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EXECUTIVE SUMMARY

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To determine the response to fishing of stunted stocks of paua, two sites at D'Urville Island were experimentally fished by removing all paua larger than 110 mm. Density, length at maturity, incremental growth, and length frequency distributions of paua at these sites and at two adjacent control sites were monitored before fishing and then 3 months and a year after fishing. There was a significant decline in density at one fished site 3 months after fishing, but a year later we detected no change in abundance, growth rates, length at maturity, or length frequency distributions between fished and unfished control sites. We conclude that fishing at this intensity and scale was insufficient to cause a measurable change after one year. This may be an artifact of the small scale of the experiment. A much higher level of fishing will be required to properly assess the sustainability of fishing stunted stocks.

1. INTRODUCTION

1.1 Overview

Many paua populations around the New Zealand coast do not reach the minimum legal size (MLS) of 125 mm (e.g. Schiel & Breen 1991, Naylor & Andrew 2000), and there is a perception that these stocks are under-utilised, especially within the commercial sector. There is no information on the impact of fishing paua from 'stunted stocks'. It has been hypothesised that fishing these populations at a smaller MLS will increase growth rates by reducing competition. Alternatively, maximum size and the rate at which individuals approach that size may be a function of environmental conditions that are independent of density. By experimentally fishing stunted stocks, we examined the effects of fishing at a particular level upon the abundance, recruitment, and growth rate of the stock.

2. METHODS

2.1 Study sites

After consultation with commercial quota holders, MFish, and iwi, the northern end of D'Urville Island was chosen as the most suitable location for this study. Two sites were selected in each of Lookout and Swamp Bays (Figure 1). This area is relatively sheltered, supports high densities of paua, and is easily accessible. The paua within many bays in this area do not reach the MLS of 125 mm (McShane et al. 1994) and it has been suggested that these stocks may be stunted (Schiel & Breen 1991, McShane et al. 1994, McShane & Naylor 1995). The west and south sites at Lookout and Swamp Bays, respectively, were the fished sites, and the other two sites at each location acted as unfished controls.

2.2 Experimental fishing

During February 2002, the west site at Lookout Bay and the south site at Swamp Bay were fished to a length of 110 mm. We had proposed that the minimum size limit for experimental fishing would be determined as the length at which 90% of the biomass was protected from fishing. Inspection of population data from a NIWA tagging study in 1994 (unpublished) initially indicated that this length would be about 105 mm. Subsequent analysis of length frequency data from the study sites indicated that 90% of the biomass would be protected at a length of 120 mm. A reduction in effective MLS of only 5 mm was considered unlikely to elicit any density dependent response from the populations, however, and a 'MLS' of 110 mm was chosen.

Divers measured paua in the water using the standard paua tool adopted in PAU 7, with an attached measuring device set at 110 mm. Three divers spent one day at each site and fished until no more paua at or above 110 mm could be found at the sites.

2.3 Abundance

Mean density was estimated at each site using 25 x 1m diver transects. At each site, two divers each deployed a 25 m tape in a haphazardly chosen direction. Divers counted and removed all paua within 1 m of the tape. Solid 1 m rods were carried to determine the edge of the transect. Where paua were obviously more than 50% inside the transect they were counted and collected. Where the rod was at or near the centre of the paua they were treated alternately as in and out of the transect. The number of 25 x 1 m transects at each site is shown in Table 1. Mean density is calculated as the mean number of paua in transects, and was estimated for each site on three occasions; before fishing in January 2002, 1 month after fishing in April 2002, and 12 months after fishing in April 2003 (Figure 2). The statistical significance of differences in density over time at sites was assessed using a bootstrapped resampling test of a difference in mean numbers of paua in transects.

Because small paua are difficult to survey reliably, mean density for two size classes of larger paua (90–109 mm and 110+ mm) was also estimated as the product of the mean density estimated from transects, and the proportions in each size class estimated from the length frequency distributions. Confidence intervals were estimated as 1.96 x the sum of the squares of the c.v.s of the estimated proportions at length, and of counts from the transects, which is approximately equal to the c.v. of the product of each factor. Confidence intervals are therefore only approximations. They are also truncated at zero.

2.4 Population length frequencies

The length frequency distributions of paua were estimated at all sites on three occasions from paua collected during the estimation of density described above. Paua from individual transects at each site were not separated for the length frequency estimation, and where the numbers of paua in transects were insufficient to adequately sample length, all paua encountered adjacent to transects were collected until an adequate sample had been obtained. To minimise disturbance at the sites, length frequency distributions were not estimated 3 months after fishing at the control sites, and at the fished sites 3 months after fishing they were estimated with only small sample sizes.

2.5 Maturity

In January 2002, 100 paua between 40 and 100 mm were collected from each site for the determination of size at maturity. Rates of maturity at length were determined by fitting this data to the logistic equation:

$$p = \frac{e^{a+bl}}{1+e^{a+bl}}$$

where p is the proportion mature, l is shell length, and a and b are parameters of the logistic function. The fitted logistic curves for each site are shown in Figure 3. Length at 50% maturity was calculated from the fitted curve, and 95% confidence intervals estimated by bootstrapping. A bootstrap permutation test was used to determine whether there were significant differences between lengths at 50% maturity between sites over time.

