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EXECUTIVE SUMMARY

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We present incidental mortality estimates for paua harvesting in PAU 7 (Marlborough). Mortality of undersize paua during removal from the reef and their subsequent return was estimated in two experiments and by examining commercial paua catches. The proportional mortalities of paua from these observations were then scaled to estimate total incidental fishing mortality in the fishery. The estimates indicated that incidental mortality from these sources was very low (about 3 paua per 1000 harvested).

1. INTRODUCTION

Stock assessments developed for paua have so far assumed that there is no mortality associated with capture of undersized animals. Undersized paua may die from wounds caused by removal, desiccation, or osmotic and temperature stress at the surface, or indirectly from being returned to unsuitable habitat or being lost to predators or bacterial infection. Because paua, along with other species of abalone, lack an effective clotting mechanism in their blood plasma, haemorrhaging may be fatal (George & Ferguson 1950, Hill & Welsh 1966, Pirker 1992, Taylor et al. 1994). If such incidental mortality is non-trivial, then an estimate of this loss should be incorporated into the assessments and fishing practices changed to minimise mortality (Tegner et al. 1989, Shepherd & Breen 1992).

In 2000–01, reported commercial landings for all paua fishstocks combined totalled 1146 t. As the exploitation rate in these fisheries increases, paua just smaller than the minimum legal size (MLS) are more likely to be removed from the reef, measured, and returned. This particularly applies to the case in PAU 7 where, in 2000–01, 69% of the landed catch was within 10 mm of the MLS of 125 mm (Breen et al. 2001).

2. METHODS

The assessment of incidental fishing mortality from fishing tools was done in three parts: laboratory experiments to examine long-term mortality caused by wounding, field observations to assess the proportion of paua in each of seven damage categories and four handling categories, and a field experiment to assess the short-term survival of damaged paua in the wild.

2.1 Long-term mortality

One hundred and fifty paua (76 females and 74 males) were allocated to treatments as shown in Table 1. They ranged in size from 100 to 154 mm with a mean of just under 134 mm.

The experiment was conducted in the NIWA aquarium facility at Greta Point using the following range of damage categories.

- Light foot cut (FC1) – shallow cut to the foot about 2–3 mm deep and 5 mm long.
- Deep foot cut (FC2) – deep cut to the foot about 10 mm deep and 20 mm long.
- Mantle abrasion (MA) – removal of about 150–200 mm^2 of the black epithelial tissue from the mantle edge.
- Foot abrasion (FA) – as for mantle abrasion, but in the centre of the foot.
- Mantle cut (MC) – a 5–10 mm long cut to the mantle edge.
- Shell damage (SD) –about 100 mm^2 broken off the shell edge
- Control – no damage

For each of the seven damage categories, at least 10 replicate 4 litre plastic tanks each containing two paua, were set up. Paua were fed, *ad libitum*, a diet of the large brown alga *Lessonia variegata*. The tanks were supplied with unfiltered seawater at a rate of about 3 litres per minute and were cleaned twice per week. All paua were checked daily for mortality by touching them to see whether they were clamped to the container, and were fed every 2 or 3 days. The injuries were inflicted on the paua using a diver's knife and were intended to mimic as closely as possible those likely to be seen during commercial operations using this type of tool. It should be noted that the tool generally used by divers in PAU 7 is a custom-made stainless steel knife with a rounded tip and no sharp edges. The design

makes cutting the paua less likely, although abrasions and shell damage may occur. The deep and shallow cuts were made at a low angle cutting diagonally across the foot rather than vertically. Data from this experiment were used to estimate proportional mortality for each damage category.

Although aquarium experiments may underestimate mortality (there are no predators and food was unlimited), countervailing assumptions about water quality, disease, and so on may reduce survival in the laboratory compared to the field. We estimated mortality in the laboratory because our inability to find all paua released after several months at liberty would have made the cause of mortality unknowable, thereby confounding analysis.

The experiment was run for 70 days. In similar experiments in the New South Wales abalone fishery, all mortality in experiments lasting up to 42 days occurred within the first 14 days (N.L. Andrew, unpublished data).

