.).

5. DISCUSSION

The combination of aerial photography and intensive sampling at known locations on reefs provided reliable estimates of the biomass of *P. lucida* at Waihau Bay. Estimation of reef area without aerial photography would have been extremely difficult because of the many small reefs present (about 500 individual reefs were identified). Further, the GIS created from the aerial photography will allow more and different questions to be asked, such as whether sand inundation causes changes in the reef area during storms and whether this has an impact on *P. lucida* populations. Aerial photography has been used to estimate algal biomass in a number of studies (Critchley 1983, Thorne-Miller et al. 1983, Meulstee et al. 1986) and most studies cite the increased accuracy possible as a major advantage of the method. In some cases (see e.g. Meulstee et al. 1986) it is possible to use false-colour infra-red film which, combined with colour density recognition software, makes it possible to survey very large areas of shoreline with minimal time spent in the field. In this study, the use of infra-red film was contemplated but rejected because *P. lucida* occurs in association with the canopy-forming *C. maschalocarpum* which would have obscured the *P. lucida*. Infra-red light is also absorbed at a depth of about 1 m (Critchley 1983) and *P. lucida* occurs at Waihau Bay down to about 3 m.

Biomass was estimated both by kriging and the more conventional stratified random sampling methods. Kriging is reliant on a well-specified spatial covariance model and works best when densities change gradually over the sampling frame. The reticulated reef structure at Waihau Bay was not well suited to the method because there were sharp discontinuities in density (the presence/absence of reef) which meant that the covariance functions were poorly determined. The empirical covariance estimates suggest that there may be as many as two or three spatial scales within the data, perhaps indicative of within reef (about 0.05 km) and between reef (about 0.5 km), and alternating clusters of reef groups at about 1.5 km.

Despite the relatively poor 'fit' of the kriging method to the circumstances at Waihau Bay, the two methods produced surprisingly similar estimates of total biomass. The confidence intervals surrounding the kriged estimate were much smaller, however, because they assumed that the covariance function was known, and hence under-represent the true level of uncertainty. We believe kriging remains a promising method, in part because of the greater flexibility it allows in sampling patches of organisms that are of variable density (see also McCormick 1990).

Stratified random sampling produced biomass estimates for the two summer samples of 201 and 146 t respectively (63.6 and 46.2 t dry weight, McCormick, 1990). Only negligible amounts of beach-cast *Pterocladia* were found during the two years of the study. This is in contrast to other areas (such as the Wairarapa coast) where large drifts of algae are frequently found washed up on beaches (McCormick 1990). Large drifts do occasionally occur on the Waihau Bay beaches but none have been reported for the last seven to eight years (T. Christie, pers. comm.). It is possible that large amounts of drift algae were present on the beaches between the times when our surveys were conducted. Decomposition of *P. lucida* occurs very rapidly and we could have missed these events, however, local residents reported that this did not occur.

Taking the average of the two summer samples gives a mean biomass of about 173 t wet weight over the 4.4 km of coast, which represents a considerable resource. Using the wet weight to dry weight regression equation from McCormick (1990) (dry weight = 0.116 + 0.316 x wet weight) there is a standing crop of about 55 t dry weight of *P. lucida* at the study site. This represents about 23% of the highest total New Zealand production of 239 t achieved in 1983 (Luxton & Courtney 1987).

Plants recovered quickly when harvested in summer and biomass had returned to pre-harvest levels 12 months later. This recovery was apparent irrespective of harvest method, although the mean biomass per quadrat from the plots in which plants were cut were slightly higher than from those which were plucked. The better recovery of the cut plants may be related to the storage of nutrients and energy reserves in the lower stems of the plants which would be removed by plucking (W. Nelson Museum of

New Zealand, pers. comm.). Given that about one third of the plant is left attached to the substrate after cutting, it is not surprising that the cut plants recovered better than the plucked ones.

The appearance of the *P. lucida* which regrew after harvest was markedly different from that pre-harvest. The regrowth was much cleaner and more lush than non-harvested plants, which tended to be straggly and usually had epiphytic growth such as sponges, coralline algae, and various filamentous red algae on them. The quality of the agar produced by clean *P. lucida* is generally better than that from old plants (W. Nelson, pers. comm.) and also requires less sorting and cleaning after harvest. The quality of agar from *P. lucida* harvested in winter is lower than that from plants harvested in summer (Guiry 1997).

From an economic viewpoint, cutting the plants using hand shears would probably be too time consuming, but more efficient mechanical methods such as those used in the *Gelidium sesquipedale* fishery in Portugal (Santos 1993b) could be developed. Harvesting in winter by either method would not be advisable as the plant densities in the manipulated plots were lower than pre-harvest levels after 12 months.

There was no discernible effect of harvesting *P. lucida* or *C. maschalocarpum* on other species present. This is in contrast to studies on various laminarian algal species which have been shown to have complex interactions with a number of different species, sea urchins in particular (e.g., Tegner & Dayton 2000). The lack of effect may have been due to the small scale of the harvesting experiments, and if large-scale harvesting was to occur, then a further study investigating these ecological impacts is recommended.

The present fishing effort restrictions alone are unlikely to provide a basis for long-term sustainability of the fishery if live plants are to be harvested. We hypothesise that future management of *P. lucida*, and other seaweed resources, is likely to take advantage of the site-attached nature of the resource and implement small scale management and the use of rotational closures in time and/or space. Such closures have been used to maximise yield and the probability of sexual reproduction in beds of red seaweeds such as *Chondrus crispus* (Chopin 1986, Chopin et al. 1992) and *Gelidium sesquipedale* (Santos 1993b). It is important, therefore, to have an explicit spatial component in the surveys (and fisher logbooks) to retain the flexibility to accommodate such management options without loss of continuity in data collection. In the short term, however, the development of management is likely to be based on a more iterative process and rely heavily on survey and experimental data. Such management may include use of small areas (e.g., Waihau Bay or Brampton Shoal), closures and, with appropriate reporting requirements, will allow more sophisticated management to develop without loss of data.

There is likely to be substantial interannual variability in the abundance of *P. lucida*. This variability will limit the extent to which the results of this study can be generalised to other places and times. Within the constraints provided by the MFish tender specifications, however, we believe the methods developed, the results of the sampling, and the experimental results provide a strong basis for improved management. The likelihood of more sophisticated management will be further enhanced by the development of a reporting system that collects catch and effort data on a small spatial scale.

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