2.6 Estimation of growth

Growth estimates were derived from mark-recapture methods. About 800 emergent and cryptic paua across the available size range were collected from each site. Paua were tagged with numbered 6 mm diameter polyethylene discs attached adjacent to the spire of the shell with cyanoacrylate glue. The shells were cleaned of epibiota if necessary, and lightly dried with a towel. Emersion times were minimised and always less than 1 hour. Tagged paua remained at liberty for about one year and were then recovered by thorough searching at and around each site. Shell lengths of recovered paua were measured to the nearest millimetre.

Growth of recaptured paua was estimated using the maximum likelihood approach of Francis (1988, 1995). This model expresses observed increments in length as functions of the observed length at tagging and time at liberty, and describes growth in terms of average annual growth for individuals of a given size (Francis 1988). Parameters estimated during this process included the mean annual growth rates at two lengths, parameters for growth variability, and the influence of outliers in parameter estimation. Four growth models describing growth variability (equations 5–8, Francis 1988) were fitted to the data.

The lengths used to compare growth rates among sites were chosen after inspection of the length-frequency distributions of recaptured tagged paua. To facilitate comparison with previously published estimates of paua growth, the von Bertalanffy growth parameters K and L_∞ were also estimated (using equation 1, Francis 1988).

2.7 Estimation of biomass

Biomass was estimated using the density estimates from diver transects and the length frequencies of paua at each site. Length was converted to weight using the length weight relationship of Schiel & Breen (1991) for D'Urville Island, where weight (g) = $(2.59 \times 10^{-5}) \times$ length (mm)$^{3.322}$. This was scaled up according to the area of suitable reef habitat at each site. estimated from aerial photographs of each location. Photographs were taken from an altitude of 8000 feet using a Zeiss RMK 30/23 large-format camera with a 305 mm lens. The positives were enlarged to 1:2500, digitised using Auto-Cad, and then rectified using ground control points, which were fixed using an Omnistar Differential GPS. The resulting maps were imported into ArcView for estimation of the reef area. Photographs were taken within 2 hours of low tide when sea surface conditions were calm.

2.8 Egg-per-recruit modelling

The Ricker (1975) formulation of egg-per-recruit equations was used. The parameters used in the model were the respective estimates of the Brody growth coefficient (K) and mean maximum length (L_∞) presented in Table 2, the parameters of the logistic function describing size at maturity (Section 3.4), the length-weight relationship of Schiel & Breen (1991), the length-fecundity relationship derived by Schiel & Breen (1991) using Wilson's (1987) data, where eggs = $(9.32 \times 10^{-12}) \times$ length (mm)$^{8.408}$, and Sainsbury's (1982) instantaneous natural mortality estimate of 0.1.

3. RESULTS

3.1 Experimental fishing

Experimental fishing in February 2002 resulted in the removal of 451 kg of paua from Lookout Bay west and 261 kg from Swamp Bay south.

3.2 Abundance

Mean density was estimated for each site on three occasions; before fishing in January 2002, 1 month after fishing in April 2002, and 12 months after fishing in April 2003 (Figure 2). Before fishing, density was similar at fished and unfished sites within each location, but different between locations. At Swamp Bay sites, initial density was about 2 paua per m^2, and at the Lookout Bay sites paua density was initially about 7–8 per m^2 (Table 1, Figure 2).

Two months after fishing there was a small but insignificant decline in overall density at the Swamp Bay control site and a relatively large and significant decline in density at the Swamp Bay fished site (about 2 to 0.4 per m^2, Table 1, Figure 2). One year after fishing, density estimates at both the fished and control sites at Swamp Bay were similar to, and not significantly different from, estimates at respective sites before fishing (Table 1, Figure 2).

At the Swamp Bay control site the estimated density of paua between 90 and 109 mm, and of paua 110 mm or larger, was similar over the entire period (0.5 to 0.9 per m^2 and 0.8 to 1.2 per m^2 respectively) (Table 3). At the Swamp Bay fished site, there was a relatively large decline in the estimated density of both larger size classes between January and April 2002, especially in the 110+ group (0.6 to 0.1 per m^2) (Table 3). A year after fishing, the estimated densities of both size classes at this site are similar to pre-fishing estimates.

The effect of fishing was evident but less pronounced at the Lookout Bay fished site, where 2 months after fishing there was a slight but insignificant decline in overall density (Table 4, Figure 2). A year after fishing the density estimate at this site was very similar to the pre-fishing estimate. At the Lookout Bay control site overall density estimates were similar and not significantly different before and one year after fishing (Table 4, Figure 2). Two months after fishing there was an increase in the density estimate at this site that was accompanied by a corresponding increase in the variance surround the estimate. This was caused by one of the four transects containing an unusually large number of paua, and the high variance was subsequently reduced a year after fishing by increasing the number of transects done at this site.

Density estimates for paua between 90 and 109 mm increased at the Lookout Bay fished site between January and April 2002, while estimates for paua 110 mm and larger showed a large decline (2.35 m^2 to 0.9 m^2) over the same period (Table 3). Density estimates for paua between 90 and 109 mm are similar between January 2002 and April 2003, but for paua over 110 mm, the estimated density remained lower in April 2003 (1.28 m^2) than it was in January 2002 (2.35 m^2) (Table 3). At the Lookout Bay control site, density estimates for paua between 90 and 109 mm were similar between January 2002 and April 2003, but for paua over 110 mm, the estimated density was also lower in April 2003 (1.34 m^2) than it was in January 2002 (2.01 m^2) (Table 3).