2.2 Field observations

Direct observation of divers while fishing would cause them to modify their normal behaviour. In addition to this, the common practice in paua harvesting in PAU 7 is for the divers to discard sub-legal sized paua without bringing them back to the boat to be measured. It was, therefore, not possible to examine catches for damage without substantially altering the current harvesting methods.

Damage done to paua harvested by divers in PAU 7 was estimated by observing the landed catches from 28 diver-days in a paua factory in Blenheim. A sub-sample of a diver's landed catch (usually one bin) was examined and the number of paua in the different damage categories was recorded. Catches from a further 3 diver-days were observed in the field, giving a total of 31 diver-days.

It was assumed that the observed proportions of damaged paua landed at the shed were similar to the damage inflicted on the sub-legal paua returned to the reef. These observations were augmented by interviewing divers to get information regarding the type of tool used, the proportion of the catch retained, their diving experience, and the way the paua were handled.

The observed damage to the landed catch was scaled by the proportion of the total landed catch examined to give the proportion of damaged paua in each damage category. These proportions were then applied to the number of under-sized paua returned to the sea estimated from the results of diver interviews.

The damage categories used were the same as in the laboratory experiment (see Section 2.1), and the handling categories were as follows.

a) *Returned immediately by the diver.* The paua was removed from the reef, measured underwater, then returned immediately to the reef without being brought back to the boat for measuring.

b) *Replaced by the diver.* The paua was removed from the reef and taken back to the boat to be measured, then replaced on the reef by the diver.

c) *Thrown on to reef.* As for (b), but the undersized paua are thrown back on to reef from the boat.

d) *Thrown on to sand.* As for (c), but the undersized paua are thrown back on to sand from the boat.

2.3 Field experiment

The damage categories used in this experiment were the same as in Section 2.1. The categories used differed slightly, however, as in order to treat the paua, it was necessary to take them back to the boat. The time the paua were out of the water was kept to a minimum, generally less than 5 minutes. The handling category 'returned immediately by the diver' was not therefore tested. Because all paua which were thrown from the boat landed on their shell, they were placed on the sand on their shells and not thrown on to sand. This allowed the divers to more easily monitor their survival.

The field experiment was conducted at Palmer Head on the Wellington south coast over 2 days. Paua were collected by divers and taken to the boat where they were treated and then either returned to the reef or sand by the divers, or thrown on to reef. Ten paua were allocated to each of the seven damage categories and three handling categories. The returned paua were observed continuously by divers for the first 5 minutes, then checked again after 30 and 60 minutes. Any deaths were recorded along with whether the paua were actively attempting to right themselves, and the numbers and behaviour of any predators.

2.4 Microbiology

Two paua from the deep foot cut (FC2) treatment were checked for abnormal bacterial infections after they had died. The area around the wound was swabbed with a sterile swab and 10^{-4} and 10^{-6} dilutions were made on the deep tissue after surface sterilising. Dilutions of 10^{-4}, 10^{-6}, and 10^{-8} of the swab material were plated on marine agar.

The bacterial growth from the wound site was compared to that found from foot swabs taken from the same animal away from the wound site.

While dissecting the paua it was noticed that there was a severe brown discoloration of the apex of the gonad and gut. Histological sections were taken along with photographs, and a fungus was isolated.

2.5 Statistical methods

Exact 95% confidence intervals are given for proportions, determined from the F-distribution, i.e., for a proportion π, where $\pi = r/n$, and r = the observed number out of the total, n, then the 95% confidence interval is determined by:

$$\pi_{0.025} = \frac{r}{r+(n-r+1)F_{0.025,2n-2r+2,2r}}$$

$$\pi_{0.975} = \frac{r+1}{r+1+(n-r)F^{-1}_{1-0.975,2r+2,2n-2r}}$$

Regression and ANOVA analyses were performed in S-Plus (MathSoft 1997) using standard methods (Cochran 1977).

3. RESULTS

3.1 Long-term mortality

The number of paua allocated to each treatment and the proportion dying within 70 days are shown in Table 1.

The deep foot cut paua (FC2) bled profusely immediately after treatment. After day 3, two of these had died, presumably due to blood loss. From this point on, about one paua per week died in this treatment group. No mortality occurred after day 40.

Table 1: Numbers of paua allocated to treatments, number surviving after 70 days, proportion dying and upper and lower 95% confidence intervals. (FA = foot abrasion, FC1 = light foot cut, FC2 = deep foot cut, MA = mantle abrasion, MC = mantle cut, SD = shell damage).

	Controls	FA	FC1	FC2	MA	MC	SD	Totals
N	24	20	20	20	24	22	20	150
N surviving	24	19	19	12	24	22	20	140
Prop^n dying	0	0.05	0.05	0.40	0	0	0	0.067
Lower 95% ci	0	0.001	0.001	0.191	0	0	0	0.034
Upper 95% ci	0.168	0.025	0.025	0.639	0.142	0.154	0.168	0.119

At day 70, 40% of the deep foot cut (FC2) treatment group had died. Only one paua in each of the light foot cut (FC1) and foot abrasion (FA) treatments died over the course of the experiment. There were no mortalities in any of the remaining treatments.

Figure 1 shows the percent survival for paua in the deep foot cut (FC2) treatment and for all other treatments combined.

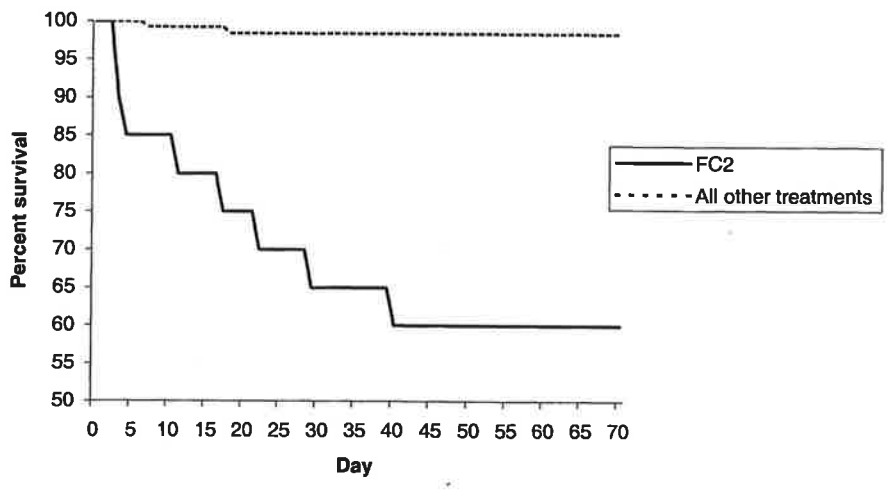

Figure 1: Percent survival for paua in the deep foot cut (FC2) treatment and for all other treatments combined.

3.2 Field observations

Table 2 shows the numbers and proportions of paua examined in the landed catch for the 31 diver-days, along with the numbers and proportions of paua removed from the reef, retained (ie landed), and returned to the sea. From 31 diver-days, 11 205 paua were removed from the reef. Of these, 7051 were landed and 4154 were estimated by interviews with the divers to have been sub-legal and returned to the sea.

Table 2: Numbers and proportions of landed paua used to calculate rates of damage in the sub-legal population. ([a] – reported by divers; [b] – observed; [c] - calculated).

	Removed [a]	Retained [b]	Returned [c]	Examined [b]
N	11 205	7 051	4 154	3 778
Proportion		0.629	0.371	0.536

The numbers and proportions of returned paua in each handling category are shown in Table 3 and in each damage category in Table 4.

Table 3: Numbers and proportions of returned paua in each of the handling categories (results of diver interviews).

Handling category	N	Proportion	Lower 95% ci	Upper 95% ci
Replaced immediately	4 112	0.990	0.986	0.993
Thrown on to reef	42	0.010	0.007	0.014
Returned by diver	0	0	–	–
Thrown on to sand	0	0	–	–
Totals	4 154	1.00		

Table 4: Numbers and proportions of landed paua in each of the damage categories (FA = foot abrasion; FC1 = light foot cut; FC2 = deep foot cut; MA = mantle abrasion; MC = mantle cut; SD = shell damage).