3.3 Population length frequencies

The length frequency distributions of paua are shown in Figure 4. The most noticeable change in distribution over time is in the relative number of paua below 70 mm. At both Swamp Bay sites, and, to a lesser extent at both Lookout Bay sites, many more paua below 70 mm were collected in January 2002 than at any other time. Differences in the number of juveniles between areas are likely to be the result of more accessible cryptic habitat at the Swamp Bay than Lookout Bay sites. Differences over time in the relative numbers of juveniles at sites are probably the result of relatively smaller sample sizes in post–fishing surveys, less accessible cryptic habitat being encountered in later surveys, or less thorough searching of cryptic habitat by divers in later surveys. In any event, the frequency of juvenile paua in post–fishing transects appear to be poorly and under-estimated.

Before fishing, the mode of the distribution for larger paua was between about 100 and 120 mm, and there were very few paua larger than 125 mm at any site.

3.4 Maturity

The proportion of paua mature at length and the fitted logistic curve described in Section 2.5 are shown in Figure 3. Lengths at 50% maturity and bootstrapped 95% confidence intervals for all sites before and after fishing are given in Table 5. Mean length at 50% maturity ranged from 81.9 mm in Lookout Bay East in 2003, to 89.6 mm in Swamp Bay South in 2002 (Table 5). Mean length at 50% maturity was generally lower at the Lookout Bay than the Swamp Bay sites (Table 5). There were no significant differences between years at any site (Table 6), and the greatest differences between years occurred at the unfished sites at Lookout Bay East and Swamp Bay North (Table 5). At the fished sites, length at 50% maturity was similar before and after fishing (Table 5).

Estimates of length at 50% maturity from all sites are higher that those recorded for stunted populations at Taranaki (58.9) and Banks Peninsula (75.5) (Naylor & Andrew 2000).

3.5 Growth

Tagged paua were at liberty for between 373 and 451 days. The number of tagged paua recovered, mean growth estimates at 70 and 100 mm, and the von Bertalanffy growth parameters estimated from recoveries are shown in Table 2. Incremental growth is shown in Figure 5. Despite four days of searching on two separate occasions, tag recoveries were low at all sites, and especially low at the Lookout Bay sites. Low recoveries at these sites are probably due to migration away from the tagging site in areas of very high paua density. One paua tagged and released at the Lookout Bay West (fished) site (length at release 81 mm) was recovered about 140 m away during a search for tagged paua at the Lookout Bay East site. Incremental growth from this paua was treated as growth at the site of release, and would confound between site differences in growth at Lookout Bay had any been found.

Using GROTAG (Francis 1988), the model was initially fitted to incremental growth data to estimate the mean annual growth rates at two lengths, with parameters to estimate the influence of outliers and growth variability (according to equation 5 of Francis (1988)). The introduction of more complex relationships describing growth variability (equations 6–8 of Francis (1988)) did not result in a significant improvement to the model fit. The lengths used to compare growth rates among sites were chosen after inspection of the length-frequency distributions of recaptured tagged paua. To facilitate comparison with previously published estimates of paua growth, the von Bertalanffy growth parameters (K and L_∞) were also estimated (using equation 1, Francis (1988)).

A likelihood ratio test (Francis 1988) indicated that growth rates at the fished and unfished Swamp Bay sites were not significantly different. Mean annual growth at length was about 18 mm for a 70 mm paua, and 3 mm for a 110 mm paua (Table 2). Estimates of asymptotic growth for both sites were similarly about 119 mm (Table 2).

Growth parameters have been estimated for the Lookout Bay sites (Table 2), but growth at these sites should be considered indeterminate because of the low number of tag recoveries. Although growth is not well defined, especially at the Lookout Bay sites, growth at length for all sites was similar to previous estimates (Breen & Kim 2003) for D'Urville Island and the Staircase.

3.6 Biomass

Biomass estimates for sites are presented in Table 1. In April, to minimise disturbance at sites, no length frequency estimates were made at control sites, and the length frequency distribution at fished sites was estimated from a relatively small sample. Biomass estimates for the control sites in April therefore assume that the length frequency distribution has remained unchanged since January. At the fished sites, the smaller sample size in April is likely to have exaggerated the post fishing biomass estimates. Changes in biomass estimates at sites over time are similar to, and reflect changes in, abundance (see Figure 2).

3.7 Egg-per-recruit modelling

At Swamp Bay, at least 40% of the virgin equilibrium egg production was conserved where *F* was less than 0.25 and the MLS was 115 mm or more (Figure 6).

At Lookout Bay, at least 50% of pre-fishing equilibrium egg production was conserved at a MLS of 115 mm, when fishing mortality was less than 0.3, and at least 40% of egg production was conserved at this length across the range of fishing mortalities considered (Figure 6).