Damage category	N	Proportion	Lower 95% ci	Upper 95% ci
FC1	7	0.001	0.001	0.002
FC2	0	0.000	–	–
MC	6	0.001	0.001	0.002
FA	1 173	0.166	0.158	0.175
MA	978	0.139	0.131	0.147
SD	76	0.011	0.008	0.013
No damage	4 811	0.682	0.671	0.693
Totals	7 051	1.000		

The most common damage types found were foot and mantle abrasions. No deep foot cuts were observed in any of the landed paua. The divers reported that they almost always measure the paua removed from the reef while they are still in the water and return any sub-legals immediately. The paua returned to the boat are measured again and any sub-legals are usually thrown back on to reef.

Estimates of the proportion of sub-legal paua removed from the reef varied from 0.03 to 0.64. Much of this variation can be attributed to the area being fished, with some areas having a higher proportion of paua close to the legal size than others. For example, on the west coast the proportion of legal-sized paua is much higher than in many areas further east. There is, however, a weak but significant relationship between the number of years experience a diver has and the proportion of sub-legals removed from the reef ($p<0.05$, Table 5). No apparent relationship between diver experience and the amount of damage inflicted was found ($p>0.05$, Table 6).

Table 5: Regression analysis of number of sub-legal paua removed from the reef against years of diving experience.

	Value	Std. error	t-value	Pr (>|t|)
Intercept	0.557	0.1181	4.716	0.000
Experience	-0.059	0.0269	-2.213	0.034

Multiple $R^2 = 0.14$

Table 6: Regression analysis of number of damaged paua against years of diving experience.

	Value	Std. Error	t-value	Pr (>|t|)
Intercept	30.404	7.063	4.034	0.001
Experience	1.305	1.606	0.812	0.423
Multiple $R^2 = 0.02$				

3.3 Field experiment

The lengths of the paua used in the field experiment ranged from 113 to 163 mm and there were no significant differences in length between the three treatment groups (ANOVA, $p>0.05$, Table 7).

Table 7: Analysis of variance results on differences in paua lengths used in the field experiment.

	df	Sum of squares	Mean square	F-value	Pr (F)
Length	1	1.82	1.82	0.038	0.84
Residuals	208	9 987	48.01		

Only two paua in the entire experiment died within 1 h following treatment – one which was returned by the diver to reef, and one which was thrown back on to reef. Both of these had been treated with deep foot cuts (Table 8).

Of the paua returned by the divers by hand, all clamped on to the reef immediately, although the deep foot cut paua were noticeably weaker than the others. The substrate was a mixture of large cobbles and flat, coralline-encrusted reef and there was a 1–1.5 m swell running, producing a strong surge at 8 m depth.

Banded wrasse (*Pseudolabrus fucicola*), spotties (*Pseudolabrus celidotus*), one blue cod (*Parapercis colias*), one *Astrostole scabra*, several variable blennies (*Forsterygion varium*), and several brittle stars (*Ophiopecta maculata*) were immediately attracted to the FC2 group, presumably by the blood flowing from the injuries. One of the FA group was attacked by an *A. scabra* but it escaped by rolling over and then moving off rapidly. Three of the SD group were being nibbled at by banded wrasse and variable blennies, but none sustained any major damage. After 1 hour, one of the FC2 group was dead with an *A. scabra* eating it.

Of the paua thrown back on to reef from the boat, all landed on their shell but most had turned on to their foot within 5 minutes, except for the FC2 group, where 5 out of the 10 turned over within 5 minutes, 2 were attempting to roll, and 3 were lying motionless. These three were all being attacked by blue cod and banded wrasse. One of the SD paua was still on its shell after 5 minutes, and another was being attacked by a cushion star (*Patiriella regularis*) attempting to eat part of the gonad protruding from the damaged shell.

After 30 minutes, four of the FC2 group still hadn't managed to right themselves and one was dead after 1 hour. All the others survived despite the presence of predators.

Of the paua placed on their shells on sand, all were still upside down after 5 minutes. Several attempted to right themselves but when their foot contacted sand, withdrew their foot. Blue cod and spotties were present and were observed nibbling several of the paua. After 30 minutes, several of the paua were still attempting to roll over and two groups of three paua had clamped to each other. One blue cod was observed eating one of the FA paua and one spotty was still nibbling one of the FC1 paua. After 1 hour, one MA paua had managed to right itself and was attempting to move across the sand with two others attached to its shell. Three of the SD paua had clamped to each other right side up, one of the FA paua was upright while three had cushion stars attacking them, and one had several whelks attached. All of the other groups were still upside down and, interestingly, although there were

fish present, none were showing any interest in eating the paua. Whelks (*Austrofusus glans*) were approaching the FC2 group, none of which were trying to right themselves.

After 1 hour, none of the paua placed on sand were dead, but very few were making any attempt to right themselves and the prospects for their survival appeared low.

Table 8: Numbers and proportions of paua dying after 1 hour following treatment in each handling category. (FA, foot abrasion; FC1, light foot cut; FC2, deep foot cut; MA, mantle abrasion; MC, mantle cut; SD, shell damage).

	Handling category						
Damage category	Returned by hand	Placed on to sand	Thrown on to reef	N dead	Prop^n dead	Lower 95% ci	Upper 95% ci
None	0	0	0	0	0	–	–
FC1	0	0	0	0	0	–	–
FC2	1	0	1	2	0.2	0.025	0.556
MC	0	0	0	0	0	–	–
FA	0	0	0	0	0	–	–
MA	0	0	0	0	0	–	–
SD	0	0	0	0	0	–	–
Totals	1	0	1	2	0.2	0.025	0.556

3.4 Microbiology

There was no substantial difference in the type of bacterial infection of the swabs taken from the wound site and from the foot area, indicating that the paua probably did not die from bacterial infection.

The fungus has been identified as *Ascomycotina* sp., this will be the subject of a paper yet to be published as it is the first time this fungus has been isolated and identified in New Zealand.

3.5 Extrapolation of results to the PAU 7 TACC

The observed proportional mortalities from the field and laboratory experiments for each damage and handling category were applied to the estimated proportions from the commercial catch to derive a total incidental mortality for PAU 7.

The PAU 7 TACC for the 2001-02 year was 187 tonnes (Annala et al. 2002). The weight of an individual paua was calculated as $W = 2.592.10^{-5} \times L^{3.32}$, where W = the weight of the paua (g), and L = its length (mm) (Schiel & Breen 1991). By using the length frequencies observed from shed measuring data for the 2001–02 fishing year (unpublished data held at NIWA, Greta Point), the average weight of a paua was calculated and from that, the total number of paua in the TACC was derived. The total number of paua discarded annually was calculated from the reported proportion of the catch returned (see Table 2) multiplied by the number of paua in the TACC (Table 9).

Table 9: Estimates of the total number of paua landed and discarded for the PAU 7 commercial catch.

Number of paua landed annually	694 935	Calculated from TACC, known length-weight relationship, and sizes of paua in landed catch
Number of paua discarded annually	252 424	Calculated from reported proportion of catch returned (Table 2) * 694 935

The short-term mortality estimates were then calculated from the results of the Field experiment (Table 8) multiplied by the proportions of the field observations (Table 4) multiplied by the number of

paua discarded annually (Table 9). Because the only paua which died in the short-term were from the deep foot cut group (FC2) and no paua in the observed commercial catch had deep foot cuts, there was no short-term mortality.

Long-term mortality estimates were calculated from the proportion of paua dying in the lab experiment and the observed proportions of paua in each of the damage categories from the field observations multiplied by the number of paua discarded annually (Table 10).

Table 10: Estimates of the long-term mortality for the PAU 7 commercial catch with their associated lower and upper 95% confidence intervals.

Damage category	Prop$^{n.}$ dead (Table 1)	Prop$^{n.}$ observed (Table 4)	N dead	Lower 95% ci	Upper 95% ci
FC1	0.05	0.001	12.6	12.0	13.2
FC2	0.40	0.000	0		
MC	0.00	0.001	0		
FA	0.05	0.166	2100.2	1997.4	2202.9
MA	0.00	0.139	0		
SD	0.00	0.011	0		
Total mortality			2113	1839	2387

The total incidental mortality and the incidental mortality rate for the commercial catch in PAU 7 are shown in Table 11.

Table 11: Estimates of the total incidental mortality for the PAU 7 commercial catch. (* - calculated as total incidental mortality / N paua landed annually * 1000).