4. DISCUSSION

A year after fishing, there were no detectable changes in overall density, length distribution, incremental growth, or length at maturity at any site. Although fishing caused an initial decline in abundance at Swamp Bay, abundance estimates a year later were similar to pre-fishing estimates. Density estimates for the two larger size classes of paua examined (90–109 mm and 110+ mm) were also similar at both the fished and control Swamp Bay sites before and after the experiment. Estimates for the 90–109 mm size group were also similar at both Lookout Bay sites before and after the experiment. In the 110+ size class, however, estimates at both the fished and control sites were lower a year after fishing (about 1.3 per m^2, Table 3) than they were before it (about 2.4 and 2.1 per m^2 respectively, Table 3). The similarity of these lower density estimates suggests they were not due to our experimental fishing.

These results suggest that the level of fishing was insufficient to cause a detectable response from the population. In the absence of a significant change in density, the lack of a density dependent response in either growth or length at maturity is not surprising. Density dependent responses in abalone have been reported in aquaria Marsden (1996), found the highest growth rates in paua in aquaria at the lowest density). Density dependence in population processes is less clear in wild populations. McShane & Naylor (1995) found no relationship between density and growth in a population of paua on Wellington's south coast, and Nash (1995) found a highly significant increase in size at maturity in one area after stunted stocks were fished below the MLS, but no change in the other area.

At Lookout Bay, about 450 kg of paua were removed from an estimated reef area of only 545 m^2 . The fished site at Lookout Bay was confined to the seaward and western sides by sand, but lateral movement to the east was possible. The collection of one tagged paua at the control site, which had been released at the fished site, demonstrates that lateral migration occurred during the course of the study. Immigration is also likely to have occurred at the other sites where the population was less confined, confounding interpretation of the lack of response of the paua within the fished sites. Although fishing by commercial paua divers on a much larger scale may resolve this issue, it was not considered appropriate for this study because of the concerns expressed by local iwi.

The estimation of the sustainability of fishing stunted stocks requires fishing on a larger spatial and temporal scale than in this study. If such an initiative were to proceed, the most suitable area would be near Lookout Bay, as paua at Swamp Bay were generally slightly larger than those at Lookout Bay (see Figure 4), and areas close to Swamp Bay support paua that are commercially fished. There is no commercial fishing along the 1 km of coastline between Lookout Bay and Trafalgar Point to the east because of the small size of paua in the area. This is supported by the estimated growth parameters and inspection of the length frequency distributions. The reef area adjacent to this coast is about 40 times that of the fished site at Lookout Bay.

Egg-per-recruit analyses suggest that at Lookout Bay a MLS of 115 mm would conserve at least 40% of the virgin equilibrium egg production across the range of fishing mortalities considered, and where F is less than or equal to 0.2, a MLS of 110 mm conserves at least 40% of egg production. A previous study (McShane & Naylor 1995) on stunted stocks in the same area of D'Urville Island similarly estimated that, at this level of fishing, a MLS of 110 mm would conserve 40% of the potential egg production. There is little guidance in the literature concerning 'safe' levels of conserved egg production. Breen (1986), Shepherd et al. (1995), and Shepherd & Baker (1998) suggested that 40–50% of virgin egg production should be considered a limit reference point. The assumptions of constant recruitment and the equality of growth and mortality required for per recruit analyses are likely to be violated (e.g., Sainsbury 1982, McShane 1993, Wilson & Schiel 1995), and consequently the results of such analyses should be approached with great caution. Nevertheless, they are consistent with the conclusion that fishing at a MLS below 125 mm may be sustainable.

We conclude that the level of fishing was insufficient to cause a density dependent response in the fished populations, but because immigration into the sites may have occurred, this conclusion should be viewed with caution.

Because of the inconclusive response at the fished sites, and current concerns over the sustainability of the PAU 7 fishery, some of the pressure on areas of current high exploitation could be relieved by the small-scale commercial utilisation of stunted stocks.

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Table 1: Mean density and biomass of paua at D'Urville Island sites.

Month	Area	Reef area (m^2)	No. of transects	Mean density (per m^2)	Biomass (kg)
January	Swamp fished	1303	10	1.96	392.72
	Swamp control	814	10	2.41	364.80
	Lookout fished	480	4	7.98	647.15
	Lookout control	545	4	6.95	649.04
April	Swamp fished	1303	4	0.42	80.91
	Swamp control	814	4	1.77	267.92
	Lookout fished	480	4	6.50	548.62
	Lookout control	545	4	8.89	830.22
April	Swamp fished	1303	6	1.55	414.65
	Swamp control	814	4	2.20	407.35
	Lookout fished	480	5	7.51	536.36
	Lookout control	545	6	5.80	470.33

Table 2: Mean annual growth estimates (mm/year) of paua at lengths 70 and 110 mm, and von Bertalanffy growth parameters from sites in Lookout and Swamp Bays. 95% confidence intervals of mean growth at length are shown in parentheses).

Area	Mean growth (g_{70})	Mean growth (g_{110})	L_∞	K	No. recovered
Swamp fished	17.84 (16.87–18.90)	3.21 (2.31–4.15)	119.10	0.452	22
Swamp control	17.85 (16.99–18.77)	3.28 (2.03–4.02)	118.99	0.453	29
Lookout Control	16.61 (12.67–20.26)	2.04 (0.00–6.00)	115.59	0.453	6
Lookout Fished	17.21 (15.42–18.76)	2.69 (1.47–3.68)	117.41	0.451	6

Table 3: Mean density (no. per m^2) of paua by size class (mm) and approximate upper (U. 95%) and lower (L. 95%) 95% confidence intervals.

Site	Date	L. 95%	90–109	U. 95%	L. 95%	110+	U. 95%
Swamp fished	Jan 2002	0.22	0.71	1.20	0.14	0.63	1.12
	Apr 2002	0.06	0.28	0.50	0.00	0.05	0.54
	Apr 2003	0.24	0.75	1.26	0.15	0.66	1.17
Swamp control	Jan 2002	0.32	0.63	0.94	0.82	1.11	1.40
	Apr 2002	0.15	0.46	0.77	0.51	0.81	1.11
	Apr 2003	0.66	0.94	1.22	0.94	1.21	1.48
Lookout fished	Jan 2002	3.52	3.95	4.38	1.91	2.35	2.79
	Apr 2002	4.68	5.16	5.64	0.29	0.90	1.51
	Apr 2003	3.61	3.88	4.15	0.96	1.28	1.60
Lookout control	Jan 2002	3.41	3.72	4.03	1.69	2.01	2.33
	Apr 2002	4.01	4.76	5.51	1.82	2.57	3.32
	Apr 2003	2.98	3.21	3.44	1.06	1.34	1.62

Table 4: Results of a bootstrapped resampling test of a difference in mean numbers of paua in transects at sites at D'Urville Island between sampling times.

Location	Area	Jan 02 & Apr 02	Jan 02 & Apr 03	Apr 02 & Apr 03
Lookout Bay	Control	0.85	0.86	0.84
Lookout Bay	Fished	0.77	0.66	0.30
Swamp Bay	Control	0.87	0.62	0.86
Swamp Bay	Fished	0.98	0.72	0.01

Table 5: Lengths at 50% maturity and bootstrapped 95% confidence intervals for paua sampled from sites at D'Urville Island.

Location	Area	Year	Mean length at 50% maturity	Lower 95% confidence interval	Upper 95% confidence interval
Lookout Bay	Control	2002	86.2	84.4	88.2
Lookout Bay	Fished	2002	83.5	80.8	86.2
Swamp Bay	Control	2002	89.5	87.3	91.8
Swamp Bay	Fished	2002	89.6	88.4	90.8
Lookout Bay	Control	2003	81.9	79.3	84.3
Lookout Bay	Fished	2003	85.4	83.1	87.6
Swamp Bay	Control	2003	86.0	83.3	88.5
Swamp Bay	Fished	2003	88.1	86.0	90.1

Table 6: Results of permutation test of a difference in the length at 50% maturity between years for paua sampled from sites at D'Urville Island.

Location	Area	Probability
Lookout Bay	Control	0.26
Lookout Bay	Fished	0.94
Swamp Bay	Control	0.57
Swamp Bay	Fished	0.81

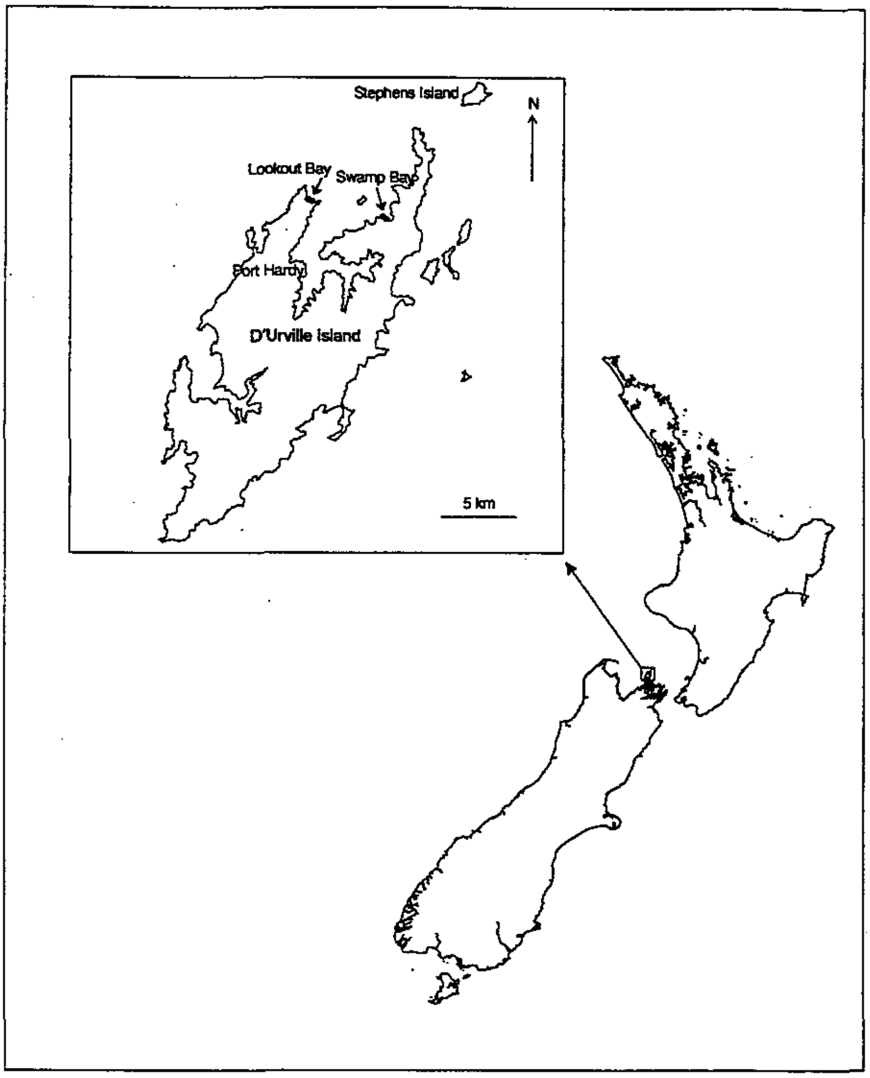

Figure 1: Map showing the study sites at D'Urville Island.