Mortality source	N	Lower 95% ci	Upper 95% ci
Short-term mortality	0		
Long-term mortality	2 113		
Total incidental mortality	2 113	1839	2387
Death rate per 1000 paua landed *	3.04	2.6	3.4

3.5 Recreational fisheries

The total catch from recreational paua fishing in PAU 7 is estimated at between 2 and 7 t (Teirney et al. 1997, Bradford 1998). Observing these catches was again difficult for the same reasons outlined earlier but, assuming that the amount of damage caused to paua is at least the same as that in the commercial sector and that the proportion of the catch returned is the same, then an incidental mortality rate of 3 per 1000 paua landed would represent the lower limit. Seven tonnes of paua translates to about 26 000 paua giving an additional 80 paua dying incidentally.

3.6 Maori customary fisheries

Although there is an important customary use of paua by Maori, there are currently no estimates of catch available.

4. DISCUSSION

Given the injuries inflicted on the FC2 treatment paua, their relatively low mortality rate in the laboratory experiment was surprising. Although paua are regarded as having no effective clotting mechanism in their blood, it is clear that they are able to suppress blood loss, presumably by muscular

contraction of the tissue surrounding the wound site. Following wound closure, a series of cellular events occurs leading to the removal of damaged tissue and the formation of new muscle tissue and vascularisation (Taylor 1993).

In addition to the loss of undersize paua, damage to legal-sized animals may also affect the worth of the harvest. Taylor et al. (1994) reported that 51% of the tissue weight of a paua (less the shell) is blood; loss of significant volumes of blood may increase the numbers of paua per landed tonne. Pirker (1992) reported that as much as 54% of paua removed from the substratum in PAU 3 may be undersized. Of these paua, he estimated up to 13% were probably damaged in some way, and up to 80% of these may have fallen victim to predation by fish or starfish following their return to the reef. Taylor et al. (1994) reported that 14% of paua removed from a reef by commercial divers were undersized and were returned to the reef, but provided no details of the method used to make this estimate or where it was made.

The lack of short-term mortality in the field experiment was also surprising in that, although there were plenty of predators present, only two paua were lost within an hour, both from the deep foot cut treatment. Although none of the paua placed on sand died within an hour, it is doubtful that they would survive the attentions of starfish and whelks before being able to move on to reef.

Our estimates of incidental mortality associated with fishing in PAU 7 may be unrealistically low, as they rely upon several assumptions that are difficult to test. Handling by the sub-sample of fishers interviewed, for example, may not be representative of the handling behaviour of fishers in PAU 7. It is also possible that handling behaviour was misreported. In interviews, fishers may not report behaviour they know to be destructive, such as returning undersized fish to sand. Anecdotal evidence suggests that this is true in this instance. The assessment of damage in sheds may also be confounded if fishers do not land paua which are badly damaged and likely to be rejected for processing. Similarly, several sources of mortality were not included in this study, the most important of which was the behaviour of 'deckies' who sort the catch as it is returned by divers. If the catch is handled poorly, for example, violent twisting of paua while separating one from another, then additional mortality may be introduced. As knowledge of these sources of mortality become better understood, they can be included in estimates of total incidental mortality.

The estimated total incidental mortality of 2113 paua in the PAU 7 fishery represents a loss of about 500 kg of paua meat, assuming a shucked paua weighs about 250g. The estimates presented in this report are probably at the lower limit of the true situation. Estimates greater than this amount will be reliant on assumptions made about the behaviour of divers and sorters/handlers on boats.

These caveats aside, the incidental mortality rate in PAU 7 appears to be very low, and there is clear evidence that education within the industry has improved the handling behaviour of divers. If the divers continue to use the recently developed purpose-built knife and return sub-legal paua to the reef as soon as possible, then there appears to be little problem with incidental mortality.

While examining the landed catches from PAU 7 in the paua factory, a catch of about 200 kg was landed from Kaikoura (PAU 3) which had been harvested using hooks, which are still widely used in that area. Of that catch, about 2.5 kg of shucked meat was rejected due to gross damage caused by the hooks and many more had shallow foot cuts, mantle damage, and shell damage. Assuming that damage to the returned paua is in the same proportion as that observed in the landed catch, then this represents an incidental mortality rate of at least 10%, which is likely to have a substantial negative effect on both the paua population and on the value of the fishery.

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