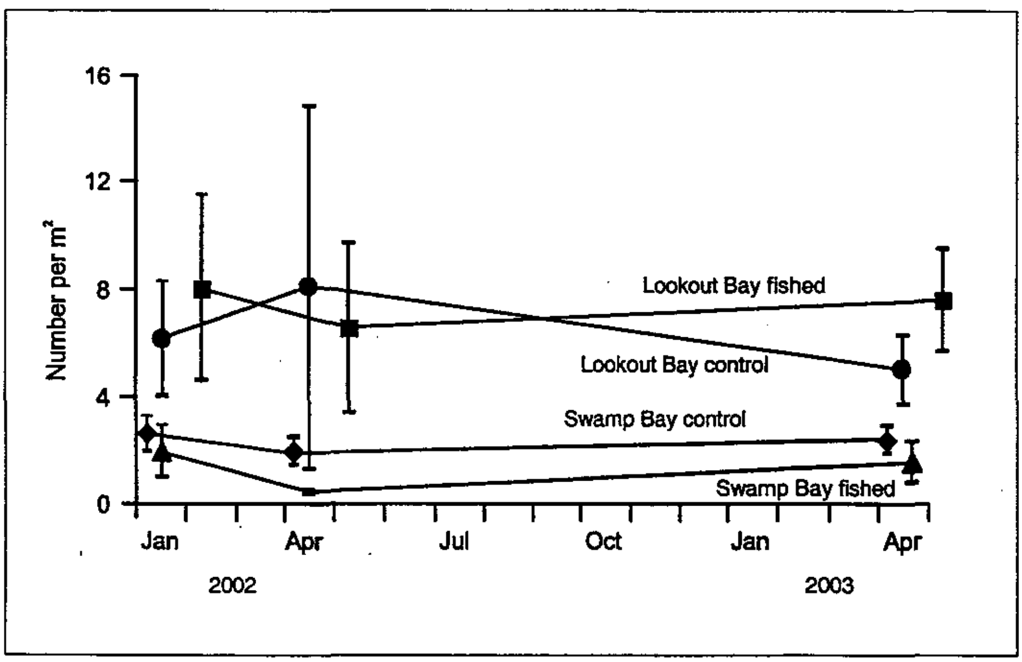

Figure 2: Mean density of paua from transects at D'Urville Island (± 2SE) before, 1 month after fishing and 1 year after fishing.

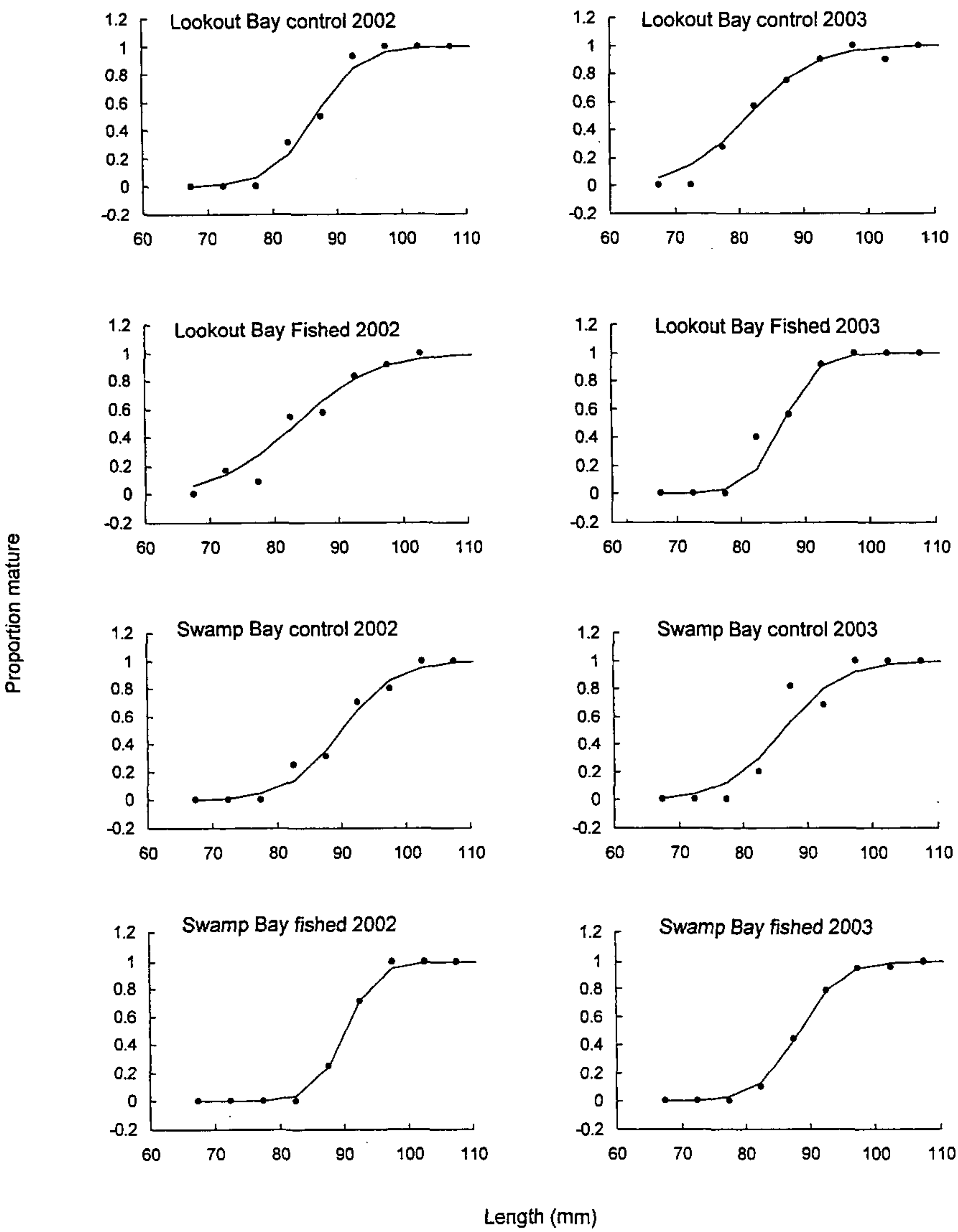

Figure 3: Maturity ogives for paua sampled from sites at D'Urville Island.

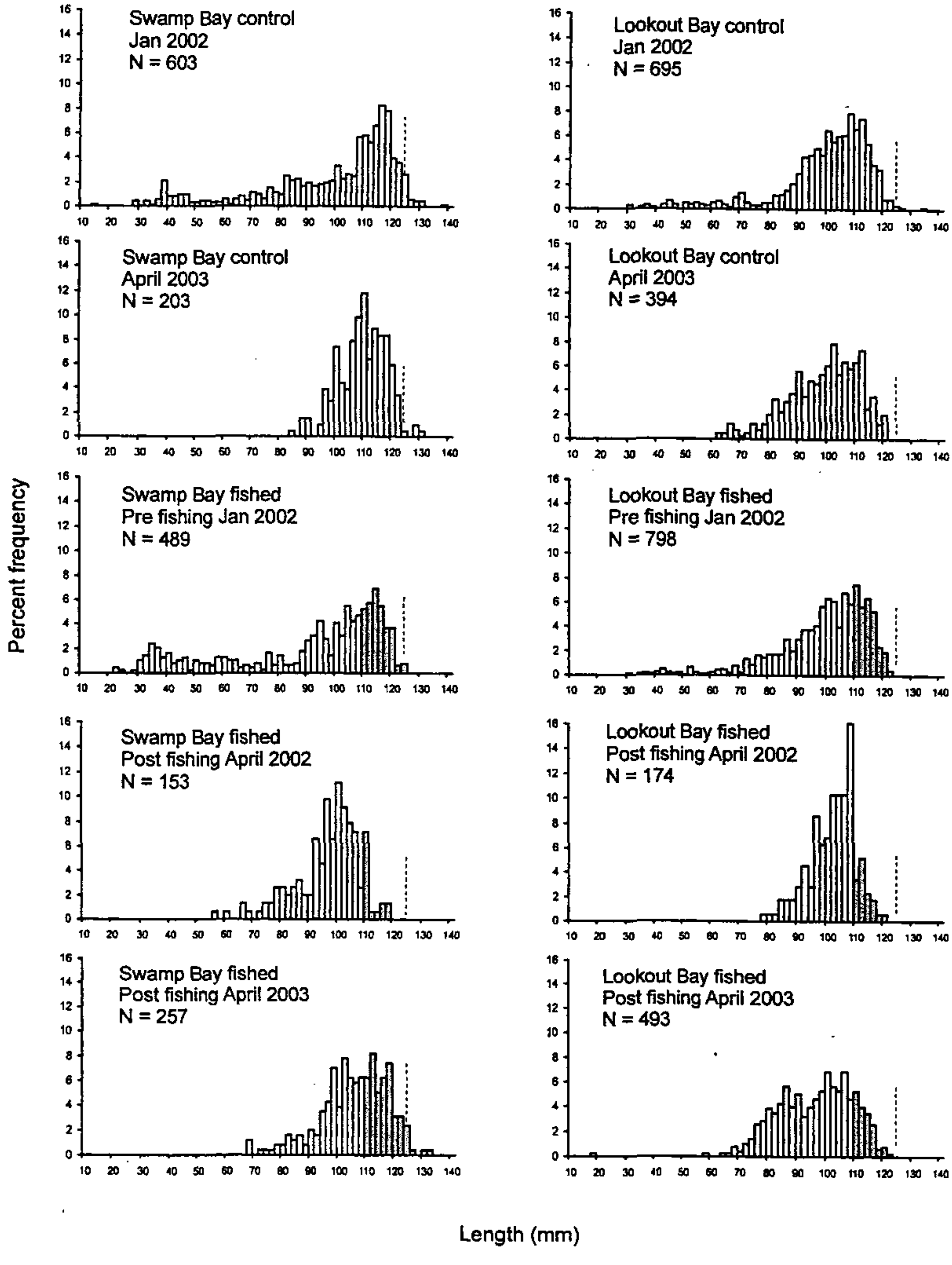

Figure 4: Length frequency distribution of paua from transects at D'Urville Island. 125 mm is indicated by vertical dashed line, percentage of paua above 110 mm at fished sites indicated by shading.

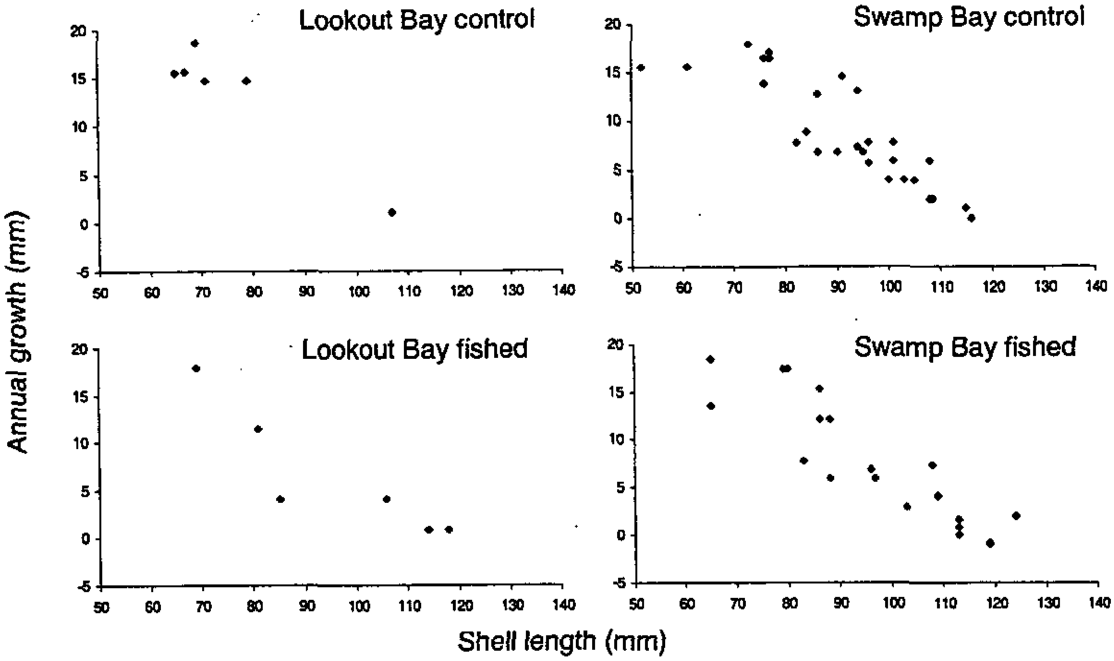

Figure 5: Incremental growth of paua tagged and recaptured from sites at D'Urville Island.

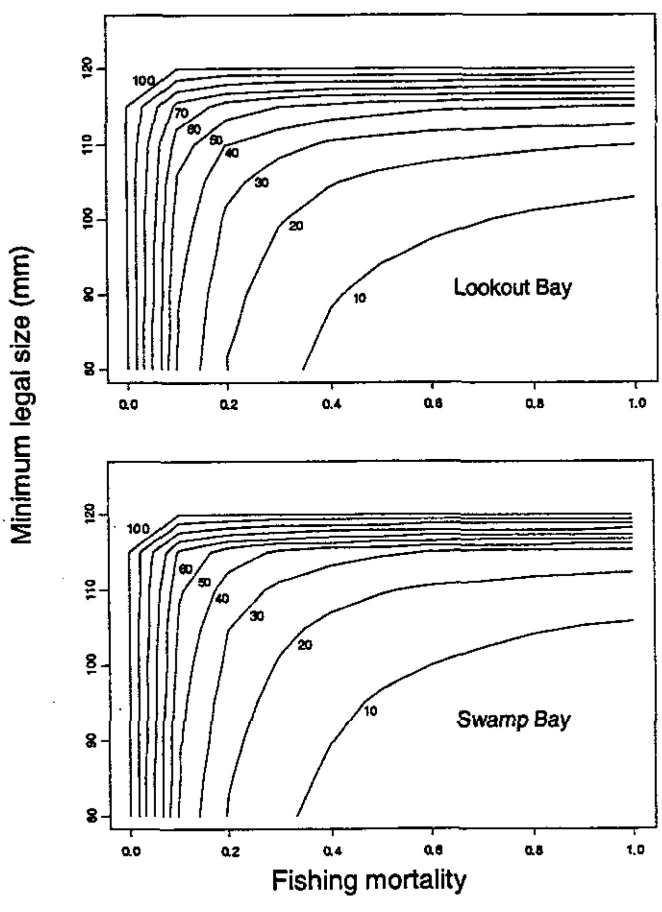

Figure 6: Egg-per-recruit contours for paua at Lookout and Swamp Bays as a function of fishing mortality *F* and minimum legal size, where natural mortality *M* is 0.1.